Brookhaven National Laboratory

U.S. DEPARTMENT OF ENERGY

Coulomb Crystals in Storage Rings for Quantum Information Science

Kevin Brown
Collider-Accelerator Department, Brookhaven National Laboratory
Electrical & Computer Engineering, Stony Brook University

August 9, 2022
NAPAC 2022

@BrookhavenLab

Outline

- Quantum Information Science (QIS)
- Crystalline beams
- Storage Rings for QIS
- Circular Radio-Frequency Quadrupoles
- Challenges
- Entanglement
- Entanglement in Ion traps

Please Join us Thursday morning for the session on "Accelerators for Quantum Technologies" with Alex Romanenko (FNAL) and Salvador Sosa (UNM).

Quantum Information Science

Simulating Physics with Computers

Richard P. Feynman

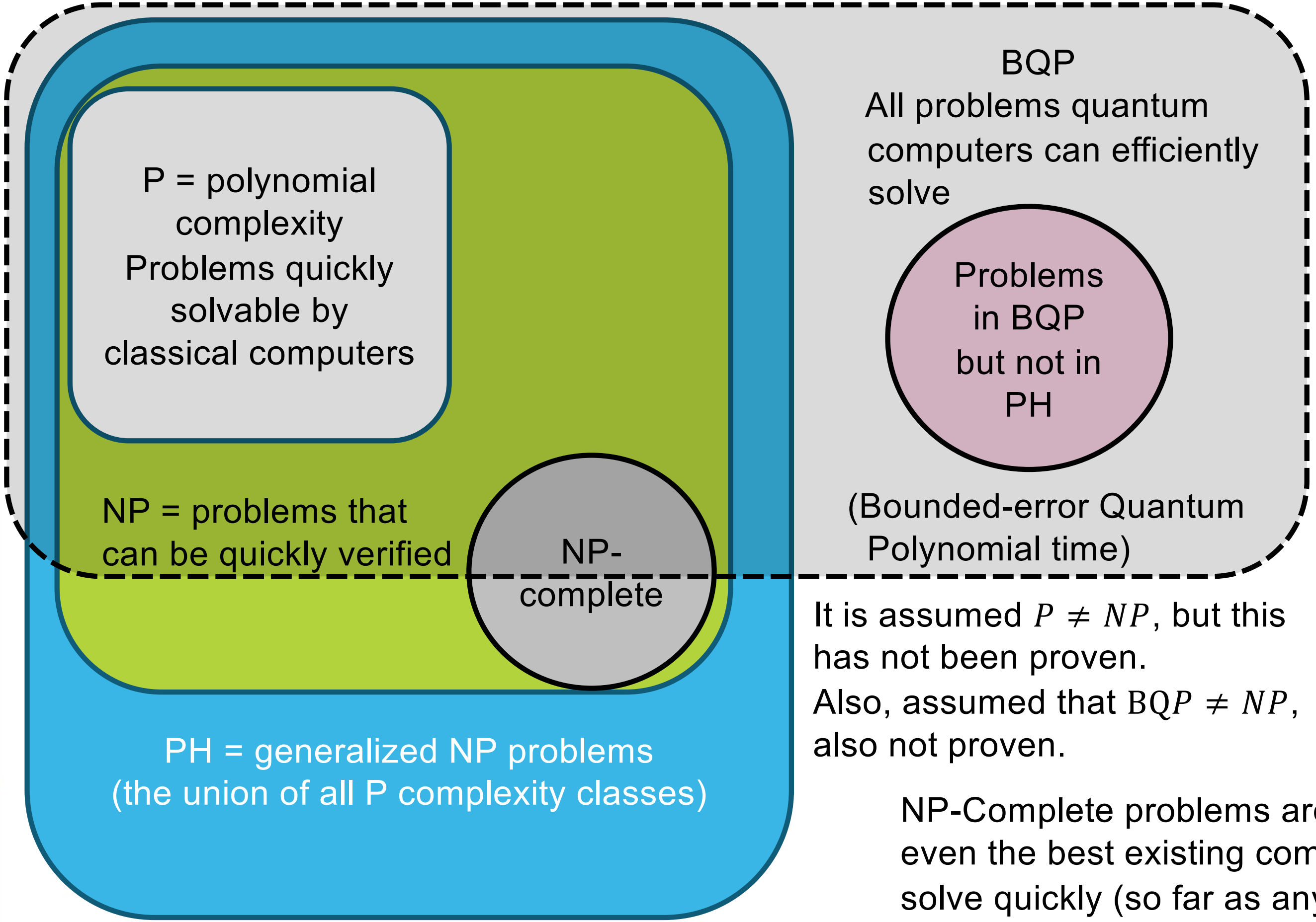
Keynote talk, 1st conference on Physics and Computation, MIT, 1981 (International Journal of Theoretical Physics, 21: 467–488, 1982)

- Can a universal classical computer simulate physics exactly?
- Can a classical computer efficiently simulate quantum mechanics?
- ”I’m not happy with all the analyses that go with just classical theory, because Nature isn’t classical, dammit, and if you want to make a simulation of Nature, you’d better make it quantum mechanical, and by golly it’s a wonderful problem!”

Richard Feynman 1981

The Limits of Quantum

The Limits of Quantum
By Scott Aaronson



P = polynomial complexity
Problems quickly solvable by classical computers

NP = problems that can be quickly verified

NP-complete

PH = generalized NP problems
(the union of all P complexity classes)

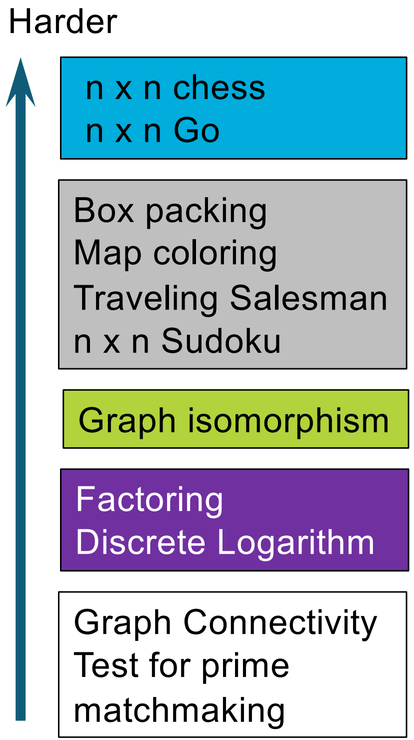
BQP
All problems quantum computers can efficiently solve

Problems in BQP but not in PH

(Bounded-error Quantum Polynomial time)

It is assumed $P \neq NP$, but this has not been proven.
Also, assumed that $\mathrm{BQP} \neq NP$, also not proven.

NP-Complete problems are those which even the best existing computers cannot solve quickly (so far as anyone knows).



Harder

n x n chess
n x n Go

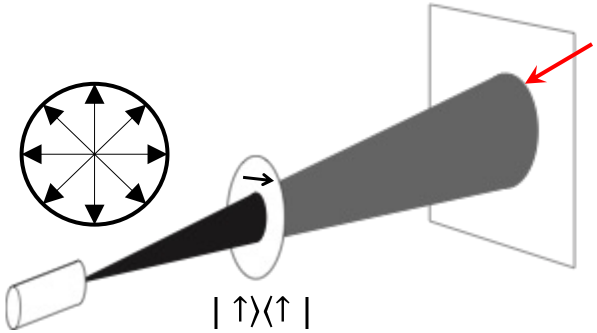
Box packing
Map coloring
Traveling Salesman
n x n Sudoku

Graph isomorphism

Factoring
Discrete Logarithm

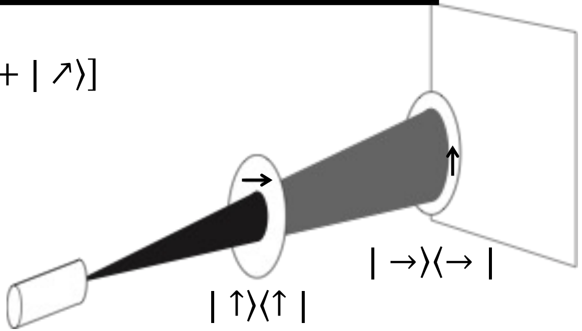
Graph Connectivity
Test for prime
matchmaking

Dirac's Three Polarizers Experiment



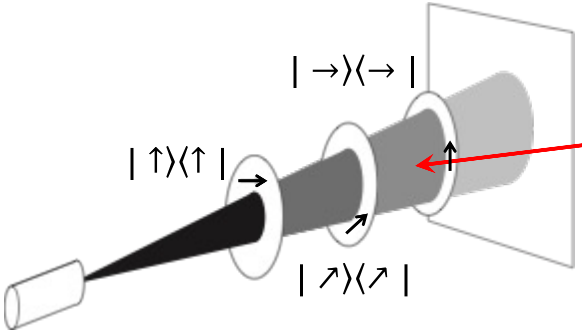
$$|\uparrow\rangle = \frac{1}{\sqrt{2}}[|\nwarrow\rangle + |\nearrow\rangle]$$

Single polaroid attenuates unpolarized light by 50 percent.



Two orthogonal polaroid's block all photons.

A photon has a probability $\sin^2\alpha$ of passing through the polarizer and a probability $\cos^2\alpha$ of being absorbed.



$$|\nearrow\rangle = \frac{1}{\sqrt{2}}[|\uparrow\rangle + |\rightarrow\rangle]$$

Inserting a third polaroid allows photons to pass.

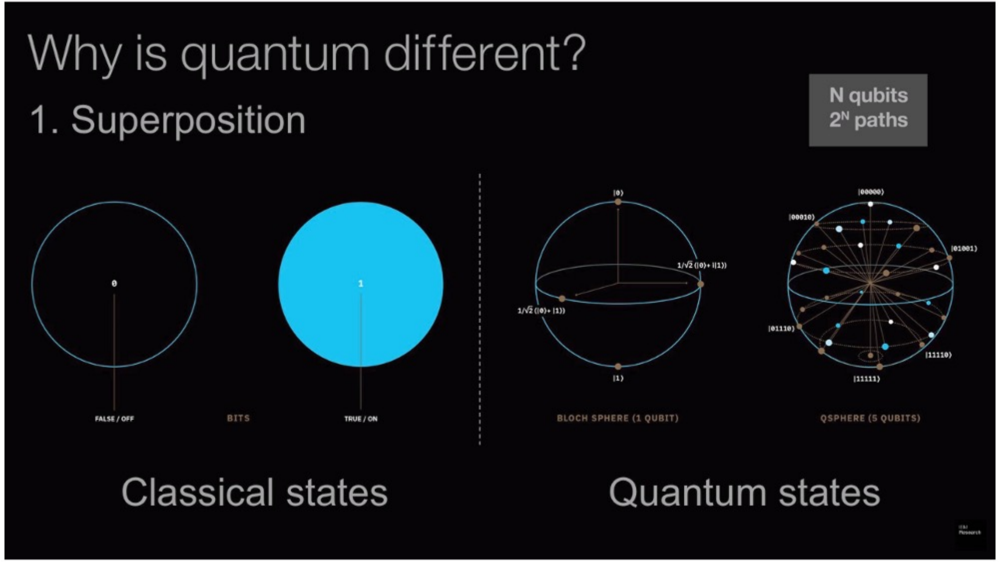
* "… the obvious experiment is to use an incident beam consisting of only a single photon …"
"In this way we preserve the individuality of the photon in all cases. We are able to do this, however, only because we abandon the determinacy of the classical theory."

