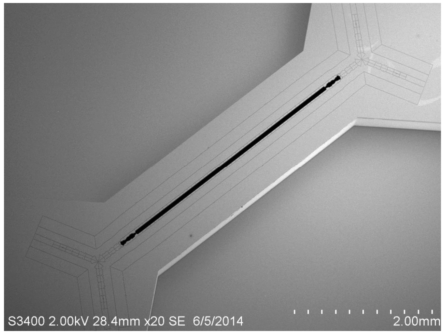
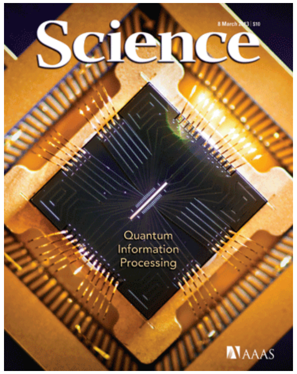
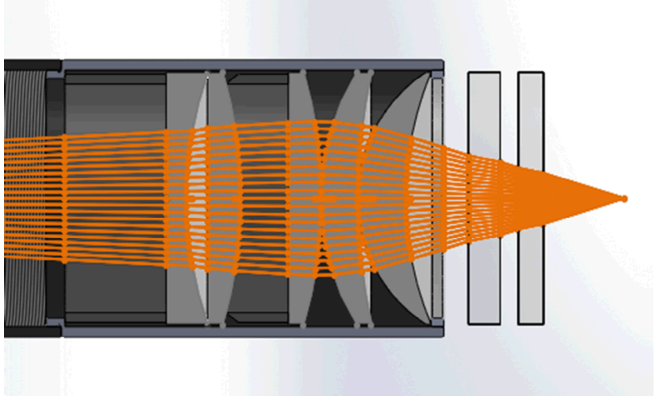
SAND2016-8591PE







An Ultra-Stable Laser to manipulate a single atom:

Efforts to stabilize a laser frequency to better than 1 part per Trillion

Kevin Fortier, Ph.D.

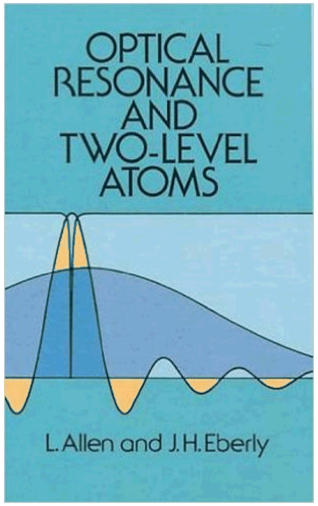
Sandia National Laboratories

Intellectual Ventures Lab

August 2016

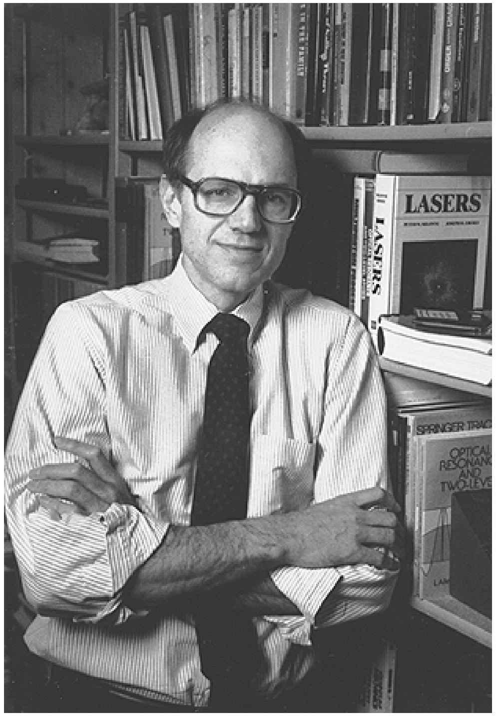
A Quote

"The interaction of a single dipole with a monochromatic radiation field presents an important theoretical problem in electrodynamics. It is an unrealistic problem in the sense that experiments are not done with single atoms or single-mode fields."



L. Allen and J. H. Eberly, *Optical Resonance and Two-Level Atoms*, (Dover, New York, 1987).

Originally published 1975



Joseph Eberly,
U Of Rochester

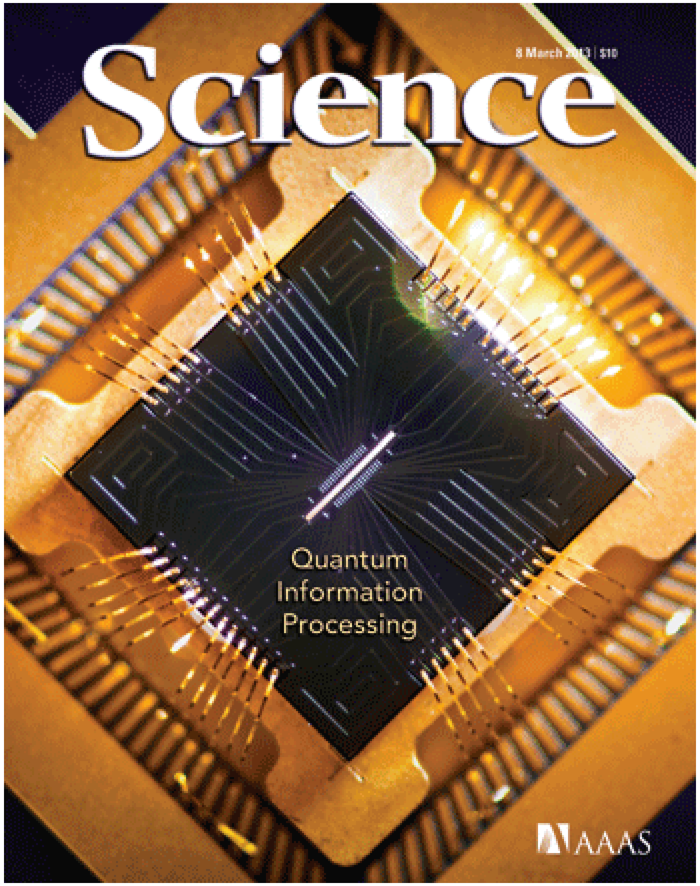
It is no longer unrealistic to do experiments with single atoms, but it still technically challenging

Outline

1. Motivation and Background
    1. Quantum information science
    2. Laser Cooling and trapping
    3. Ion Trap Technology

2. Experimental Development of Cryogenic Ion Trap
    1. Custom Optics

3. Laser Frequency Stabilization
4. Quadrupole Transition in Calcium

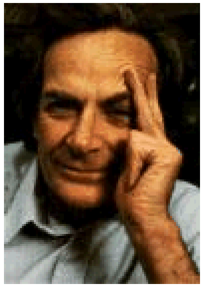


Monroe C, Kim J. Scaling the ion trap quantum processor. *Science* (2013) **339**:1164–9.

Quantum Computers: What are they good for?

Quantum Computers operate on the principals of quantum mechanics and solve a few “designer” problems that are hard for classical computing

Quantum Simulators



Richard Feynman, 1982

Unordered Search

Grover’s Algorithm

Classical: O(N)
Quantum: O($N^{1/2}$)

Lov Grover, 1996

Factoring Large Numbers

Shor’s Algorithm
Peter Shor, 1994

DiVincenzo Criteria (Part 1)

Five Criteria that guide physical implementations of quantum information

1. A scalable physical system with well characterized qubits
2. Ability to Initialize qubits
3. Long decoherence times relative to gate operations

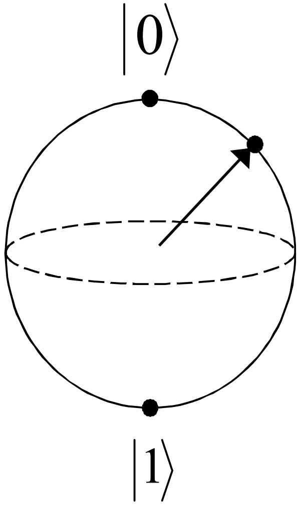
Building Blocks of Quantum Information: *Qubits*

Quantum bit (qubits)

- Two Level Quantum system
- Classical Analog: 0, 1

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

$$|\alpha|^2 + |\beta|^2 = 1$$



Bloch Sphere Representation

Implementations

- Photon polarization
- Atomic hyperfine ground states
- Atomic Zeeman states
- Solid State

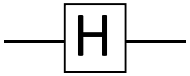
$$|\psi\rangle = \cos\frac{\theta}{2}|0\rangle + e^{i\varphi}\sin\frac{\theta}{2}|1\rangle$$

DiVincenzo Criteria (Part 2)

4. Universal Gates
   Classical -> NAND Gate
   Quantum: Single qubit + C-NOT gate
4. Qubit specific measurement

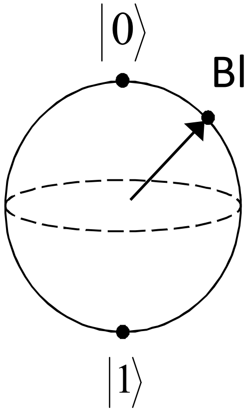
Single qubit gates

- Rotations on Bloch sphere
- Unitary 2x2 Matrices



$$\hat{H} = \frac{1}{\sqrt{2}}\begin{pmatrix} 1 & 1 \\ 1 & -1 \end{pmatrix}$$

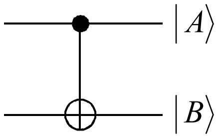
Hadamard Gate



Bloch Sphere

Two qubit gates:

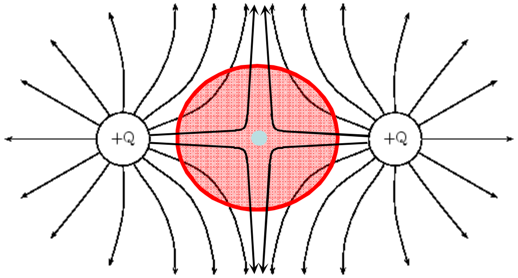
CNOT



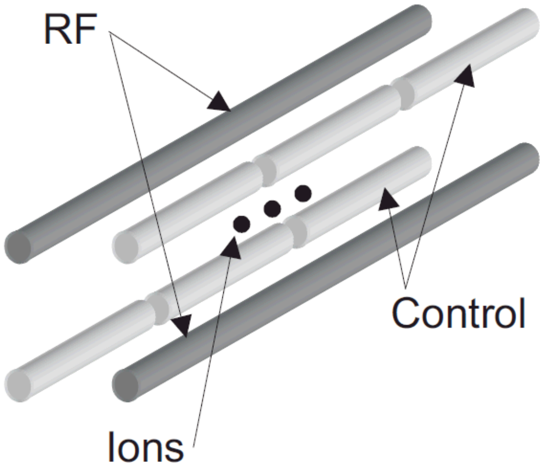
$$\hat{U}_{CN} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \end{pmatrix}$$

Laser cooled trapped ions are a leading Qubit technology. Many of the DiVincenzo criteria have been demonstrated and small scale algorithms have been performed with systems 1 – 10 qubits

