Fun with Ultracold Atoms

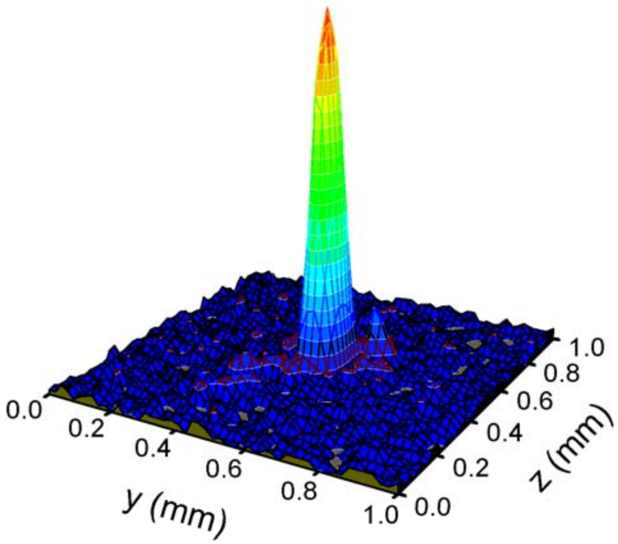
a) Ultracold Atom Generation

i) BEC in Magnetic Trap
ii) Optical Trap
iii) Microtrap Array

b) Precision Spectroscopy

W. A. van Wijngaarden

Physics Dept., York University



Statistical Mechanics Background

K. Stowe, Intro. Stat. Mech. & Thermo., (J. Wiley, Toronto, 1984)

Fermions

Half integral spin (electron, proton, neutron)

$$n = \{\exp(\varepsilon - \mu)/kT + 1\}^{-1}$$

Bosons

Integral spin (photon, meson)

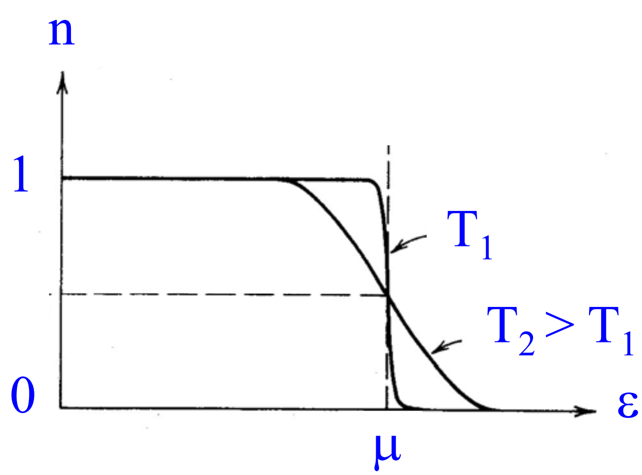
$$n = \{\exp(\varepsilon - \mu)/kT - 1\}^{-1}$$

where: n = # particles in state of energy ε

μ = chemical potential found by $\Sigma_\varepsilon\, n(\varepsilon) = N_{tot}$

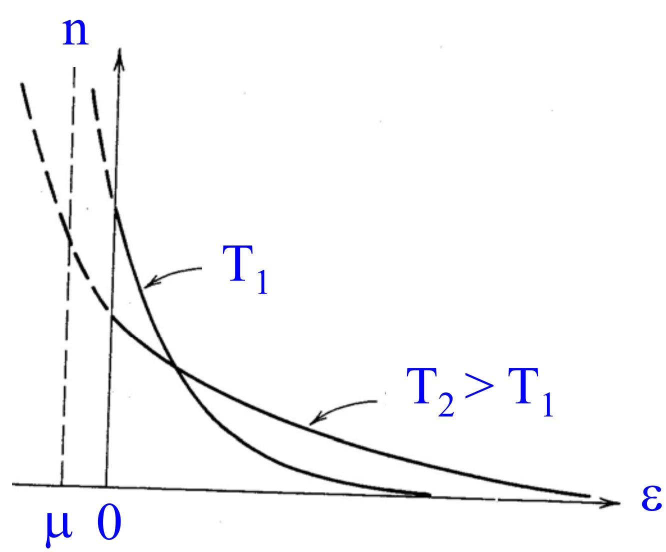
k = Boltzmann constant

T = temperature



Paul Exclusion Principle:

Identical fermions can't occupy same state.