Diagrams from: QUANTUM COMPUTING A Gentle Introduction
Eleanor Rieffel and Wolfgang Polak
©2011 Massachusetts Institute of Technology

*The Principles of Quantum Mechanics by Paul Dirac first published by Oxford University Press in 1930.

Qubits

A quantum bit is quantum 2-level system.



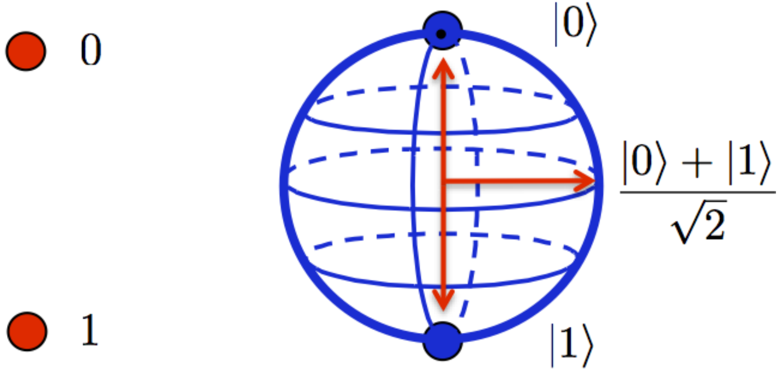
Why is quantum different?

1. Superposition

N qubits
2^N paths

Classical states

Quantum states



Classical Bit **Qubit**

A measurement gives either a 0 or a 1

Between measurements it is in a superposition of both 0 and 1

$$|\varphi\rangle = a|0\rangle + b|1\rangle$$

$$\{a, b\} \in \mathbb{C}$$
$$P(\varphi \longrightarrow 0) = |a^2|$$

https://towardsdatascience.com/the-need-promise-and-reality-of-quantum-computing-4264ce15c6c0

How to make Qubits?

You need a quantum system or something that simulates a quantum system.

1. Quantum systems include
    1. Ions in a trap
    2. Quantum states in quantum materials (chiral magnetic effect)
2. Simulations of quantum systems include
    1. Same as above (since an ion is used to simulate a quantum system)
    2. Superconducting circuits such as Josephson junctions and Squids (transmon's)
    3. Quantum annealing in a quantum material (limited applications, e.g. DWave)
3. Other approaches?
    1. Trapped molecules in crystal lattices (e.g., flaws in diamonds)
    2. Neutral trapped ions
    3. Photonic systems

References:

Christopher R. Monroe and David J. Wineland, *Quantum Computing with Ions*, © 2008 SCIENTIFIC AMERICAN, INC.

D. J. Wineland, et al., *Experimental primer on the trapped ion quantum computer*, Fortschr. Phys. 46, 363 (1998)

C. Monroe et al., *Programmable quantum simulations of spin systems with trapped ions*, Rev. of Mod. Phys., 93, April-June 2021

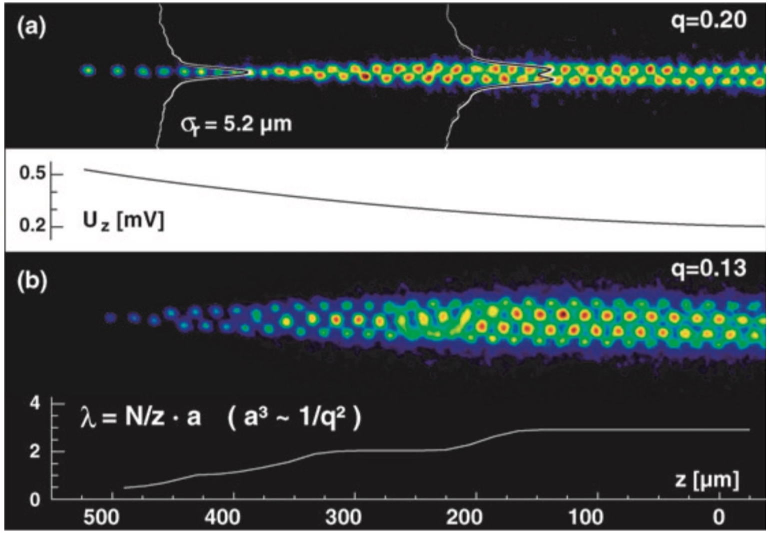
Kharzeev, Dmitri E. and Li, Qiang, *The Chiral Qubit: quantum computing with chiral anomaly*, https://arxiv.org/abs/1903.07133, 2019

A.Antony, et al., *Miniaturizing Transmon Qubits Using van der Waals Materials,* Nano Lett. 2021, 21, 23, 10122–10126

A.Chandra, A. Das, & B. Chakrabarti, eds. (2010). *Quantum Quenching, Annealing and Computation.* Lecture Note in Physics. Vol. 802

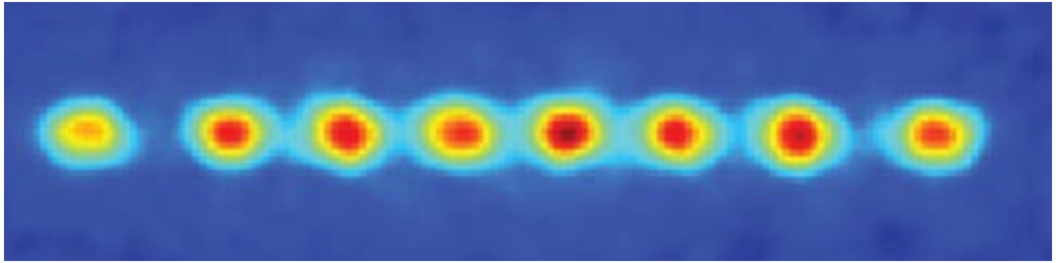
S. Pezzagna and J. Meijera, *Quantum computer based on color centers in diamond*, Applied Physics Reviews 8, 011308 (2021)

Crystalline beams



U Schramm, T Schätz, M Bussmann and D Habs
Plasma Phys. Control. Fusion **44** (2002) B375–B387

Sektion Physik, LMU München,
D-85748 Garching, Germany

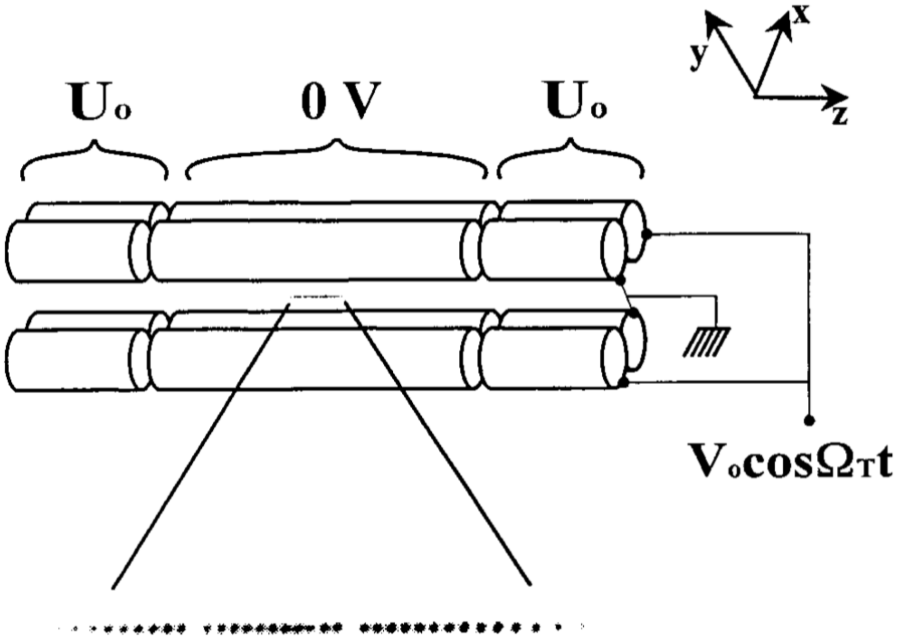


Christopher R. Monroe and David J. Wineland

- By using beam cooling techniques, ion beam temperatures can be reduced to the point that repelling Coulomb forces balance against external forces
- When this happens, a new form of matter is created, a chain of particles locked into a sequence

Storage Rings for QIS

Ion Traps (or Paul Traps)



Earnshaw's theorem
one cannot construct a stable ion trap using electrostatic fields alone

Paul and Dehmelt got around Earnshaw's theorem by using oscillating electric fields, since the theorem strictly applies only to static fields.

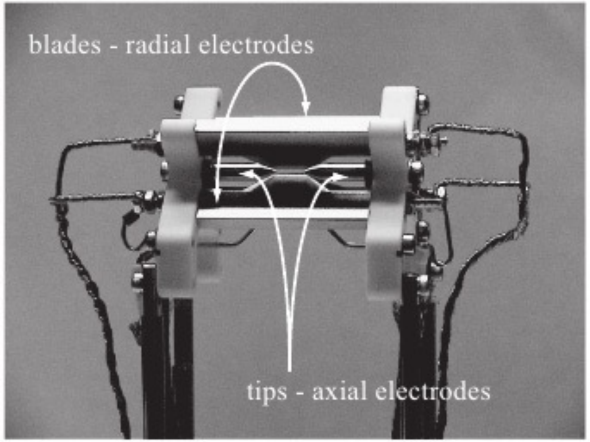
potential $V_0\cos\Omega_T t$ is applied between diagonally opposite rods , fixed in a quadrupole configuration

static potentials U_0 are applied to the end segments

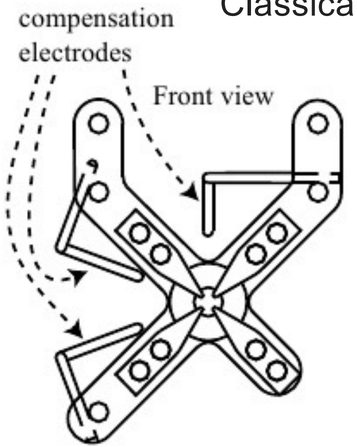
RF frequency must be high enough such that E-field oscillates faster than particles can escape

