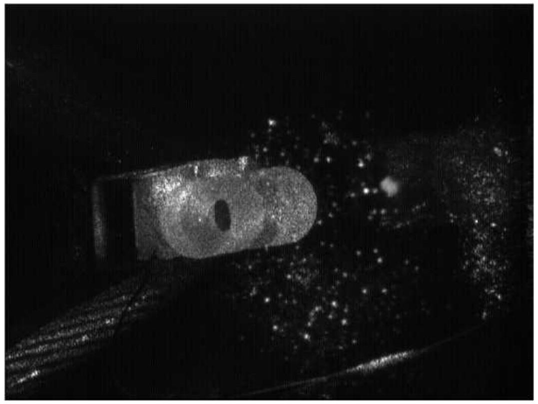
Engineered Systems for Quantum Applications Using Cold Atoms

SAND2008-3171C

First Transistor

Bell Labs, 1947



Cloud of 1 million laser cooled atoms 8 mm from a high finesse cavity

Kevin M. Fortier

Sandia National Labs

Photonic Microsystem Technologies

NIST/Sandia Workshop

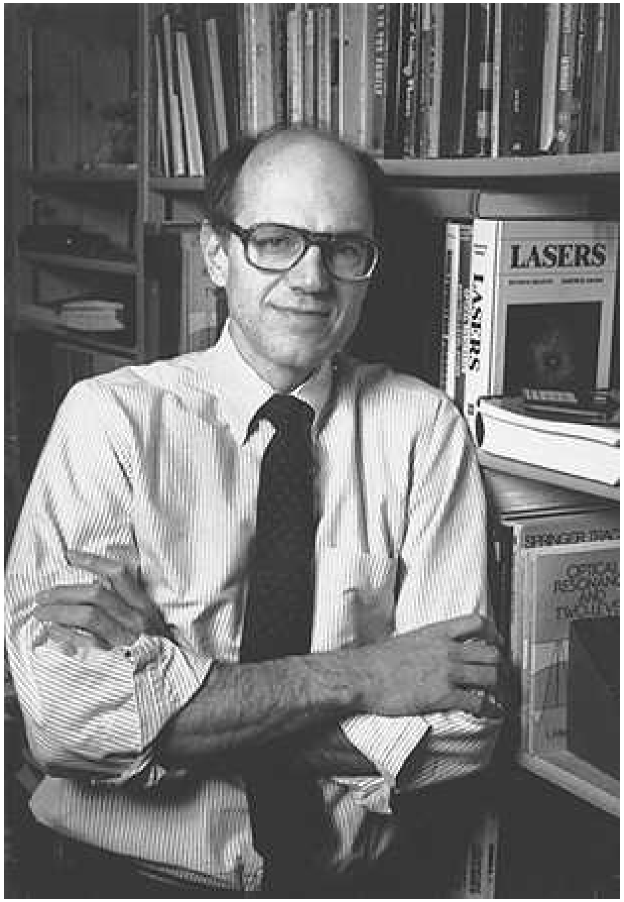
14 May 2008

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



J. H. Eberly

2007 president of the Optical Society of America

We attempt and experiment with the **Unrealistic**

Outline

Background

- Cavity QED based Quantum Computer
- Strong Coupling in Cavity QED

Experimental Results

- Single Atom Trapping
- MOT production
- Observation of cavity-assisted cooling

Engineered Solution for Quantum Cavity QED

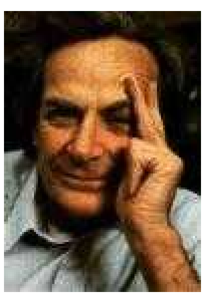
Conclusion

Why Build a Quantum Computer?

Factoring Large Numbers

Shor's Algorithm
RSA Encryption

Quantum Simulators



Unordered Search

Grover Algorithm

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

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DiVincenzo Criteria

QC Approach	The DiVincenzo Criteria: Quantum Computation #1	#2	#3	#4	#5	QC Networkability #6	#7
NMR	red	orange	orange	green	orange	red	red
Trapped Ion	orange	green	orange	green	green	orange	orange
Neutral Atom	orange	green	orange	orange	orange	orange	orange
Cavity QED	orange	green	orange	orange	green	orange	orange
Optical	orange	orange	green	orange	orange	orange	green
Solid State	orange	orange	orange	orange	orange	red	red
Superconducting	orange	green	orange	orange	orange	red	red
Unique Qubits	This field is so diverse that it is not feasible to label the criteria with "Promise" symbols.						

Legend: green = a potentially viable approach has achieved sufficient proof of principle

orange = a potentially viable approach has been proposed, but there has not been sufficient proof of principle

red = no viable approach is known

The column numbers correspond to the following QC criteria:

#1. A scalable physical system with well-characterized qubits.

#2. The ability to initialize the state of the qubits to a simple fiducial state.

#3. Long (relative) decoherence times, much longer than the gate-operation time.

#4. A universal set of quantum gates.

#5. A qubit-specific measurement capability.

#6. The ability to interconvert stationary and flying qubits.

#7. The ability to faithfully transmit flying qubits between specified locations.

http://qist.lanl.gov

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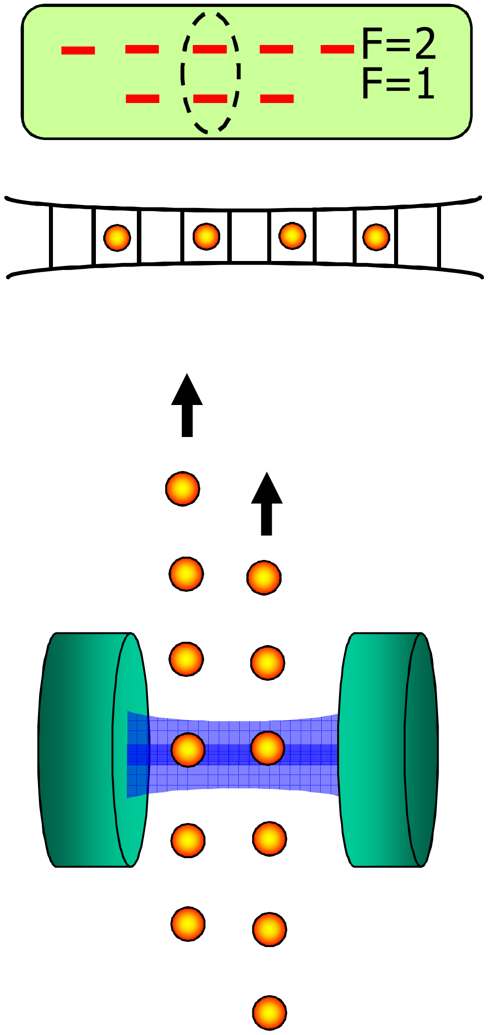
- **Qubits**
  – hyperfine states of neutral Rb
- **Qubit storage**
  – optical dipole lattice trap
- **Qubit interactions**
  – 2 trapped atoms inside optical microcavity
- **Detection**
  – single atom inside cavity



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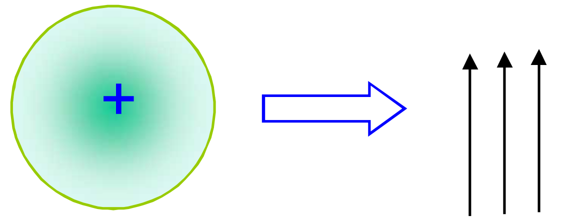
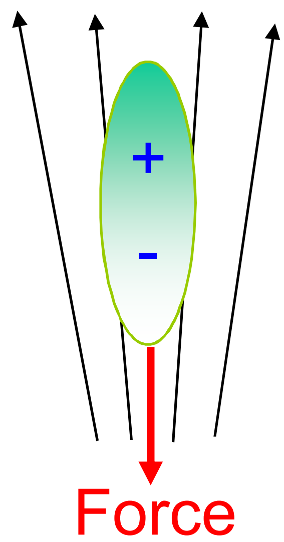
- **<u>Trapping with electric fields</u>**
  - Neutral atoms
    - E- field induces electric dipole



$$p = \alpha E$$

  - Induced electric dipole attracted to regions of high field for red detuned traps
    - Use focused laser beams

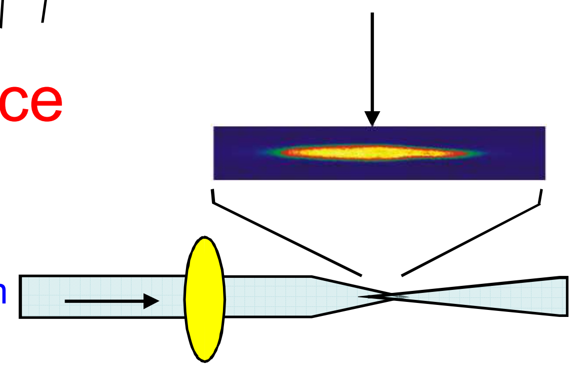


α, atomic polarizability

$$U = -\frac{1}{2}\alpha\left\langle E^2 \right\rangle = -\frac{\alpha}{2c\varepsilon_0} I$$

  - Spontaneous photon scattering causes heating
    - Use laser wavelength far from atomic resonance

$$\lambda_{\text{Yb Fiber laser}} = 1064\ \text{nm}$$



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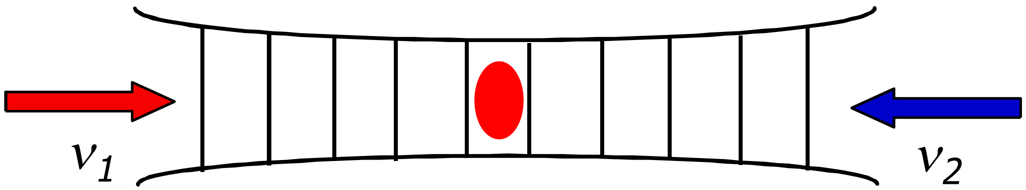
Optical Trapping II: One dimensional optical lattice

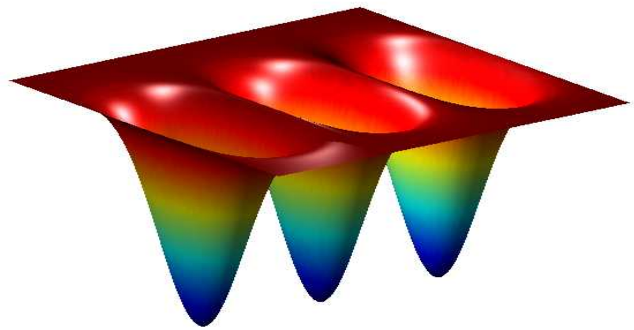


"walking wave"

Trapping Potential

$$U_{dip} = 4\frac{3\pi c^2}{2\omega_0^3}\left(\frac{\Gamma}{\Delta}\right)I(r,z)$$

$$\approx 1\ \mathrm{mK}$$

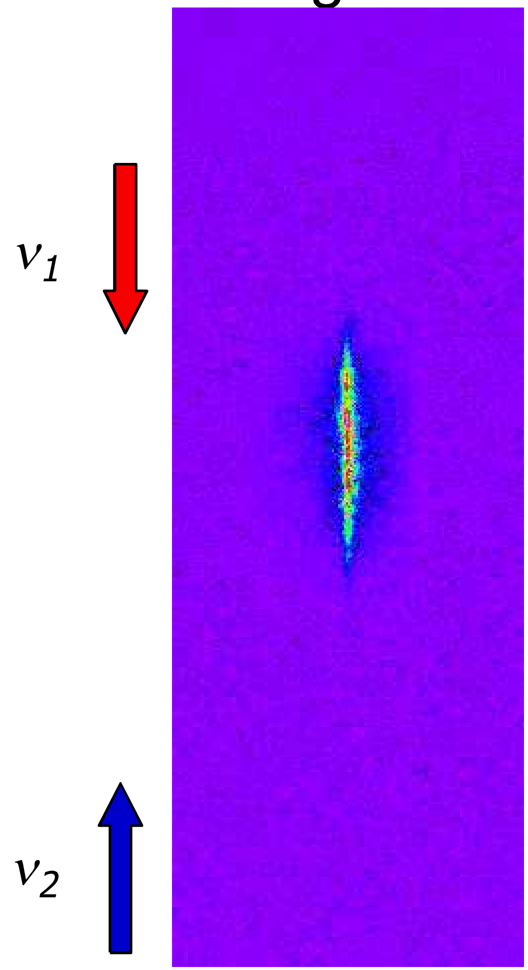


$$I(r,z,\delta) = \frac{2P}{\pi w^2(z)}\exp\left(-\frac{2r^2}{w^2(z)}\right)\cos^2\left(kz - \frac{\delta}{2}t\right)$$

$$I_0 \approx 8\times 10^8\ \mathrm{mW/cm^2}$$

Velocity of Walking Wave

$$\mathrm{v} = \frac{\lambda\delta}{4\pi} \sim 0-30\ \mathrm{cm/s}$$



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Atomic Conveyor Belt
D. Meschede, *Science* (2001).