Identical bosons can occupy same state.

Behaviour of Bosons at Low Temperature

D & J Tilley, Superfluidity & Superconductivity (U. Sussex Press,1986)

Consider system having energy levels separated by $\Delta\varepsilon \approx kT$
All bosons populate lowest state causing weird macroscopic effects.

Superfluidity

At temperature < 2.2 K liquid helium has

a) No viscosity – flows unimpeded through tiniest cracks
– climbs up walls of container

b) Vortices – whirlpools that never stop rotating

Superconductivity

Zero electrical resistance. In late 1980's high temperature superconductors with transition temperatures of $\approx$ 100 K

Bose Einstein Condensation (BEC)

C. Pethick & H. Smith, BEC in Dilute Gases, (Cambridge Press, 2002).

Macroscopic manifestation of quantum mechanics proposed in 1924.

Superfluid ^{4}He in 3D Square Well

BEC Criterion: $\rho\,(T) > 2.612$

Phase space density $\rho = n\,(\lambda_{dB})^3$

where: n = atom density

$\lambda_{dB} = h \,/\, (2\pi\, M\, k_B\, T)^{1/2}$

h = Planck's constant

M = atom mass

Superfluid ^{4}He: $n = 2 \times 10^{22}$ atoms/cm^3

$\Rightarrow$ Transition Temperature $T_c = 3$ K

^{87}Rb in Harmonic Potential

$$V = M\,(\omega_x{}^2 x^2 + \omega_y{}^2 y^2 + \omega_z{}^2 z^2)\,/\,2$$

BEC Criterion: $kT < 0.15\, h\, \varpi\, N^{1/3}$

where: $\varpi = (\omega_x\, \omega_y\, \omega_z)^{1/3}$

N = # trapped atoms

^{87}Rb in Trap: $n \approx 10^{14}$ atoms/cm^3

$\Rightarrow$ Transition Temperature $T_c \approx 100$ nK

Technology to generate nanoKelvin temperatures not created until 1990s.

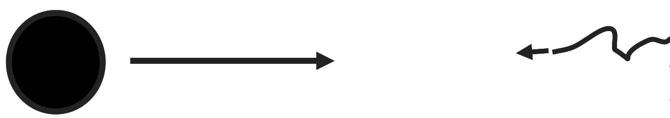
Laser Cooling

H. Metcalf & P. v. d. Straten, Laser Cooling & Trapping(Springer,1999)

Analogous to stopping transport truck on highway (atom) by bouncing beam of ping pong balls (photons) off it.

Velocity v

Mass M



h / λ

Photon Momentum

h = Planck's constant

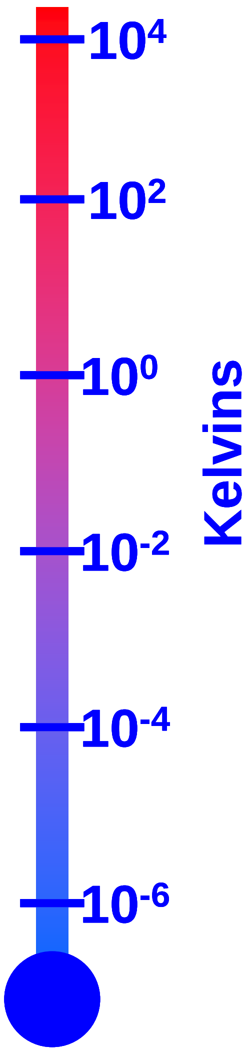
photons to stop thermal ^{87}Rb atom = $M v / (h / \lambda)$ = 50,000 photons

Stopping Time $T = 50{,}000 \times \tau$ excited state lifetime = 1.4 msec

Stopping Distance = $v \tau / 2$ = 20 cm

Laser Power to stop 10^9 atoms/sec = $10^9 \times 50{,}000\, h \nu / T \approx 10$ mW

Doppler cooling limit = $h \Gamma$ transition linewidth $/2 k \approx 100\ \mu$K



Experimental Requirements for BEC

For detailed recipe see: B. Lu & WvW, *Can. J. Phys*. **82**, 81 (2004)