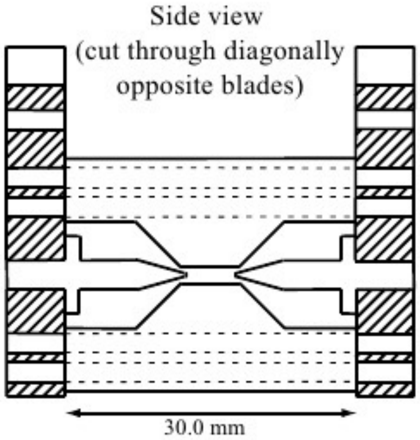
Fortschr. Phys. 46 (1998) 4-5
D. J. Wineland et al.: Experimental Primer …

Ion Traps

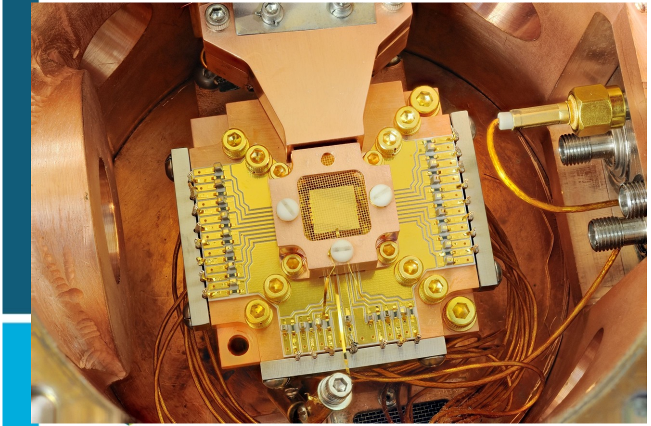


Classical linear Paul trap

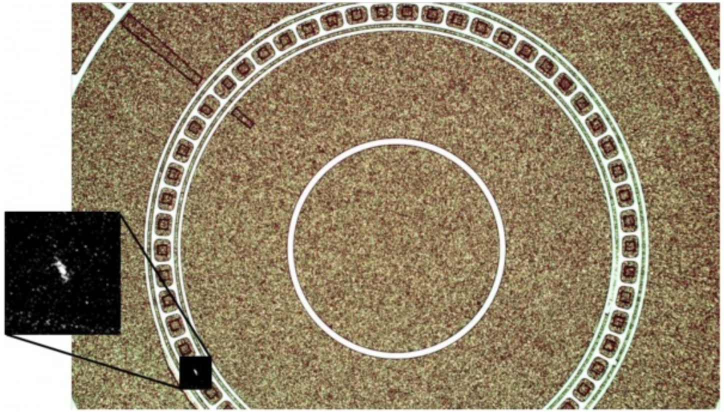




P. Schindler, et al., A quantum information processor with trapped ions, New J. Phys. 15 123012 (2013)



Chip ion trap for quantum computing from 2011 at NIST.

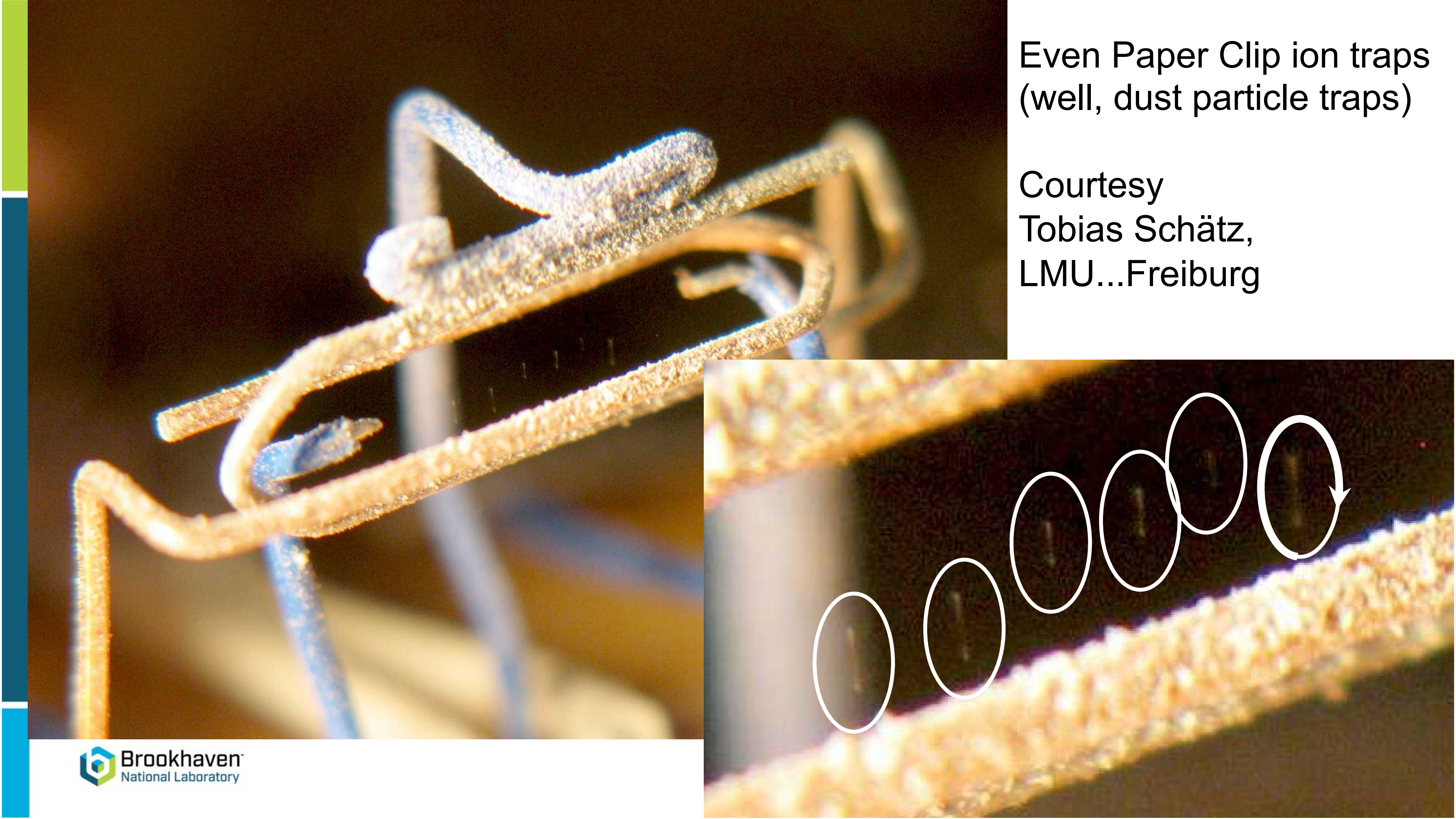


Microscope image of the ring trap surface, and image of an ion trapped above the surface. Microchip developed in collaboration between Univ. of Sussex and University of Nottingham

https://www.sussex.ac.uk/physics/iqt/rsearch/ion-microchips/

Even Paper Clip ion traps (well, dust particle traps)

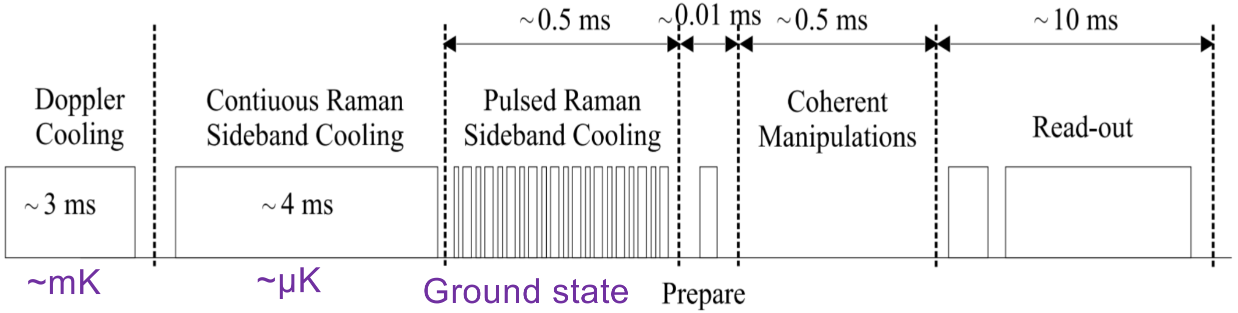
Courtesy
Tobias Schätz,
LMU...Freiburg



Challenges with Ion Traps

- Small number of ions/trap (~100's)
- Require very cold crystalline beams
  - Quantum phonon modes
  - Spatial Locality
- Each trap needs its own lasers

- Completely asynchronous
  - Characteristic times associated by decoherence and laser excitation and measurement times
- Error correction (requires many qubits)
- Entanglement limited to ions in single trap



An operation cycle for Quantum Computer

Entanglement of Two Trapped-Ion Spin Qubits, J. Home's PhD thesis, 2006

Conditions for creating crystalline beams in storage rings

Advantages of storage rings

- Can contain larger number of ions (>> thousands)
- Can contain large number ion chains
  - Each chain can be ~hundreds of ions
  - Each storage ring can contain ~thousands of chains
- Storage rings can be self-clocked (e.g., based on revolution freq.)
- Smaller set of lasers can operate on large number of ions.
  - Large degree of parallelism and multiplexing possible
- Having large number of ions and ion chains opens the way to new methods for error correction – even self-error correction
- Can employ multiple ion species – new opportunities

Conditions for a Crystal : review

Two conditions are necessary to form and maintain crystalline beams

1. The storage ring must be alternating-gradient focusing and the energy must be less than the transition energy; $\gamma < \gamma_{tr}$

This is required for stable motion under Coulomb interactions when particles are subject to bending in a storage ring. This condition is required for formation of a crystal.

2. The lattice periodicity is at least $2\sqrt{2}$ greater than maximum betatron tune

This is to avoid linear resonances between phonon modes of the crystal and the lattice periodicity. This condition is required to maintain a crystal structure.

J. Wei, H. Okamoto, & A. Sessler, “Necessary Conditions for Attaining a Crystalline Beam,” Phys. Rev. Let., V. 80, No. 12 (1998)

J. Wei, X. Li, & A. Sessler, “Crystalline beams,” AIP Conf. Proc. 335,224 (1995) https://aip.scitation.org/doi/abs/10.1063/1.48243

X. Li, et al., “Phonon Modes and the Maintenance Condition of a Crystalline Beam,” Proc. of 2005 PAC, Knoxville, TN

Lattice with an imaginary γ_{tr} (or $-\alpha$) ?