Ion Trapping Basics



$$\nabla \cdot \mathbf{E} = 0 \Leftrightarrow \oiint \mathbf{E} \cdot d\mathbf{S} = 0$$



Earnshaw's Theorem: A charge cannot be confined in three dimensions by static potentials

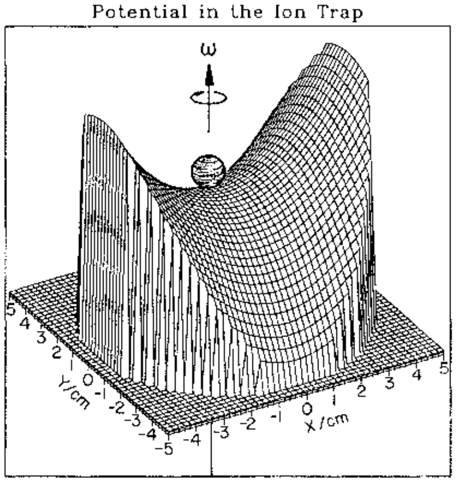


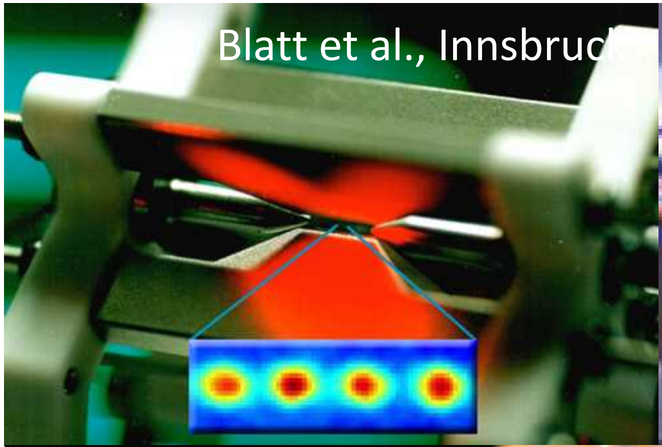
FIG. 8. Mechanical analogue model for the ion trap with steel-ball as "particle."

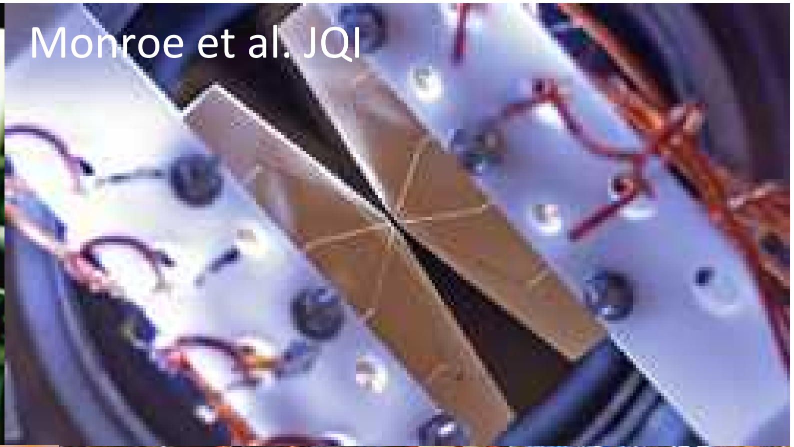
Rev. Mod. Phys., Vol. 62, No. 3, July 1990

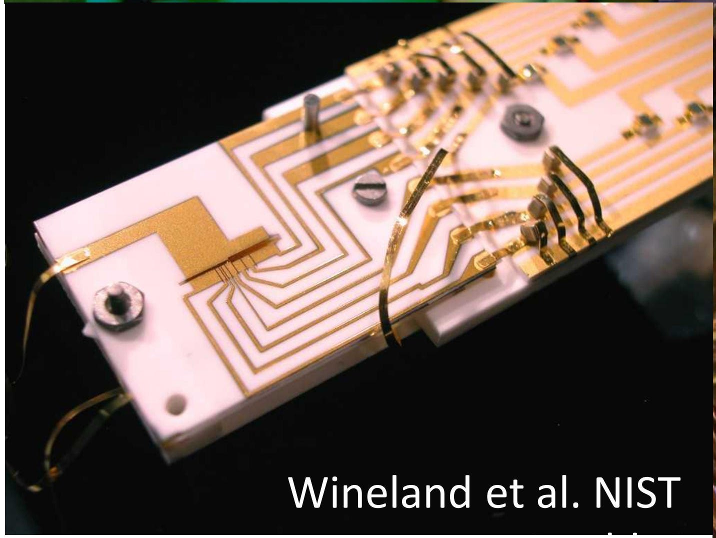
Nobel Prizes:

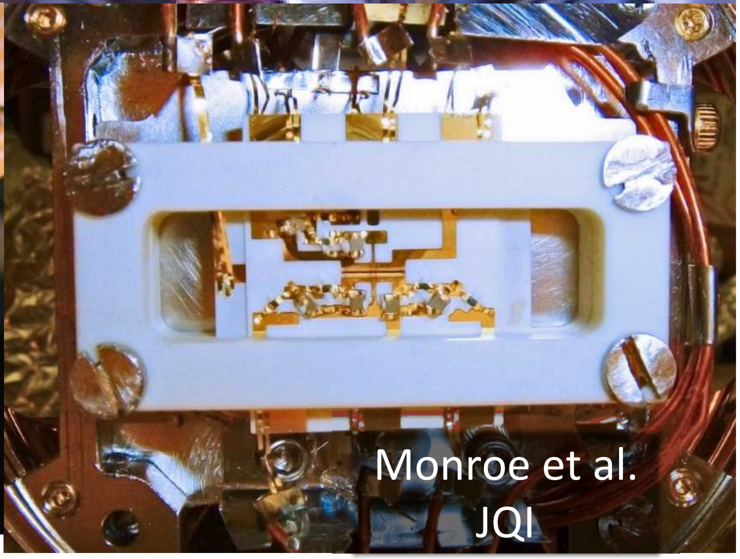
1989 - Hans Dehmelt (U of Washington) and Wolfgang Paul (Universität Bonn)
2012 – Dave Wineland (NIST Boulder)

Ion Trap Gallery:


