Towards Large-Scale Ion Trap Quantum Computation

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OP Education for Competitiveness
INVESTMENTS IN EDUCATION DEVELOPMENT

Outline

- Computation and Processing
- Qubits
- Ion Traps
- Scaling-up Ion Traps into 2D

Computation/Information Processing

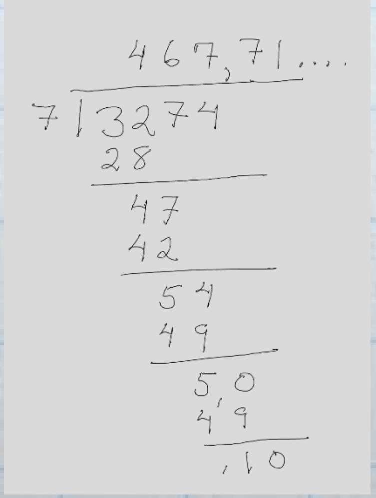
- Encode an idea (number, word, etc) into a physical state

- Encode the manipulation of that idea into a mechanism that works with that physical state

Computational Power

Power = computational rate x *word size*

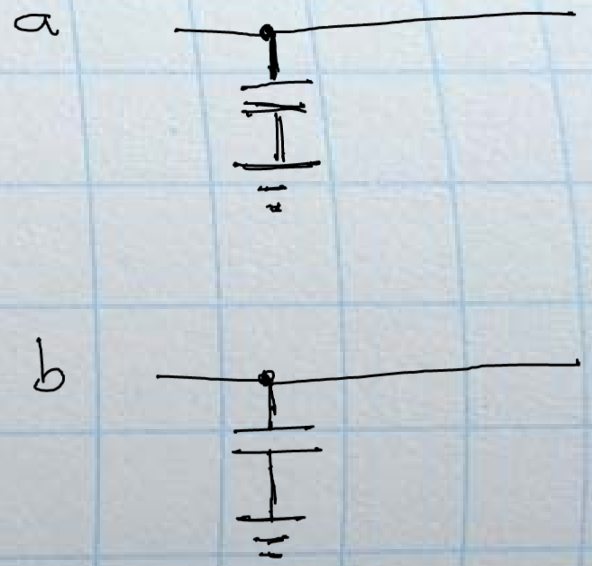
- P_{muir}=12 bit x 0.05 Hz



- Ie. 64 bit computer at 1 GHz is roughly as powerful as a 32 bit computer at 500 MHz or 10^11 times more powerful than P_{muir}

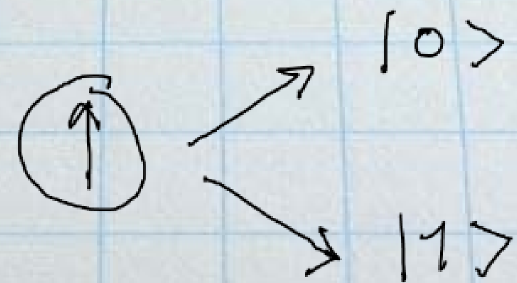
Hilbert Space of Classical Channels

- Each variable is associated with a degree of freedom
- N channels, have N degrees of freedom
- For instance, two capacitors with voltage “a” and “b”



Qubits

Two level quantum system



$$|\Psi\rangle = \alpha|0\rangle + \beta|1\rangle$$

$$\alpha = e^{i\phi} \sin(\theta/2)$$

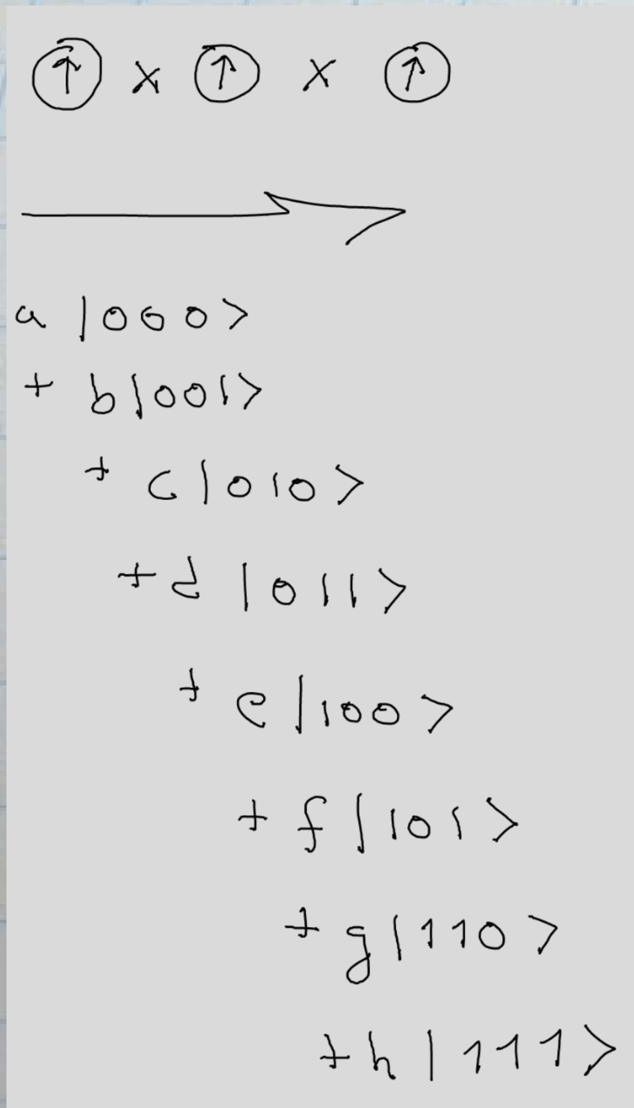
$$\beta = \cos(\theta/2)$$

ie. $\alpha^2 + \beta^2 = 1$

$$e^{i\gamma}|\Psi\rangle \longrightarrow |\Psi\rangle$$

not measurable

Hilbert Space of Multiple Qubits



- *Entanglement* means Hilbert space grows exponentially : 2^(2N)
  - Overall phase is not measureable
  - Normalization

Quantum Computation

- Aims to use the large Hilbert space of multi-bodied quantum systems to perform difficult computations and simulations

- Hilbert space of N q-bits is 2^{2N}-2 degrees of freedom

Exponential Growth

- 1 qubit = 2 degrees of freedom
- 10 qubits = 1048574 degrees of freedom
- 100 qubits = 1.6×10^{60} degrees of freedom

- With 136 qubits, the Hilbert space has more degrees of freedom than the number of atoms in the observable universe (10^{82})

Immediate Applications of Quantum Information Processors

- Direct simulation of quantum many-bodied systems

  Feynman, R. P. Simulating physics with computers. *Int. J. Theor. Phys.* **21,** 467–488 (1982).

- Solving linear systems of equations

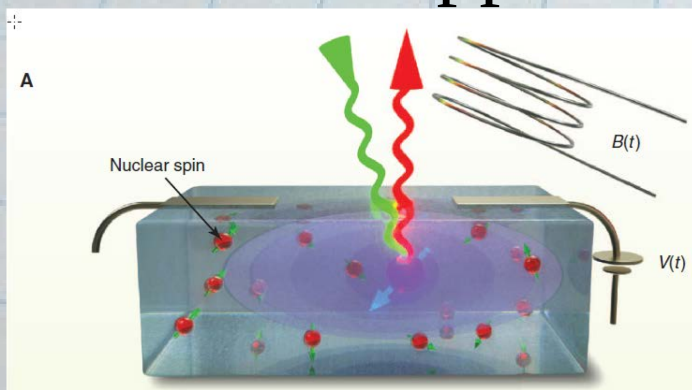
  Harrow, A. W., Hassidim, A. & Lloyd, S. Quantum Algorithm for Linear Systems of Equations. *Phys. Rev. Lett.* **103,** 150502 (2009).

- Number theory and cryptography

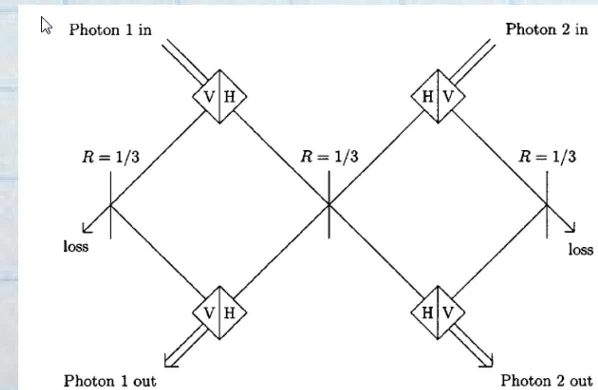
  Shor, P. W. Algorithms for Quantum Computation: Discrete Logarithms and Factoring. in *35th Annu. Symp. Found. Comput. Sci.* 124 (IEEE Computer Society Press, 1994). doi:10.1109/SFCS.1994.365700

Single qubit

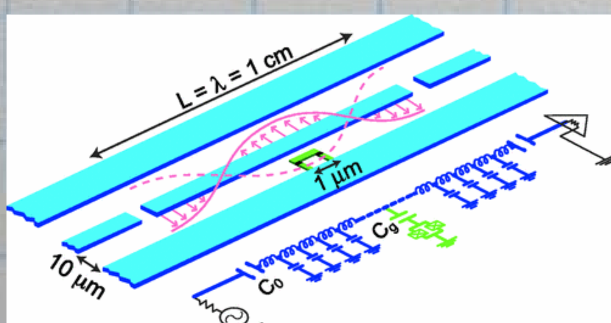
- can be mapped to any 2 level quantum system



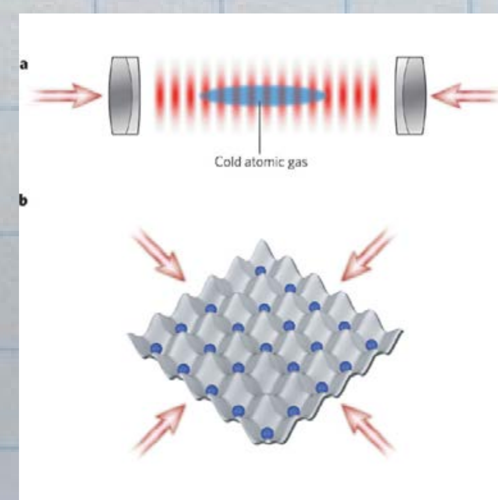
Awschalom, D. D., Bassett, L. C., Dzurak, A. S., Hu, E. L. & Petta, J. R. Quantum spintronics: engineering and manipulating atom-like spins in semiconductors. *Science* **339,** 1174–9 (2013).