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How to get an atom in micro-cavity

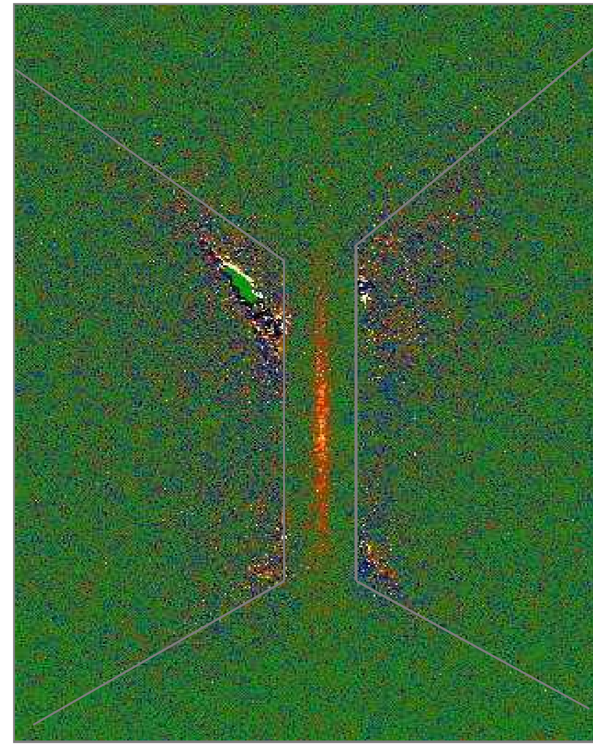
Probabilistic Loading

- Atomic beams
- Falling cold atoms
- Catching the falling atoms with cavity modes

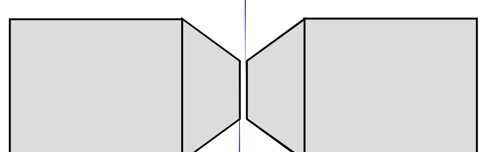
Caltech
MPQ (Rempe)

Deterministic Loading

- Trapping the atoms and transferring them into the cavity (GaTech, Bonn (Meschede))



Mirror Separation $= 225\mu$m



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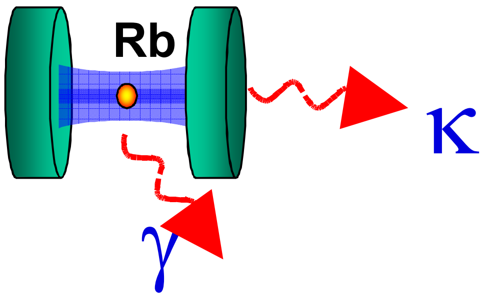


Jaynes-Cummings Hamiltonian

$$\hat{H} = \frac{1}{2}\hbar\omega_A\hat{\sigma}_Z + \hbar\omega_C\left(\hat{a}^\dagger\hat{a} + \frac{1}{2}\right) + \hbar g(\vec{r})(\hat{a}^\dagger\hat{\sigma} + \hat{a}\hat{\sigma}^\dagger)$$

Atom **Field** **Interaction**

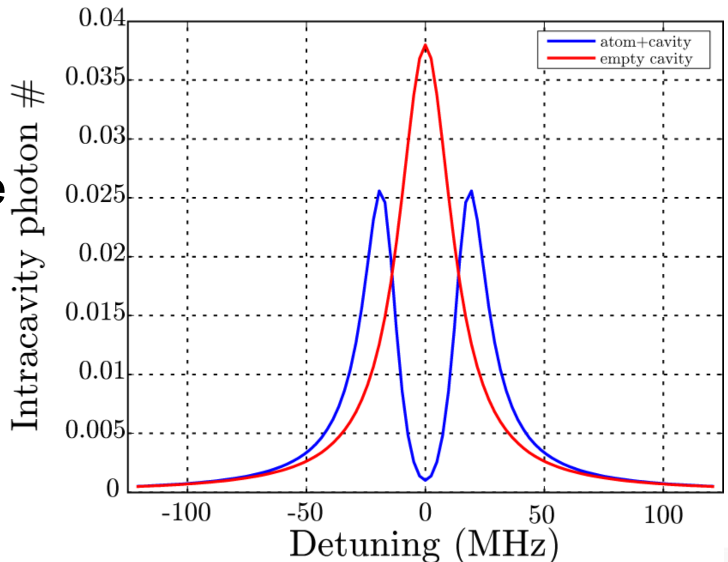
Strong Coupling requires that controlled quantum dynamics occur ***faster*** than dissipations

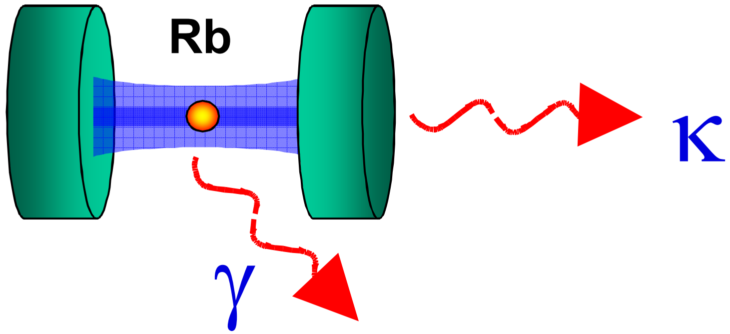
$$g_0 >> (\kappa, \gamma)$$

κ -- Decay into the one privileged cavity mode

γ -- Decay into all other modes

g_0 -- coherent coupling rate





Coherence

$$g_0 = \left(\frac{\mu^2 \omega_c}{2\hbar \varepsilon_0 V_M} \right)^{1/2}$$

For g_0 to be large, the mode volume must be small.

Implies short cavities, length << 1 mm

Decoherences:

Spontaneous Decay(γ)

$$\gamma = 6 \text{ MHz}$$

Given by Nature for ^{87}Rb

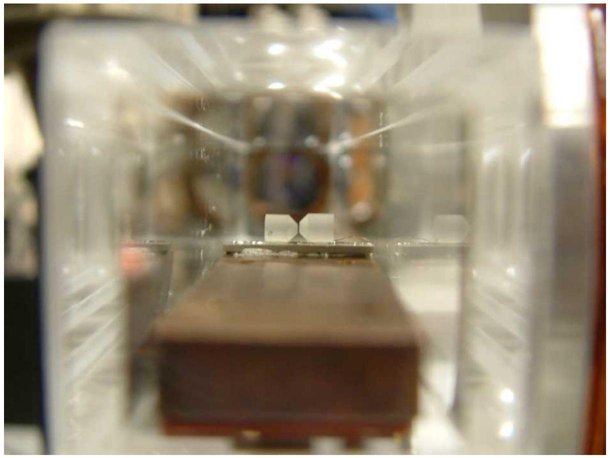
Cavity's Decay(κ)

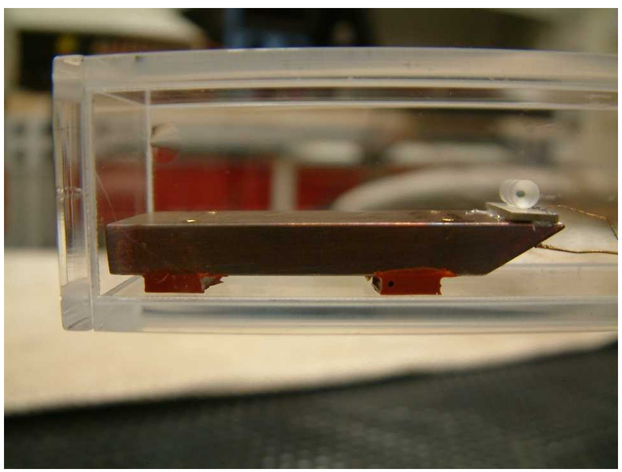
$$2\kappa = \text{Cavity's FWHM}$$

$$2\kappa = \frac{FSR}{\Im} \qquad \Im = \frac{2\pi}{\text{losses}} \qquad FSR = \frac{c}{2L}$$

To make κ small requires **low loss mirrors**.
Typically T < 100 ppm

Science Cavity Chamber





CAVITY

$l = 221.5\ \mu m$

$R = 2.5\, cm$

$\frac{\kappa}{2\pi} = 6.85\ MHz$

$\frac{g_0}{2\pi} = 17.11\ MHz$

$\Im = 24,400$

FORT Parameters

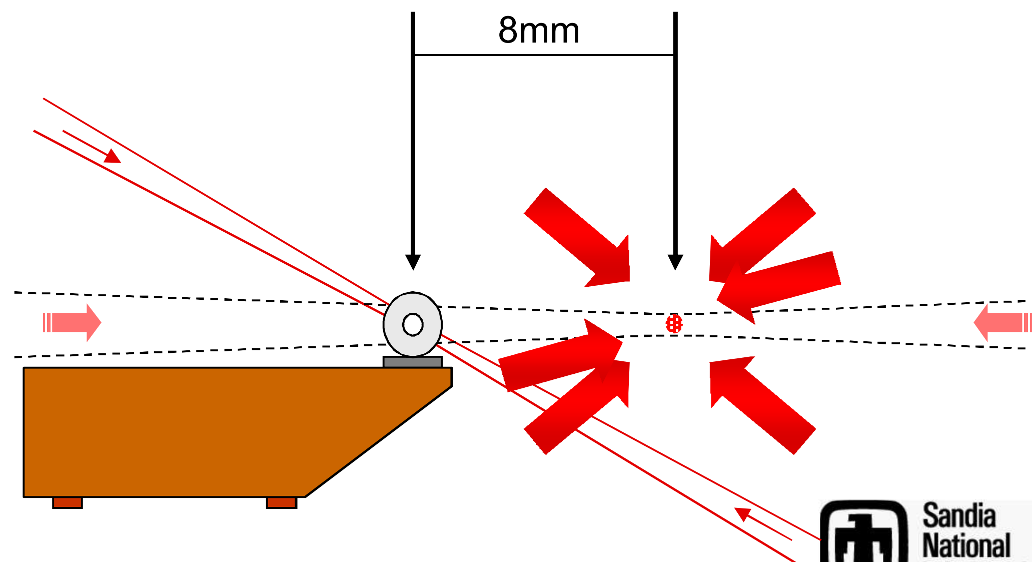
λ=1064 nm

P=4 W per beam

U~1 mK at cavity

U~ 100 μK at MOT

~ 16,000 lattice sites between MOT and cavity



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Detection:

High NA Lens

Limit Scatter Noise

MOT beams ~1-2 mm

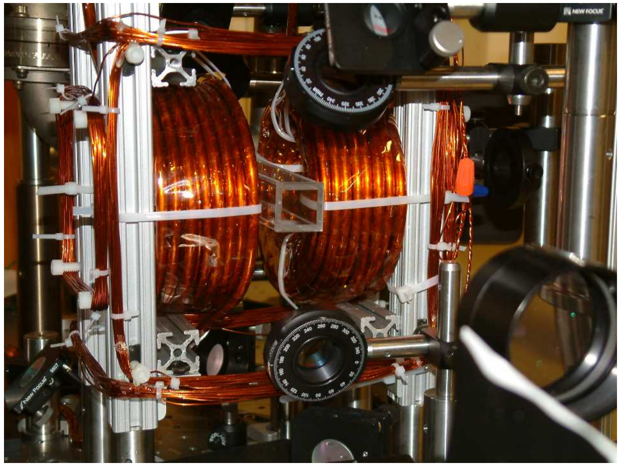
Magnetic Gradient Generation:

To generate ~300 G/cm field

Large current supply ~ 400-500A

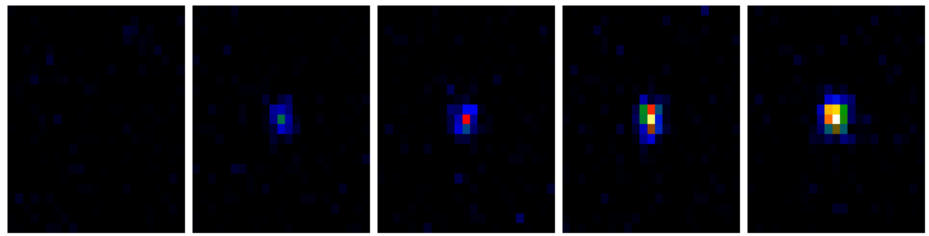
Water cooling to dissipate heat

Single atom chamber

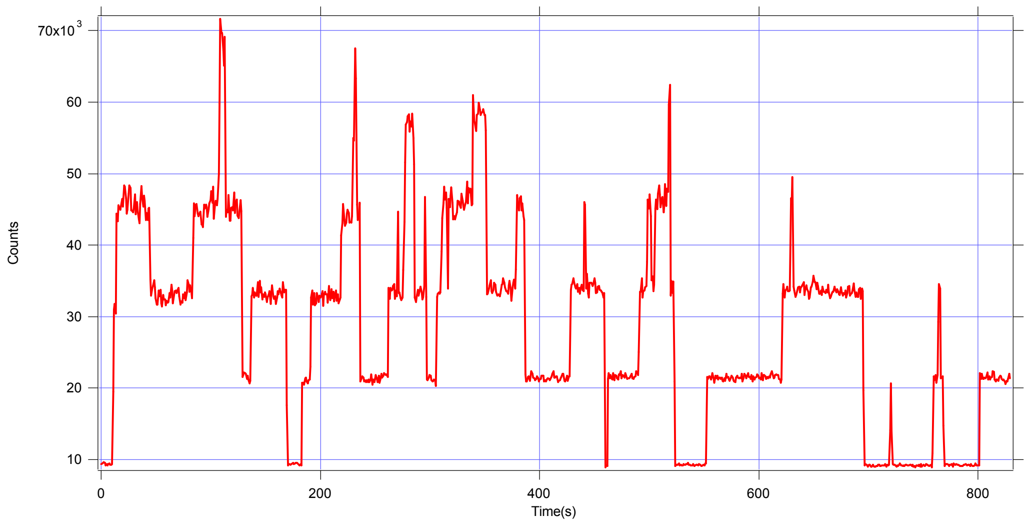


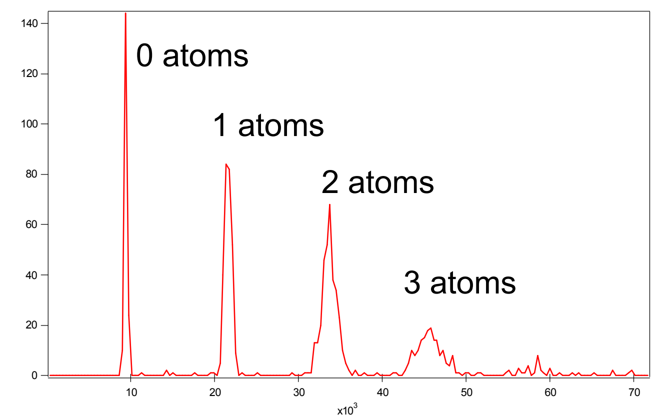
New Direction – Single Atom MOT

Using a high-gradient MOT, ~300 G/cm we are able to image single atoms using a EMCCD camera.