Blatt et al., Innsbruck

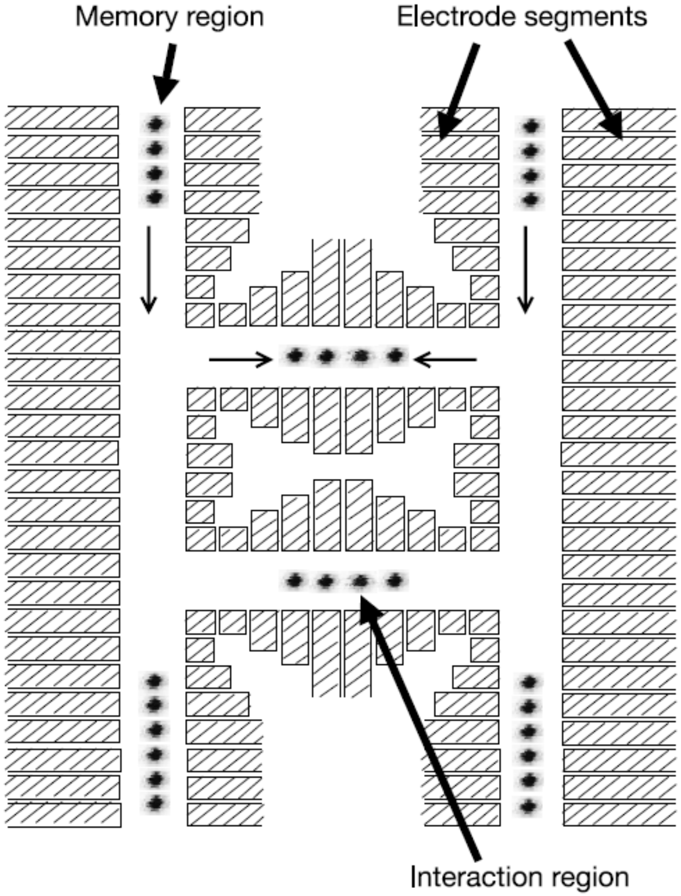

Monroe et al. JQI

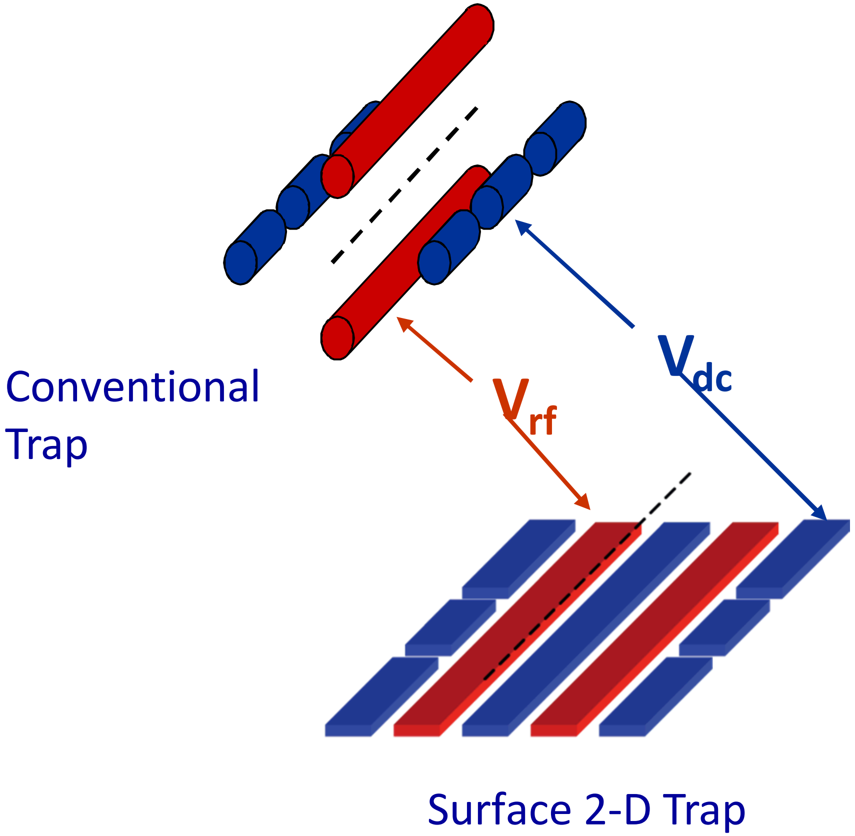

Wineland et al. NIST


Monroe et al. JQI

Ion traps before microfabrication are artisan, hand crafted systems

Trapped Ions as Qubits

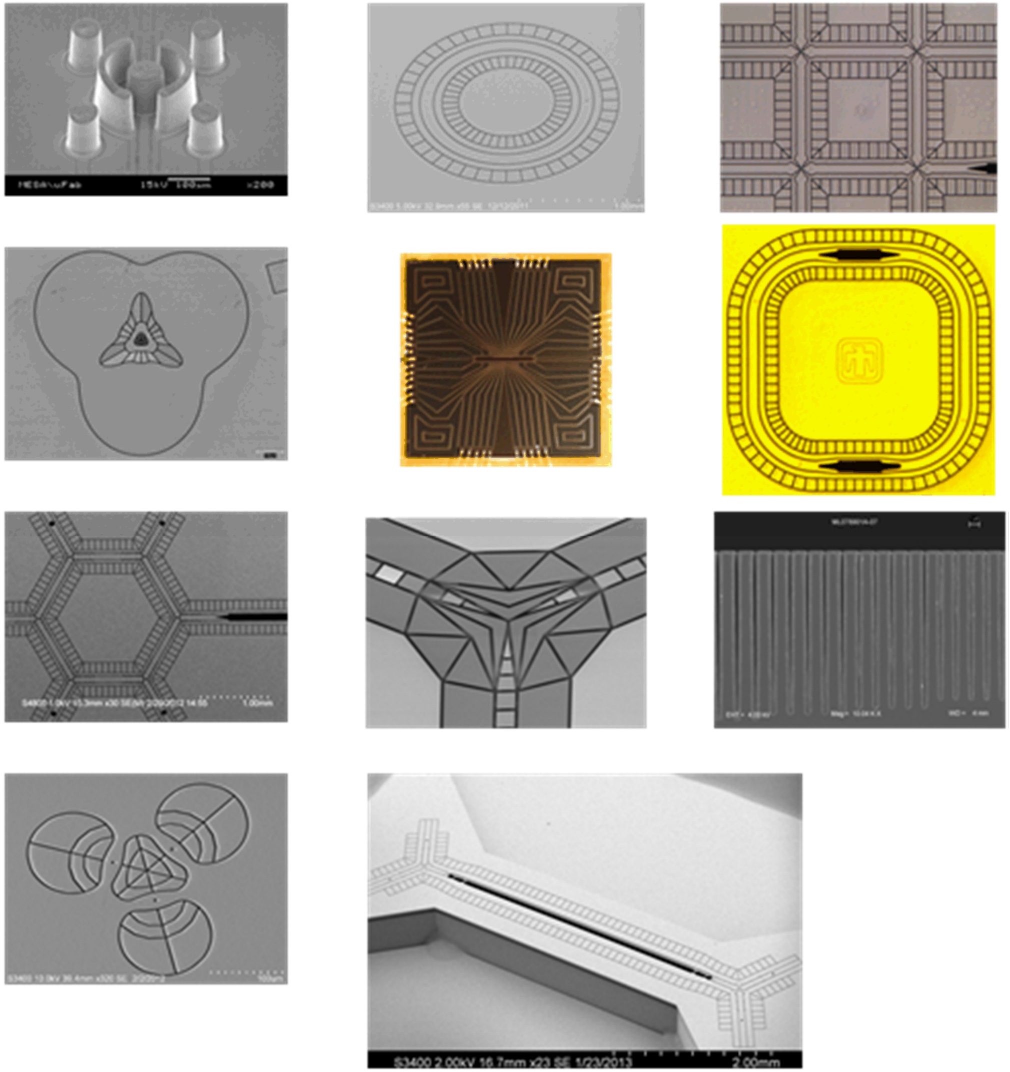




Kielpinski D, Monroe C, Wineland DJ. Architecture for a large-scale ion-trap quantum computer. *Nature* (2002) **417**:709–11.

Seidelin S, et al. Microfabricated Surface-Electrode Ion Trap for Scalable Quantum Information Processing. *Phys Rev Lett* (2006) **96**:253003

The Ion Trap Foundry at Sandia

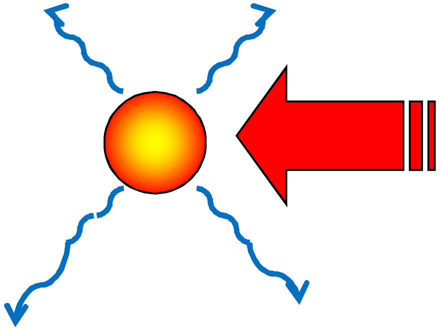


- Multiple designs delivered to multiple customers
  - 12 institutions, 5 countries
  - 8 institutions have successfully trapped using SNL designs
- Traps used with Ca^+, Yb^+, Mg^+
- Examining key device issues through:
  - Integrated diffractive optical elements (eliminate bulk optics)
  - Microwave on-chip control of ions (decrease laser/optics requirements)
  - Multiple metal layers (routing of control signals, increased design flexibility)

Doppler Cooling

Doppler cooling uses the spontaneous scattering force to cool an atom,

$$\vec{F} = (photon\ momentum) \times (scattering\ rate) = \hbar\vec{k}\,\gamma_p$$



Where scattering rate, γ_p, is given by,

$$\gamma_p = \frac{\frac{s_0\gamma}{2}}{1 + s_0 + \left[\frac{2(\delta + \omega_D)}{\gamma}\right]^2}$$

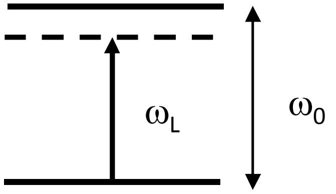
$s_0 = I/I_s$, on resonance saturation parameter

$\gamma = 1/\tau$, decay rate of excited state, typically ~20 MHz for ions

$I_s = \frac{\pi hc}{3\,\lambda^3\tau}$, saturation parameter, typically mW/cm^2

$\delta = \omega_L - \omega_0$, laser detuning

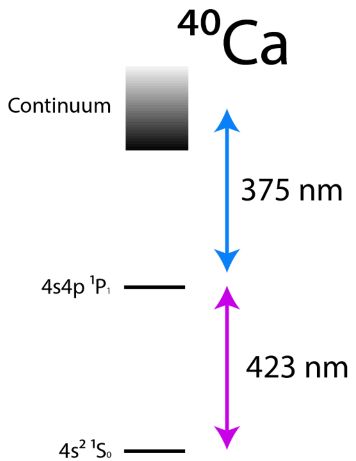
$\omega_D = -\vec{k}\cdot\vec{v}$ Doppler Shift

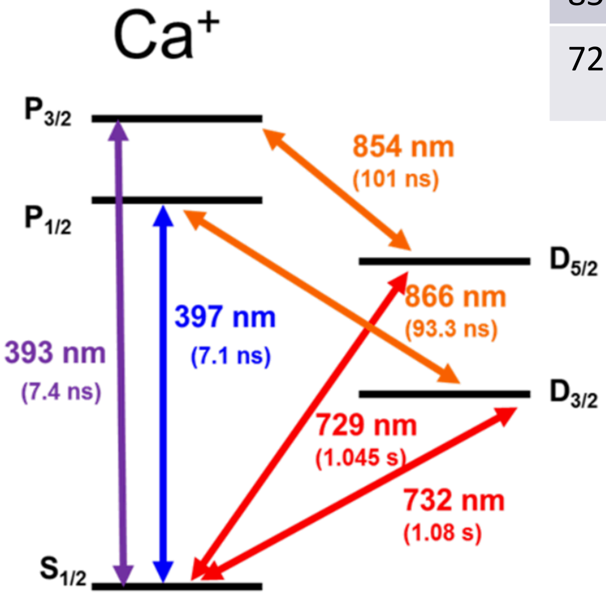


For δ<0, "red detuned," the atom experiences a viscous damping force that opposes the velocity of the atom. The atom absorbs a Doppler shifted, lower energy photon than it emits.

Doppler Cooling can cool atoms/ions to T < 1 mK

Laser Cooling Ca$^+$





Laser Wavelength (nm)	Function	Laser Type	Natural linewidth Γ / (2 π)
423	Photo-Ionization	ECDL	34.7 MHz
375	Photo-Ionization	Diode	
397	Doppler Cooling State Preparation Detection	ECDL + TA + SHG	22.4 MHz
866	Repump	ECDL	1.71 MHz
854	Repump	ECDL	1.58 MHz
729	Quantum Operations	Ti:S	0.15 Hz

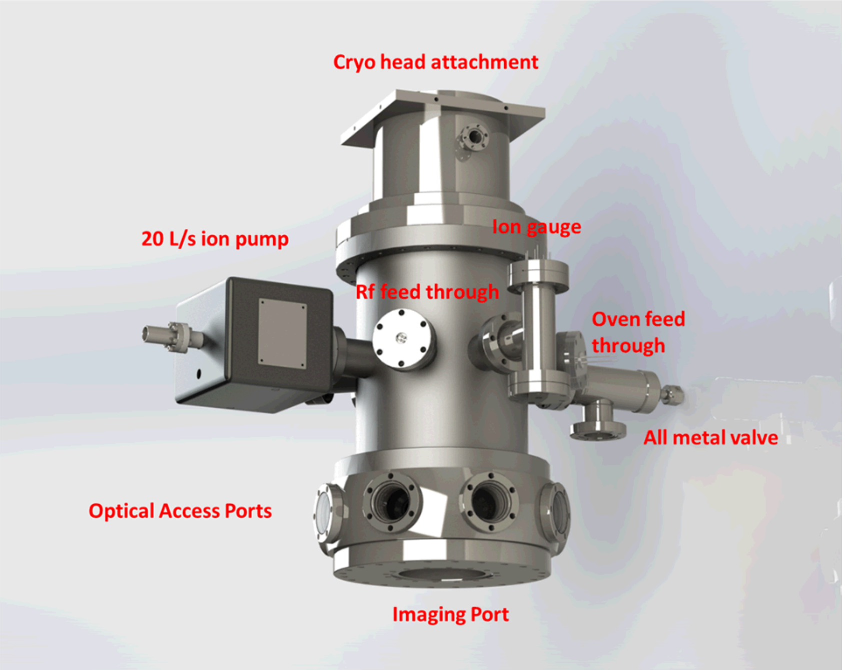
Laser cooling of Calcium Ions requires multiple laser technologies that span the UV to the NIR all stabilized to atomic references.