Azimuthal motion will be unbounded (from below) if $\gamma \geq \gamma_{tr}$

The Hamiltonian can be expressed as[1],

$$\widetilde{H} = \upsilon_x J_x + \upsilon_y J_y + \frac{1-\gamma^2 F_z}{2} \widetilde{P_z^2} + \widetilde{V_C},$$

Where, $\widetilde{V_C} \approx \frac{k_z}{2} \bar{z}^2$, $\bar{z} \ll \Delta_z$, $k_z \geq 0$ and $\langle F_z \rangle = \frac{\rho}{2\pi R} \oint_{Bend} D dt \equiv \frac{1}{\gamma_{tr}^2}$

If,

$\gamma > \gamma_{tr},\ \ 1 - \gamma^2 F_z < 0$, negative-mass regime, no ground state

$\gamma < \gamma_{tr},\ \ 1 - \gamma^2 F_z > 0$, motion is bounded (no negative energy states)

$F_z < 0,\ \ \ 1 - \gamma^2 F_z > 0$, motion is bounded always

However, to maintain, lattice periodicity still needs to be high. So, a large γ_{tr} lattice would still need high periodicity/tune ratio.

[1] J. Wei, X. Li, & A. Sessler, “Crystalline beams,” AIP Conf.Proc. 335,224 (1995)

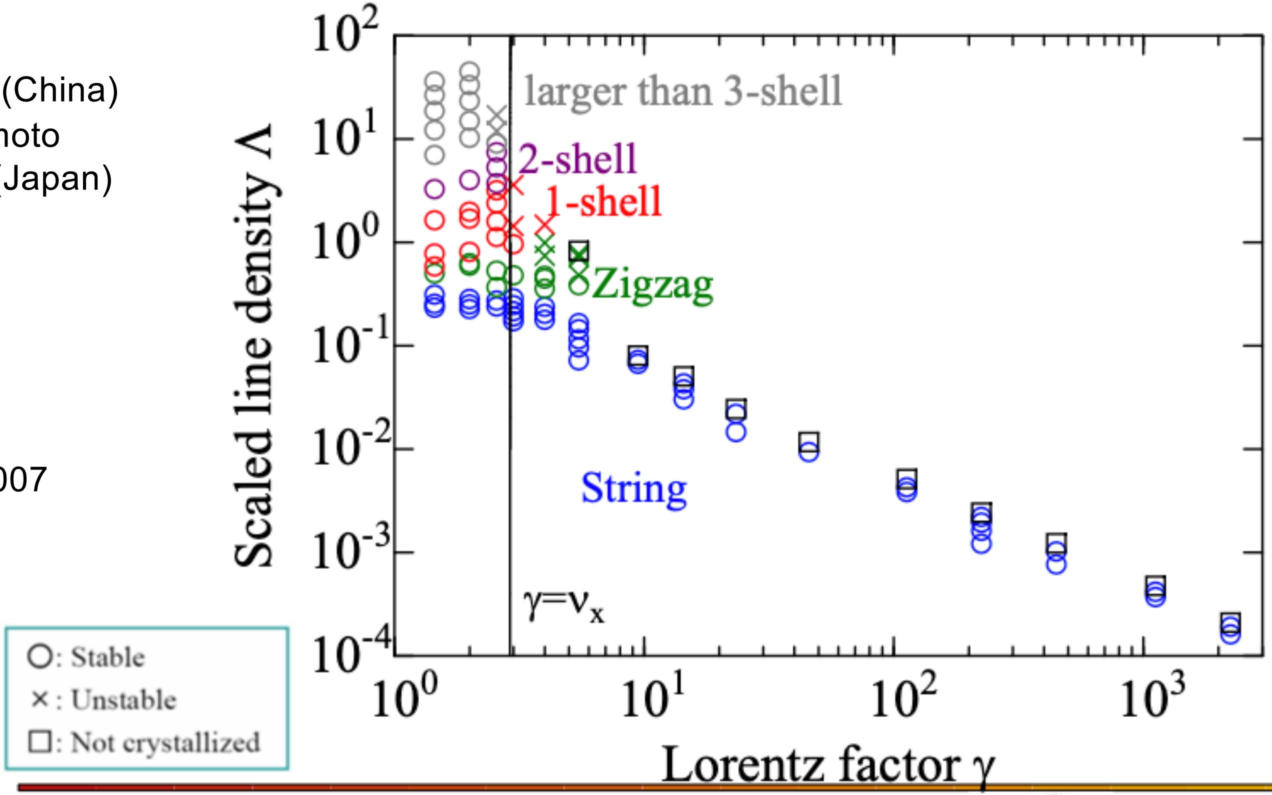
https://aip.scitation.org/doi/abs/10.1063/1.48243

1D crystal at very high energy

- Imaginary transition energy lattice

Jie Wei
BNL (USA) and IHEP (China)
H. Okamoto, H. Sugimoto
Hiroshima University (Japan)
Y. Yuri
JAEA (Japan)
A.M. Sessler
LBNL (USA)

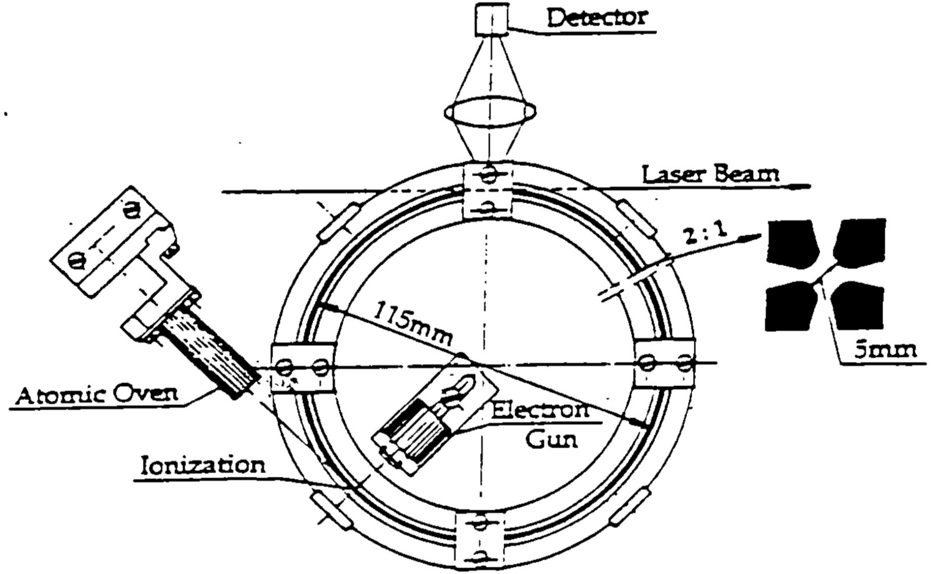
COOL’07 Workshop,
September 10 - 14, 2007



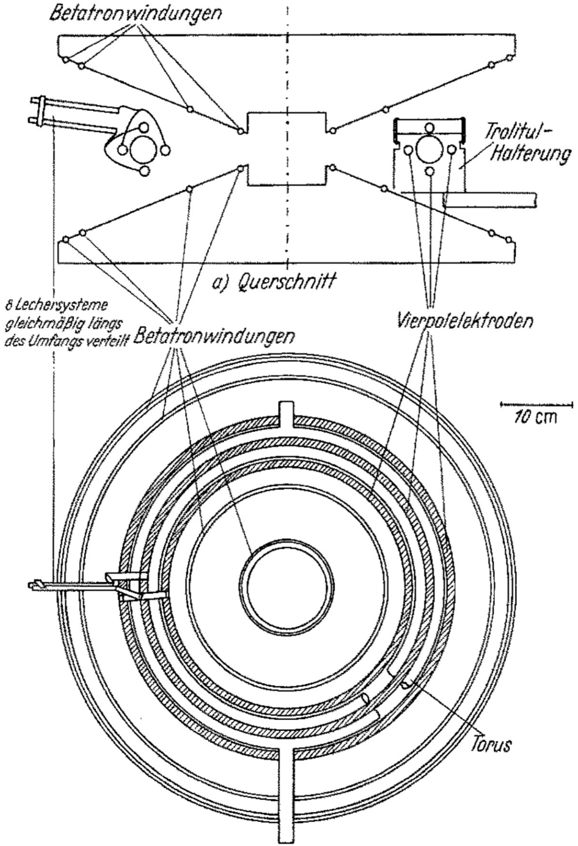
Circular Radio-Frequency Quadrupoles

Circular RFQ Ion Traps

Example concept from A.G. Ruggiero



A. G. Ruggiero, The Circular RFQ Storage Ring, BNL Internal report, BNL-65920 (1998)



a) Querschnitt

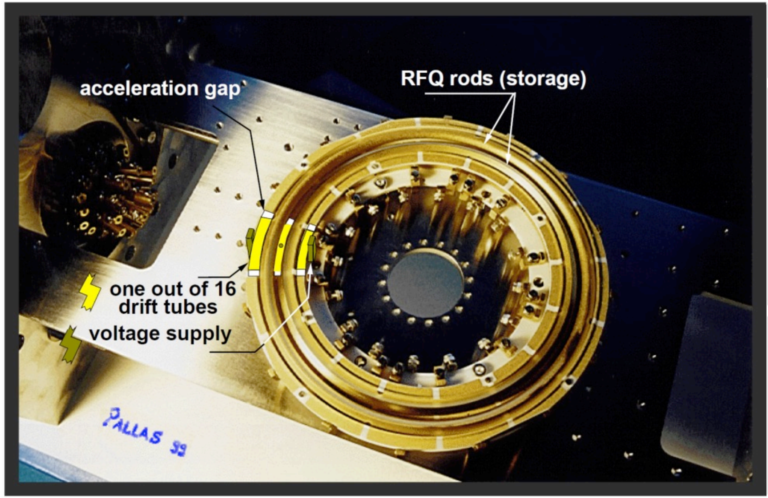
b) Aufsicht (obere Hälfte des Betatrons entfernt)

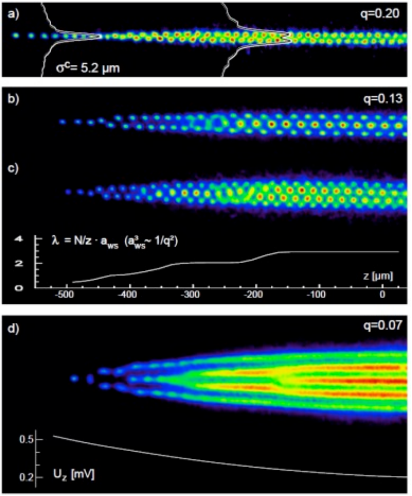
Fig. 1a u. b. Aufbau des Plasmabetatrons (schematisch)

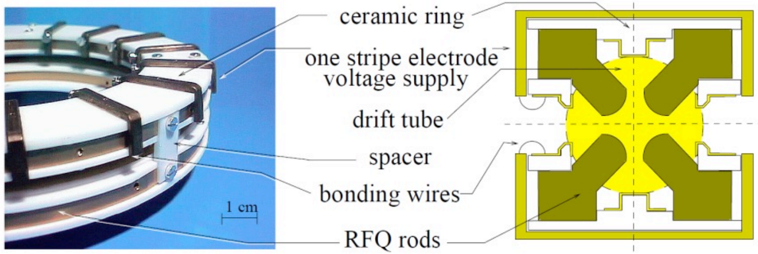
J. Drees & W. Paul, Zeitschrift für Physik 180, 340-361 (1964)