0 atoms 1 atom 2 atoms 3 atoms 4 atoms





First single atom MOT construct Aug 2005

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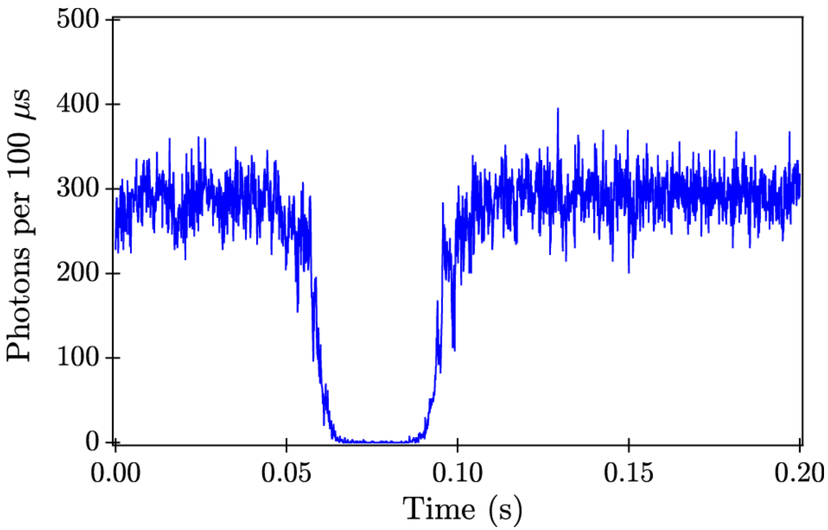
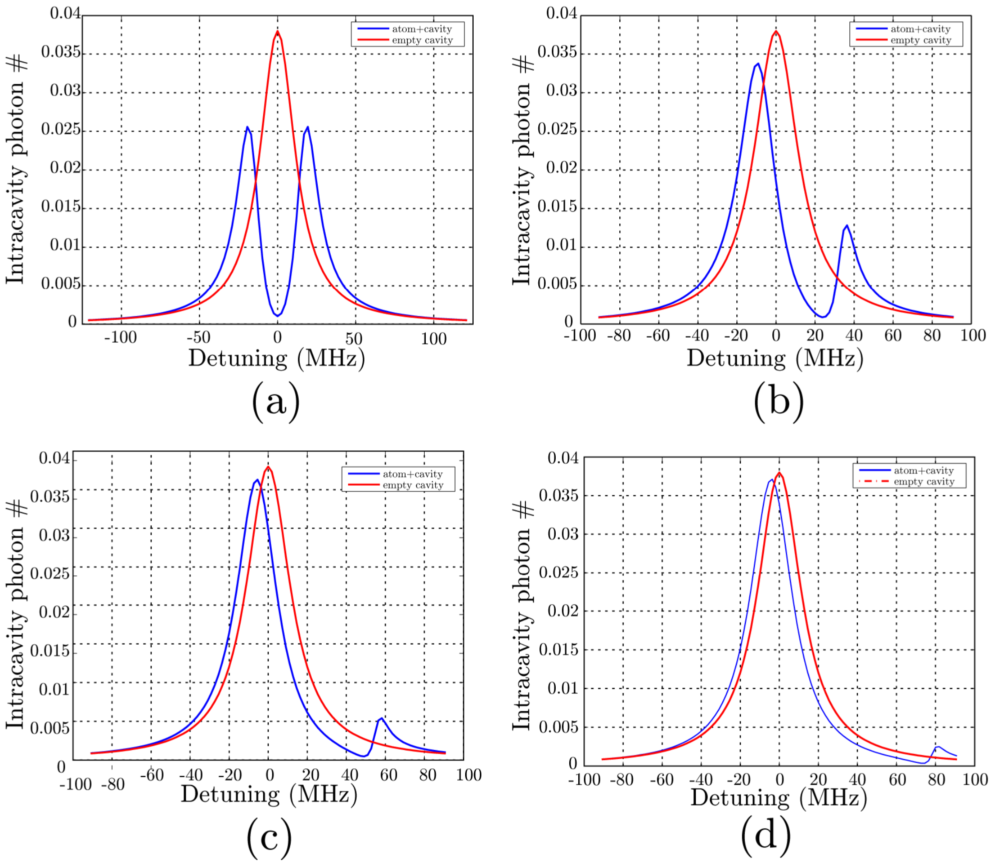
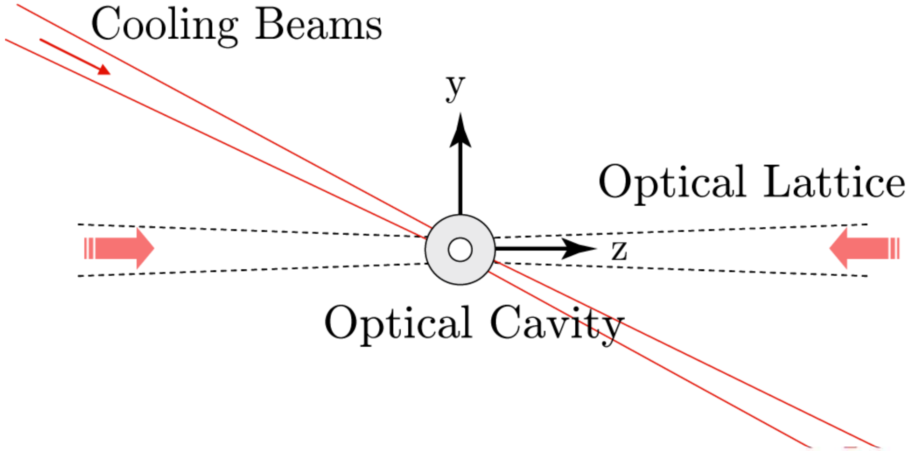
Intra-cavity photon absorption





Numerical solutions for one atom's master equation incorporating AC Stark shift of the optical trap



$$F_{\text{Trap}} = 4\hbar\nabla\Delta_a(\nabla\Delta_a\cdot\mathbf{v})\frac{\kappa\Delta_c}{(\Delta_c^2+\kappa^2)^2}\frac{g^2P_e}{\Delta_a^2+\gamma^2}$$

$$F_{\text{pump}} = 4\hbar\mathbf{k}_L(\mathbf{k}_L\cdot\mathbf{v})\frac{\kappa\Delta_c}{(\Delta_c^2+\kappa^2)^2}g^2P_e$$

$$F_{\text{cavity}} = 4\hbar\nabla g(\nabla g\cdot\mathbf{v})\frac{\kappa\Delta_c}{(\Delta_c^2+\kappa^2)^2}P_e\ .$$

1 set of cooling beams provide cooling in 3-D

Detune cavity-probe so that emissions that remove energy are favored

$$\Delta_c < 0$$

$$\Delta_c = \omega_p - \omega_c$$
$$\Delta_a = \omega_p - (\omega_0 + \Delta_s)$$

Nußmann *et al*., Nat. Phys (2005)
Murr *et al*., PRA (2006)

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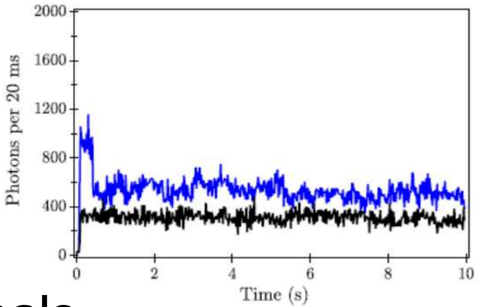
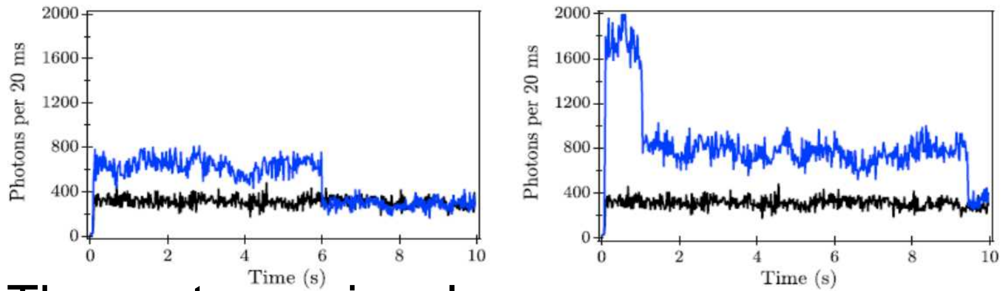
Storage of an atom is approximately 10 seconds

One atom signal

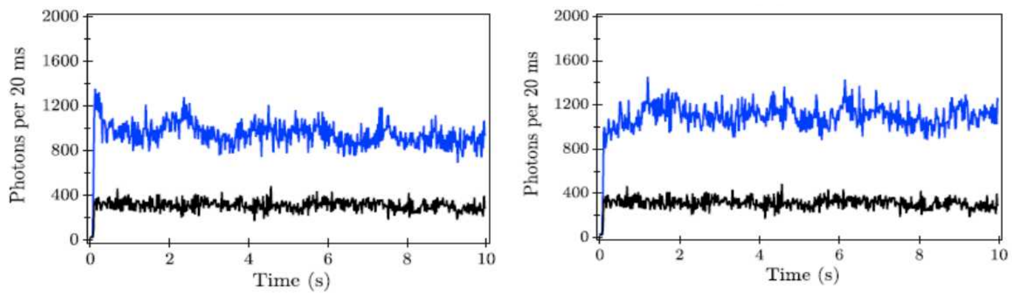


Two atoms signals



Probed with a cavity field an atom survives $t_{storage}<1$ ms

Three atoms signals



Cooling increase storage time by a factor 10,000!!

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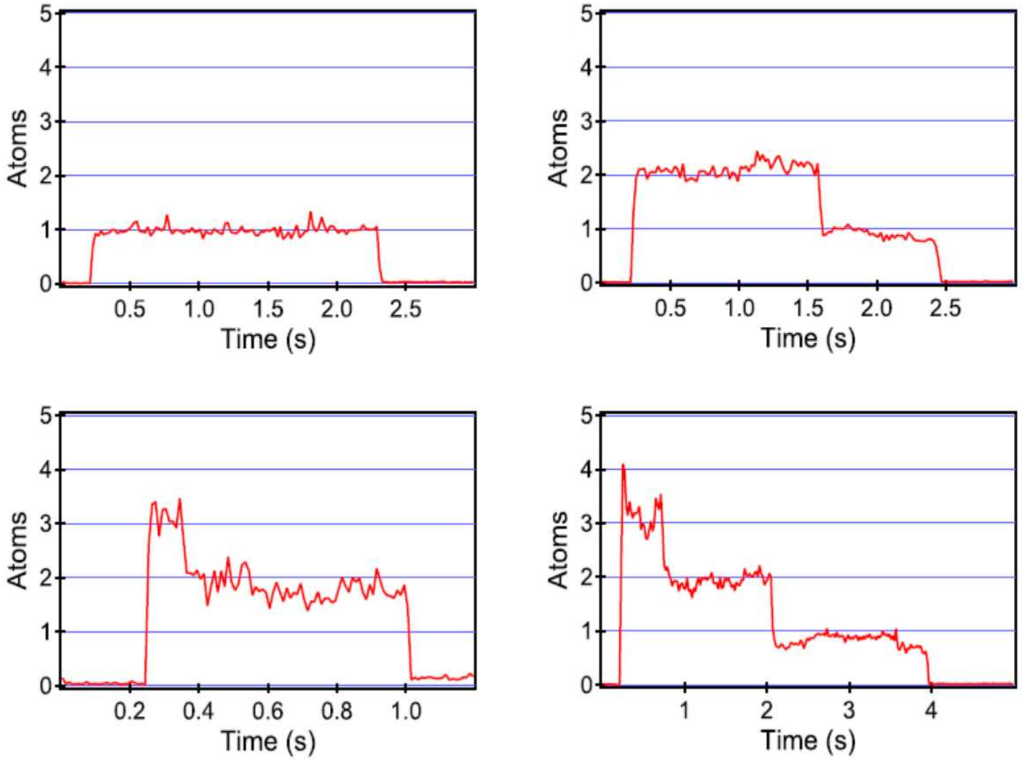
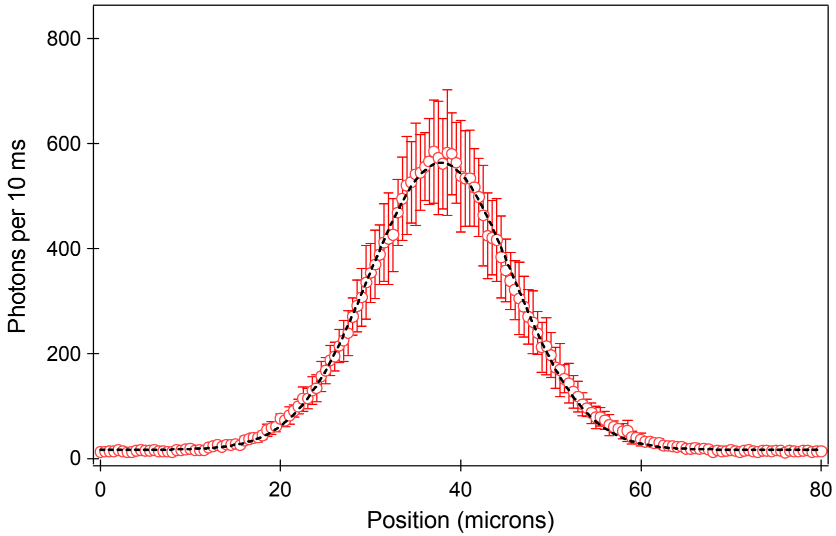
Cavity Cooling of single atoms