Hofmann, H. & Takeuchi, S. Quantum phase gate for photonic qubits using only beam splitters and postselection. *Phys. Rev. A* **66,** 024308 (2002).

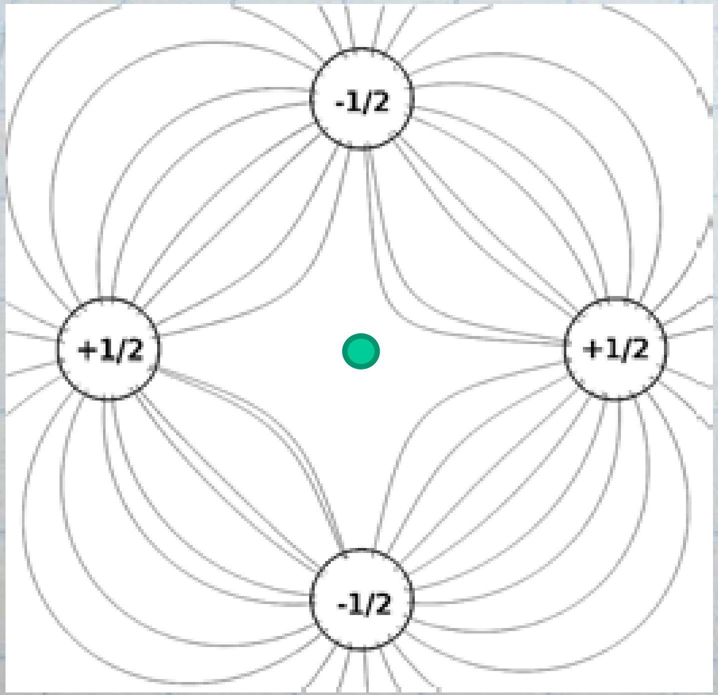


Blais, A., Huang, R.-S., Wallraff, A., Girvin, S. & Schoelkopf, R. Cavity quantum electrodynamics for superconducting electrical circuits: An architecture for quantum computation. *Phys. Rev. A* **69,** 062320 (2004).



Bloch, I. Quantum coherence and entanglement with ultracold atoms in optical lattices. *Nature* **453,** 1016–22 (2008).

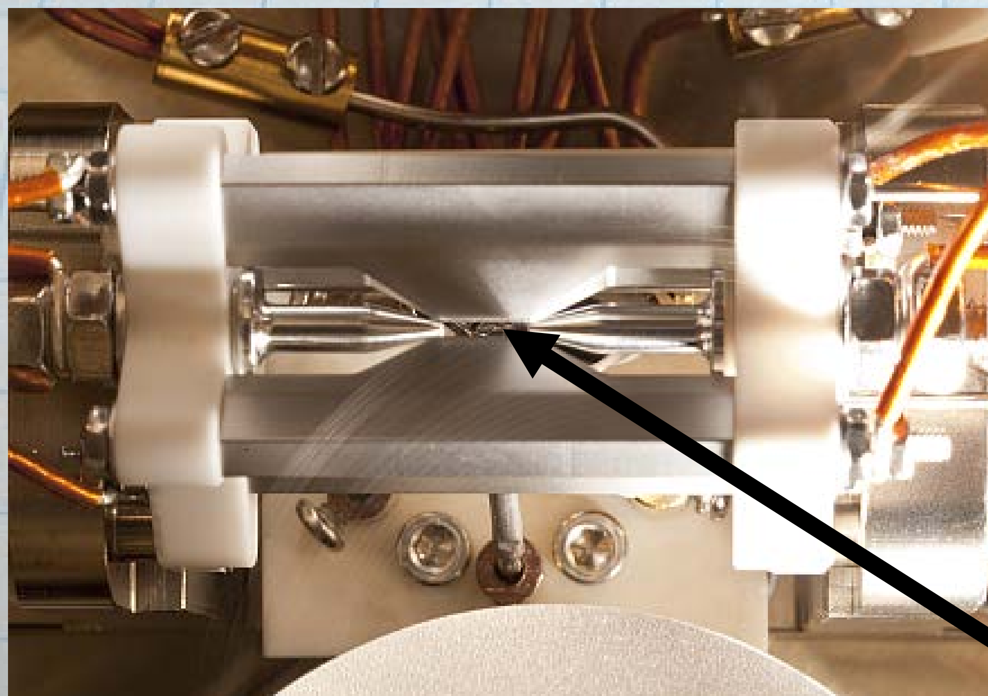
Ion Traps



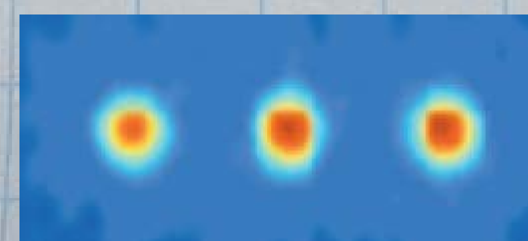
quadrupole field allows for trapping of ion

Steane, A. M. The ion trap quantum information processor. *Appl. Phys. B Lasers Opt.* **642,** 623–642 (1997).