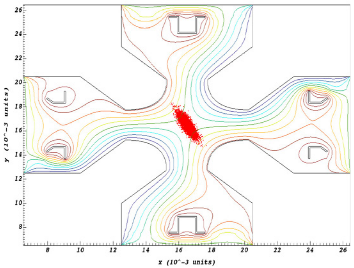
PALLAS RF-Quadrupole Ring Trap

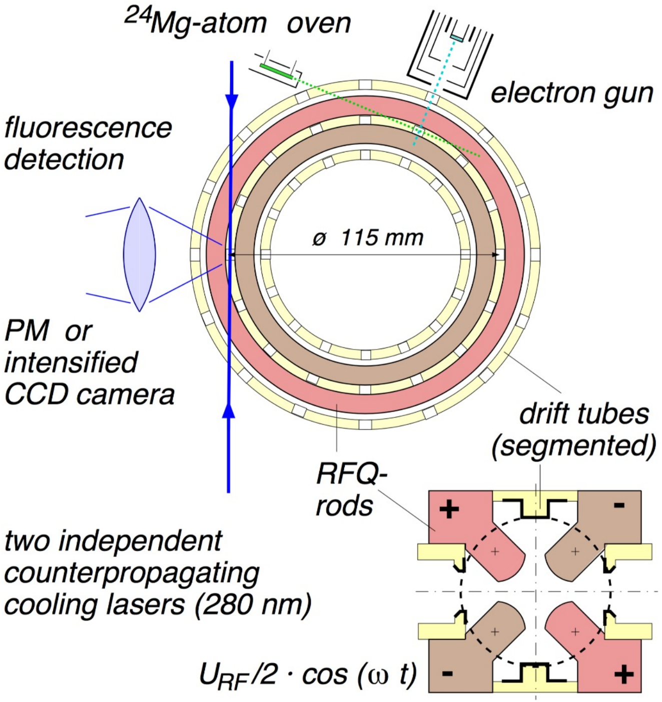
U Schramm[1], T Schätz, M Bussmann and D Habs
Sektion Physik, Ludwig-Maximilians-Universität München, D-85748 Garching, Germany











Difference between AGS* and CRFQ

CRFQ follows Mathieu's differential equation,

$$\frac{d^2u}{d\xi^2} + [b_u - 2q_u\cos(2\xi)]u = 0, where\ \xi = \frac{1}{2}\Omega t$$

AGS follows Hill's differential equation,

$$\frac{d^2x}{ds^2} + K_x(s)x = 0, K_x \equiv \frac{B'}{B\rho} + \rho^{-2}, B' \equiv \partial B_y/\partial x$$

In an AGS, the beam traverses through FODO elements, experiencing sharp gradients at the entrances & exits to the magnets.

In a CRFQ, the RF traverses past the beam (an ion in a trap is stationary) but the gradients are gradual, following the sinusoidal rf potential.

* Alternating Gradient Synchrotron

A Storage Ring Ion Trap

For a circular RFQ, ion azimuthal motion is an angular precession at

$\omega_0 = \beta c/R$, where *R* is radius of curvature of the ring.

The alternating focusing period is

$L = \beta\lambda$, where $\lambda = \frac{c}{f_{rf}}$, the rf field wavelength

Periodicity, a function of velocity, is

$P = \frac{C}{L}$, where $C = 2\pi R \; and \; L = \frac{v_0}{f_{rf}}$

Electric potential for RFQ configuration is

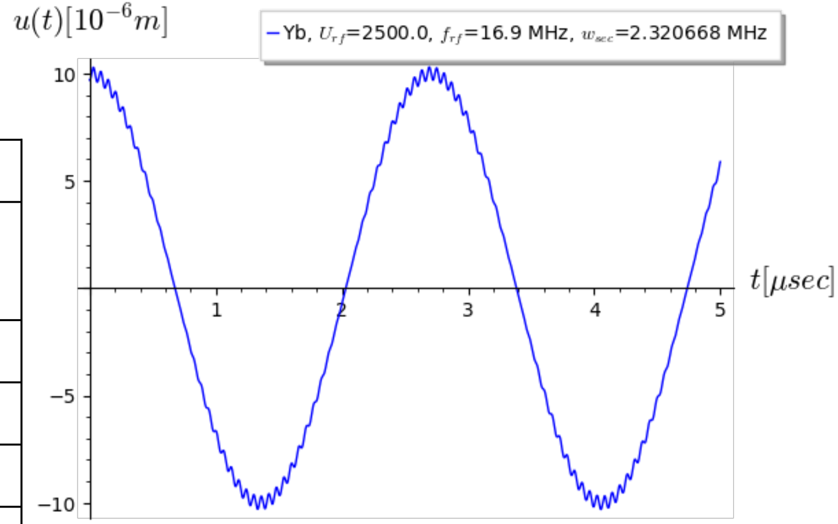
$$\phi(\hat{x}, \hat{y}, \hat{z}) = \frac{\phi_0(t)}{2r_0}(\hat{x}^2 - \hat{y}^2), where \; \phi_0(t) = U_{dc} - U_{rf}\cos(\Omega t)$$

A Storage Ring Ion Trap

Given this description and taking that $\lambda_\beta \gg L^*$, the storage ring can be described using very simple relations

Periodicity	$P = C/L$
Tune	$Q = \frac{C}{\lambda_\beta} = \frac{\omega_{sec} C}{2\pi v_0}$
Beta-function	$\beta_0 = R/Q$
phase	$\phi(z) = Qz/R$
dispersion	$D_0 = R/Q^2$
Momentum compaction	$\alpha = {}^{D_0}/_{R} = {}^{1}/_{Q^2}$
Transition energy	$\gamma_{tr} = Q$

* $L = \frac{v_0}{f_{rf}}$, the alternating focusing period



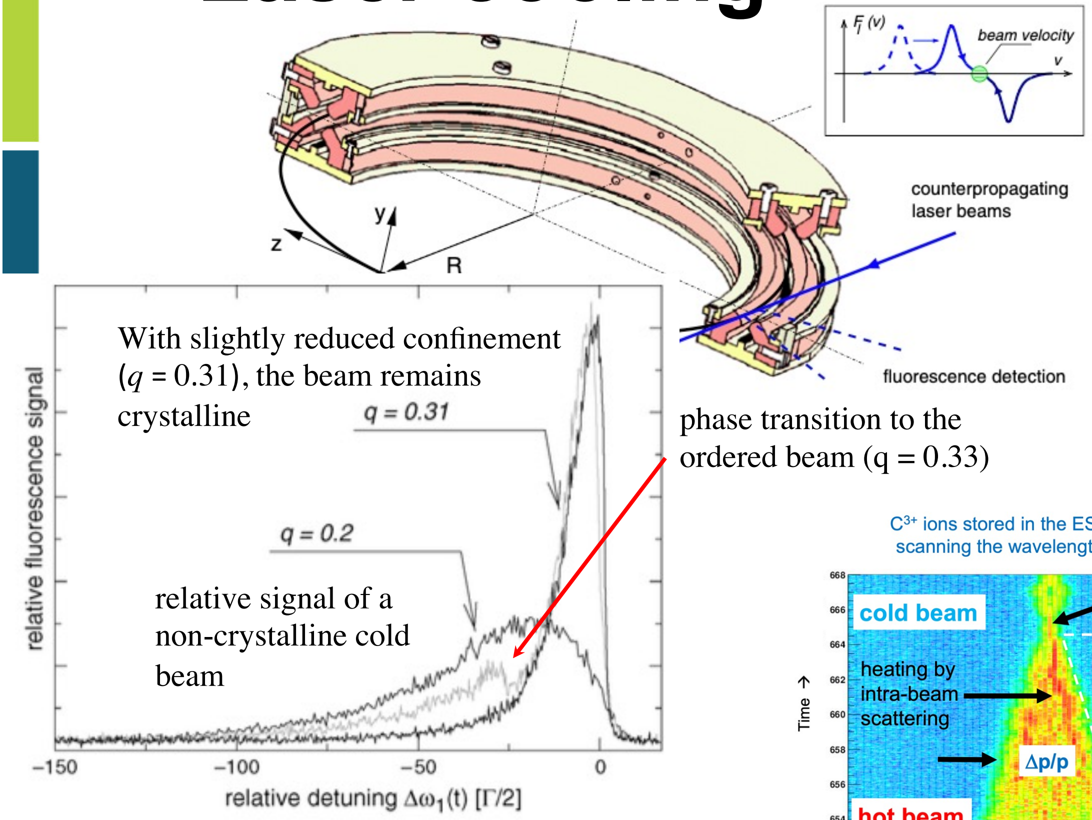
When $b_u < q_u \ll 1$, there is a simple solution to Mathieu's equation,

$$u(t) = u_{max}\left(1 + \sqrt{2}\,\frac{\omega_{sec}}{\Omega}\cos\Omega t\right)\cos\omega_{sec} t$$

Cooling

https://what-if.xkcd.com/119/

Laser cooling



With slightly reduced confinement ($q = 0.31$), the beam remains crystalline

phase transition to the ordered beam (q = 0.33)

relative signal of a non-crystalline cold beam

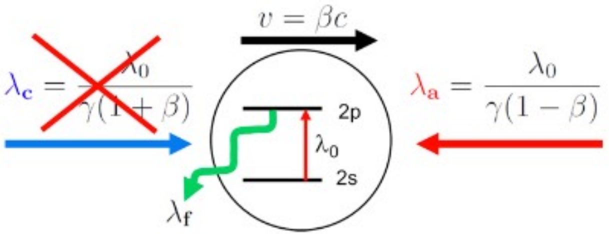
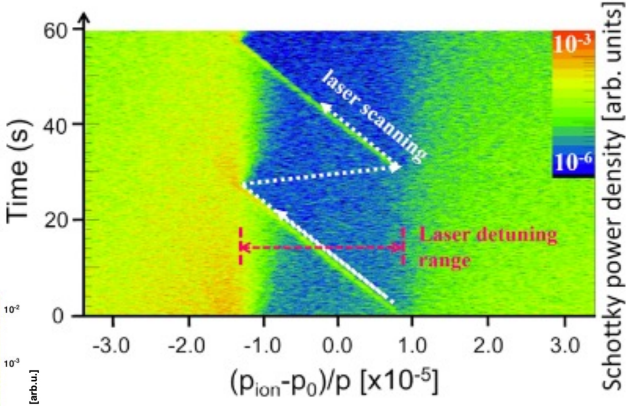
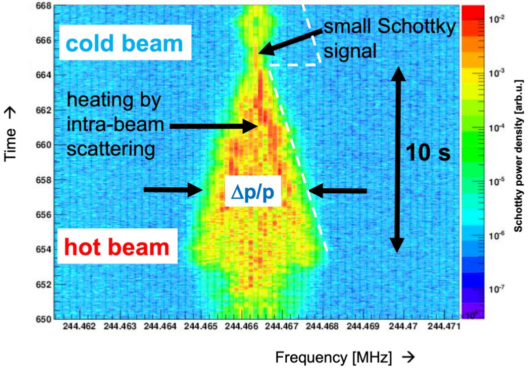


Figure 1. The principle of laser cooling: the ion absorbs a photon—thus momentum—from a counter-propagating laser beam, and deexcites by fluorescence. The counteracting force, required for laser cooling, is provided by the 'rf-bucket', which comes from *bunching* the ion beam.