Beginning with MOT N=1, 2, 3, 4 we detect N=1, 2, 3, 4 in cavity



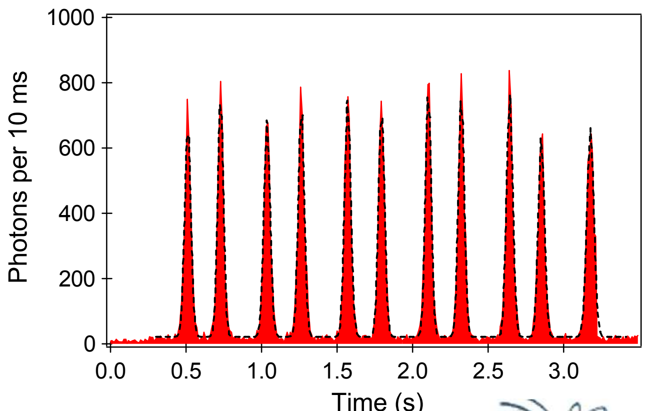
Slowly sweeping 1 atom over the cavity mode

Atoms moved in z dir at $v = 50\ \mu\text{m/s}$

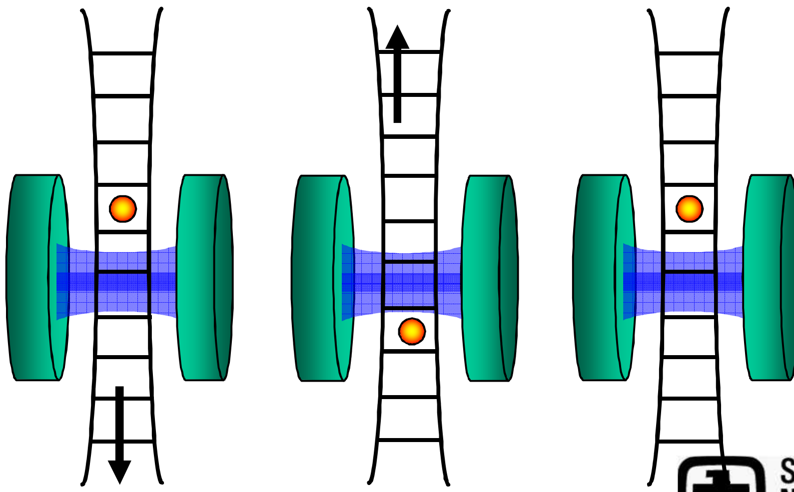
$$R \approx 2\kappa \frac{g^2}{\Delta_C^2 + \kappa^2} \frac{\Omega^2}{\Delta_a^2 + 4\gamma^2}$$

$$g = g_0 \cos(kx) \exp[-((y^2 + z^2)/w^2)]$$

Single atom passes mode 11 times



Atoms moved in z dir at $v = 440\ \mu\text{m/s}$



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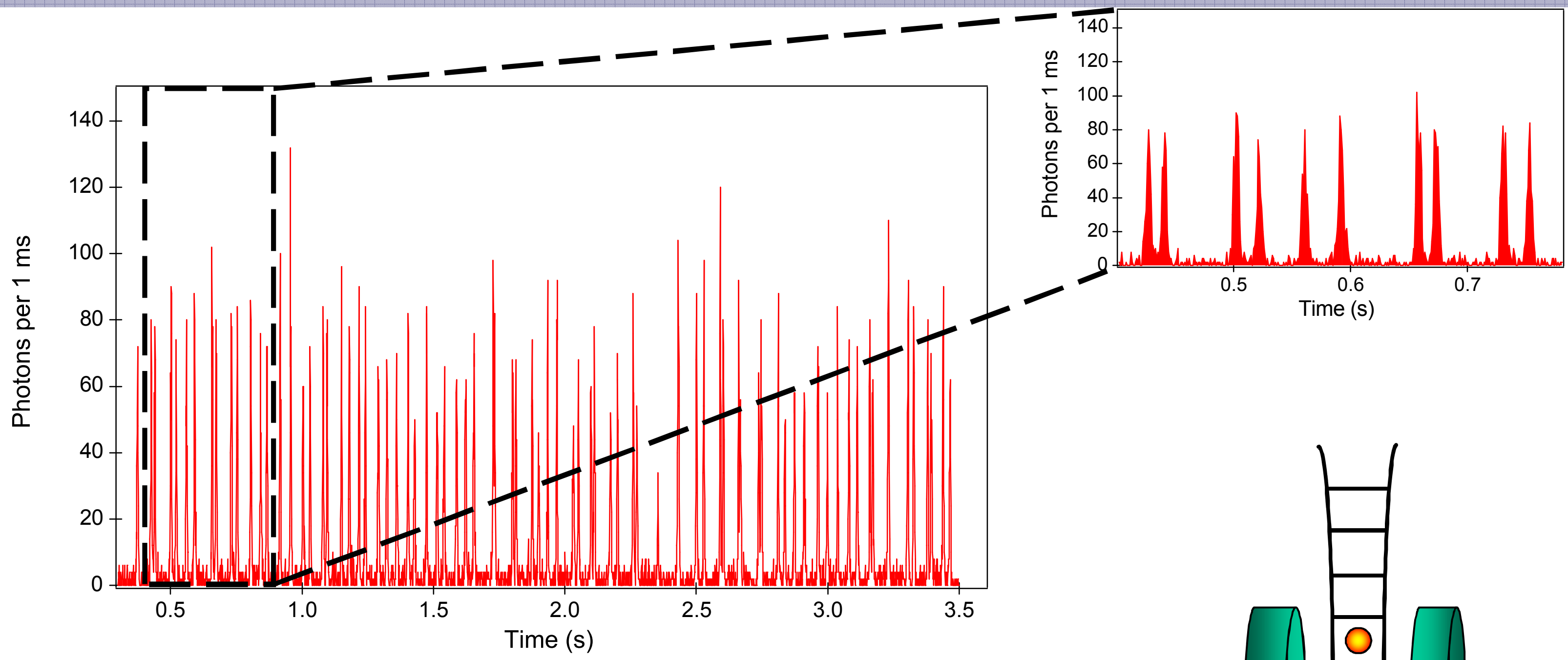

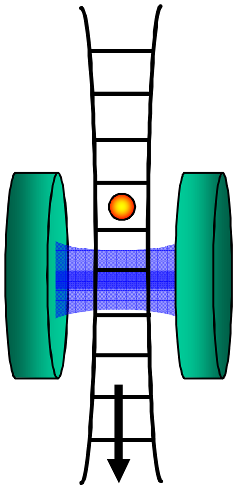

Atoms moved in z dir at $v = 4.40\ \mathrm{mm/s}$

K. M. Fortier, et. al, *Phys. Rev. Lett.*, **98,** 233601 (2007).

Invited talk at *CLEO/QELS 2008*

QELS 01: Quantum Optics of Atoms, Molecules and Solids

QTuB1, ***Deterministic Cavity QED with Single Atoms,*** *Soo Y. Kim, Michael J. Gibbons, Kevin M. Fortier, Peyman Ahmadi, Michael S. Chapman; Georgia Tech, USA.*

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What was demonstrated

Loading 1 single atom in cavity
Long storage times

Moving a single atom in/out of cavity

What's left to show a qubit
Initialize -> Optical Pump
Singe Qubit gates -> microwaves

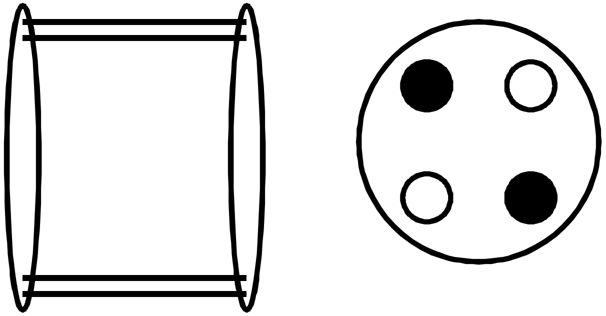
What was hard

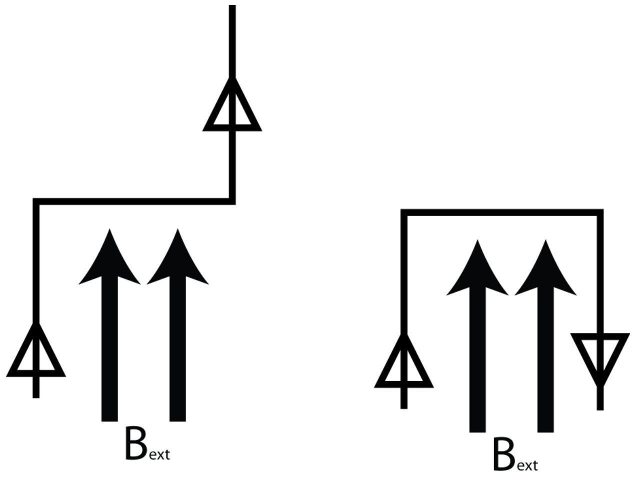
Cavity Construction
- Each cavity unique
- Very difficult to get 1 working

Optical Transport
- Introduces Gaussian problems
- AC stark shift problems

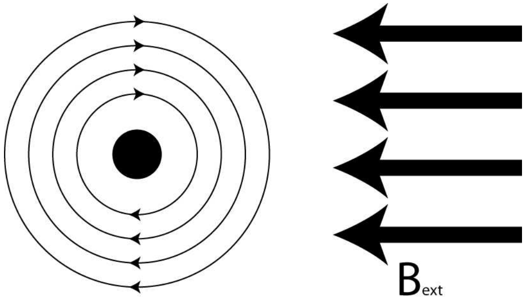
Number of lasers
- 6 diodes lasers all locked to Rb

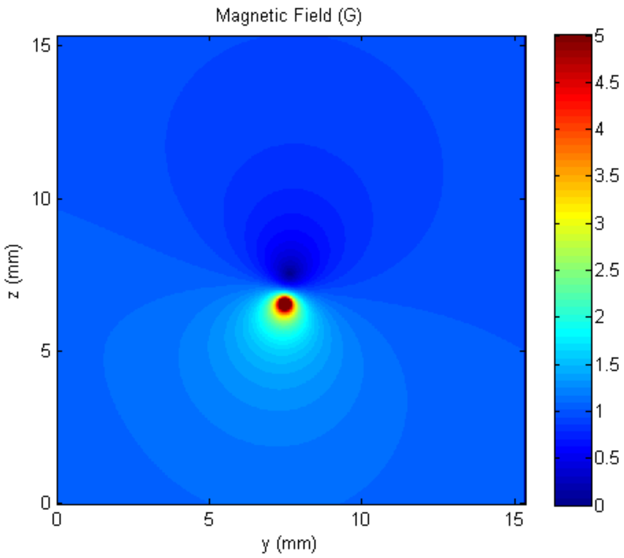
Macroscopic coils:
Anti-Helmholtz Coils, Ioffe Pritchard





