Trapped Ion Quantum Computing

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Quantum Computing Cookbook

What does our hardware have to accomplish?

Qubits → Quantum Bits

- Classical Bits → 0 or 1
- Qubits → Can be in a probabilistic combination ('superposition') of 0 and 1
- Trapped ion QCs use individual atoms as qubits
- Properties we need:
  - **Initialization** → reliably prepare qubits in known states
  - **Control** → perform operations
    - Change the amplitudes and phases of our qubits
  - **Coupling** → qubits should interact
  - **Readout** → measurable qubits

Key Metrics

- **Coherence** → Qubits must remain stable long enough to complete our computation
- **Low error rates** → Tiny disturbances ruin computations
- **Scalability** → Ability to grow our hardware sizes to tens → thousands → millions of qubits

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Trapping Ions

Why use ions?

- **Ion:** atom or molecule with a net electrical charge, caused by unequal number of protons & electrons
  - Electrical Charge → controllable with electric fields
- **Electromagnetism:** study of interactions between charged particles
  - Hundreds of years old
  - Well-studied & many existing technologies
- Ions work as great qubits!
  - Naturally long coherence times
  - Charged → Easily controllable

History of trapping ions

- **1950s-60s**: Birth of ion trapping
  - Wolfgang Paul invents the Paul trap using oscillating electric fields
  - David Wineland experimentally demonstrates laser cooling of atoms (2012 Nobel Prize winner)
- **1980s:** Cooling ions to near absolute zero
- **1990s**: First quantum logic experiments
- **2000s:** First multi-qubit operations
- **2010s:** Small trapped-ion processors
- **2020s and beyond:** scaling systems

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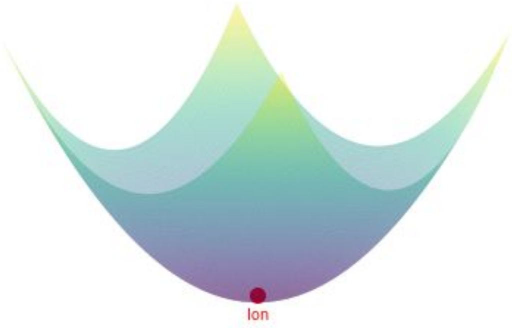
How We Trap Ions

Why Trapping Ions is Hard

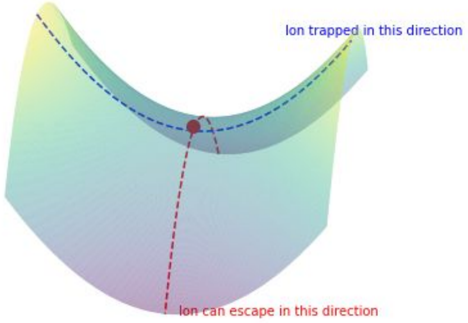
- Ideally, we could use a static electric field to surround the ion, keeping it trapped in the middle
- However, laws of electrostatics limit this (Earnshaw's Theorem)

Core Principle: Dynamic (RF) Trapping

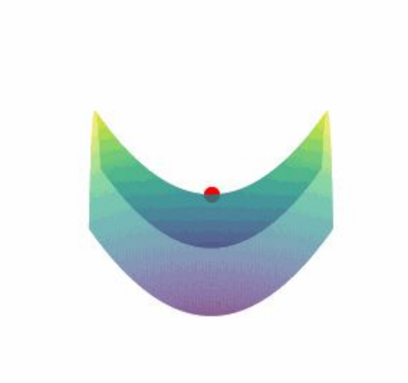
- Rapidly oscillating electric fields → effective potential that confine the ion
- **Paul Trap**