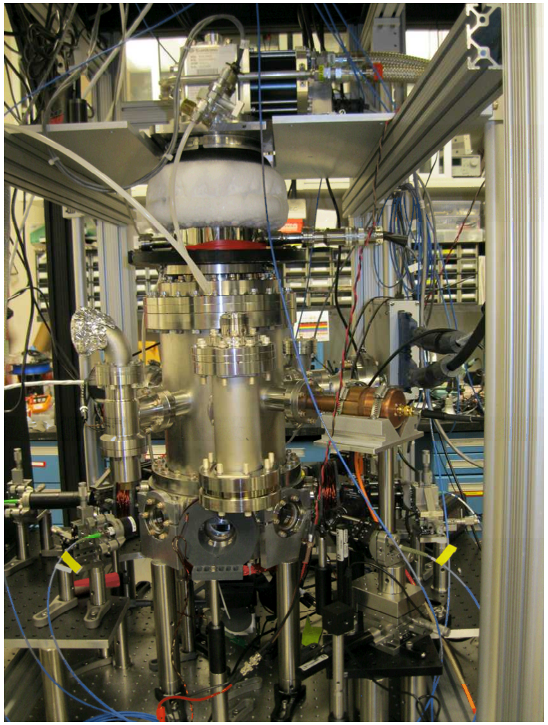
The Experiment:
Cryogenic Ion Trap Chamber Specifications

To isolate laser cooled trapped ions from the environment requires operating at Ultra-High Vacuum (P< 10^{-9} torr)

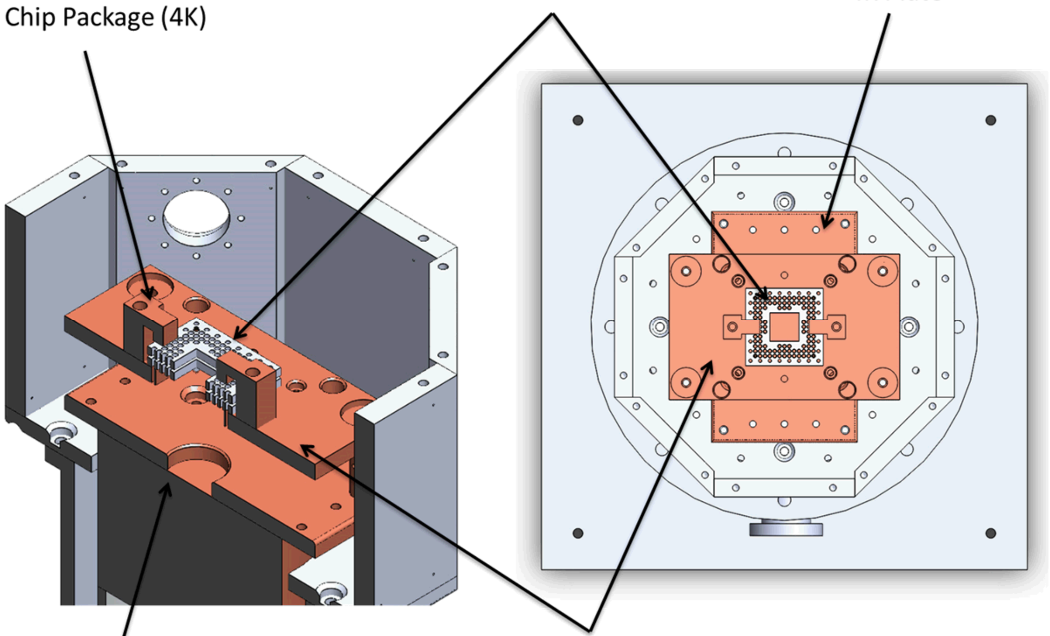
Cryo Industries of America

- 1.0 Watt @ 4K Cooling
- 34.0 Watt @ 40K Cooling
- Gifford McMahon (GM) – Closed Cycle
- Rubber Bellows Isolate Vibration from cold finger
- Full system is UHV compatible





Details of Cryo Chip Carrier



Additional Thermal Sink between 4K Plate and Chip Package (4K)

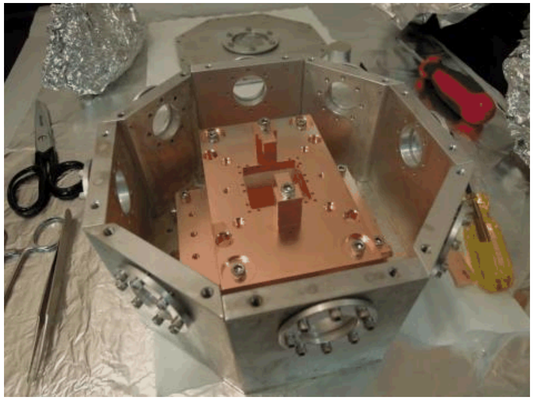
Chip Package (4 K)

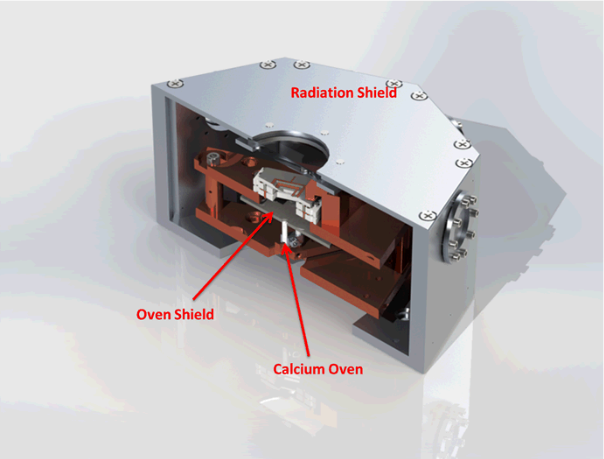
Top View

4K Plate

4K Plate

Custom Chip Carrier (4K)

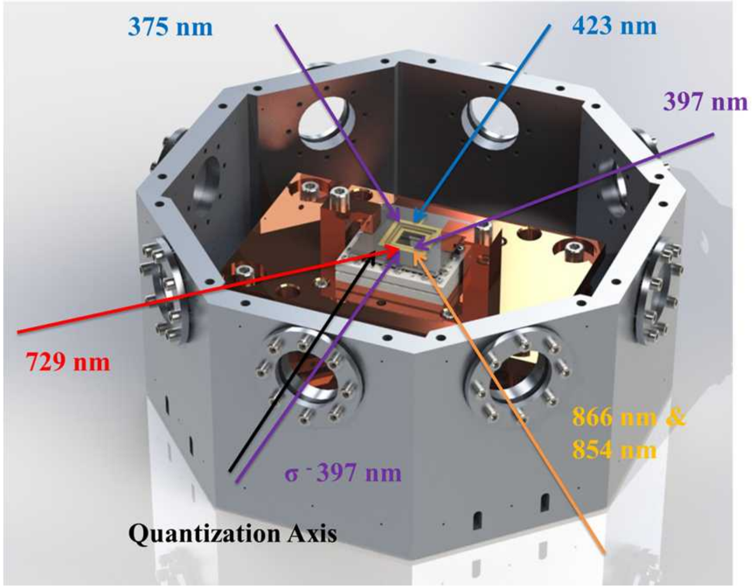


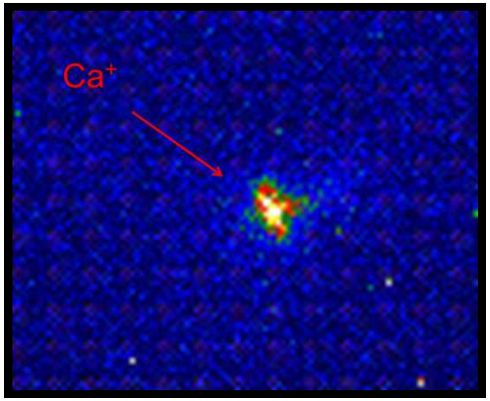


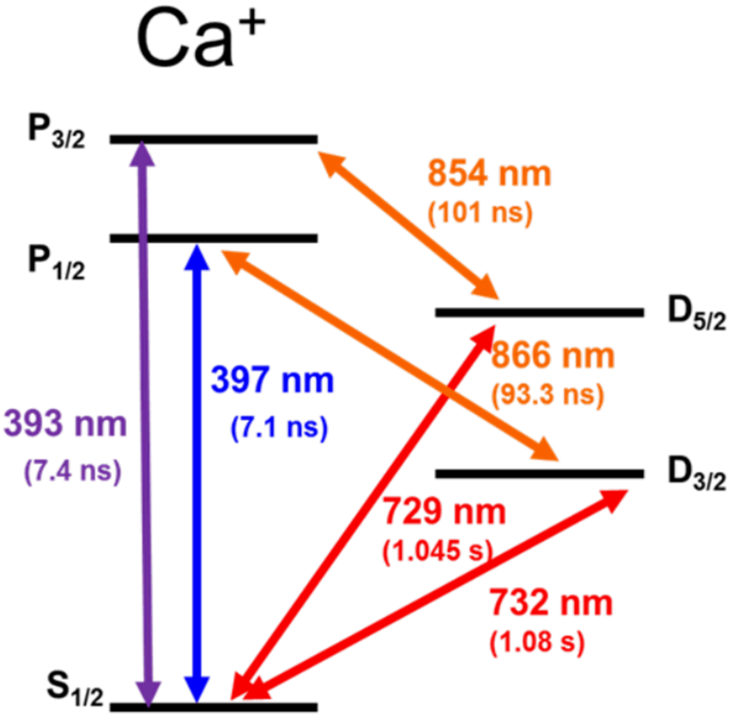
Heat sinking is primarily through CPGA pins and additional thermal heat-sink clamps

96 DC control channels to manipulate the trapping potential

Optical and Laser Access



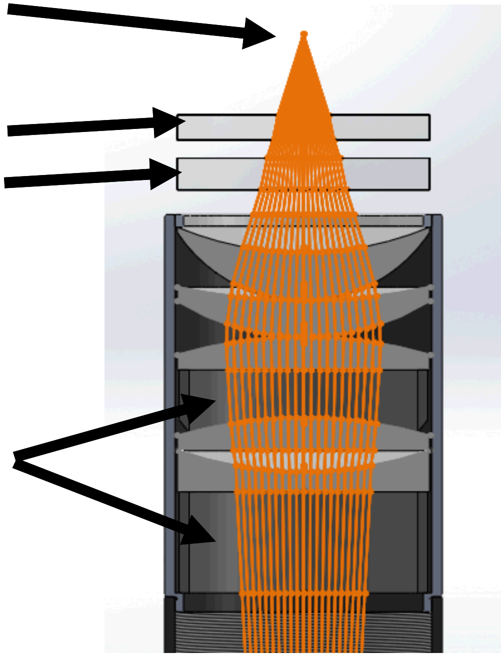




First trapped Calcium ion in Cryo System September 2015

COTs-Custom Imaging

Detection of Single Ion requires high NA, diffraction limited objective to collect a “larger” fraction of the solid angle



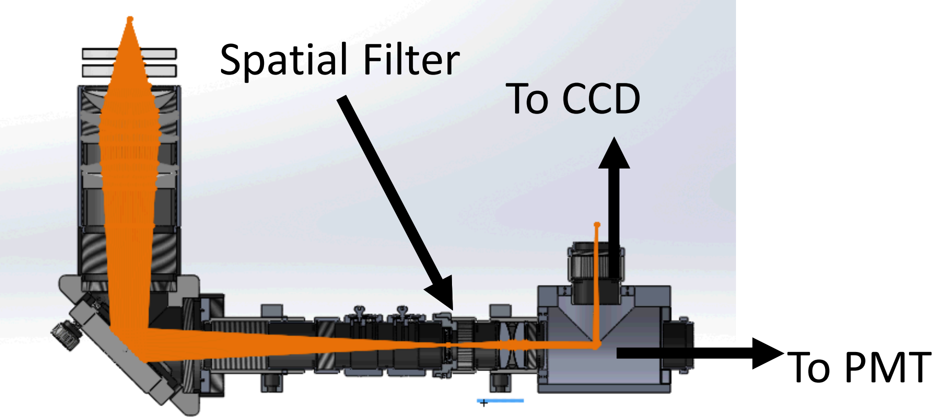
Ion

40K window

300K window

3D Printed Spacers

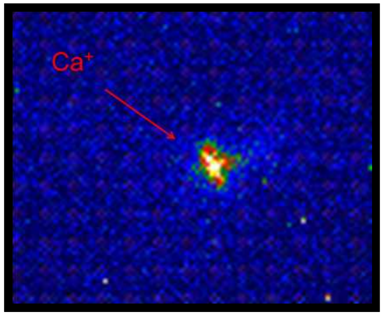
- 5 Lens custom objective using stock Thorlabs Lenses
- Optimized for 300 micron FOV
- Diffraction limited, STRL ratio > 0.8
- NA = 0.25
- 5 mm working distance from 300K window
- 5x mag