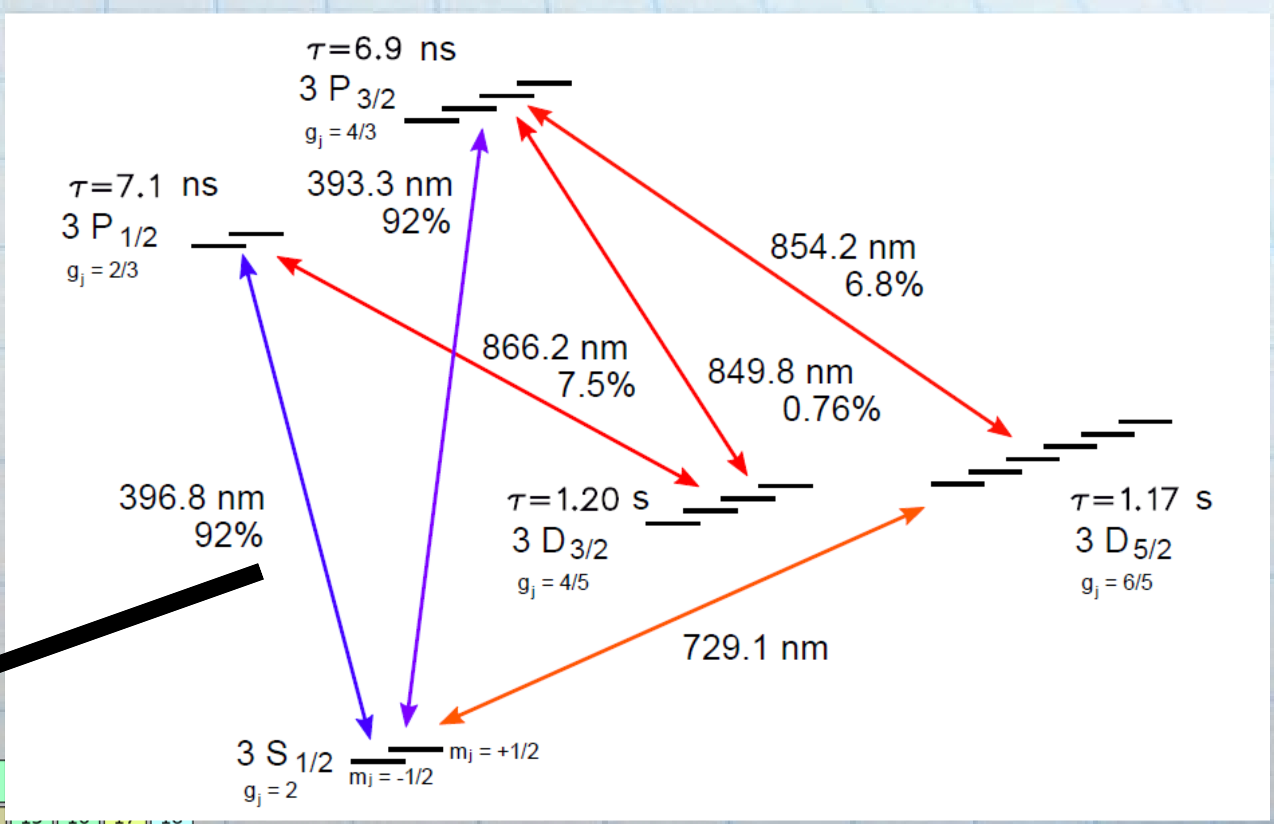
Ion Trap Quantum Computing

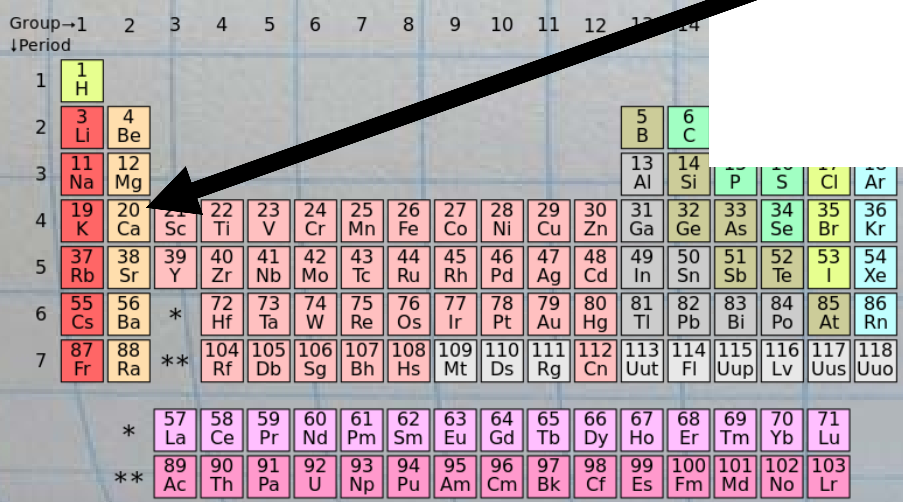


3 Ca ions

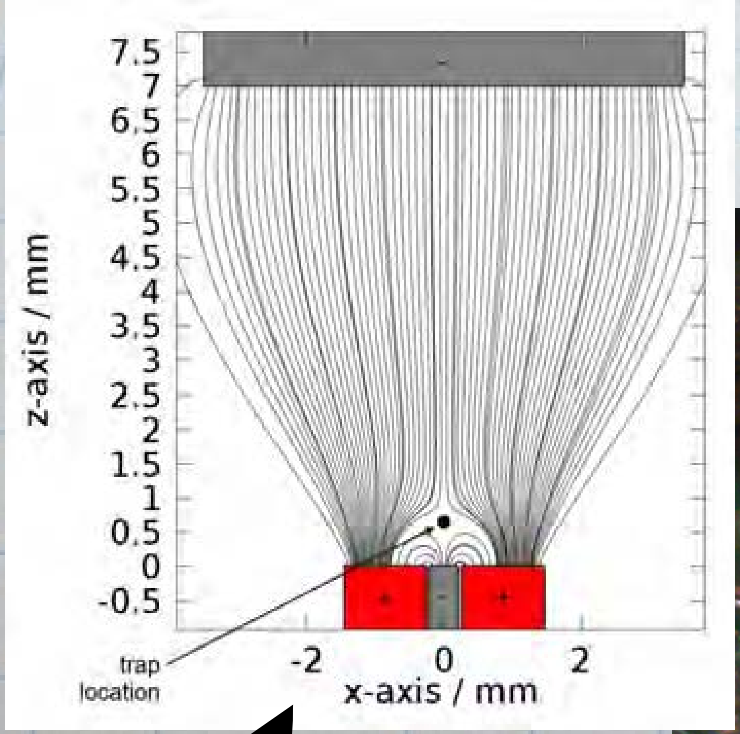


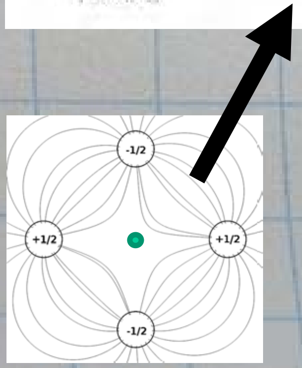
$^{40}Ca^+$ Atomic Structure [Ar] $4s^1$

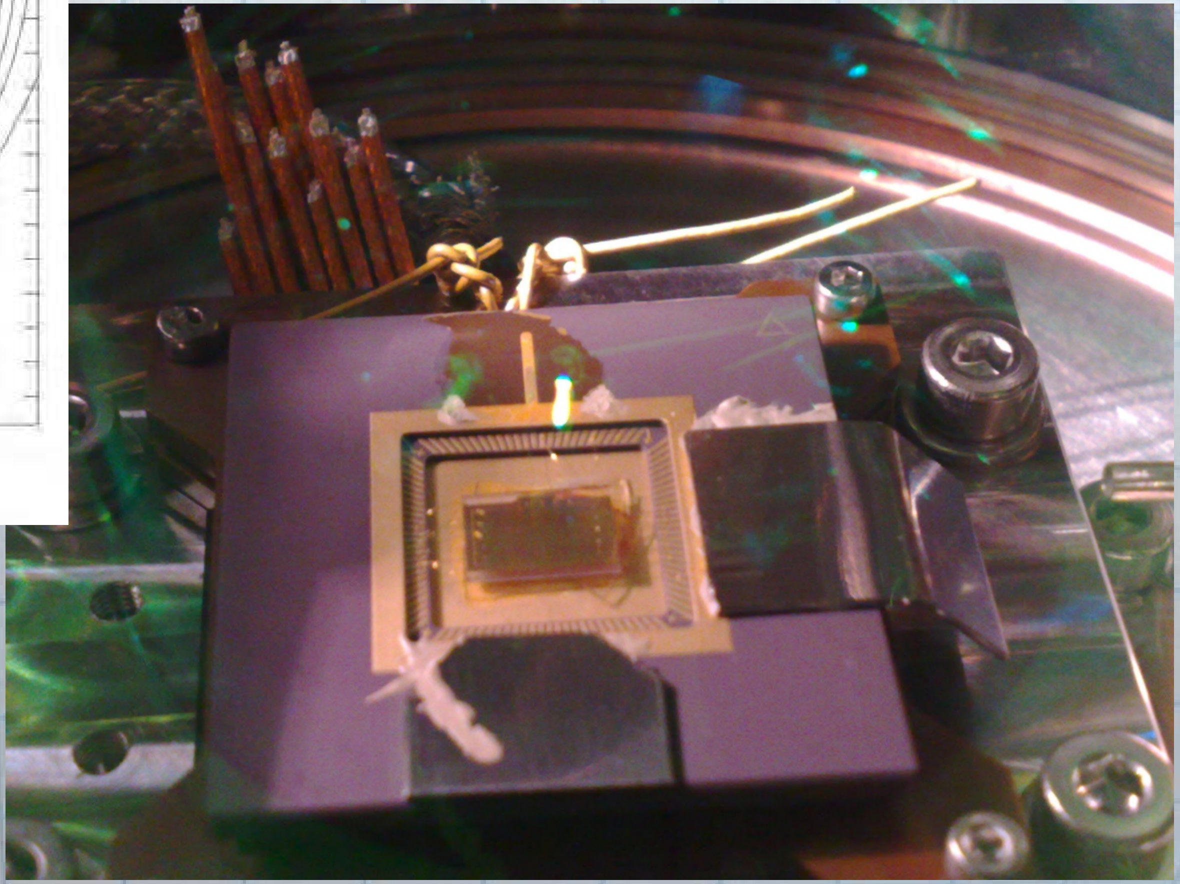




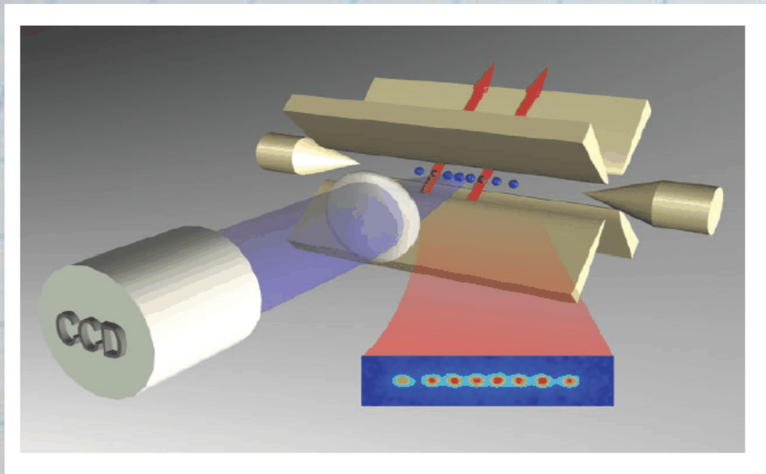
Planar Electrode Ion Traps





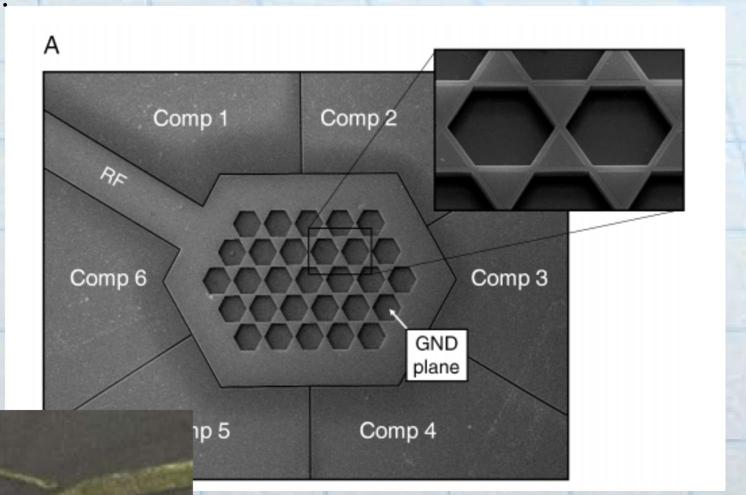


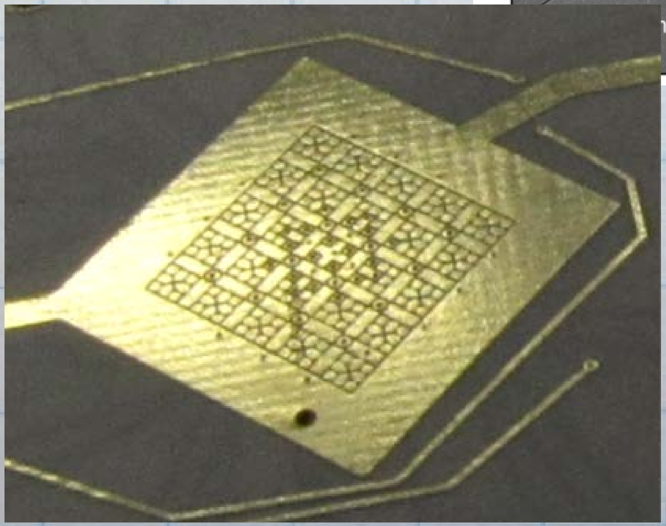
2D Arrays of Ion Traps



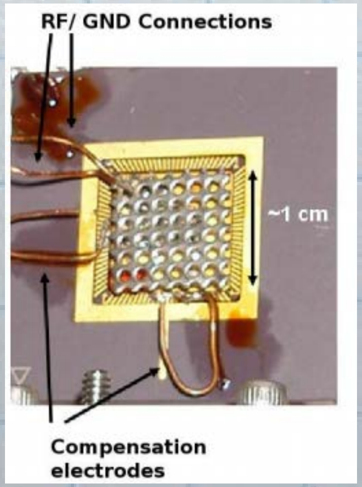
http://heart-c704.uibk.ac.at/

Sterling, R. C. *et al*. Two-dimensional ion trap lattice on a microchip. *Nat. Commun.* **5,** 4637 (2014).