C^{3+} ions stored in the ESR @ 122 MeV/u, scanning the wavelength of the cw laser



"The logarithmically color-coded Schottky power density shows that ions within the scanning range are decelerated to lower momenta by the laser force, leaving the revolution frequency range covered by the laser scan depopulated of ions"

U. Schramm, D. Habs, Progress in Particle and Nuclear Physics 53 (2004) 583–677
Danyal Winters, et al., Laser cooling of relativistic heavy-ion beams for FAIR, Phys. Scr. T166 (2015) 014048 (6pp)

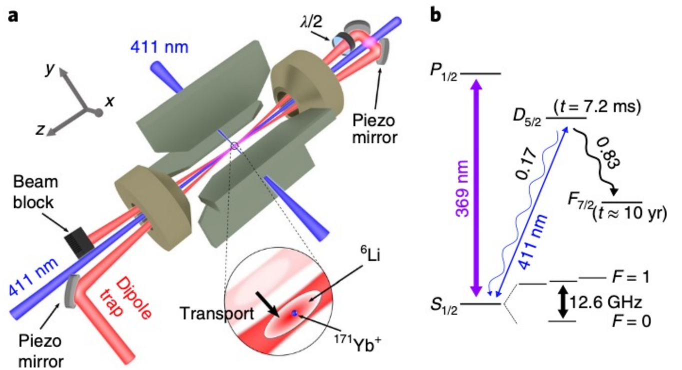
3D COOLING

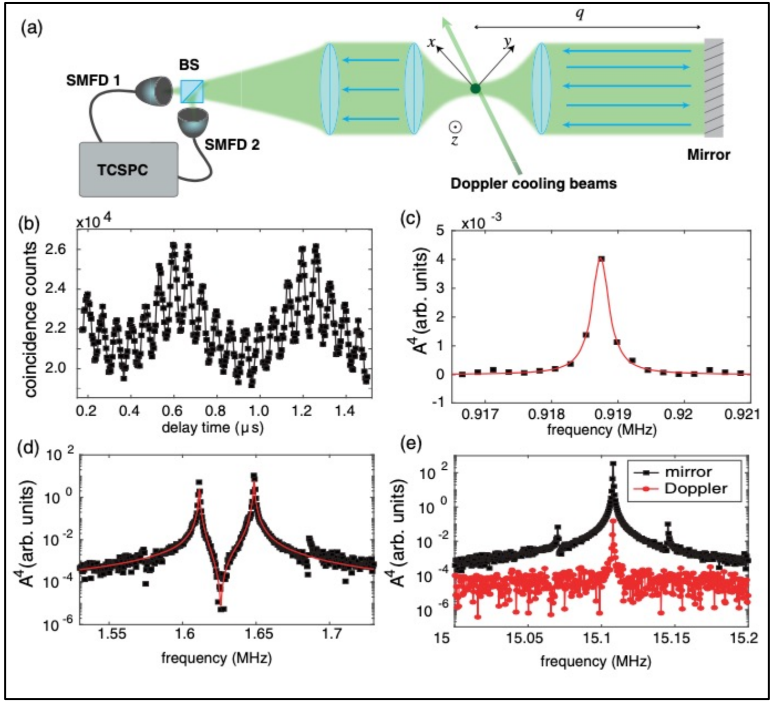
- 1D Doppler Laser Cooling cannot cool below below ~ 1 mK.
  - Theoretical minimum is given by a balance between the dissipation and fluctuations. The doppler cooling limit is a result of the recoil energy averaged in all directions from the emitted photons and corresponds to $kT_{min} = \frac{1}{2}\hbar\gamma$
- Sympathetic cooling has been done in ion traps. Different species of ion beams travelling together with the same velocity will exchange energy via Coulomb interaction. (micro-motion limits?)
- 3D cooling can be simulated using an electrostatic wiggler in the CRFQ storage ring lattice, with two counter-propagating lasers. (micro-motion limits?)
- Ultra-cold buffer gas cooling?
- Wild Idea = single ion detection cooling?

Micromotion-Induced Limit to Atom-Ion Sympathetic Cooling in Paul Traps
Marko Cetina, Andrew T. Grier, and Vladan Vuletic´, PRL 109, 253201 (2012)

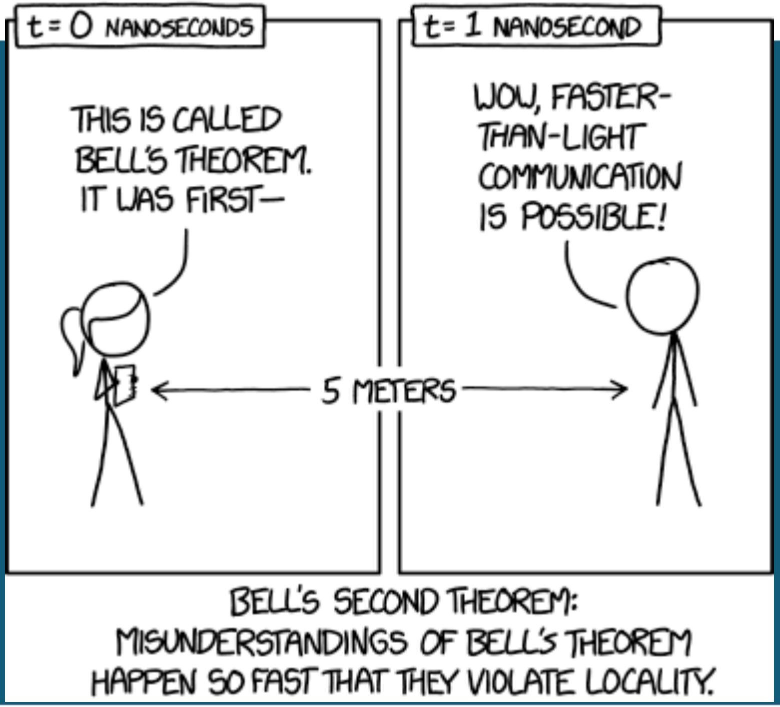
Buffer gas cooling of a trapped ion to the quantum regime
T. Feldker, H. Fürst, H. Hirzler, N. V. Ewald, M. Mazzanti, D. Wiater, M. Tomza and R. Gerritsma, Nature Physics Vol 16 April 2020 413–416

Measuring Ion Oscillations at the Quantum Level with Fluorescence Light
G. Cerchiari, G. Araneda, L. Podhora, L. Slodička, Y. Colombe, and R. Blatt
Phys. Rev. Lett. 127, 063603 – Published 4 August 2021





Entanglement



- Two independent wave functions interact
  - $|v\rangle = a_0|0\rangle + a_1|1\rangle$ and $|w\rangle = b_0|\downarrow\rangle + b_1|\uparrow\rangle$
  - $|v\rangle \otimes |w\rangle = a_0 b_0|0\rangle|\downarrow\rangle + a_1 b_0|1\rangle|\downarrow\rangle + a_0 b_1|0\rangle|\uparrow\rangle + a_1 b_1|1\rangle\,|\uparrow\rangle$
  - $|v\rangle|w\rangle = r|0\rangle|\downarrow\rangle + s|1\rangle|\downarrow\rangle + t|0\rangle|\uparrow\rangle + u|1\rangle\,|\uparrow\rangle$
  - $r^2 + s^2 + t^2 + u^2 = 1$
  - If $ru = st$, states are not entangled
  - If $ru \neq st$, **states are entangled**
  - $\therefore (a_0 b_0\,|0\downarrow\rangle)(a_1 b_1|1\uparrow\rangle) \neq (a_0 b_1|0\uparrow\rangle)(a_1 b_0|1\downarrow\rangle)$, are entangled (combined states are not a tensor product)
  - The wavefunctions can no longer be described independently even if moved far apart
- We must keep track of all eigenstates (accounting)
- To entangle internal spin states of two ions, we perform a gate operation using an external eigenstate (shared by the two ions)

Quantum C-NOT Gate

Combined wave function is,
$|v\rangle|w\rangle = r\,|0\rangle|0\rangle + s\,|0\rangle|1\rangle + t\,|1\rangle|0\rangle + u\,|1\rangle|1\rangle$
Where spin states are expressed as
$|\downarrow\rangle = |0\rangle$ and $|\uparrow\rangle = |1\rangle$. $a_0 b_0 = \mathrm{r}$, etc. $= \frac{1}{\sqrt{2}}$

$$\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \end{bmatrix} \begin{bmatrix} \frac{1}{\sqrt{2}}|1\rangle \\ |0\rangle \\ \frac{1}{\sqrt{2}}|1\rangle \\ |0\rangle \end{bmatrix} = \frac{1}{\sqrt{2}} \begin{bmatrix} |1\rangle \\ |0\rangle \\ |0\rangle \\ |1\rangle \end{bmatrix} = \frac{|00\rangle + |11\rangle}{\sqrt{2}}$$

The original vector tensor product is unentangled.
The new vector outer and inner tensor products are not equal, so the wavefunctions are entangled.
In this case, eigenstates of two ions have become entangled.

Entanglement is the key to having fast algorithms in quantum computing. Changing the state of an entangled qubit will change the state of the paired qubit. Entanglement is necessary for a quantum algorithm to offer an exponential speed-up over a classical algorithm.