Spatial Filter

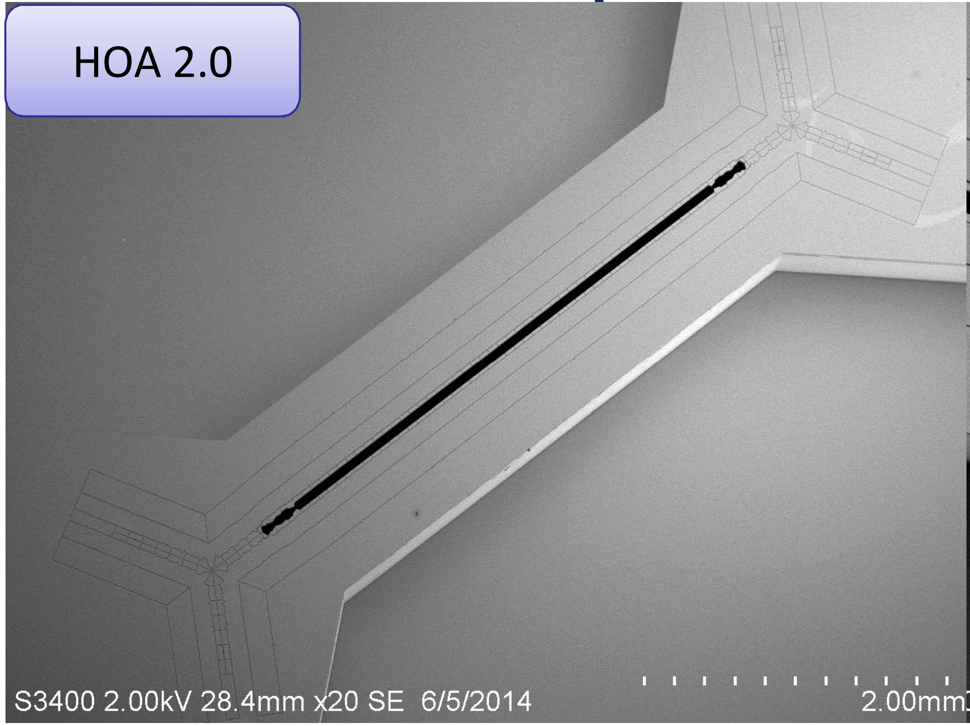
To CCD

To PMT

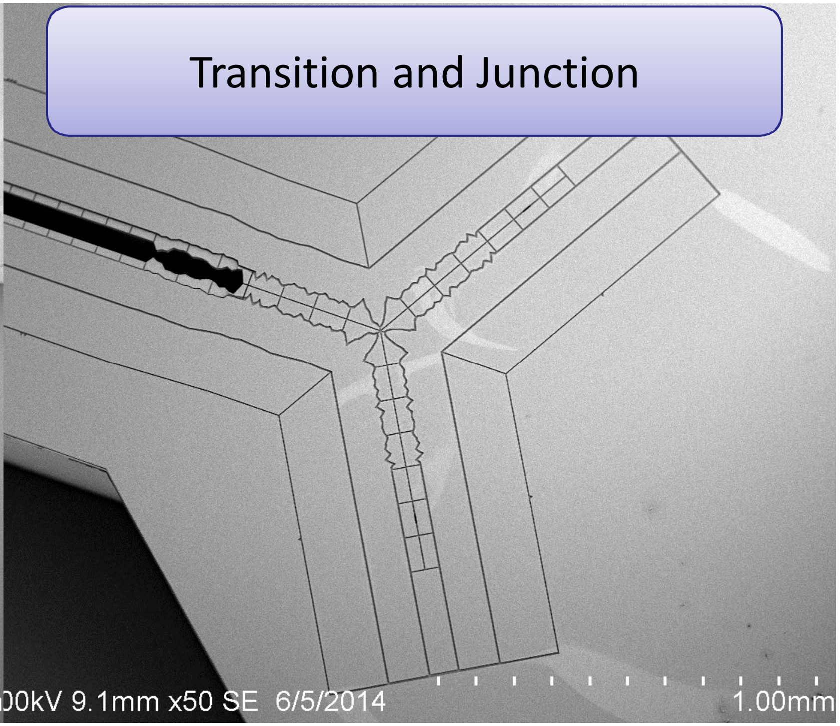


Full system 20x mag
Imaged on CCD or detected via PMT

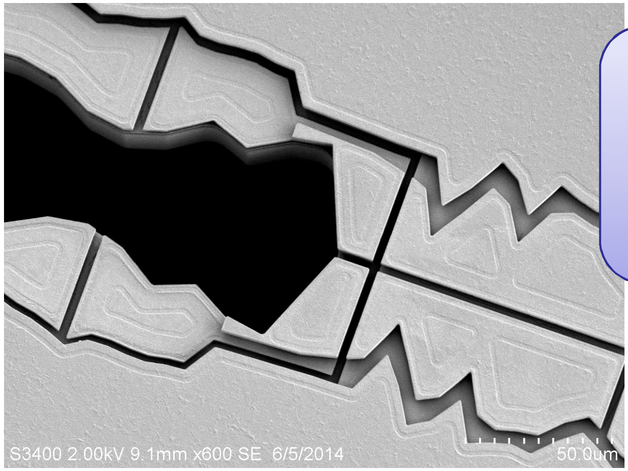
The Ion Trap details: HOA2



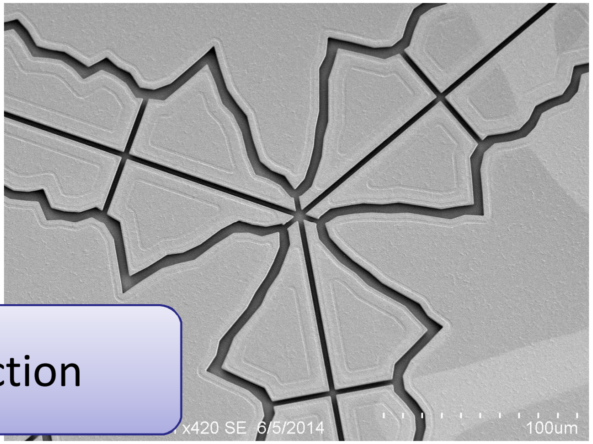
HOA 2.0



Transition and Junction



Segmented DC electrodes



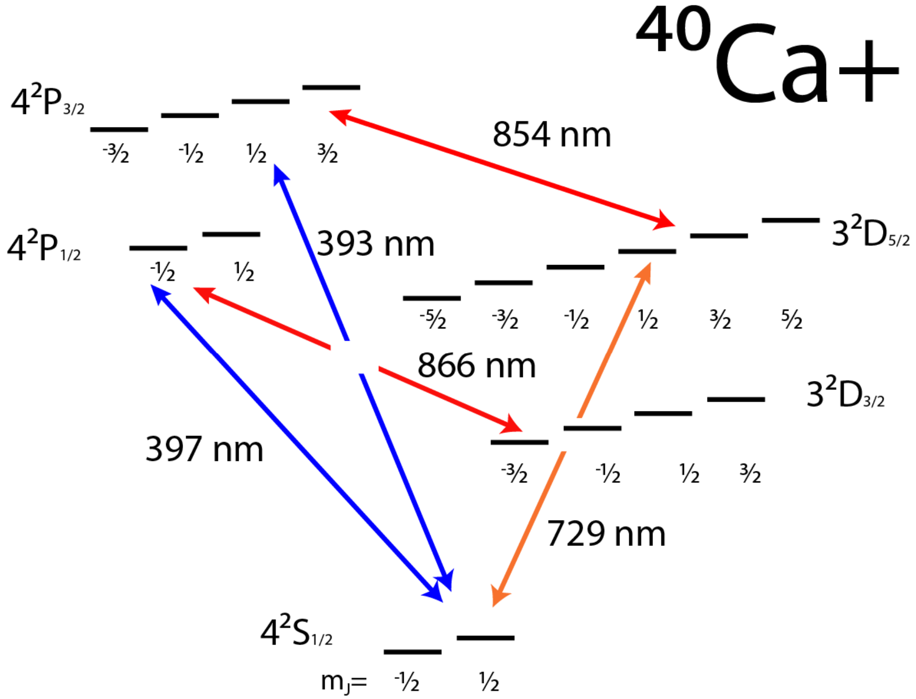
Junction

Quadrupole Transition in Ca^+

Construct a Zeeman Qubit by using a magnetic field to split the degeneracy of the states

$$|0\rangle = 4S_{\frac{1}{2}}, m_j = -\frac{1}{2}$$

$$|1\rangle = 3D_{\frac{5}{2}}, m_j = -\frac{1}{2}$$



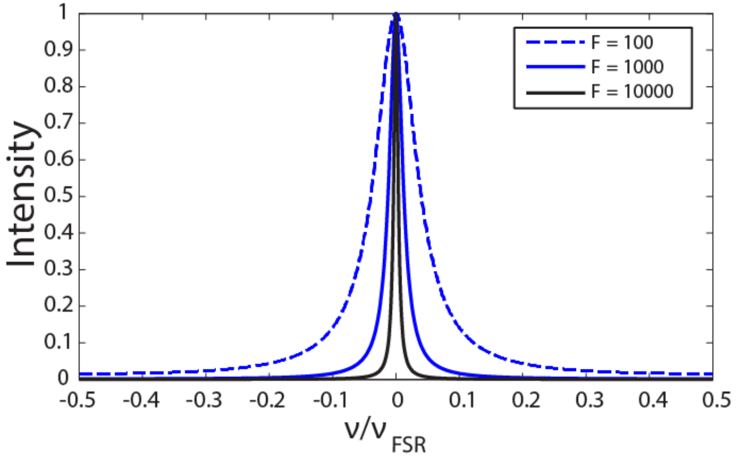
This transition has been demonstrated by Blatt's group in Innsbruck for high fidelity two-qubit gates. Due to $D_{5/2}$, long natural lifetime(τ = 1.045) requires an ultra-stable laser (Linewidth < 1 Hz)

Ultra-Stable Lasers to Probe Narrow Optical Transitions

Applications:

Atomic Optical Clocks (~10^{-16})

Quantum Information



<u>Key requirements of Narrow lasers:</u>

High Finesse optical cavities

Passive + Active stabilization

High Finesse, Ultra-Low Expansive Glass Cavity

Stable Laser Systems/ATF

Temperature stabilized vacuum housing

Acoustic Enclosure: 30 – 50 dB of Sound Damping

Cavity held at center-of-mass to reduce sensitivity to acceleration

Notcutt M, Ma L-S, Ye J, Hall JL. Simple and compact 1-Hz laser system via an improved mounting configuration of a reference cavity. *Opt Lett* (2005) **30**:1815.