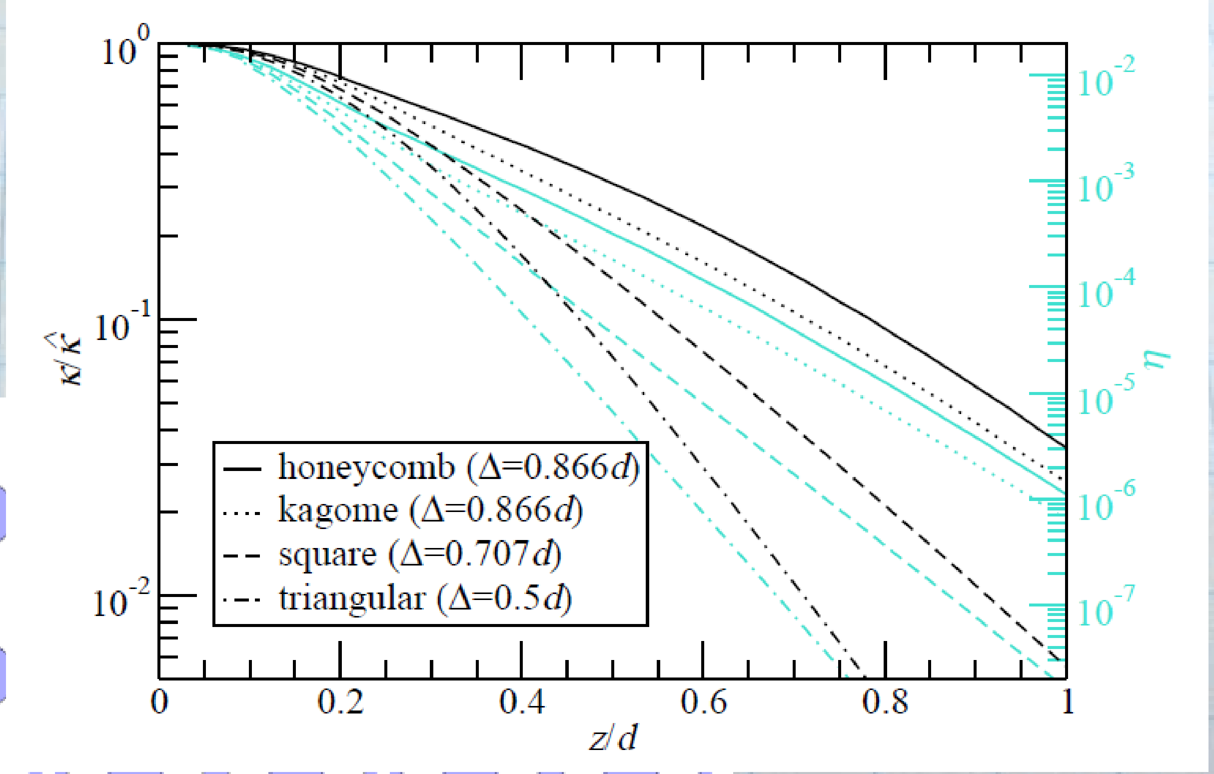


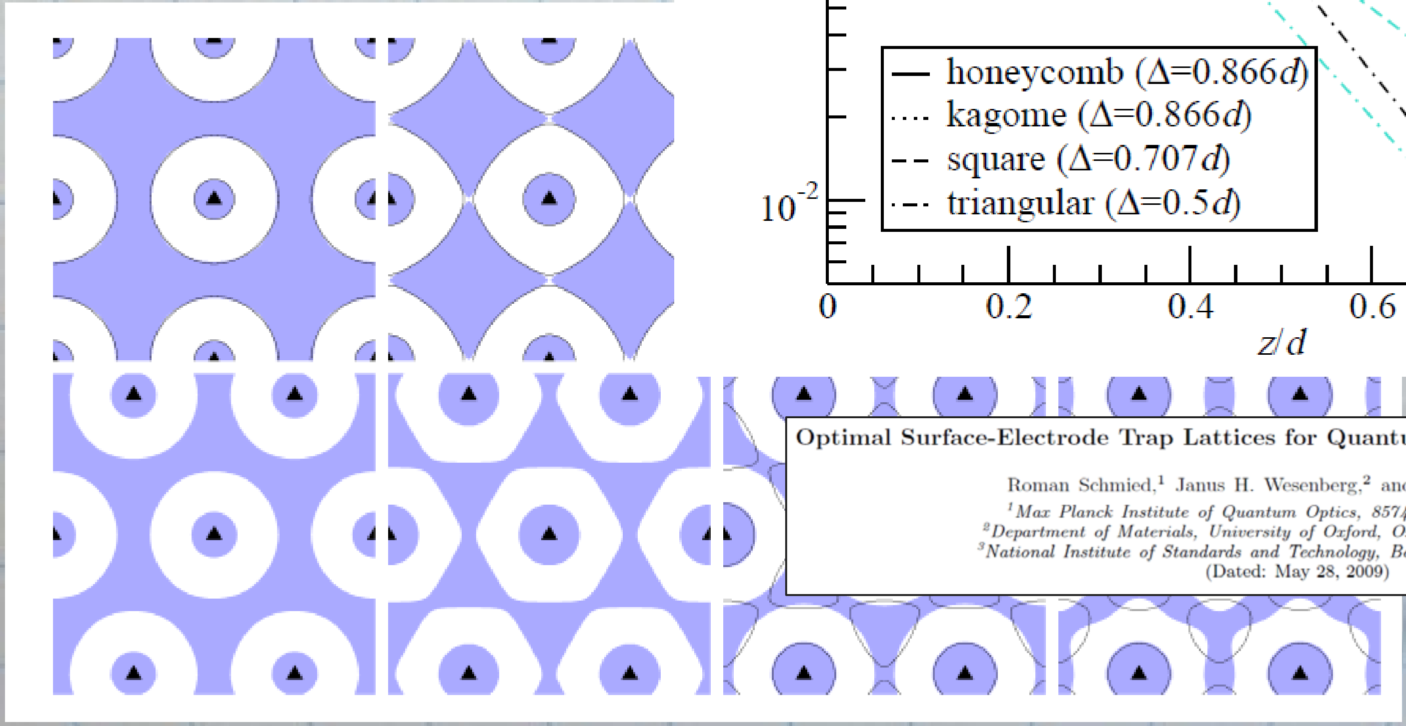
Kumph, M., Brownnutt, M., & Blatt, R. (2011). Two-dimensional arrays of radio-frequency ion traps with addressable interactions. *New Journal of Physics*, *13*(7), {073043}. doi:10.1088/1367-2630/13/7/073043



Clark, R. J., Lin, T., Brown, K. R., & Chuang, I. L. (2009). A two-dimensional lattice ion trap for quantum simulation. *Journal of Applied Physics*, *105*(1), {013114}. doi:10.1063/1.3056227

Optimization of 2D arrays of planar point Paul Traps





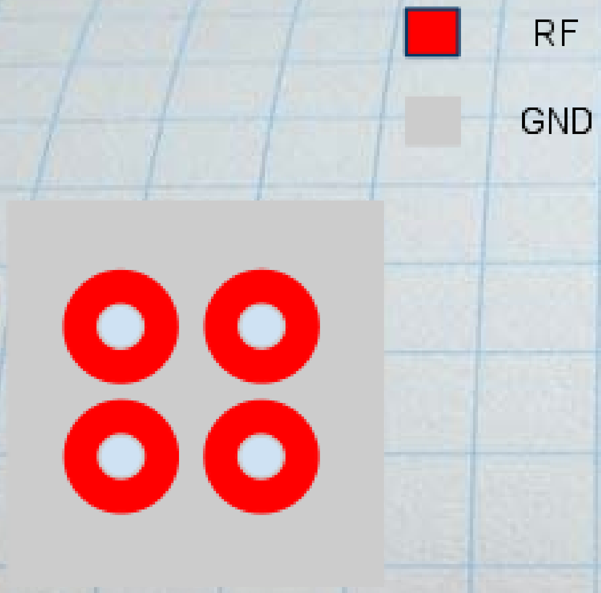
Optimal Surface-Electrode Trap Lattices for Quantum Simulation with Trapped Ions

Roman Schmied,[1] Janus H. Wesenberg,[2] and Dietrich Leibfried[3]

[1]Max Planck Institute of Quantum Optics, 85748 Garching, Germany
[2]Department of Materials, University of Oxford, Oxford OX1 3PH, England
[3]National Institute of Standards and Technology, Boulder, CO 80305, U.S.A.