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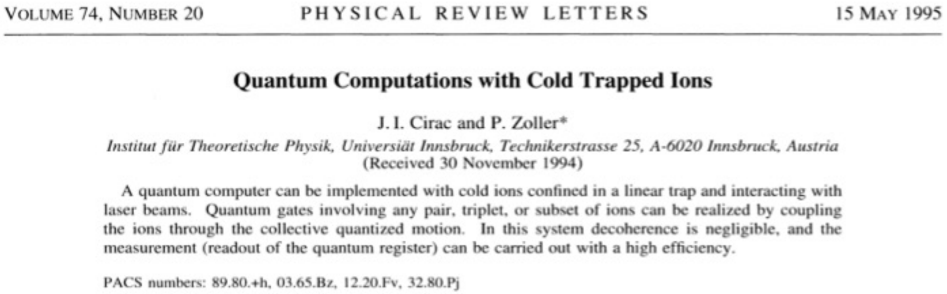
Entanglement in Ion traps



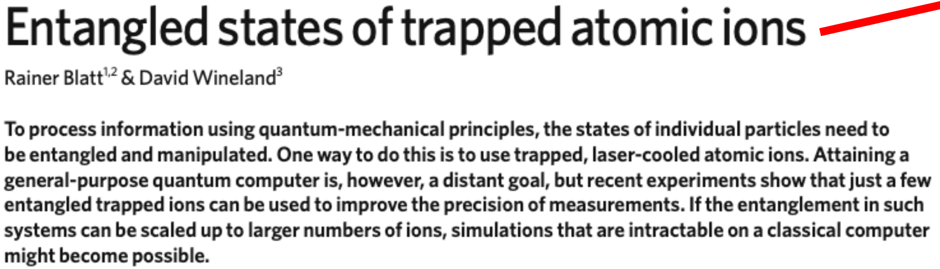
VOLUME 74, NUMBER 20 PHYSICAL REVIEW LETTERS 15 MAY 1995

Quantum Computations with Cold Trapped Ions

J. I. Cirac and P. Zoller*
Institut für Theoretische Physik, Universität Innsbruck, Technikerstrasse 25, A-6020 Innsbruck, Austria
(Received 30 November 1994)

A quantum computer can be implemented with cold ions confined in a linear trap and interacting with laser beams. Quantum gates involving any pair, triplet, or subset of ions can be realized by coupling the ions through the collective quantized motion. In this system decoherence is negligible, and the measurement (readout of the quantum register) can be carried out with a high efficiency.

PACS numbers: 89.80.+h, 03.65.Bz, 12.20.Fv, 32.80.Pj

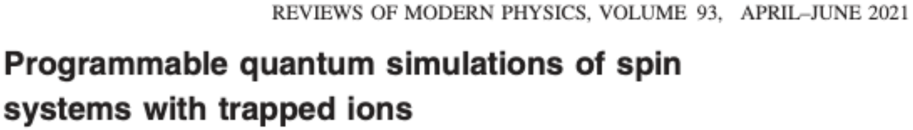


Entangled states of trapped atomic ions

Rainer Blatt[1,2] & David Wineland[3]

To process information using quantum-mechanical principles, the states of individual particles need to be entangled and manipulated. One way to do this is to use trapped, laser-cooled atomic ions. Attaining a general-purpose quantum computer is, however, a distant goal, but recent experiments show that just a few entangled trapped ions can be used to improve the precision of measurements. If the entanglement in such systems can be scaled up to larger numbers of ions, simulations that are intractable on a classical computer might become possible.

Nature **453,** 1008–1015 (2008).
https://doi.org/10.1038/nature07125

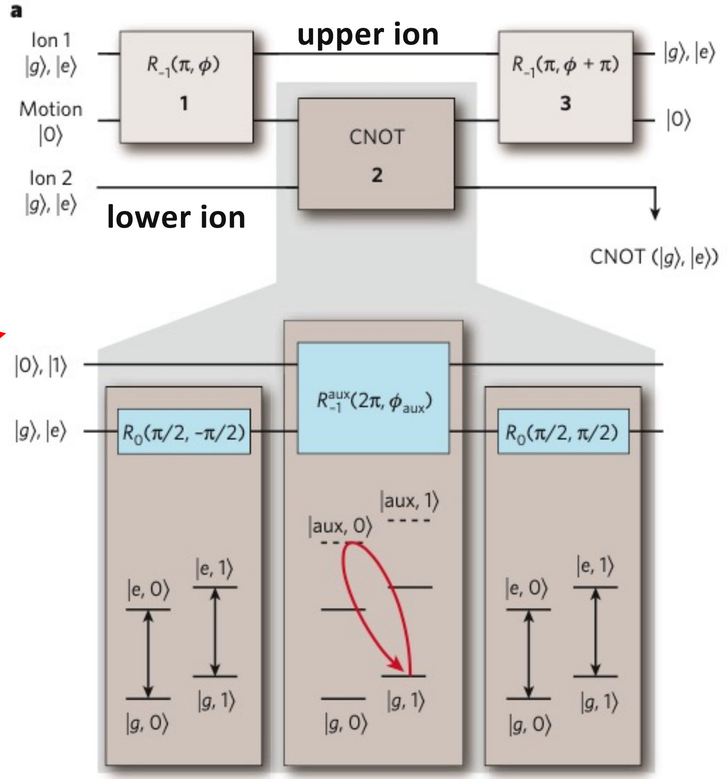


REVIEWS OF MODERN PHYSICS, VOLUME 93, APRIL–JUNE 2021

Programmable quantum simulations of spin systems with trapped ions

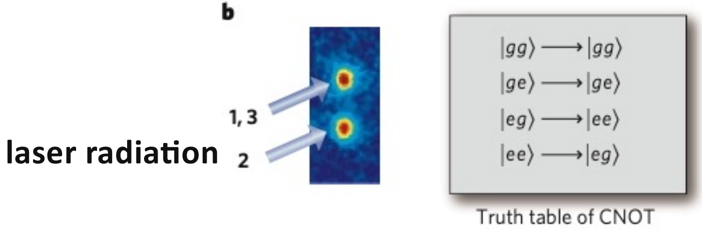
C. Monroe et al.

Brookhaven National Laboratory



upper ion

lower ion



laser radiation

Truth table of CNOT

Tackling Challenges

Keeping track of thousands of ions

1. Need to locate – learn the equilibrium positions (EPs)
   1. Figuring them out is too complex[1] (although it only has to be done once, in principle = there are caveats)
   2. Mix ions of different isotopes to force dark area's and learn the pattern[2] (also problematic in a ring where the different ions follow different trajectories) – possible in linear ion traps.
   3. Don't worry about = learn and track on demand. Need precise clocks!
2. Need to index and uniquely identify, to allow precise operations
3. Need to know if an ion is lost – relearn the EP's and indices

$$H_0 = \sum_{\xi}\sum_{j=1}^{N}\frac{p_{\xi,j}^2}{2m} + V$$

Where $V = V_{trap} + V_{Coulomb} = \frac{m}{2}\sum_{\xi}\sum_{j=1}^{N}(\omega_\xi^2 \xi_j^2) + \sum_{n,j}\frac{e^2}{4\pi\epsilon_0 r_{n,j}}$

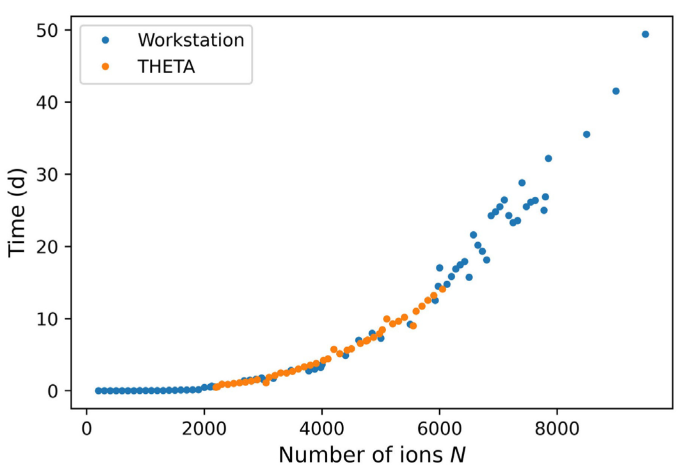
Equilibrium positions are determined by

$$\left(\frac{\partial V}{\partial \xi_i}\right)_{\xi_i=\xi_{i,0}} = 0, \qquad (i = 1,2,\dots,N)$$

$$\xi_{i,0} is\ the\ equilibrium\ position\ (x_i, y_i, z_i = 0)\ for\ ion\ i$$

Define the dimensionless parameter $u_i \equiv \xi_{i,0}/z_s$

Then, for ion j, $u_j - \sum_{n=1}^{j-1}\frac{1}{(u_j-u_n)^2} + \sum_{n=j+1}^{N}\frac{1}{(u_j-u_n)^2} = 0$

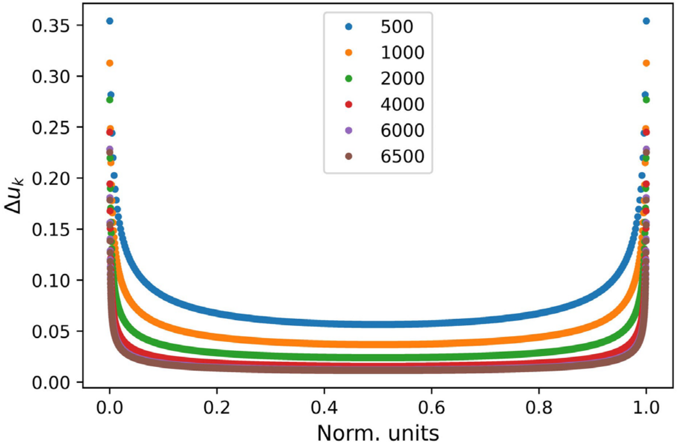


Computation time as function of the number of ions N, in days. The computation time grows as ~ N^3.

[1] B. Huang, C. González-Zacarías, S. Sosa Güitrón, A. Aslam, S. G. Biedron, K. Brown, T. Bolin, IEEE Access, Volume 10, 2022, pp.14350-14358