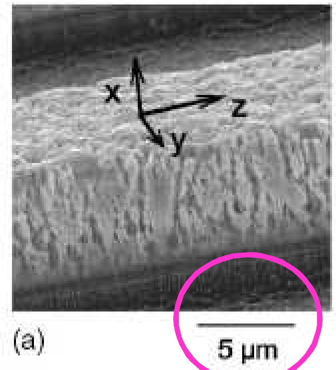
Chip solutions: currents + bias

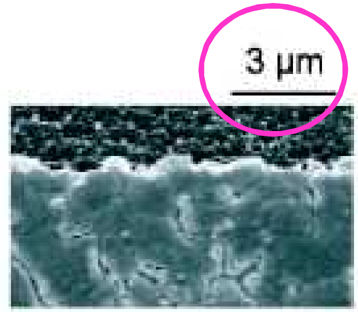




I = 25 A, Bias = 10G

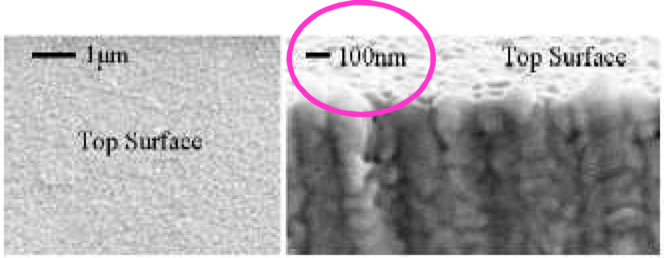
Electroplated Au wire sidewalls



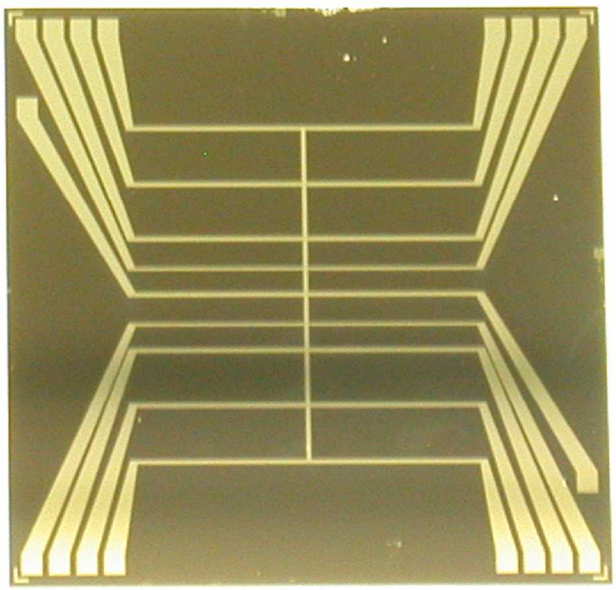


Aspect group, Orsay
PRA **70**, 043629 (2004)

Lift-off Au wire sidewalls

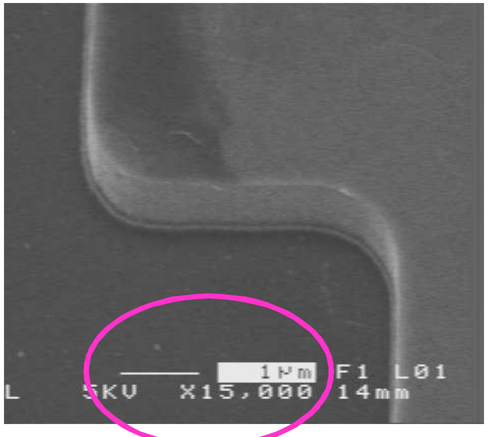


arXiv:cond-mat/0504686v1 [cond-mat.other] 26 Apr 2005
Schiedmayer group, U. Heidelberg



Potential disorders
current fluctuations
wire edge roughness

Etched Al wire sidewalls



Blain, Stevens, Nakakura, SNL

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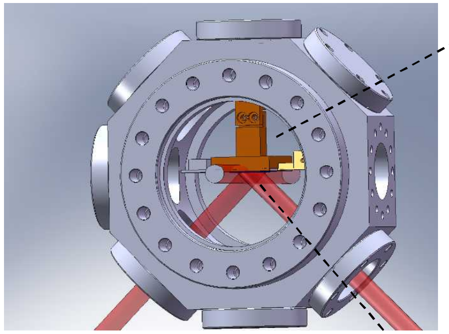
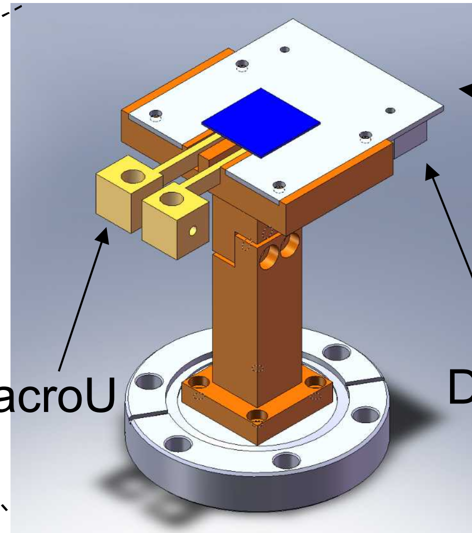
Sandia's Atom Chip testing apparatus.

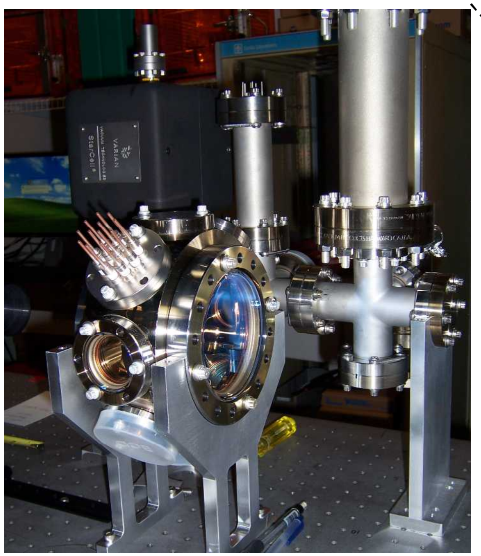


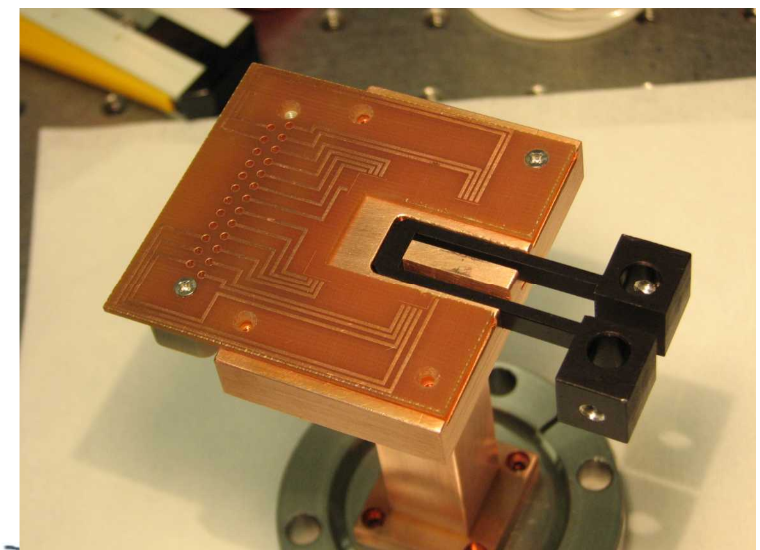


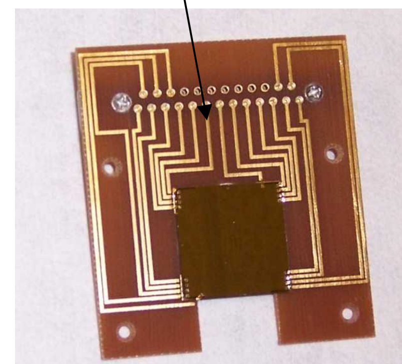
Atom Chip

MacroU

D-sub





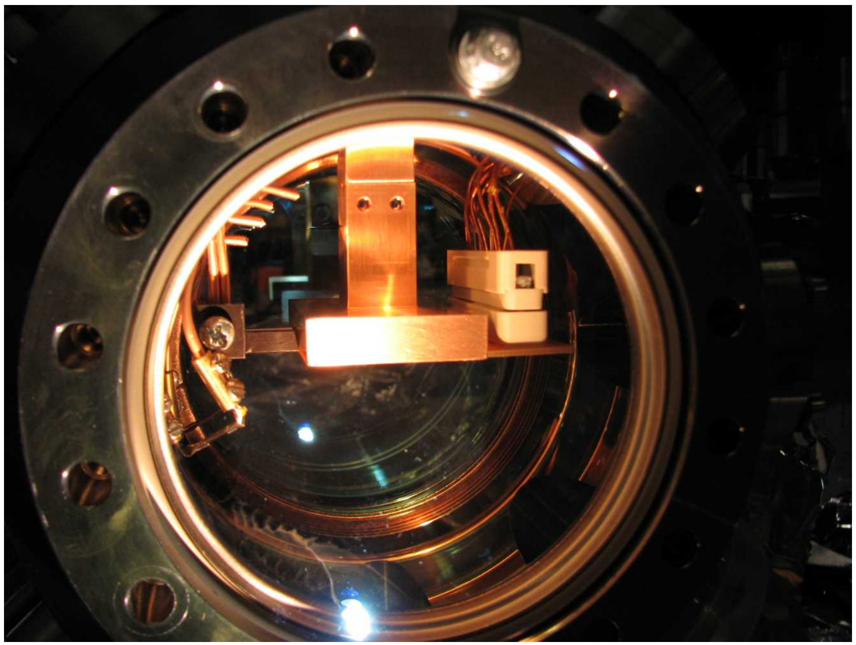


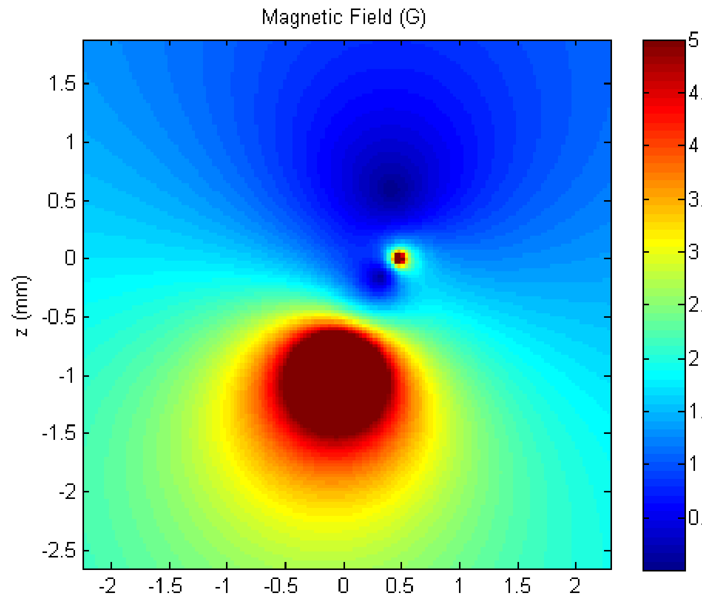
First Atom Chip shipped to Mabuchi on 26 Mar 08

Collaboration with H. Mabuchi at Stanford and JM Germia at UNM

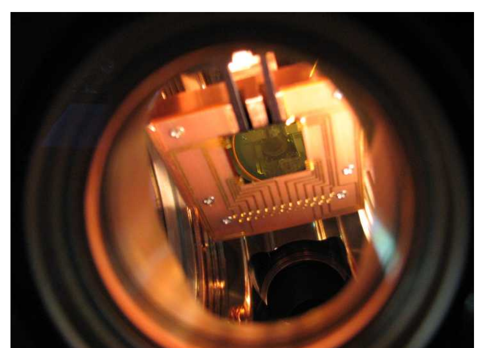
Loading Procedure

- Produce a Mirror MOT using Macro U and bias field
- Turn off lasers and store atoms in Macro U magnetic trap
- Transfer atoms from Macro U to atom chip

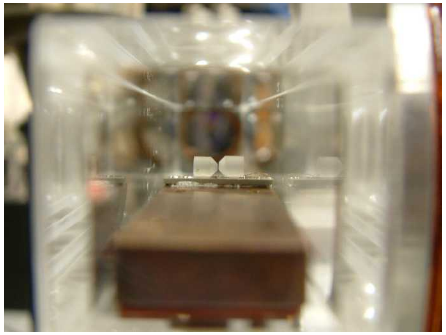




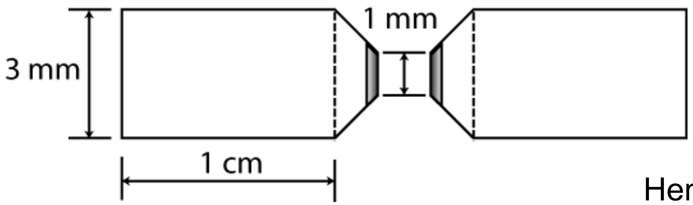
Biot-Savart solver provided by Chris Tiggis



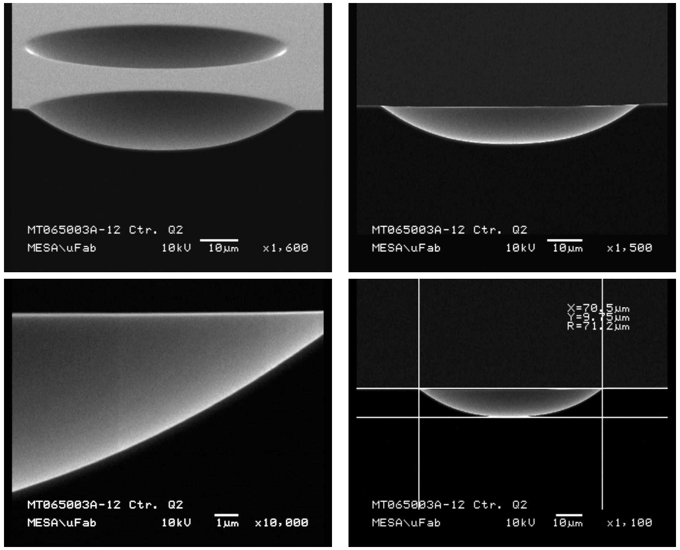
Microfabrication allows one to design engineered high finesse cavities.