(Dated: May 28, 2009)

RF address the trap

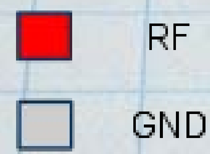


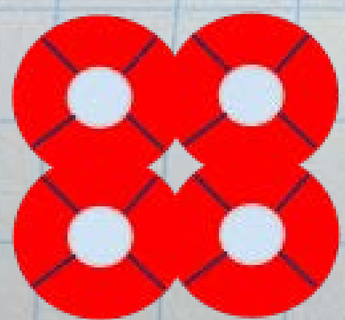
conventional array of ring traps

segment each microtrap

- squeeze the microtraps next to each other
- neighboring RF electrodes become one

neighboring RF electrodes become one

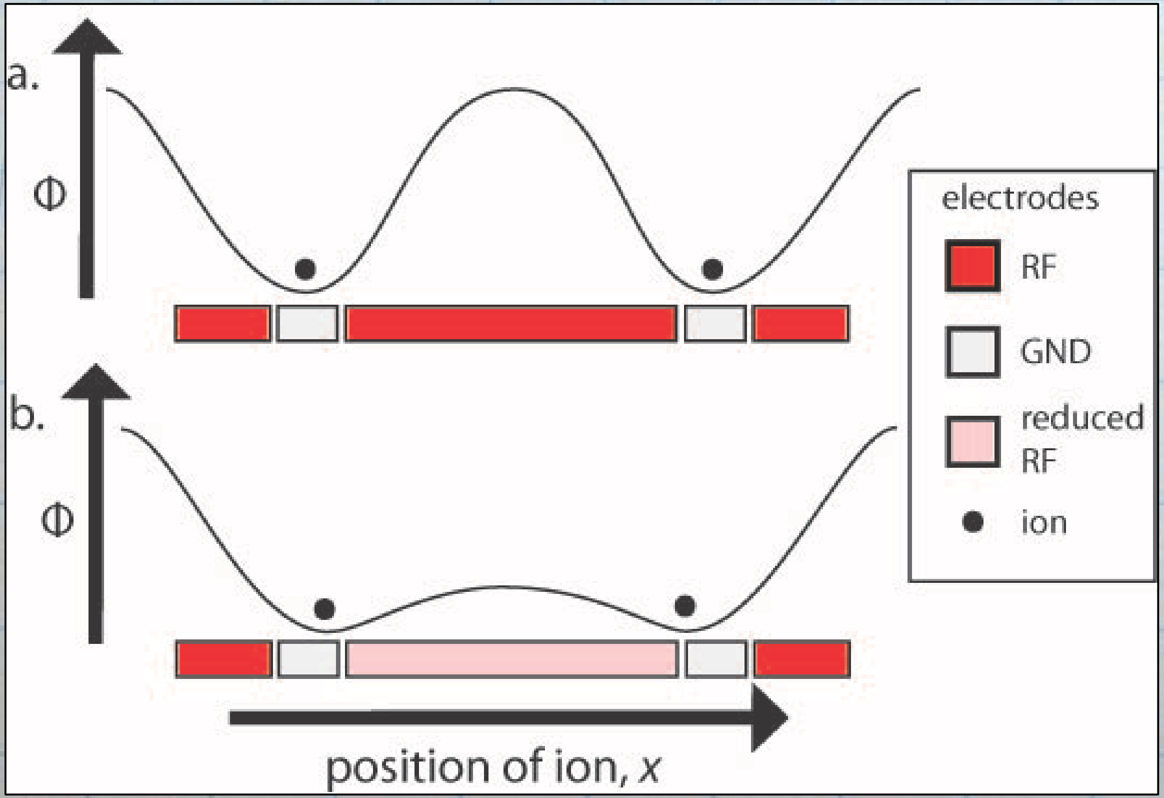


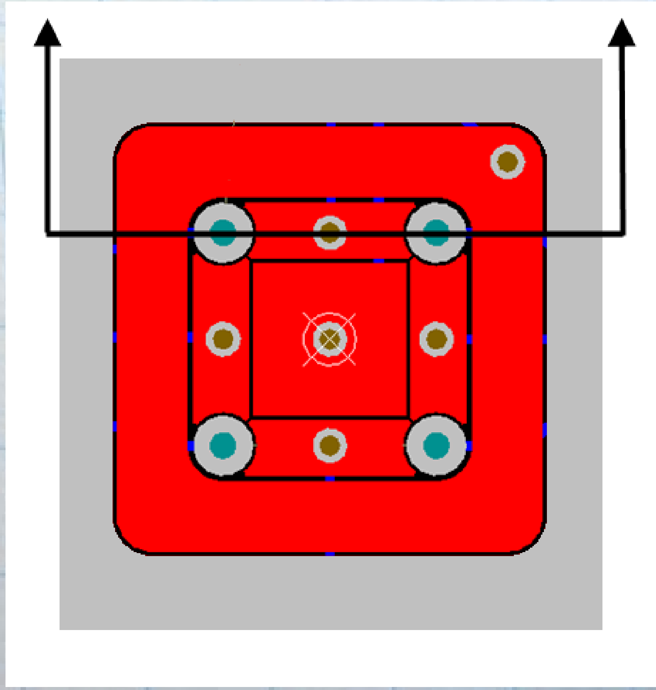


- each ground still holds one RF null and appears as part of a 2D trap array

but now see what happens when we adjust the RF amplitude on the middle electrode

Addressable Ion Traps





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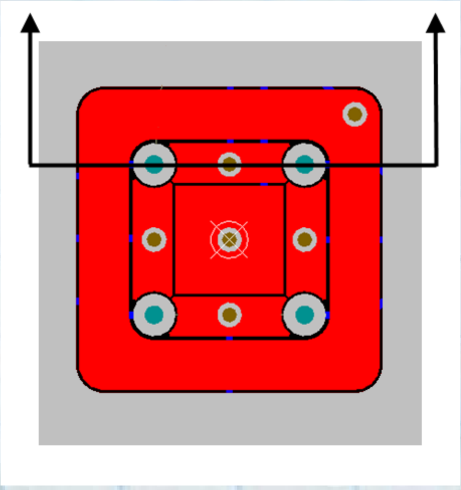
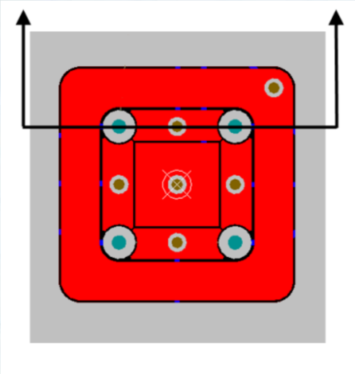
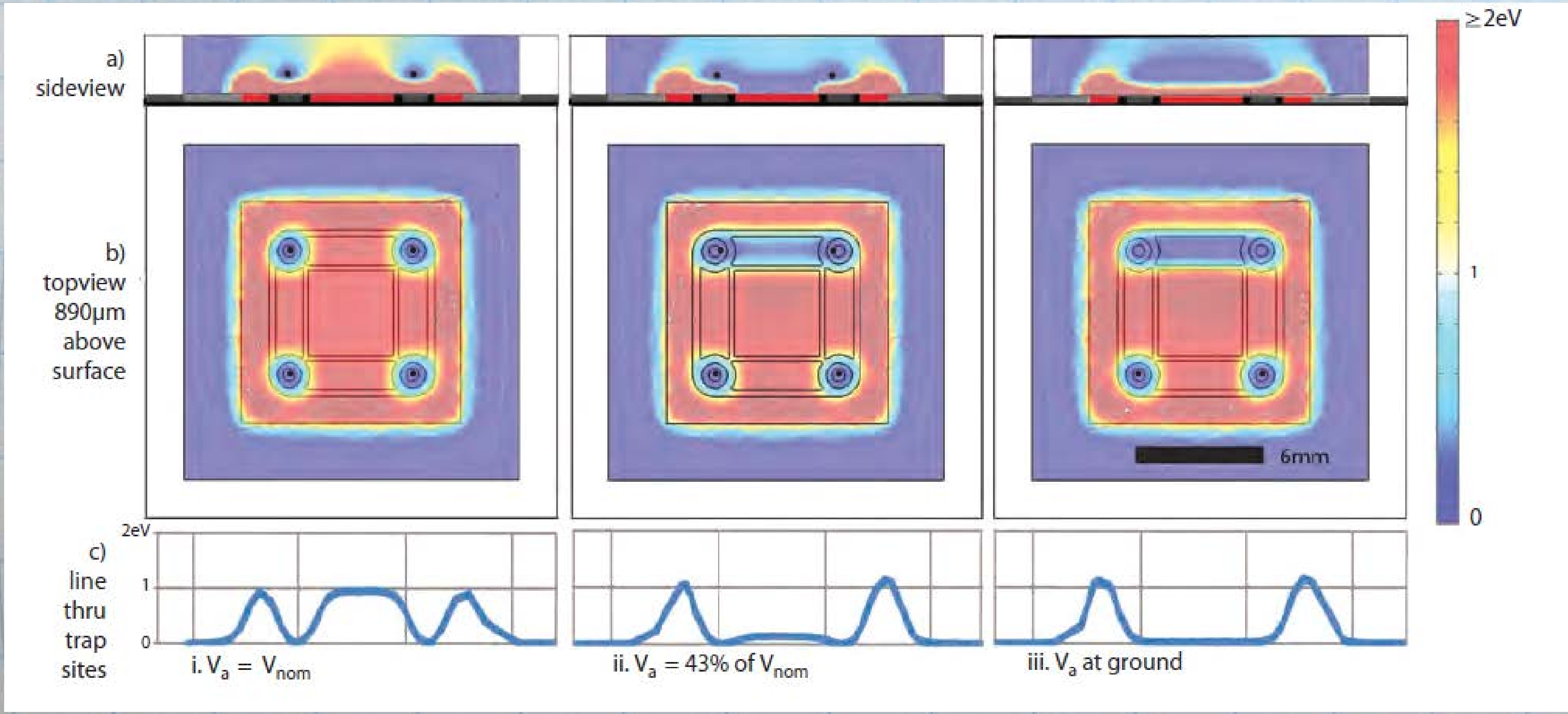
Addressable 2D Arrays



- A possible path to scale up ion traps for large scale computation and simulation
- RF addressing can be used to tune the strength and the frequency of the coupling