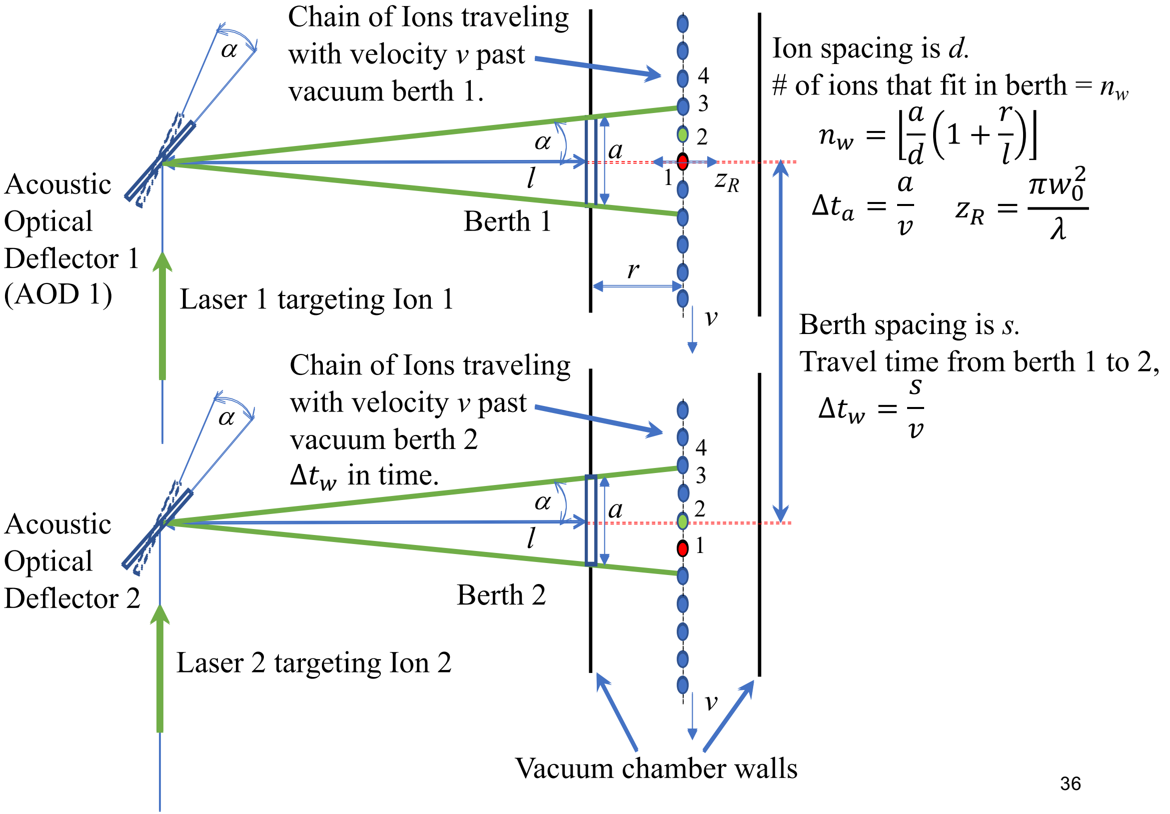
[2] T. Shaftan and Boris B. Blinov , Phys. Rev. Accel. Beams 24, 094701 (2021)

Don’t worry about it?



The distance between adjacent ions in the ICC for different values of N. Note that Δu_k converges to a finite distance as N becomes larger.

As you find them, you can quickly learn them and deduce *d’s*.



Chain of Ions traveling with velocity v past vacuum berth 1.

Acoustic Optical Deflector 1 (AOD 1)

Berth 1

Laser 1 targeting Ion 1

Ion spacing is d.
# of ions that fit in berth = n_w

$$n_w = \left\lfloor \frac{a}{d}\left(1+\frac{r}{l}\right) \right\rfloor$$

$$\Delta t_a = \frac{a}{v} \qquad z_R = \frac{\pi w_0^2}{\lambda}$$

Berth spacing is s.
Travel time from berth 1 to 2,

$$\Delta t_w = \frac{s}{v}$$

Chain of Ions traveling with velocity v past vacuum berth 2 Δt_w in time.

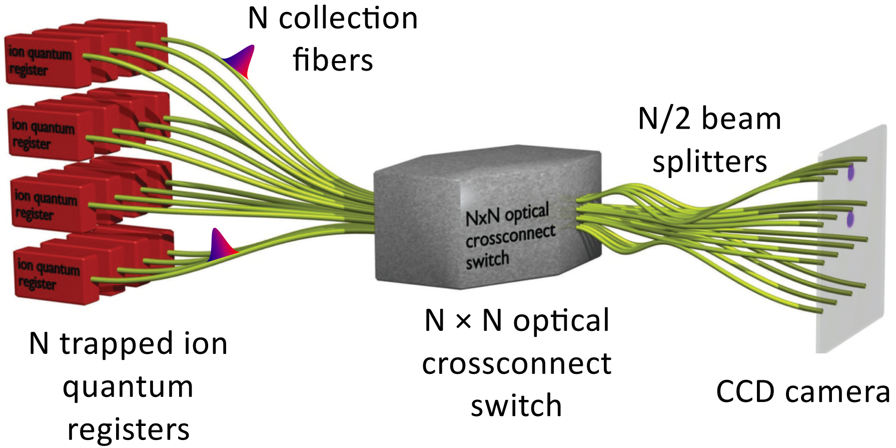
Acoustic Optical Deflector 2

Berth 2

Laser 2 targeting Ion 2

Vacuum chamber walls

(to 1,000,000 qubits?)



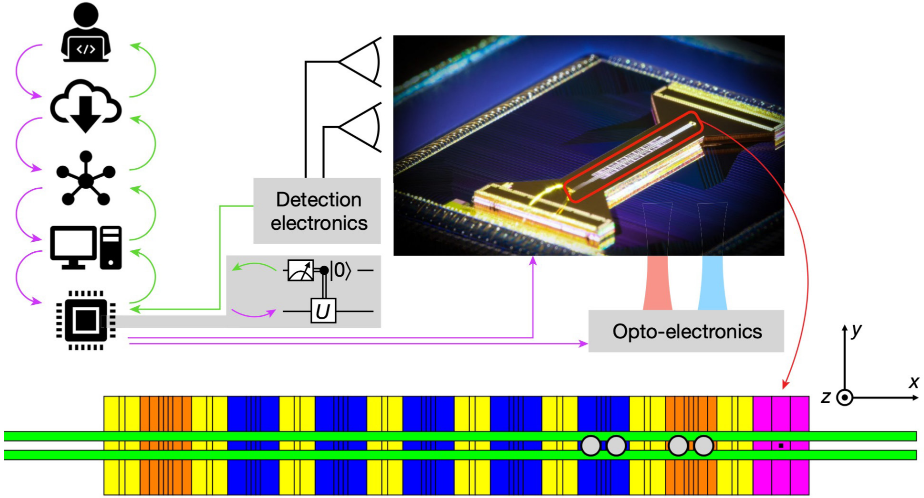
N collection fibers

N/2 beam splitters

N trapped ion quantum registers

N × N optical crossconnect switch

CCD camera



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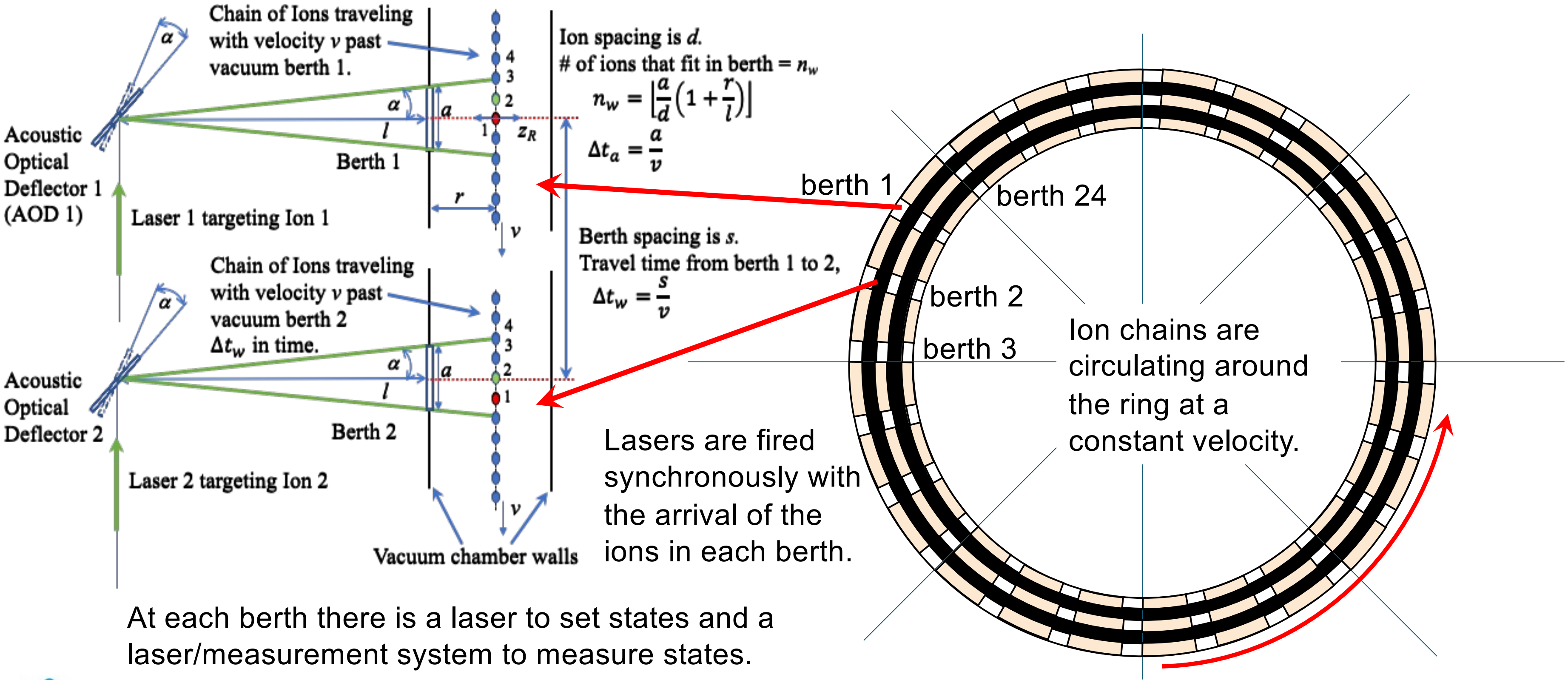
Conceptual Example, for a circular accelerator. Other configurations are allowed; racetrack (2 straight sections), triangular (3 straight sections), rectangular/square (4 straight sections), etc. Here there are 24 berths (or physical windows in a vacuum chamber in this case). Laser operations will take place at each berth, allowing many operations to be happening simultaneously.



Lasers are fired synchronously with the arrival of the ions in each berth.

Ion chains are circulating around the ring at a constant velocity.

At each berth there is a laser to set states and a laser/measurement system to measure states.

Note: just schematic, nothing is to scale.

Summary +

- Storage rings for QIS are a viable and perhaps, even, a necessary technology, with the ability to scale to large numbers of qubits, but also offering improved error correction (which I didn't talk about but is an important topic)
- QIS with relativistic beams is a new topic. Since we are dealing with quantum systems, the process involves setting a state and then making a measurement. The quantum states will be destroyed in the process. Other quantum properties can be used as qubits.
- There are many interesting problems to work on. We encourage folks to get involved and dive into the problem that interest you.

To Learn More, see

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Thank you

Contributors & collaborators, who have all been invaluable;

C-A Department, BNL
- K.A. Brown, J.M. Brennan, G. Mahler, F. Meot, S. Peggs, T. Roser, Z. Zhao

NSLS II, BNL
- T. Shaftan

Physics, BNL
- A. Nomerotski

University of New Mexico
- A. Aslam, S.G. Biedron, T. Bolin, C. Gonzalez-Zacarias, S. Sosa Guitron

Stony Brook University
- R. Chen (Student), W. Dai (PhD Student), T. Robertazzi, B. Huang (PhD Student)

TechX
- J. Cary

University of Washington
- B. Blinov