Ideal Trapping Scenario



Saddle-shaped potential allowed by electrostatics



Rotating Potential Containing Ion

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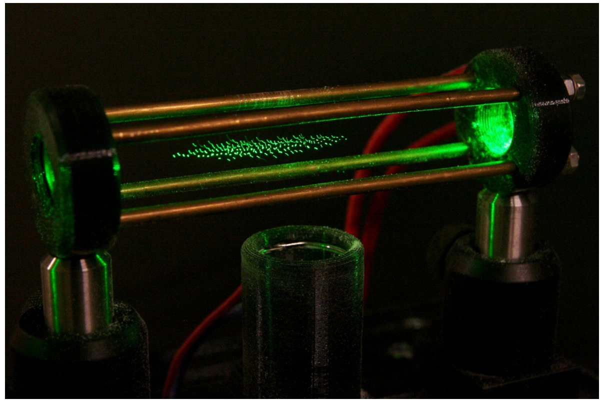
Common Trap Techniques

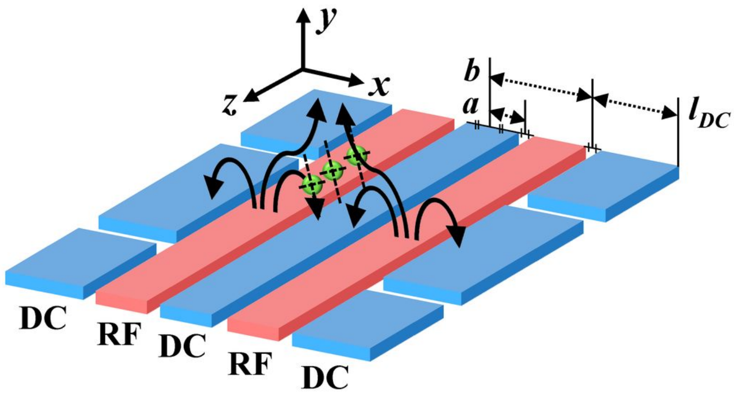
3D Paul Trap

- Four rods + two endcaps
  - RF electrode rods confine in XY directions
  - DC endcaps confine in Z
  - Ions line up in single 1D chain
- **Hackathon Challenge Type**



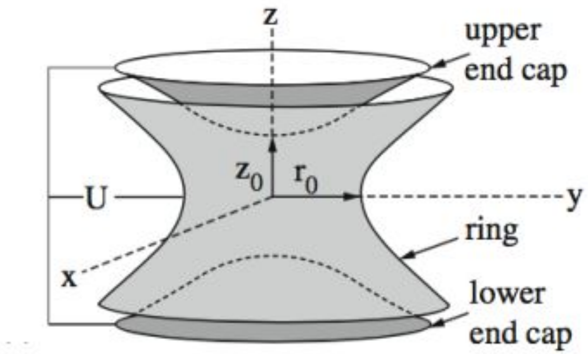
Surface Electrode Trap

- These traps ‘flatten’ the 3D geometry into a 2D microchip
- Electrodes patterned on flat substrate
- Ions float just above surface
- Confinement produced by RF potentials on electrodes
- Used very commonly in industry



Penning Trap

- Uses static magnetic + electric fields for confinement
- One ion for every trap → hard to scale
- Mostly used in spectroscopy + antimatter experiments, not so much for QC



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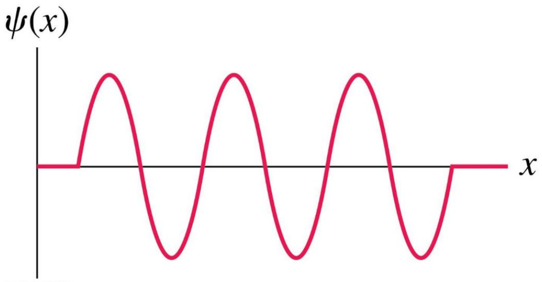
Using Trapped Ions as Qubits

Representing Qubit States

- Abstract quantum states → Internal energy states of an ion
- Then manipulated using laser/microwave beams (usually laser)
- Quantum Amplitudes → probability amplitude for ion to be in either internal atomic energy level
- Quantum Phase → relative timing of oscillation between energy states