Simulation Results
Addressable 2 × 2 array



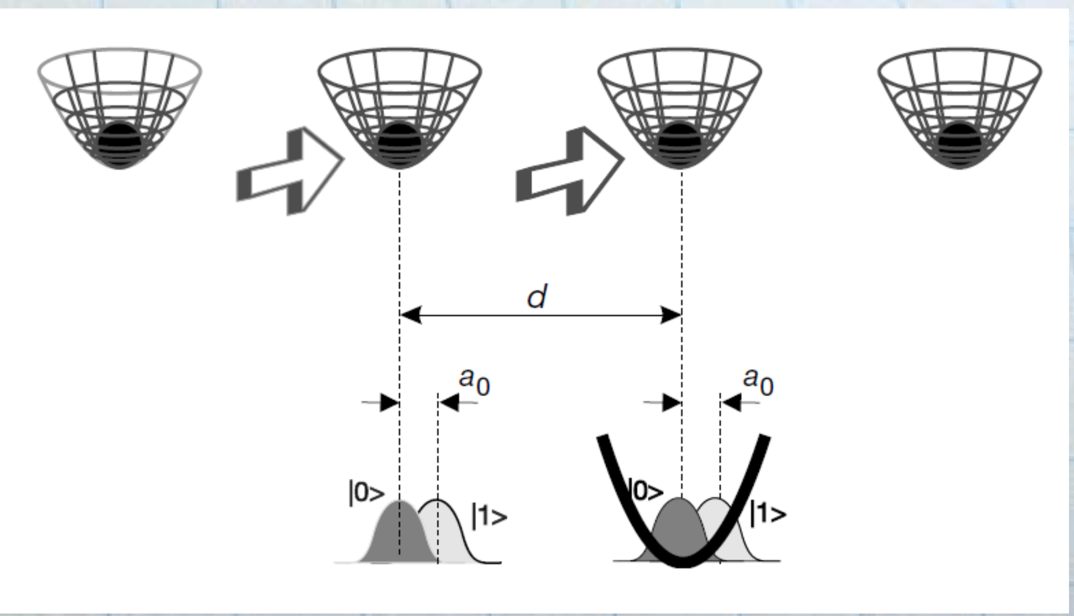


Motional Splitting

- 2 coupled harmonic oscillators can be considered as two independent oscillators with COM and squeeze modes

controlled phase-gate between ions in separate traps

$$T_{gate} = 2\pi\varepsilon_0 m\omega d^3 / e^2$$



Cirac, J. I. & Zoller, P. A scalable quantum computer with ions in an array of microtraps. *Nature* **13,** 579 (2000).

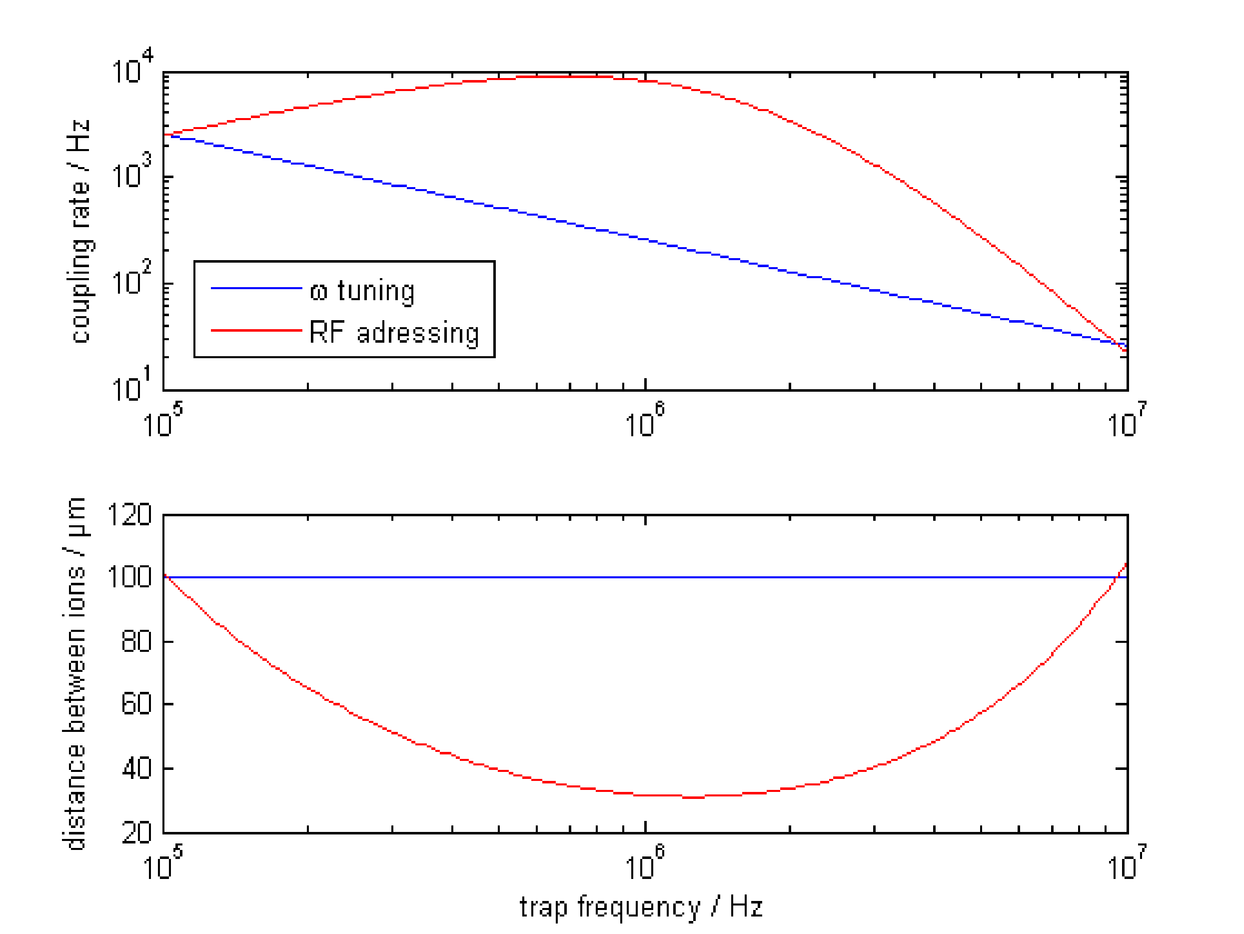
if both ions are displaced,
phase is shifted
|SS> + |DD> → |SS> - |DD>

Dipole-Dipole Coupling Rate with RF Addressing

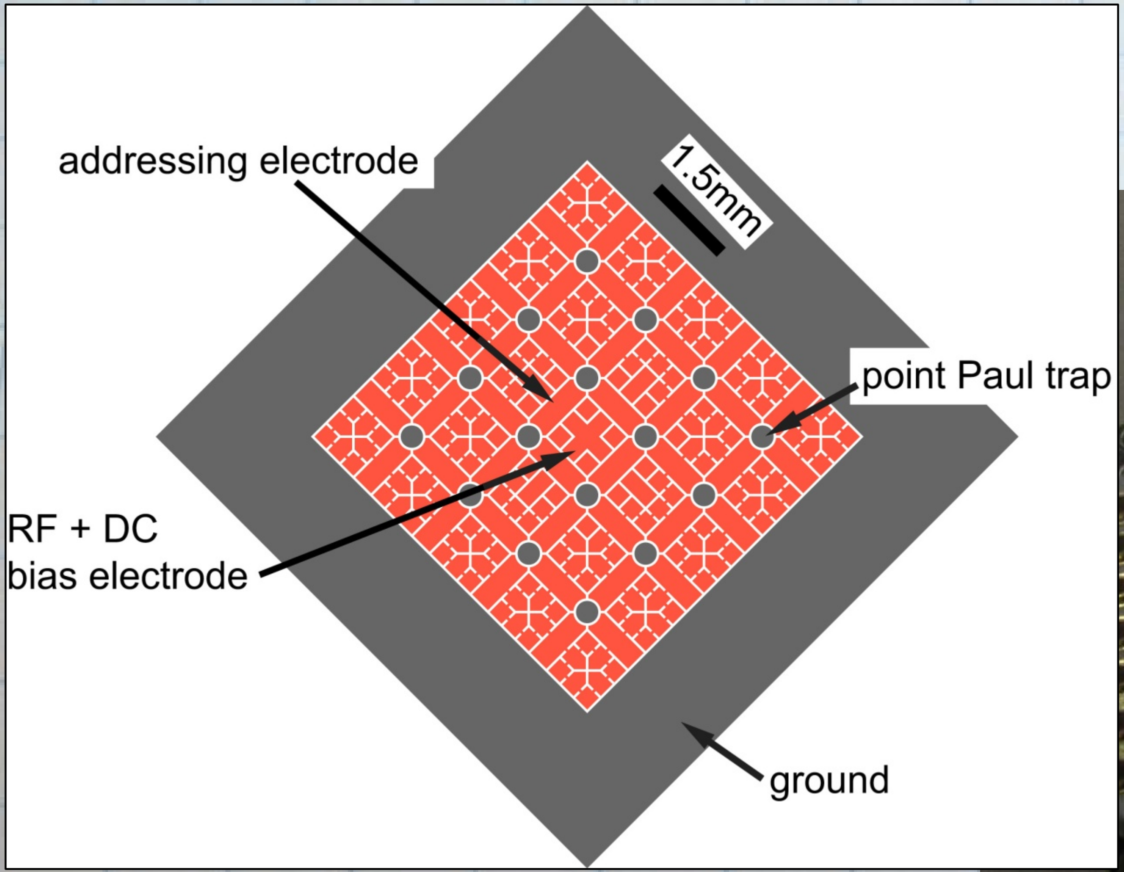
$$\delta\omega = \frac{q^2}{2\pi\epsilon_0 m\omega d^3}$$