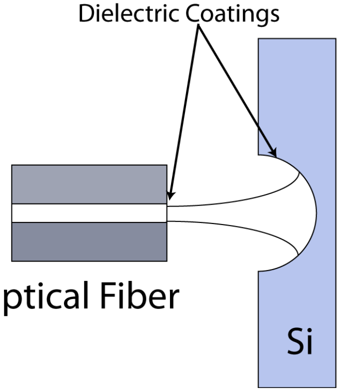
Un-scalable Cavity QED system



Hemisphere R = 68.6 µm

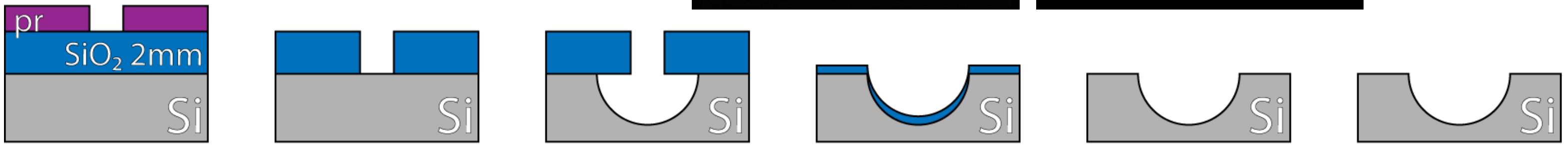


Scalable Cavity QED system



Engineering Design Goals

- Open access Fabry-Perot cavity
- Finesse > 10,000
- Low mode volume
- Process compatible with Atom Chip fabrication



Plasma etch SiO_2 | Chemical etch with fluorine radicals | Strip SiO_2 with HF. Smoothing etch with SF_6 and Ar plasma | Thermal oxidation smoothing | Strip SiO_2 with HF

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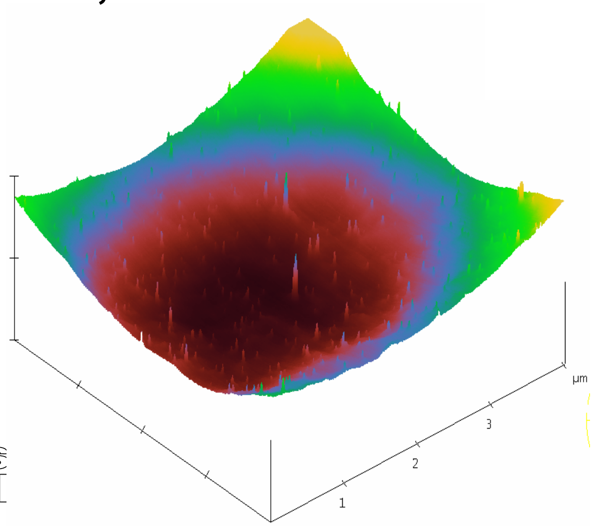
Surface Roughness of microfabricated cavity mirrors

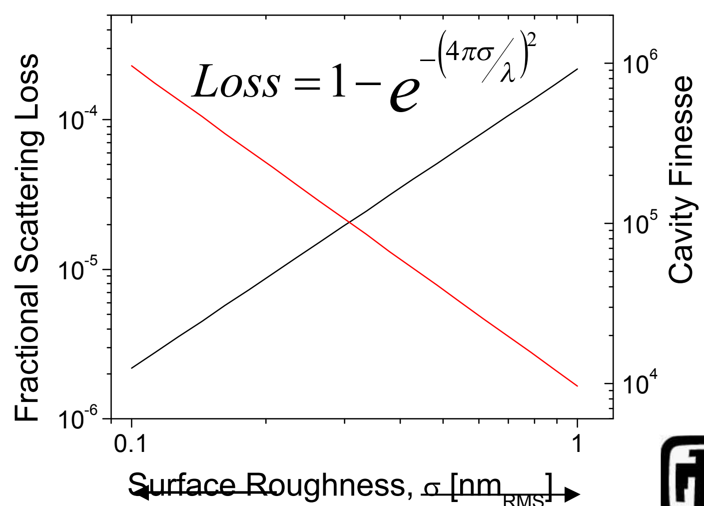
AFM measurements at bottom of mirror
Units: nm_{rms}; 1 μm SiO_2 aperture

Wafer	1st plasma etch	2nd plasma etch	Oxidation	Anneal	Wet etch
1	1.13	0.67	-	-	0.30 cavity 0.30 field
2	0.98	0.62	0.55	0.48 well 0.66 field	0.46 cavity 0.58 field
3	0.94	0.85	0.48	Yes	0.216 cavity 0.218 field

Post 1st plasma etch AFM scan, Wafer 1



Scattering loss versus surface roughness



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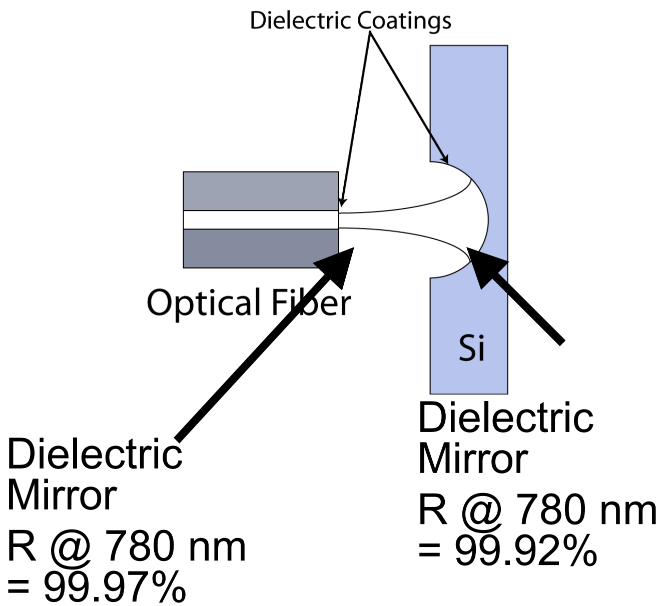
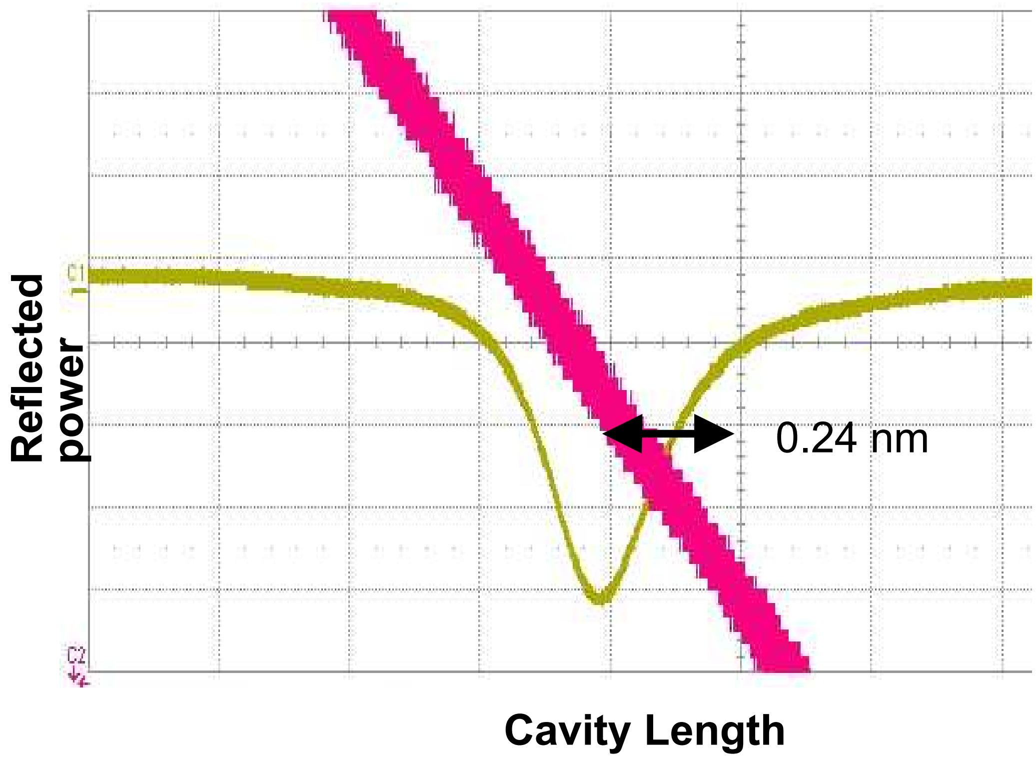
Microfabricated cavity resonance





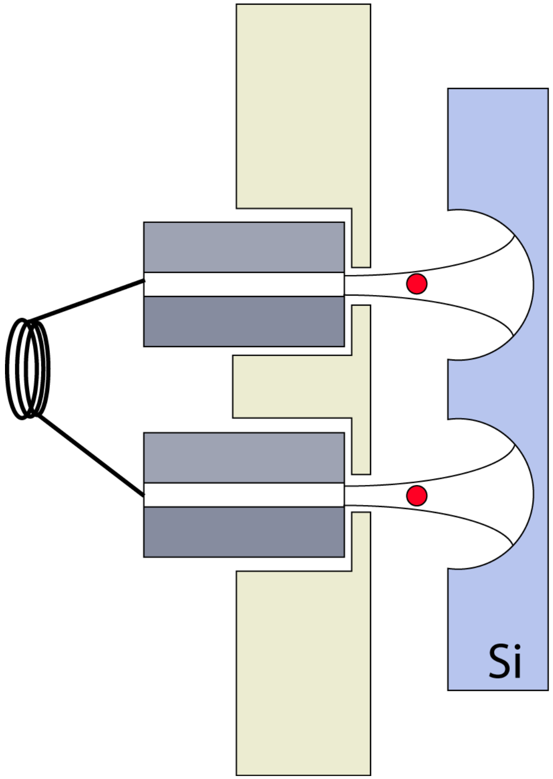
Measured at 852 nm:
Finesse = 1750
Expected Finesse = 2400
Cavity Length = 15 μm
Q = 60,000

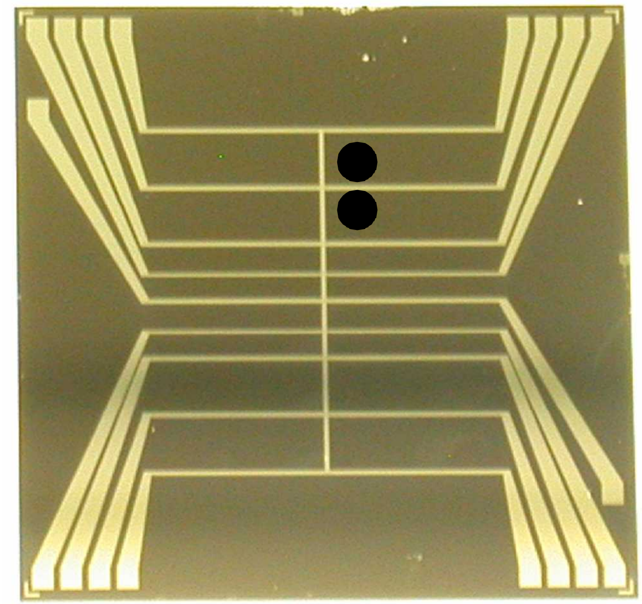
$$g_0 / 2\pi = 525 \text{ MHz}$$

$$\kappa / 2\pi = 1100 \text{ MHz}$$

$$g_0^2 / \kappa\gamma = 36$$

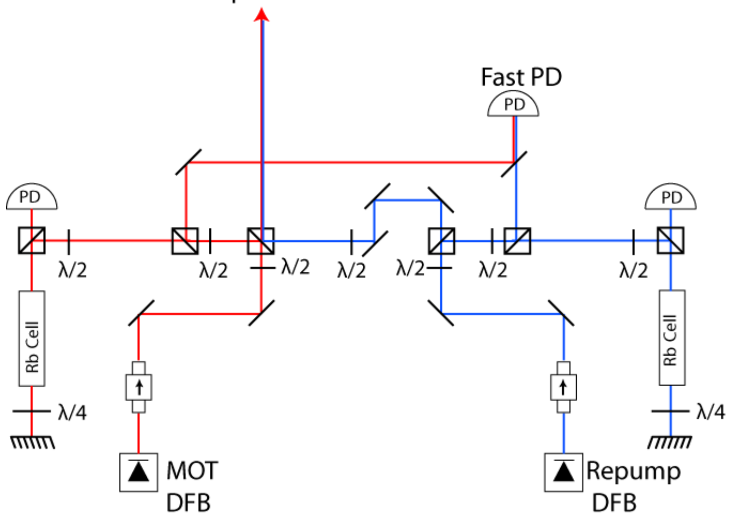
In the strong coupling regime



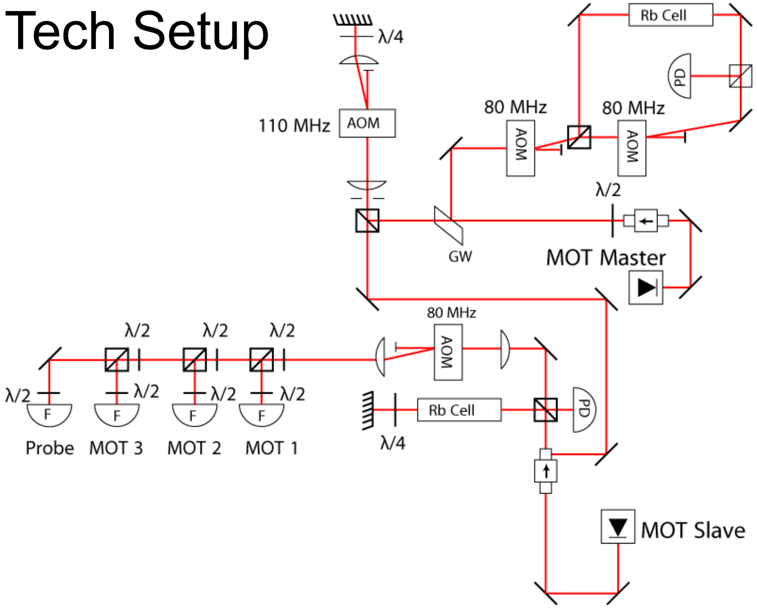


Modeling Currently being done by Michael Pack as part of late start FY08 LDRD #08-1359 internal funding.