Techniques to frequency stabilize a laser

Laser cooling and trapping requires a single frequency laser that is both precise and accurate.

Technique	Linewidth	Requirements	Limitations
Stabilize to wavemeter	~ 1 MHz	Reference laser stabilized to absolute reference	Accuracy limited by how close reference laser is to target laser
Stabilize to Vapor Cell (atomic or molecular)	< 1 MHz	Absorption line needs to be near transition of interest	Linewidth limited by natural lifetime of transition
Stabilize laser to cavity	< 1 Hz	A cavity with appropriate mirror selection. Wavemeter to find "right" mode.	Linewidth of cavity is "tuneable" and set by choice of mirror coatings

Pound-Drever Hall

Standard technique to stabilize the a laser to a cavity is the Pound-Drever Hall (PDH) method.

Requires modulation of the laser frequency at Ω with a depth of β

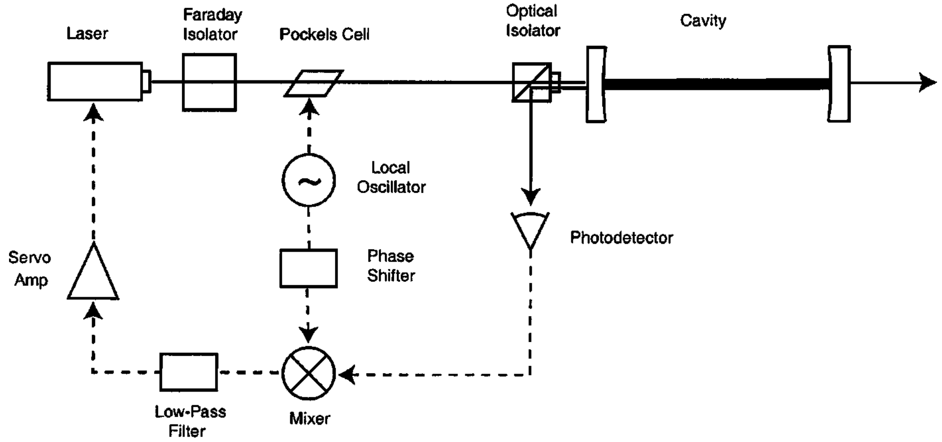
$$E_{inc} = E_0 e^{i(\omega t+\beta\sin\Omega t)} \approx E_0 e^{i\omega t}(1+\beta\sin\Omega t) = \mathrm{E}_0\mathrm{e}^{i\omega t}\left(1+\frac{\beta}{2}e^{i\Omega t}-\frac{\beta}{2}e^{-i\,\Omega t}\right)$$

Frequency modulation the laser frequency Reflected E-field at the photo detector.

$$E_{ref}(\omega) = \mathrm{E}_0\left(R(\omega)\mathrm{e}^{i\omega t} + R(\omega+\Omega)\frac{\beta}{2}e^{i(\omega+\Omega)t} - R(\omega-\Omega)\frac{\beta}{2}e^{i(\omega-\Omega)t}\right)$$

Reflection coefficient for symmetric cavity

$$R(\omega) = \frac{E_{ref}}{E_{inc}} = \frac{r\left(\exp\left(\frac{i\omega}{\Delta\nu_{FSR}}\right)-1\right)}{1-r^2\exp\left(\frac{i\omega}{\Delta\nu_{FSR}}\right)}$$



PDH Error Signal

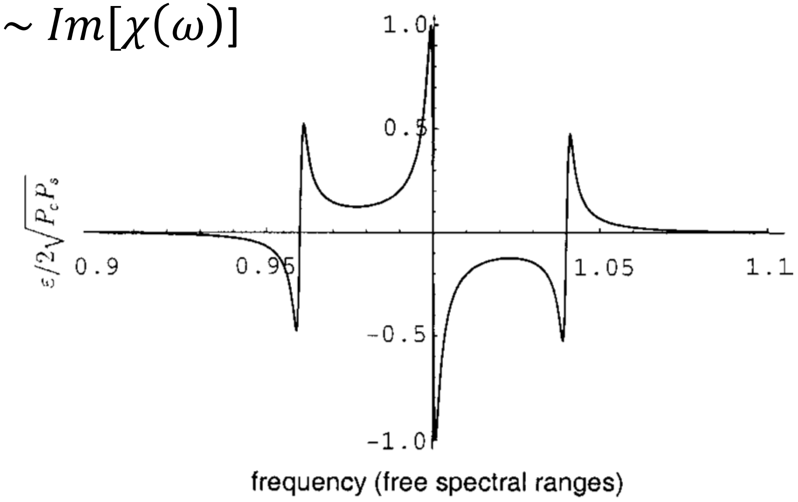
Photo-dectors are sensitive to optical power not electric field

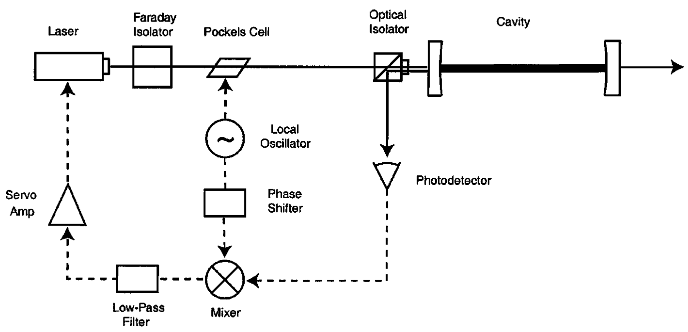
$$P_r = \left|E_{ref}\right|^2 \sim DC\ terms + Re[\chi(\omega)]cos\Omega t + Im[\chi(\omega)]\sin\Omega t + terms\ at\ 2\Omega$$

$$\chi(\omega) = \mathrm{R}(\omega)R^*(\omega+\Omega) - R^*(\omega)R(\omega-\Omega)$$

After mixing and filtering the error signal is,

$$V \sim Im[\chi(\omega)]$$



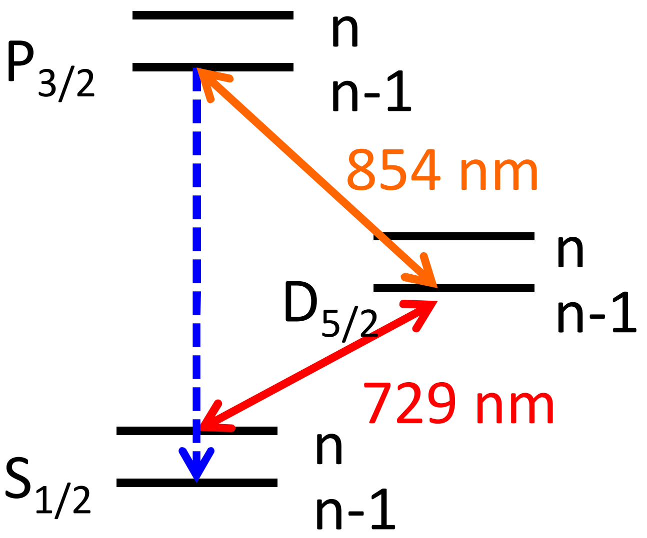


Near carrier resonance the error signal is proportional to the changes in cavity length, $V \sim \delta L$

Black, E. D. An introduction to Pound–Drever–Hall laser frequency stabilization. *Am. J. Phys.* **69,** 79 (2001).

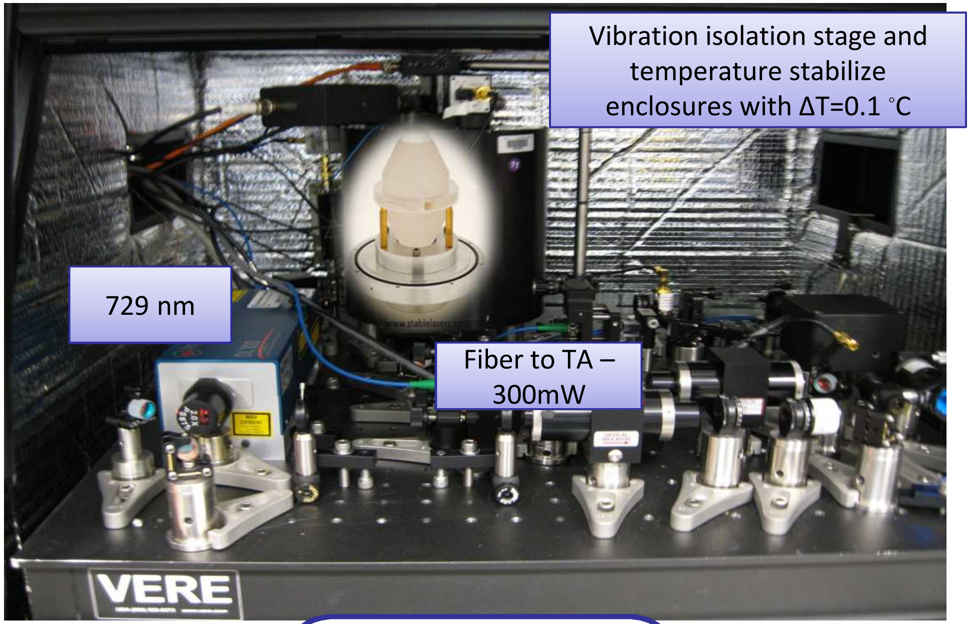
Ultra-Stable Diode laser for Quadrupole Ca^+

Calcium Optical Quibit



ULE Optical Cavity

Fabry-Perot cavity (ATFilms 6030)



Vibration isolation stage and temperature stabilize enclosures with ΔT=0.1 °C

729 nm

Fiber to TA – 300mW

$F = 200{,}000$

$\nu_F = 1.93$ GHz

$\delta_\nu = \frac{\nu_F}{F} = 9.65$ kHz

$T_c = 24.2$ °C

Optical Frequency = 411042129776393.2(1.0) Hz

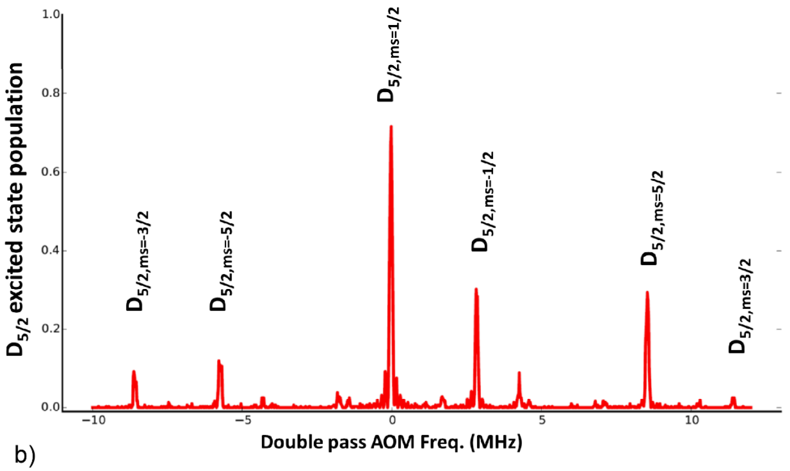
Transition Linewidth = 0.15 Hz

Requires stabilizing the laser frequency to better than 1 part-per-trillion

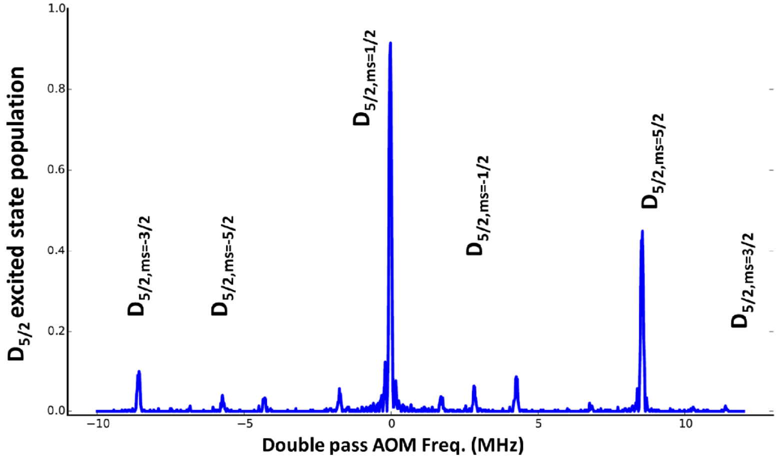
Zeeman Spectroscopy of Quadrupole Transition