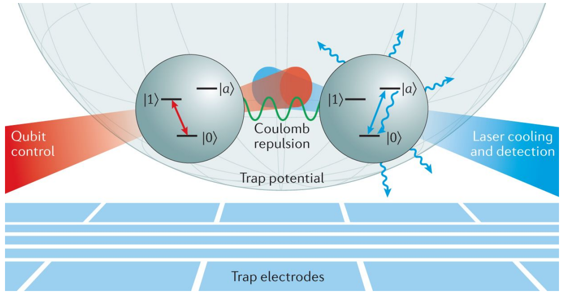
Quantum Operations

Single Qubit:

- Laser pulses applied to ion
  - Duration → rotation angle
  - Phase → rotation axis
  - Frequency → Which atomic level is excited

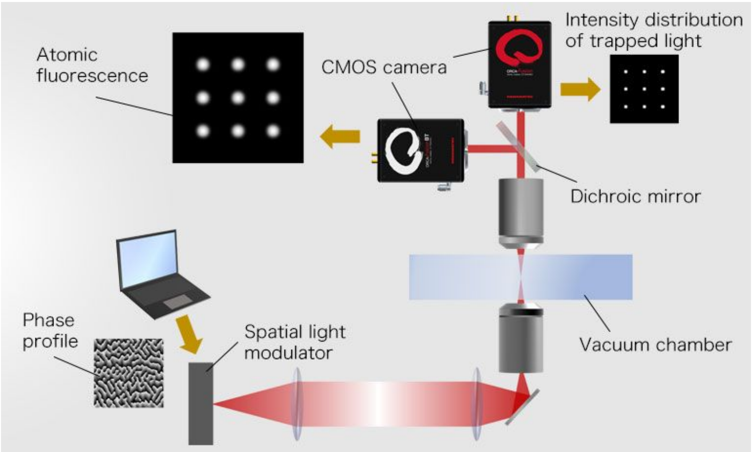
Multi-Qubit:

- Move targets into adjacent zones OR
- Send out a specially-pulsed laser beam so that only specified targets pick up a phase



Measurements

- Shine detection laser → ion fluoresces in excited state
- ‘Bright = 1 | Dark = 0’



Commentary & Takeaway

Pros

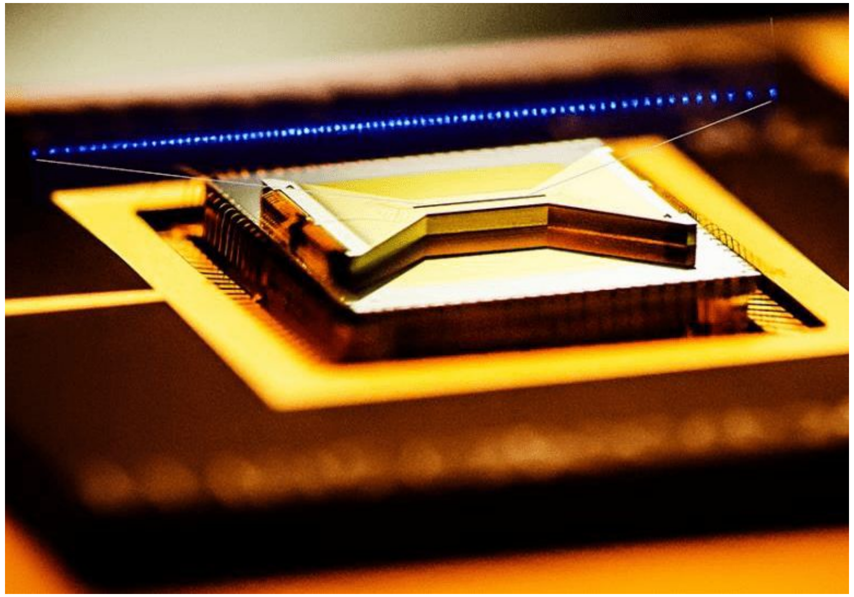
- Highest fidelity gates amongst all quantum platforms
- Long coherence times
- All-to-all qubit connectivity
- Excellent measurement accuracy