Sandia Setup

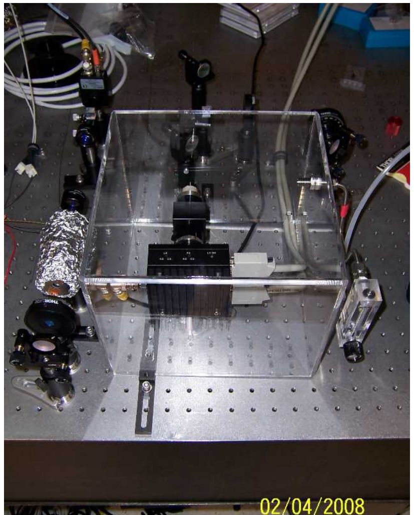


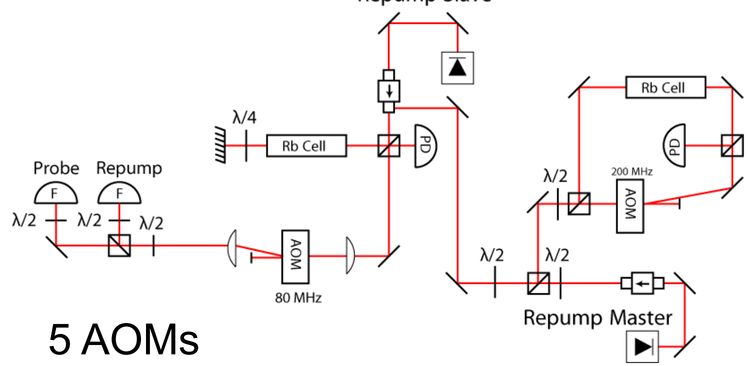
Georgia Tech Setup



DFB lasers -> mechanical noise insensitive
Frequency offset locking -> stabilize beatnote between two lasers

0 AOMs
0 Slave Diodes
4’ x 2’ optical footprint





5 AOMs
2 ECDLS
2 Slave Diode Lasers
4’ x 5’ optical footprint

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Potential Ways Sandia could impact cold atom research

The Sandia Atom Chip Foundry Model:

Utilize Sandia's $465M MESA facility for atomic physics research
Success in past as part of DTO/IARPA Ion trap foundry

We want to form collaborations with top experimental groups

Sandia has capabilities in:

Modeling
Fabrication
UHV packaging
In house testing via atom trapping

MESA
Microsystems and Engineering Sciences Applications

Benefit to research groups: **we will provide a chip that traps atoms**

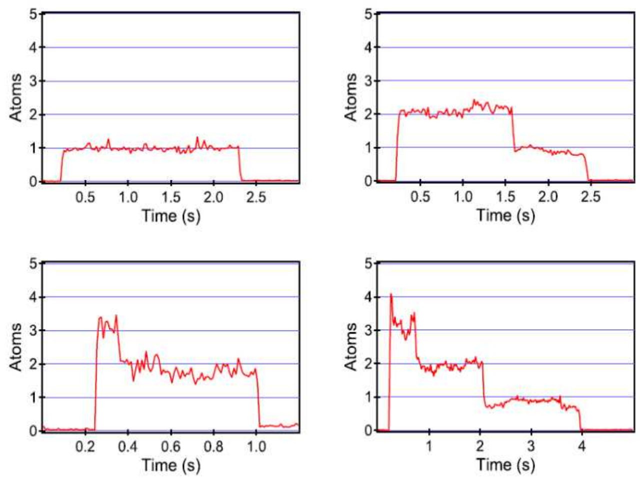
Conclusion

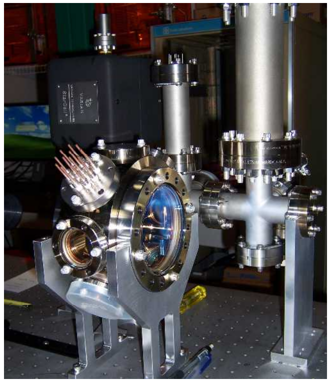
First Neutral atomic Qubit in a cavity

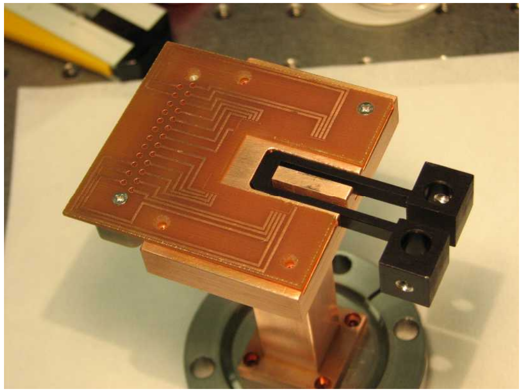
Single atom stored in cavity
Optical pumping
Single Qubit Rotations -> Microwaves
Perform 100-1000 experiment on one atom

Sandia's Neutral atom experiment

System will be baked out by mid May 2008
Laser construction completed June 2008
First laser cooled atoms August 2008
2nd Generation chip in design to incorporate cavities







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Classical vs Quantum Memory

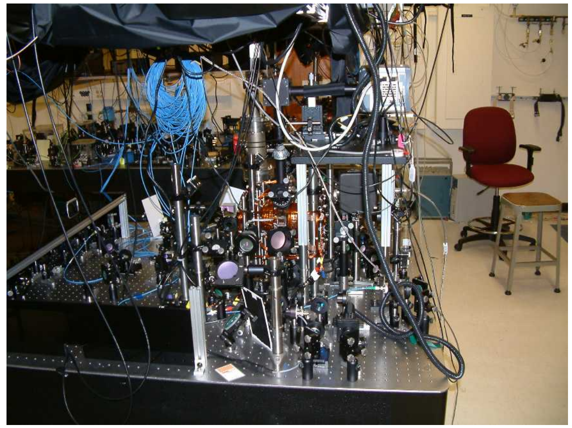
Classical Memory

Storage:1GB

Cost: $17.99

First Transistor

Bell Labs, 1947



Quantum Memory alpha: GaTech

Storage: ~1 qubit

2 Optical tables, 1UHV System

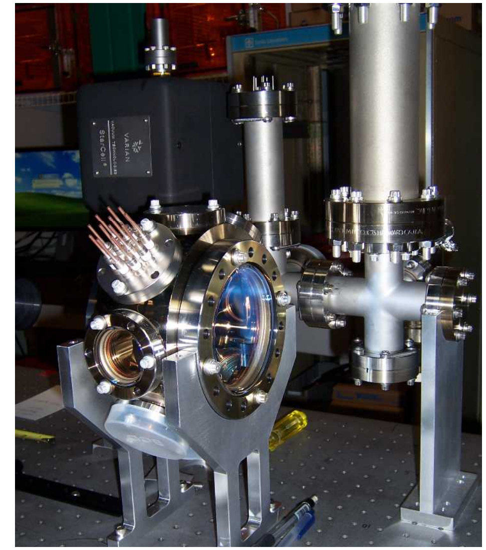
6 Diode lasers

1 Cavities

1 Yb Doped Fiber laser

3 Grad Students

Cost: >> $17.99



Quantum Memory beta : Sandia

Storage: ~1 qubit

1 Optical tables, 1UHV System

2 Diode lasers

1->n Cavities

Cost: >> $17.99

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Acknowledgements

Georgia Tech

Prof. Michael Chapman

Soo Kim

Michael Gibbons

Paul Griffin

Jacob Sauer

$$$

NSF

NASA

NSA

ARDA

Sandia National Labs

Dan Stick

Matt Blain

Peter Schwindt

Michael Pack

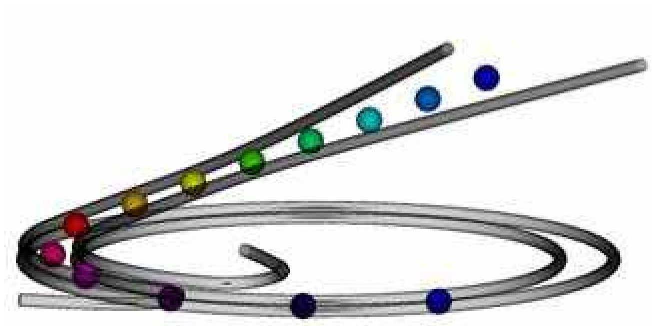
Chris Tigges

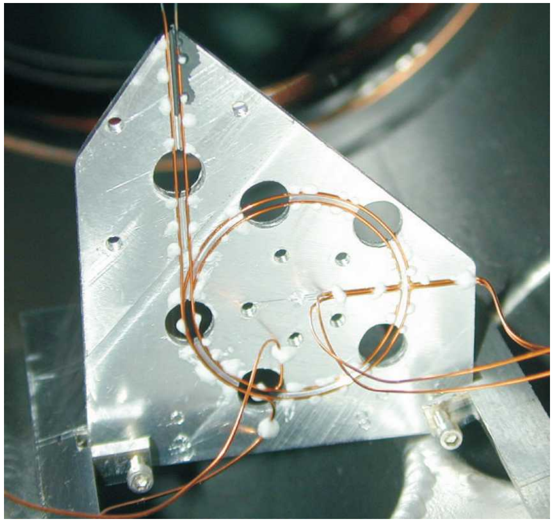
$$$

NINE

Appendix

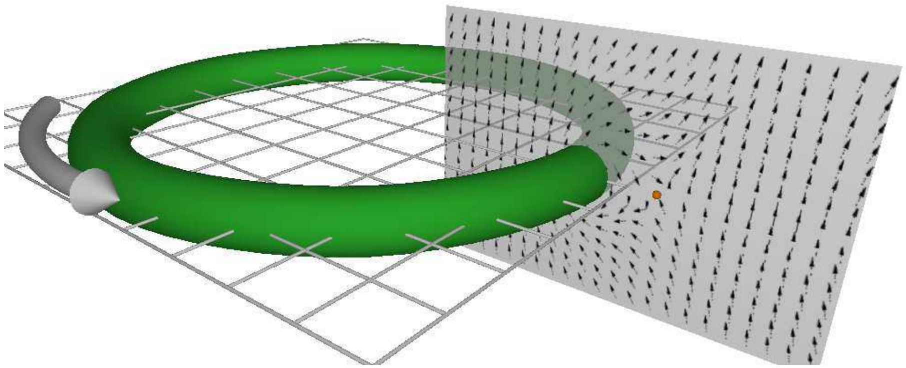
Improved Neutral Atom Storage Ring/Sagnac Interferometer





Potential bumps limited atoms to only 7 revolutions of the Nevatron

J.A. Sauer, M.D. Barrett, and M.S. Chapman, *Phys. Rev. Lett*, **87**, 270401 (2001).