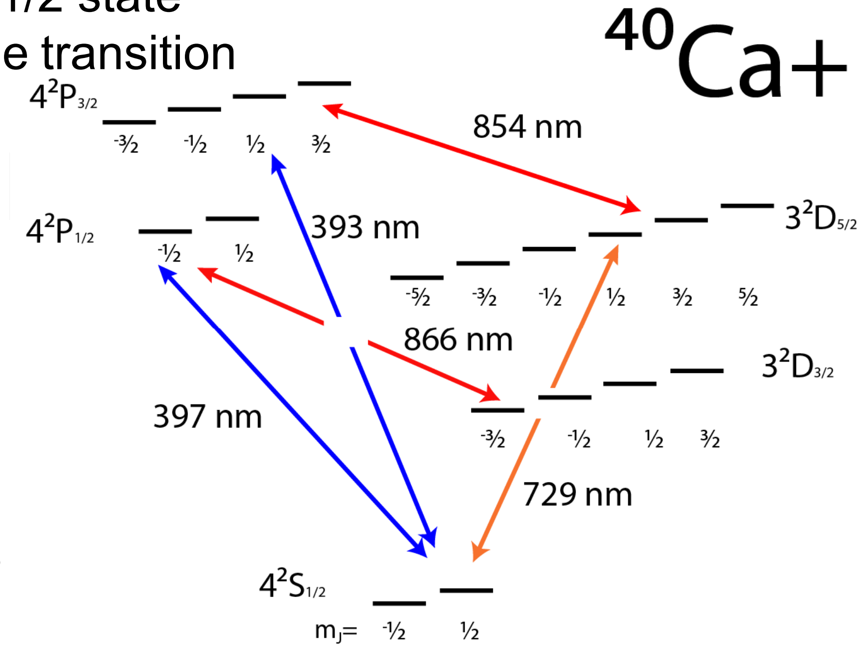
Spin polarize the atom in the $S_{1/2}$, m_j=-1/2 state
Apply 729 nm pulse to drive quadrupole transition

a)



b)



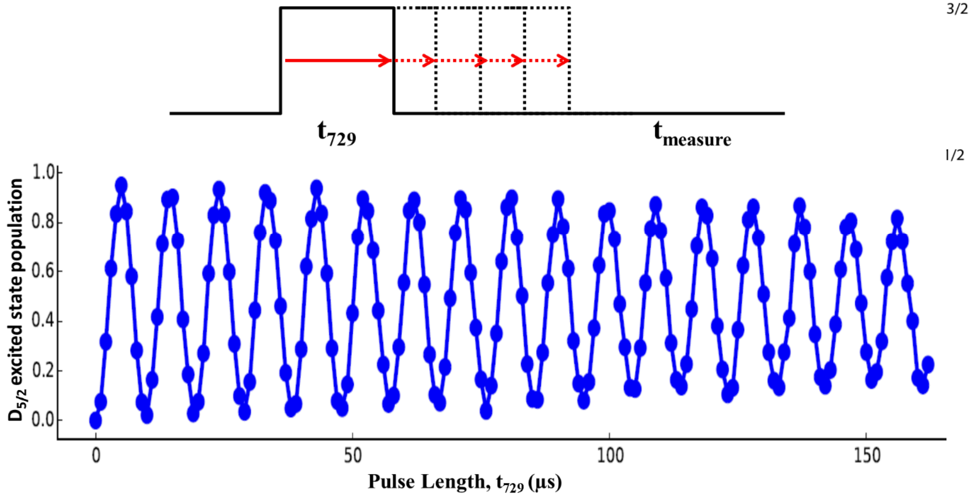


We can drive the 6 allowed transitions for experimental polarization/magnetic field

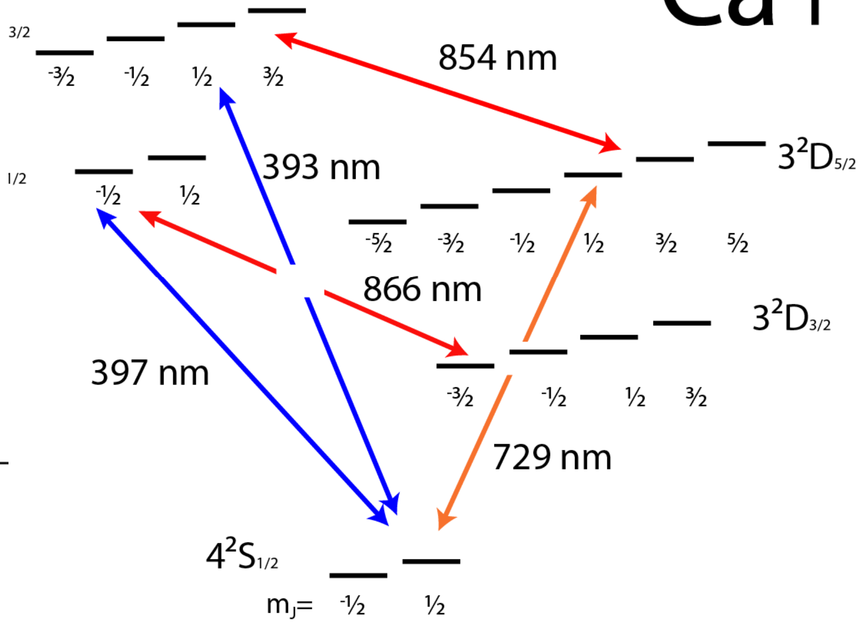
Selection Rule: $\Delta m_j = \pm 2, 0$.

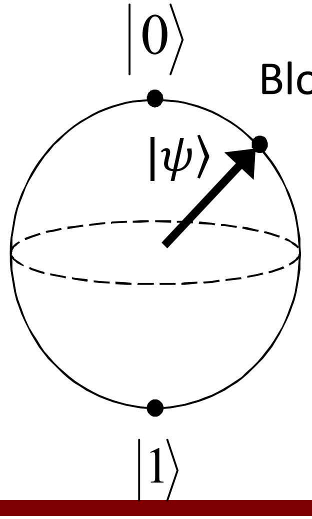
Coherent Rabi Oscillations

Perform coherent operations on 729 nm optical qubit transition



^{40}Ca+



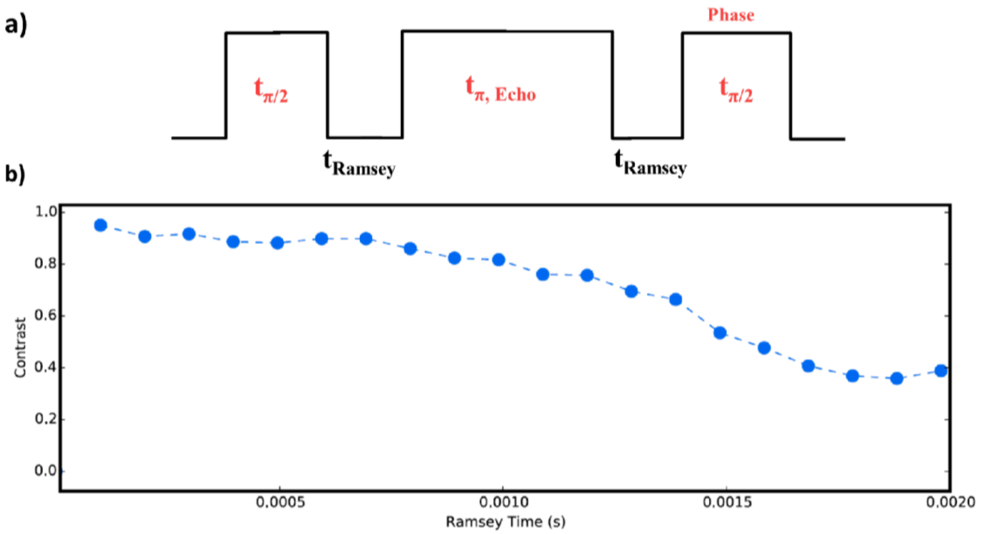


Bloch Sphere

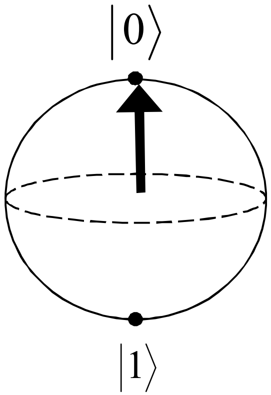
$$|\psi\rangle = \cos\left(\frac{\theta}{2}\right)|0\rangle + e^{i\phi}\sin\left(\frac{\theta}{2}\right)|1\rangle$$