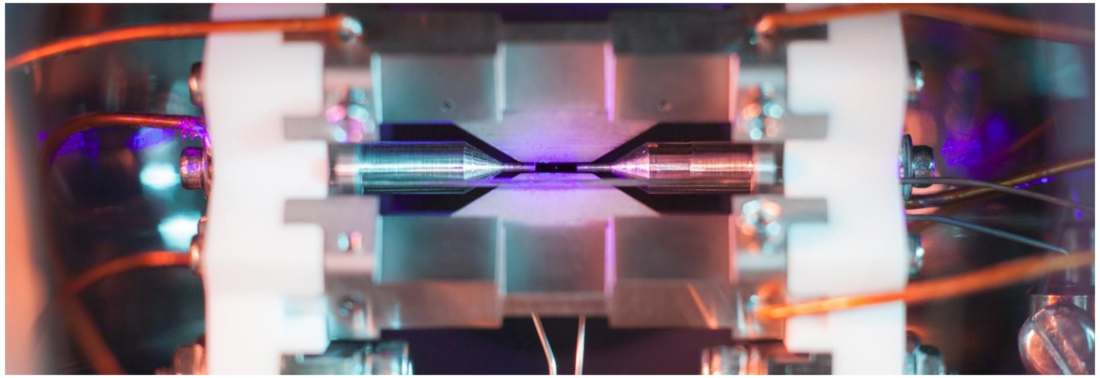
Cons

- Slower operation speeds
- Moving ions requires very precise control
- Supercooling needed
- Dense systems:
  - More ions = more closely spaced vibration modes
  - Crowding causes difficulties in laser use

Paths to Scalability

- Modular & networkable architectures with photonic links
- Surface traps with shuttling networks
- Integrated photonics for many, many uses
  - Laser routing
  - Quantum memory
- Better lasers, better vacuum, cryogenic environments





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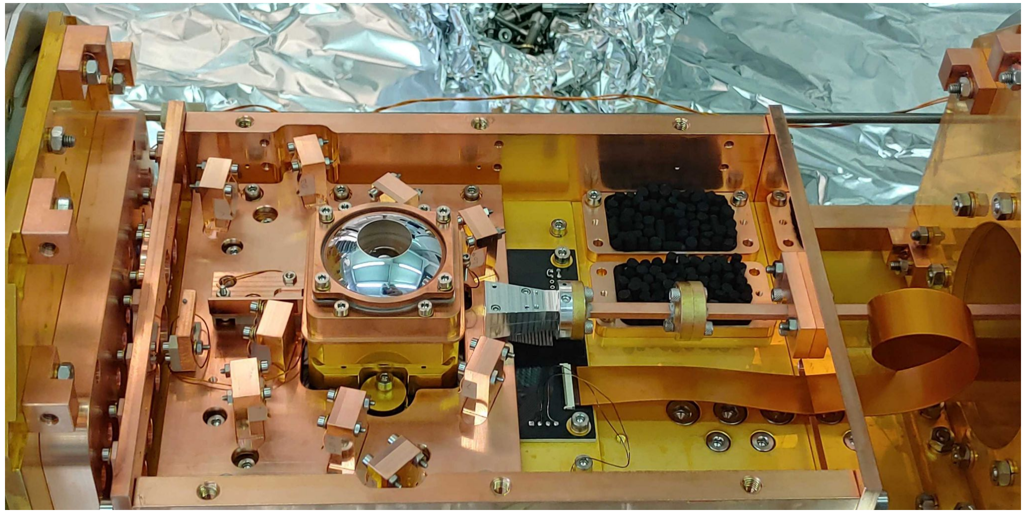

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