Using an induced current from a microfabricated pickup coil one can make a very smooth magnetic potential

P. F. Griffin, A. S. Arnold, and E. Riis, *arXiv:0803.0940v1* (2008).

Atom Interferometry offer amazing sensitivity

$$10^{11} = 100,000,000,000$$

Building block of Quantum Information: *Qubits*

Quantum bit (qubits)

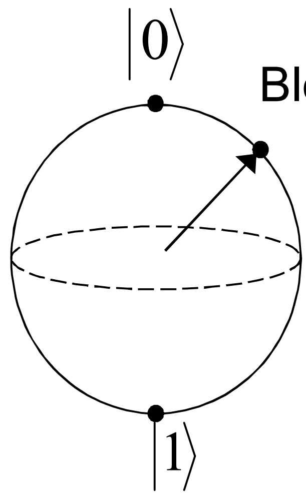
- Photon polarization
- Atomic electronic states

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

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

Classical Analog: 0, 1

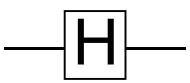
Bloch Sphere



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

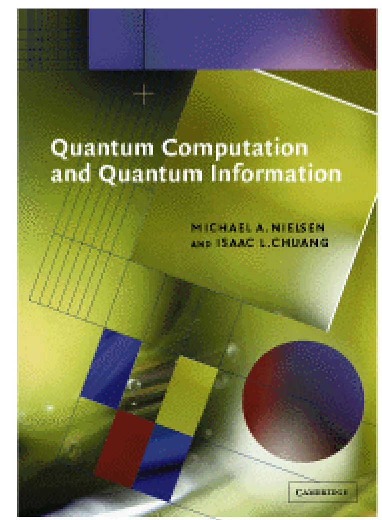
Single qubit gates

- Rotations on Bloch sphere
- Unitary 2x2 Matrices



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

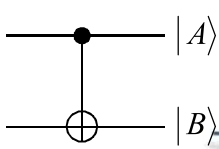
Hadamard Gate



Two qubit gates:

- harder

CNOT



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

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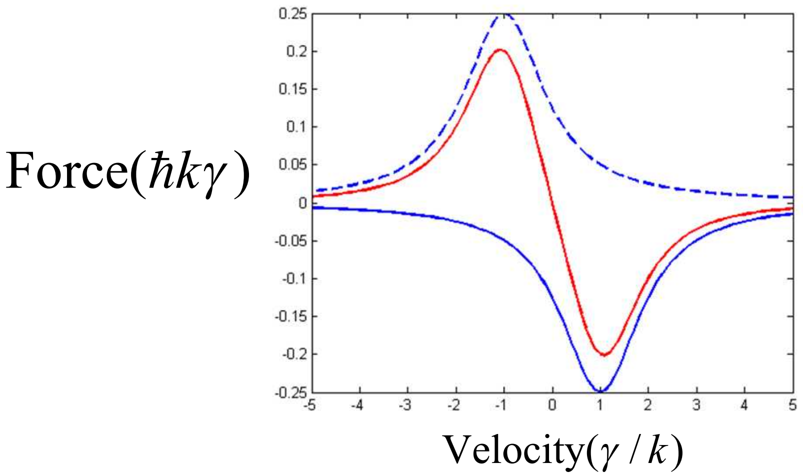
Toolbox

Optical Molasses – Laser Cooling
Magneto-Optical Trap (MOT)
Optical Trapping
Magnetic Trapping

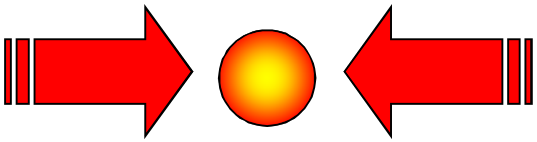


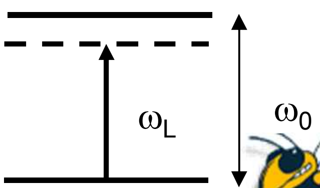
Laser cooling (1975)

Hänsch & Schallow
Wineland & Demhelt

$$\vec{F}_{\pm} = \frac{\hbar\vec{k}\gamma}{2}\frac{s_0}{1+s_0+(2(\delta \mp |\omega_D|)/\gamma)^2}$$

1-D optical Molasses

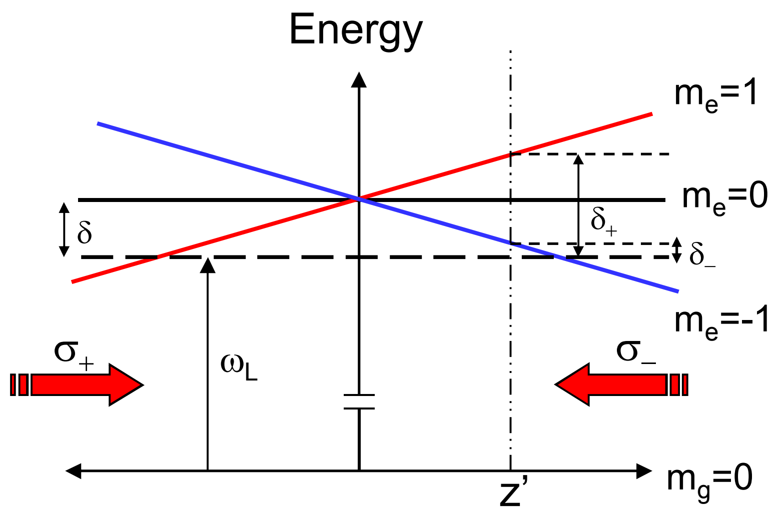




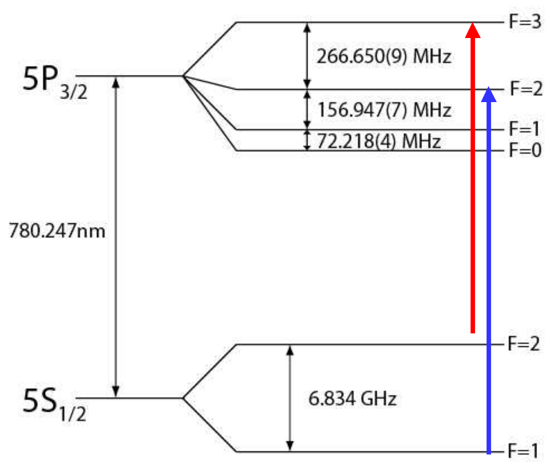
Expanded about v=0

$$\vec{F} = \vec{F}_+ + \vec{F}_- \approx \frac{8\hbar k^2\delta s_0\vec{v}}{\gamma(1+s_0+(2\delta/\gamma)^2)^2} = -\alpha\vec{v}$$

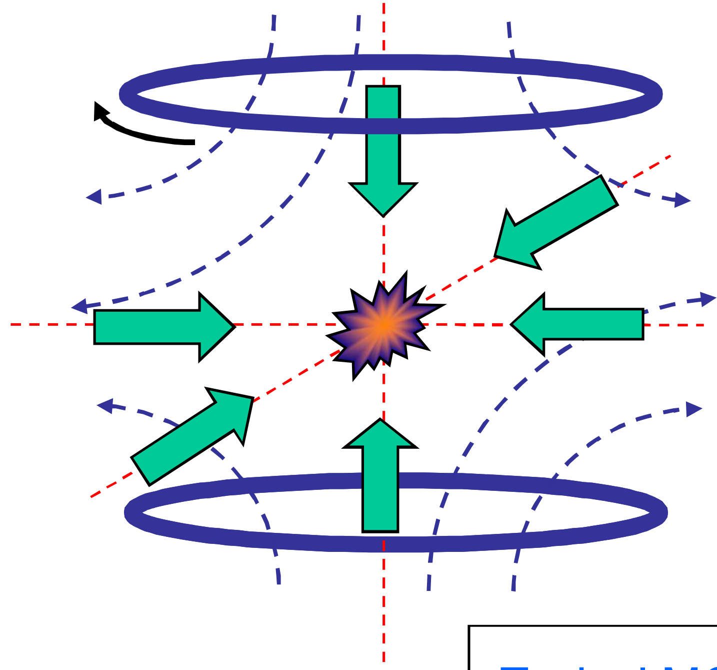
For $\delta<0$, viscous damping force that opposes the velocity of the atom



^{87}Rb D_2 Transistion



MOT-Cold Atom Source



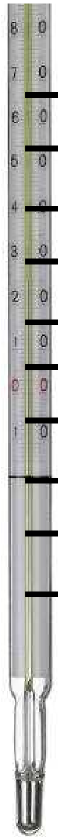
MOT (Cycling) Transition

Repump Transition

Typical MOT
^{87}Rb
$N=1\text{-}10^6$
$T = 20\ \mu K$

Before we attempt the Unrealistic a review of where we've been

How Cold is Cold?



- 300K – Room Temp
- 77K – Liquid N_2
- 3K – Big Bang Cosmic Background
- 300 mK – He Cryostat
- 30 mK – Dilution refrigerator
- 3 mK – Optical Cooling
- 140 μK – Doppler Cooling (Rb)
- 20 μK – Sub-Doppler Cooling
- 500 nK – Average BEC
- 100 pK – Coldest BECs

3 Nobel Prizes in 10 years!!

1997 – Chu, Phillips, Cohen-Tannoudji – Cooling Atoms with laser light
2001 – Wieman, Cornell, Ketterle – BEC (Predicted in 1927 produced 1995)
2005 – Glauber, Hall, Hänsch – Quantum Optics Theory, Frequency Comb

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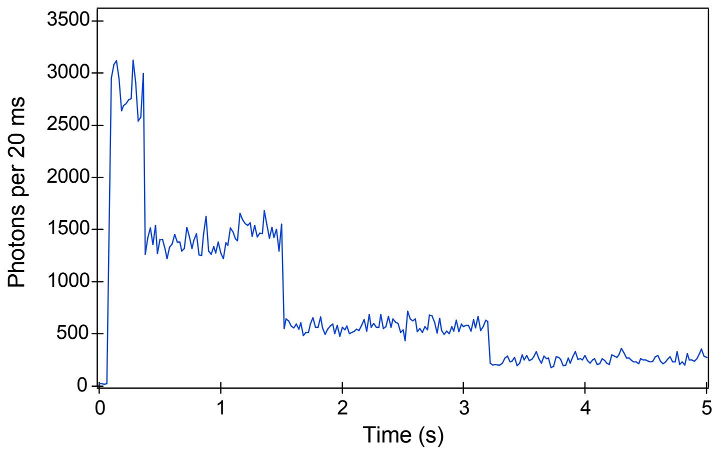
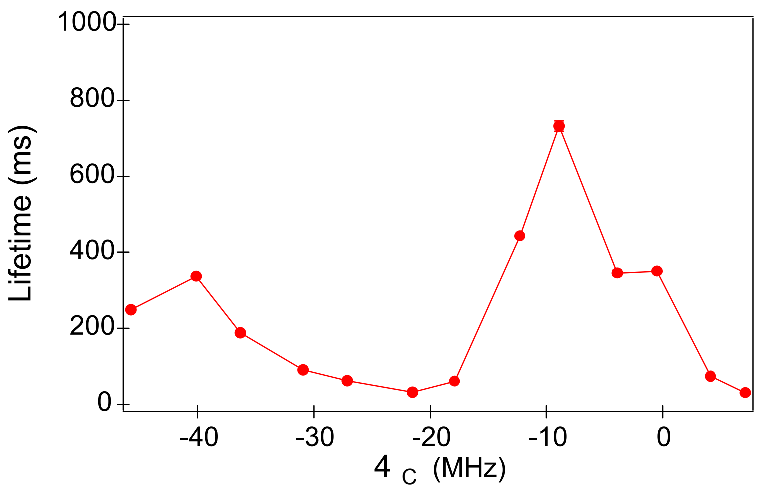
Cavity Cooling of Many atoms



Atomic Steps in cavity emission

$$\Delta_c = -8.9 \text{ MHz}$$

Individual atoms are stored for seconds



- MOT of 40 atoms
- Cool in Cavity
- Vary frequency of cavity

Max observed lifetime

$$\Delta_c = -8.9 \text{ MHz}$$

Theoretical Max Cooling

$$\Delta_c = -\frac{\kappa}{\sqrt{3}} = -7.99 \text{ MHz}$$

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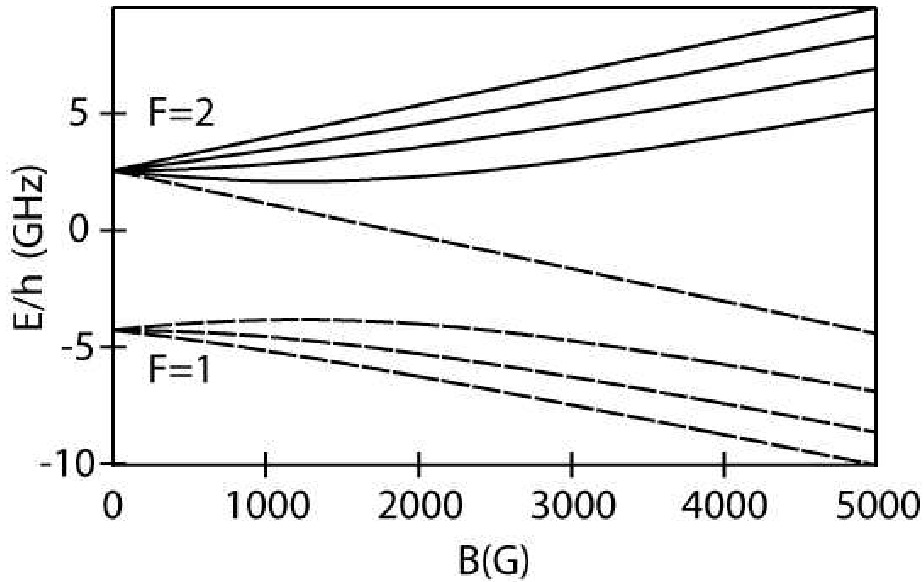
Magnetic Trapping

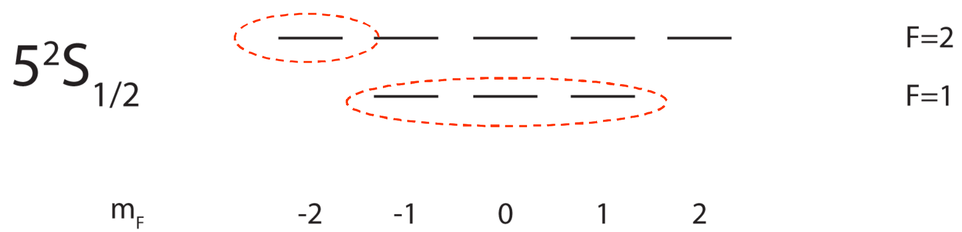
Use magnetic fields to trap atoms

$$E = -\mu \cdot B = -g_F \mu_B m_F B$$

$$\vec{F} = \nabla(\vec{\mu} \cdot \vec{B}) = g_F \mu_B m_F \nabla \vec{B}$$

Trap weak field seeking states in magnetic potential minimums





Rubidium-87 ground state

$$|F, m_F\rangle = |1,-1\rangle, |1,0\rangle, |1,1\rangle, |1,-2\rangle$$