$|0\rangle$ = $S_{1/2}$, m_J=-1/2
$|1\rangle$ = $D_{5/2}$, m_J=-1/2

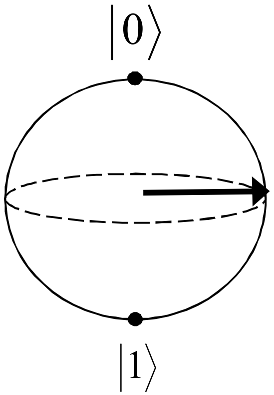
Ramsey (Spin Echo) Experiment



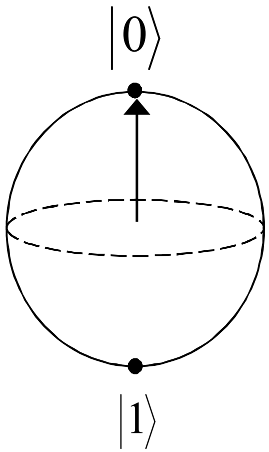
Without dechorence Ramsey contrast would be perfect until the Ramsey time equaled the lifetime of the transition



init



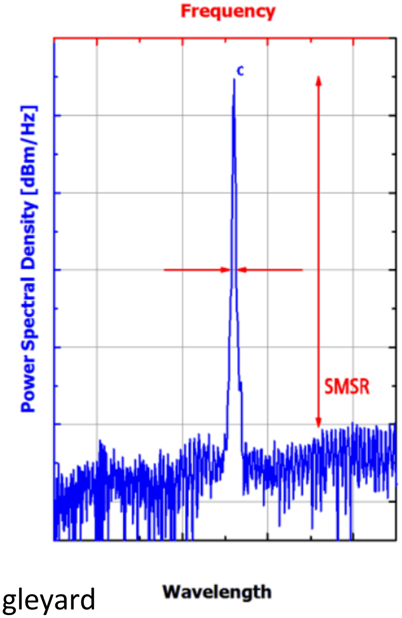
π/2



π/2

Limitation with Diode Lasers

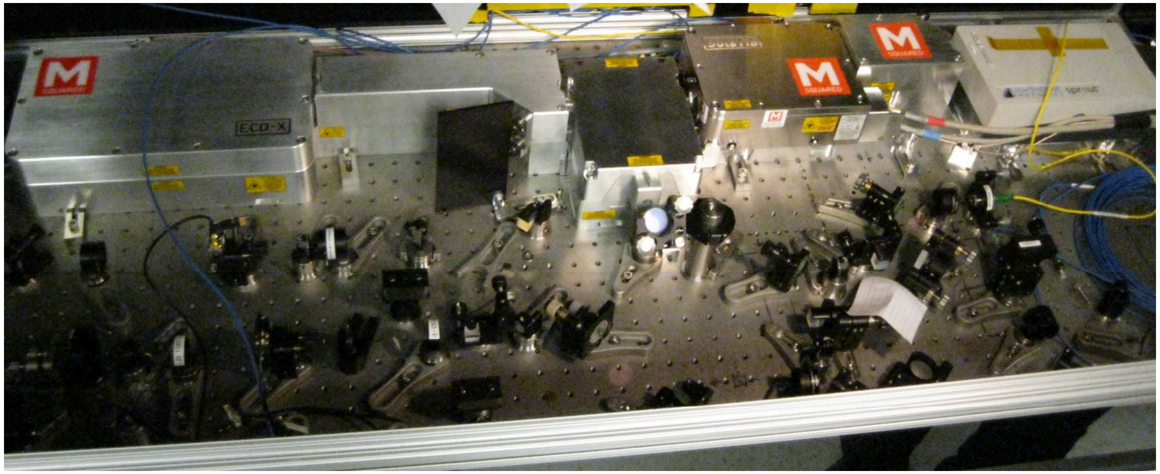
Diode lasers suffer from an amplified spontaneous emission pedestal. This noise pedestal will limit future quantum gates based on quadrupole transition.



Eagleyard

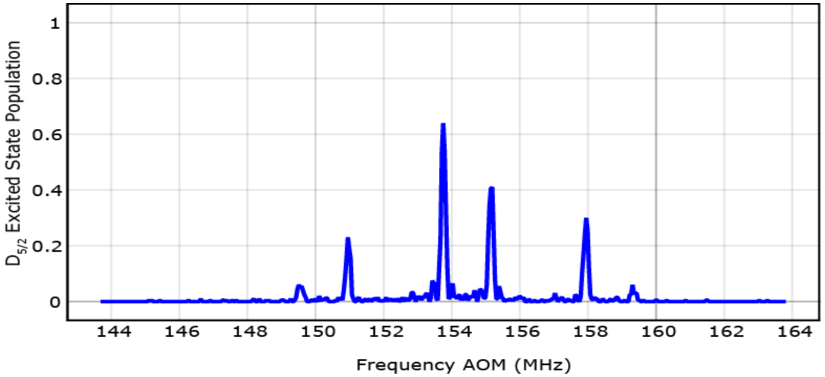
Typical Diode ASE suppression is 40 dB

Solution:
Ti:Sapphire laser from M-squared.
Installed 6/1/16

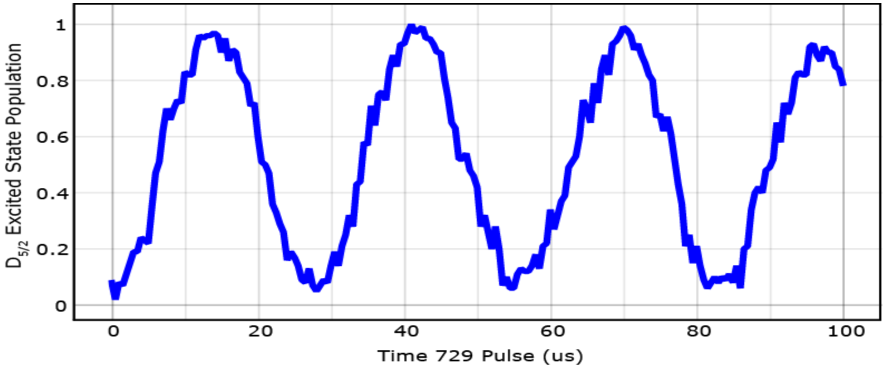


System identical to one used at Universität Innsbruck to perform quantum gates

Data with Ti:Sapphire



Zeeman Spectroscopy



Rabi Flopping

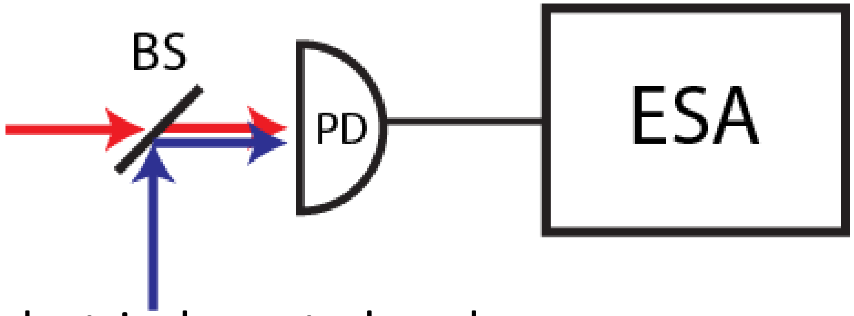
Ti:Sapphire laser lock on ULE cavity looks much tighter (narrower) than old diode laser but how do we measure its linewidth?

How to Measure a 1 Hz linewidth: Heterodyne

"Beat" two lasers together and measure the spectrum with a fast photo-diode and a RF spectrum analyzer

Lasers need to be close in frequency

- 40 GHz corresponds to $\Delta\lambda = 0.085$ nm at 800 nm



The resulting spectrum's linewidth on electrical spectral analyzer:

$$\Delta\upsilon = \Delta\upsilon_1 + \Delta\upsilon_2$$

Usually assumed that two lasers have nearly the same linewidth:

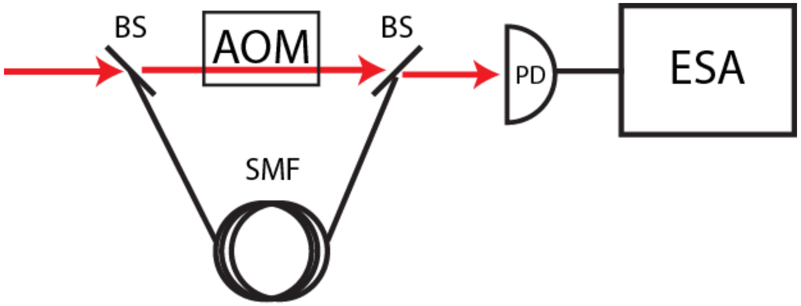
$$\Delta\nu = 2\Delta\nu_{Laser}$$

Requires building two independent 1 Hz laser systems which is expensive ($$$$$)

Delayed Self Heterodyne Measurement Interferometer

- Requirement the length of optical fiber needs to be longer than coherence length of laser
- Coherence Length, $L = \frac{c}{n \ \Delta \upsilon}$

Linewidth	**Coherence Length (m)**	
10 MHz	30	
1 MHz	300	Typical ECDL
100 kHz	3,000	
10 kHz	30,000	Typical Fiber Laser
1 Hz	30,000,000	Narrow Lasers



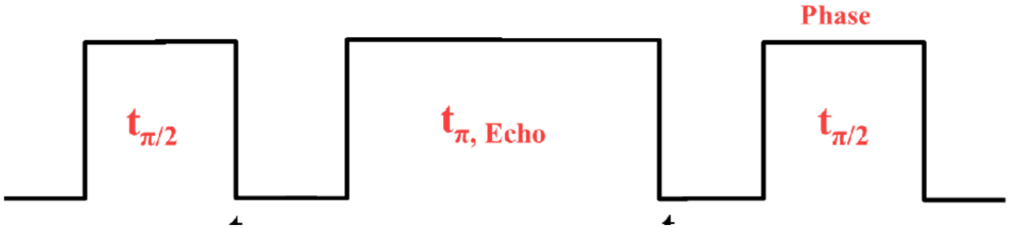
Fiber Optical Delay Line

For very narrow lasers it is often "easier" to build two systems to evaluate their performance

Current Efforts: Use The Ion to measure the linewidth

Use ion as an "imperfect" frequency detector.

Measurement is convoluted because ion is sensitive to magnetic and electric field fluctuations.



Measure the Ramsey Contrast assumes a Gaussian noise model for the laser which changes the detuning

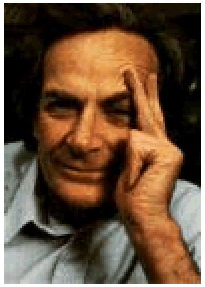
$$C(\tau_{RAMSEY}) = \exp\left(-\frac{\pi^2 \Delta\nu_{FWHM}^2 \tau_{RAMSEY}^2}{4\ln 2}\right)$$

In terms of the time delay when contrast equals ½,

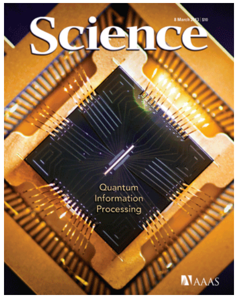
$$\Delta\nu_{FWHM} = \frac{2\ln 2}{\pi} \frac{1}{\tau_{\frac{1}{2}}}$$

Chwalla MM. Precision spectroscopy with 40 Ca + ions in a Paul trap. Ph.D. Thesis, Innsbruck, (2009)

Summary

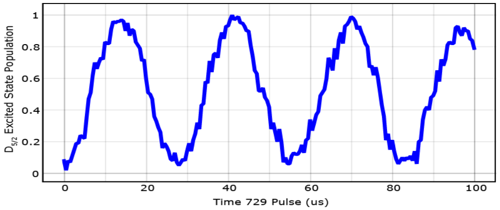


Basics of quantum computing, ion traps, and laser cooling.



Microfabrication has revolutionized ion trapping moving from hand crafted experiment to repeatable devices

Techniques to build ultra-stable lasers



Manipulations of the ultra-narrow quadrupole transition in Ca^+

Thanks to SNL Ion Trapping Team Members, ***Especially:***
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Matt Blain