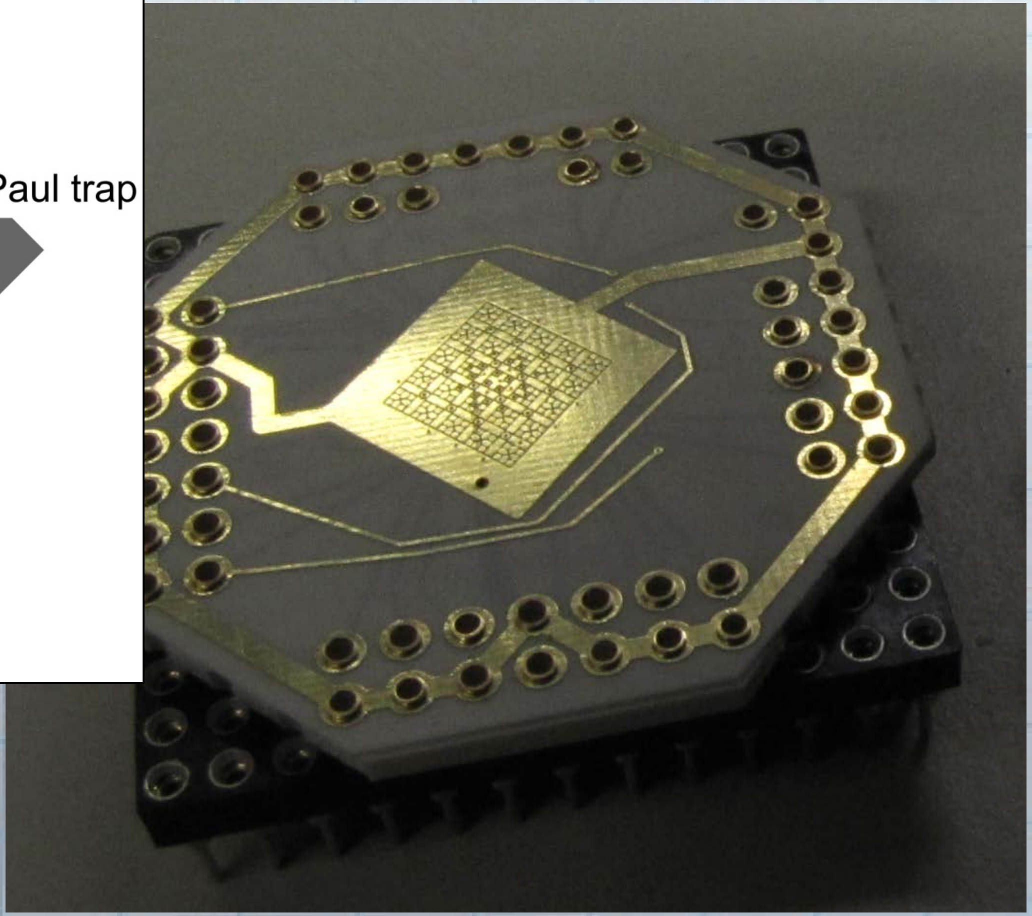
$^{40}Ca^+$ ions

100 µm trap spacing

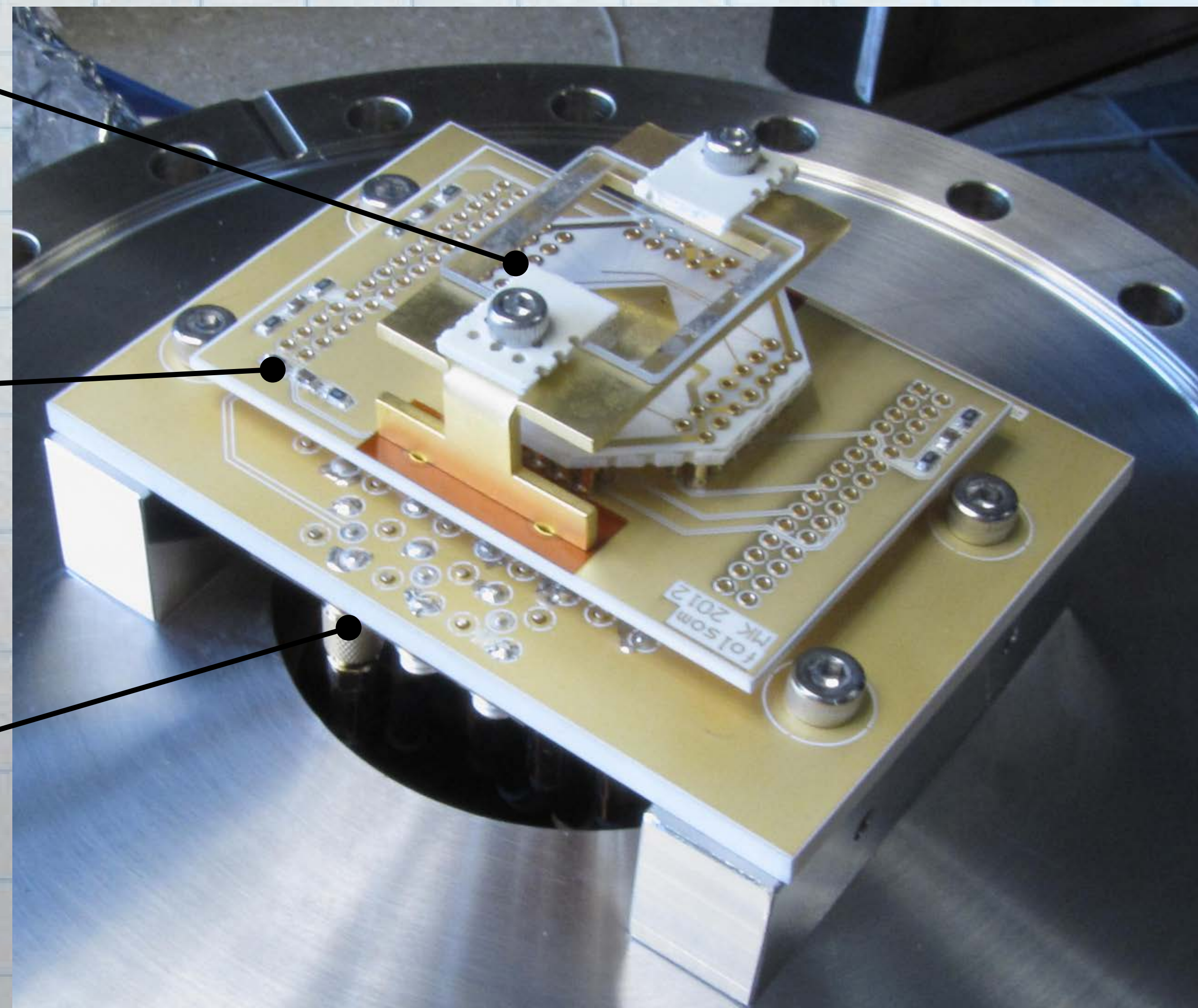


4 × 4 array *Folsom*

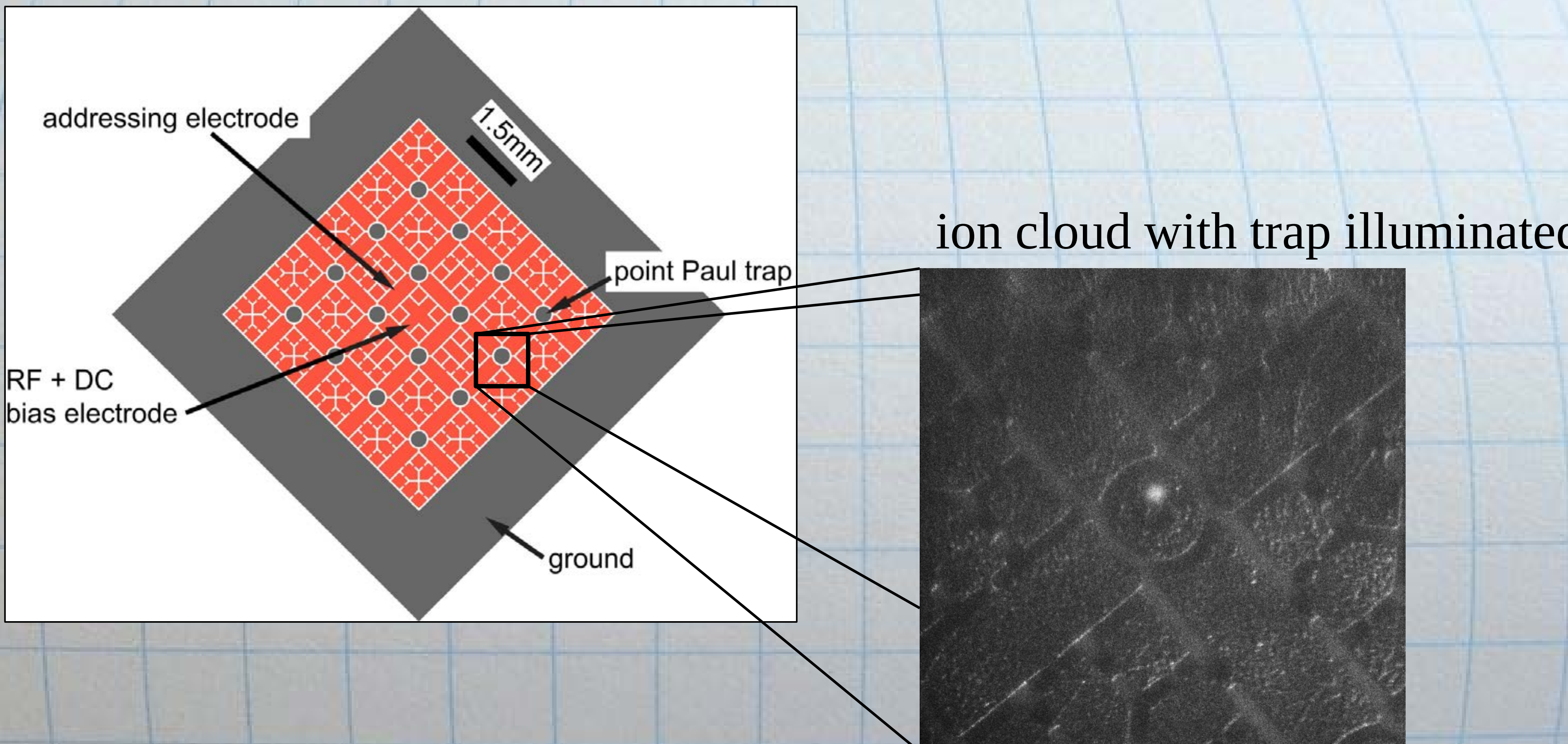




Trap Wiring

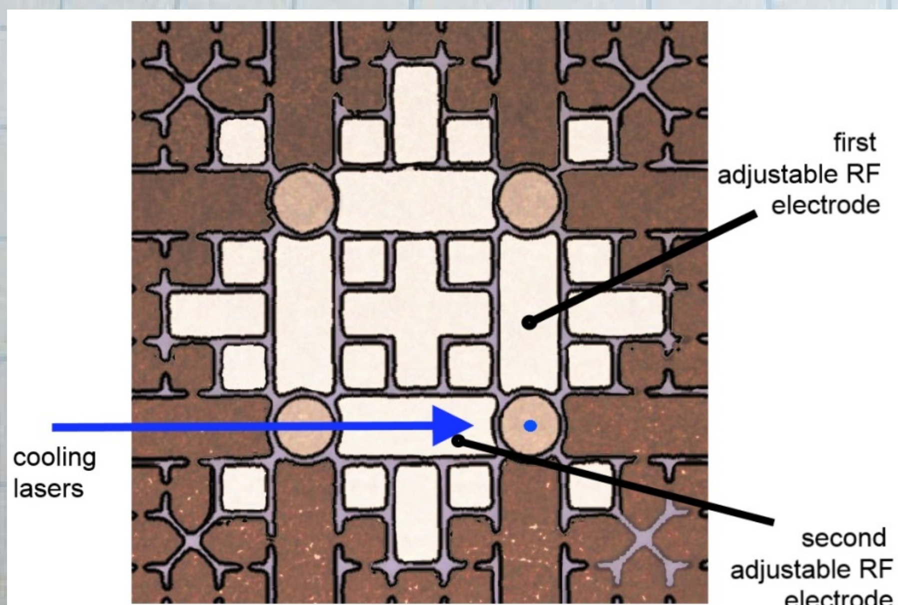


Ion Trapping in Folsom

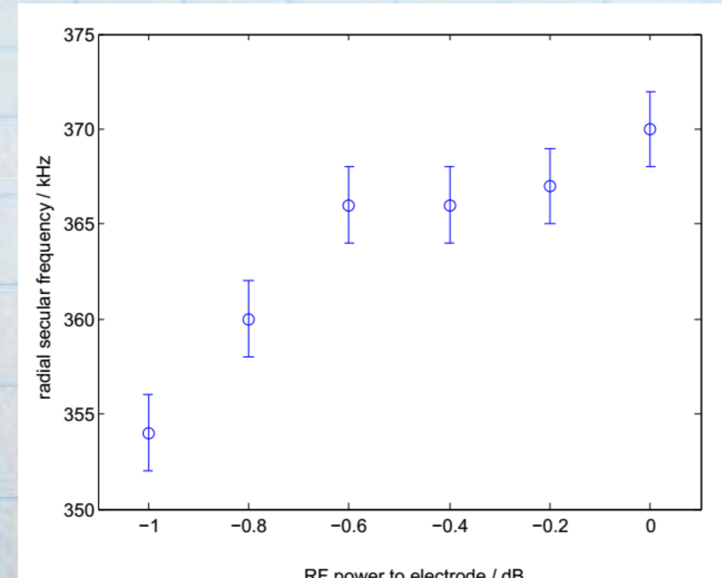


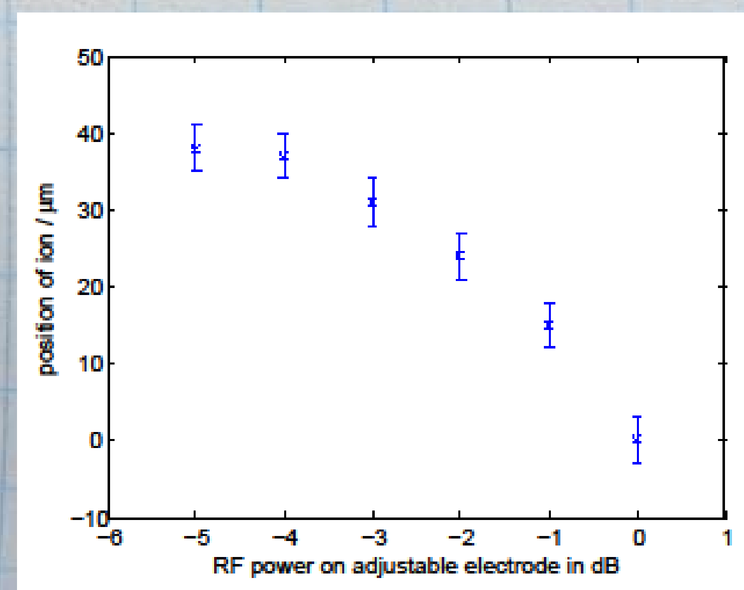
Shuttling and Frequency Tuning

with an adjustable RF electrode

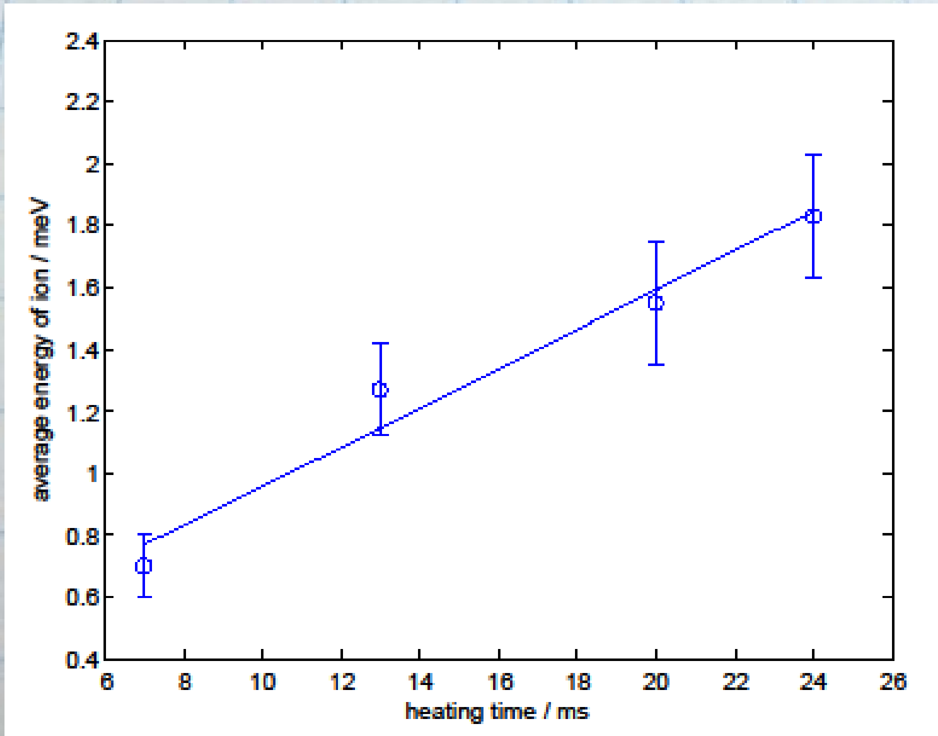


Kumph, M., Holz, P., Langer, K., Niedermayr, M., Brownnutt, M., Blatt, R. (2014). Operation of a planar-electrode ion trap array with adjustable RF electrodes. *ArXiv E-Prints*. quant-ph/1402.0791





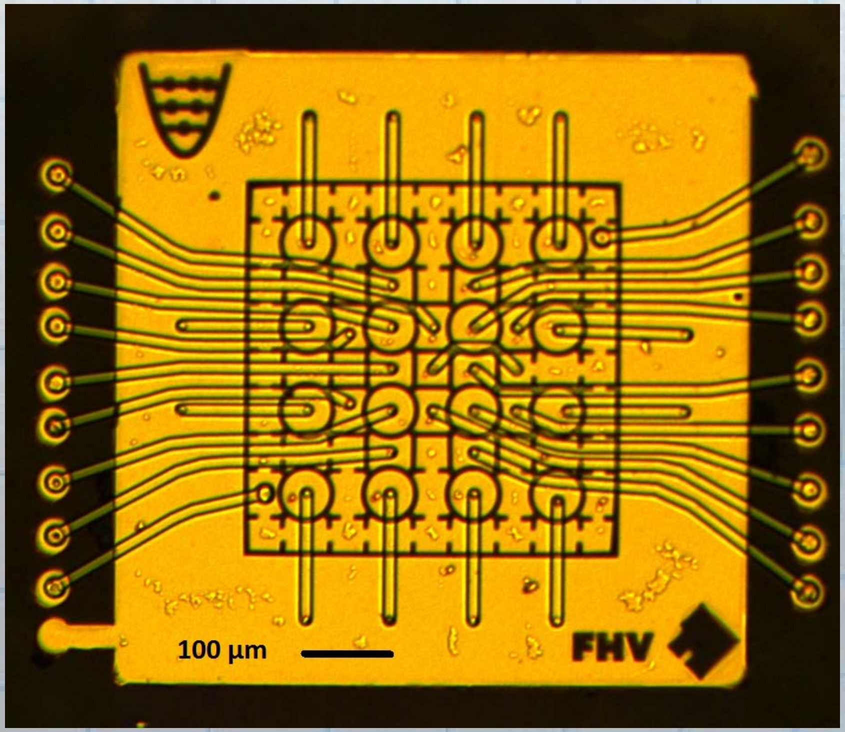
Heating Rate



single ion recooling heating rate measurement

Summary and Future

- Technology to electronically adjust adjust coupling between traps in a 2D array now exists
- Microtrap array “Ziegelstadl“ up-next



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