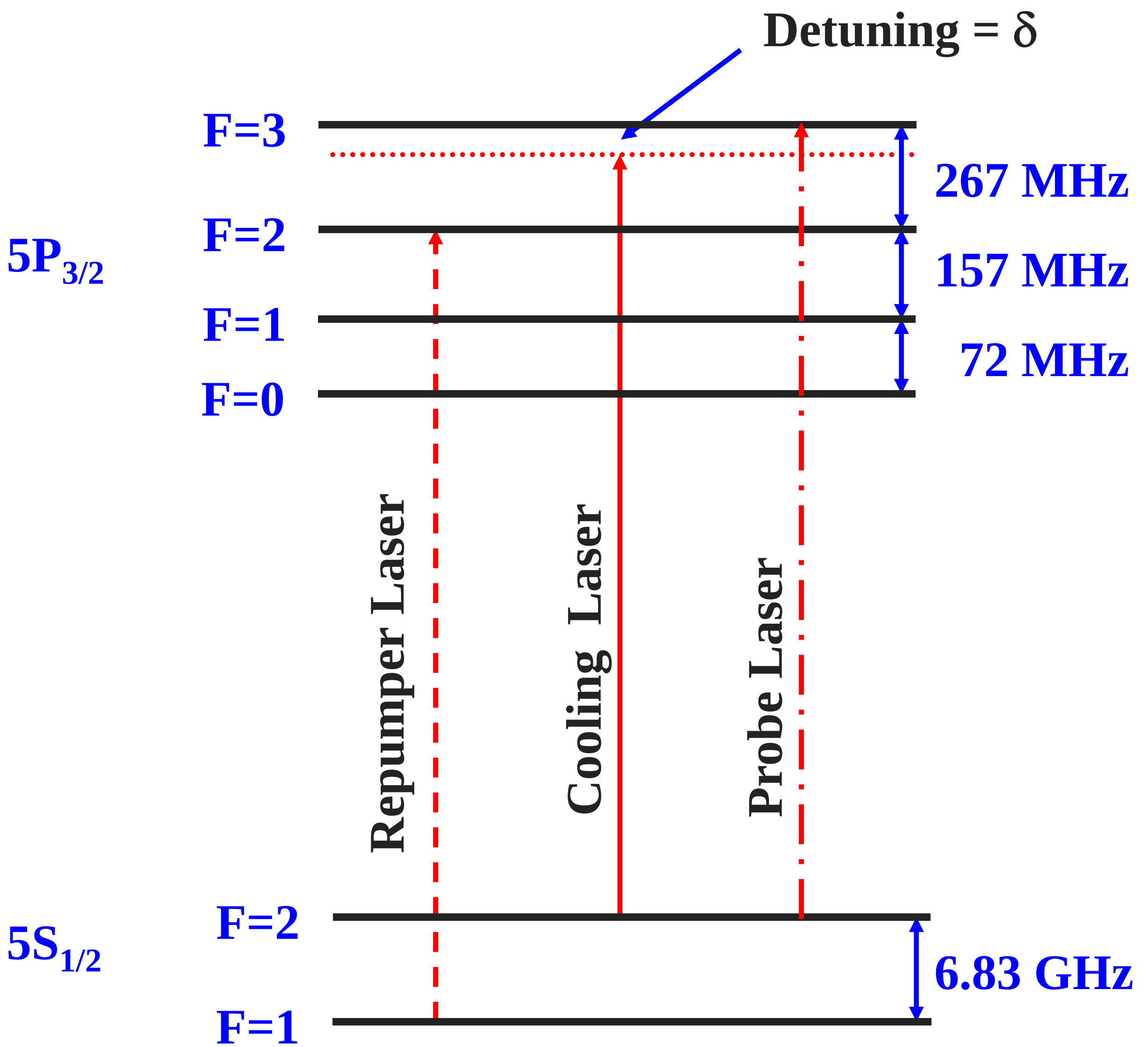
1. Excellent Vacuum ≈ 2 x 10^{-11} torr

2. Laser Control
   a) Frequency
   b) Spatial Profile
   c) Polarization
   d) Power
   e) Pulse Duration

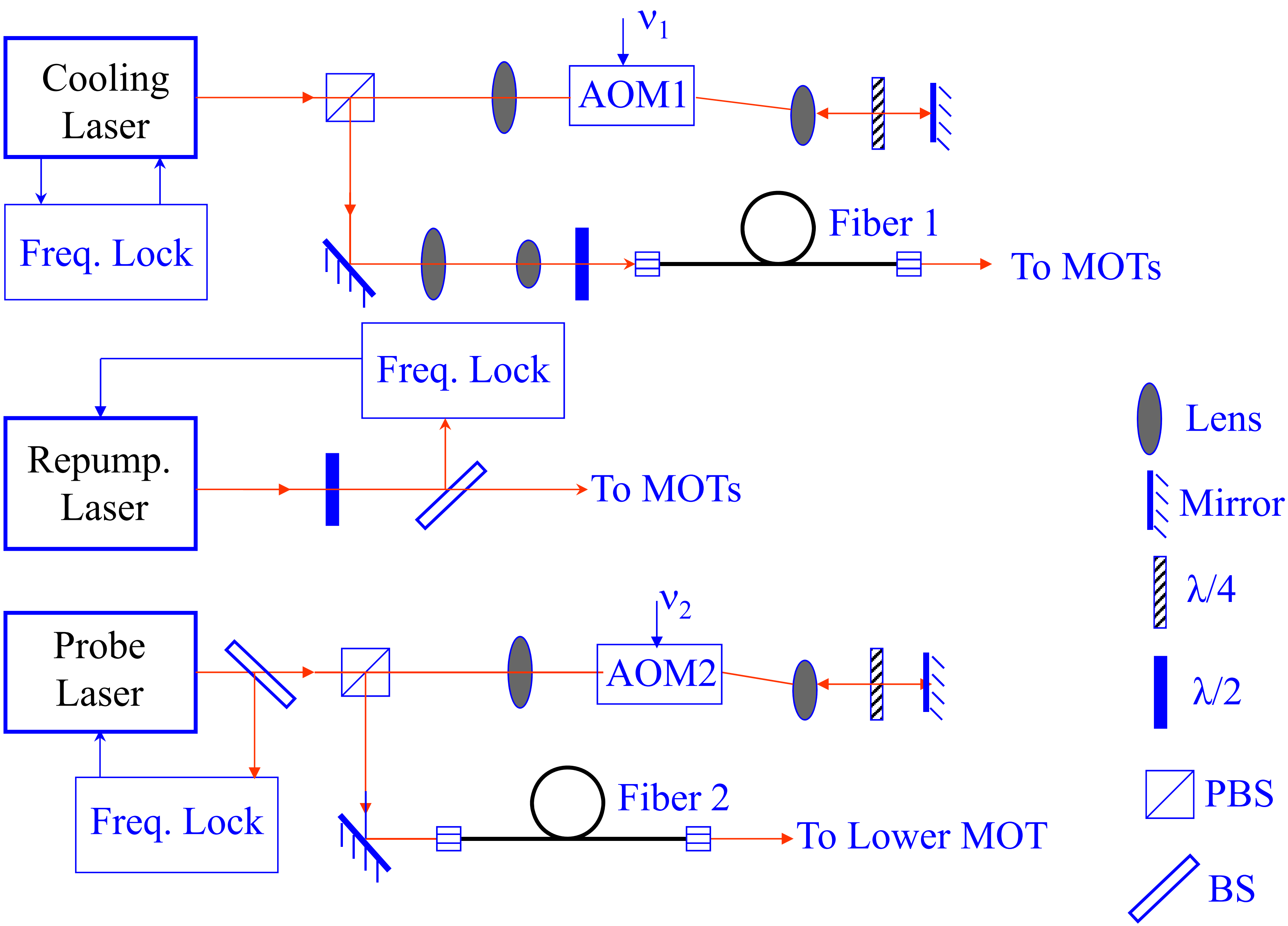
3. Magnetic Fields
   a) Precise control of fields
   b) Rapid Switching of Currents

4. Coordination/Timing of:
   a) Laser beams
   b) Magnetic Fields
   c) Evaporative Cooling
   d) Probing

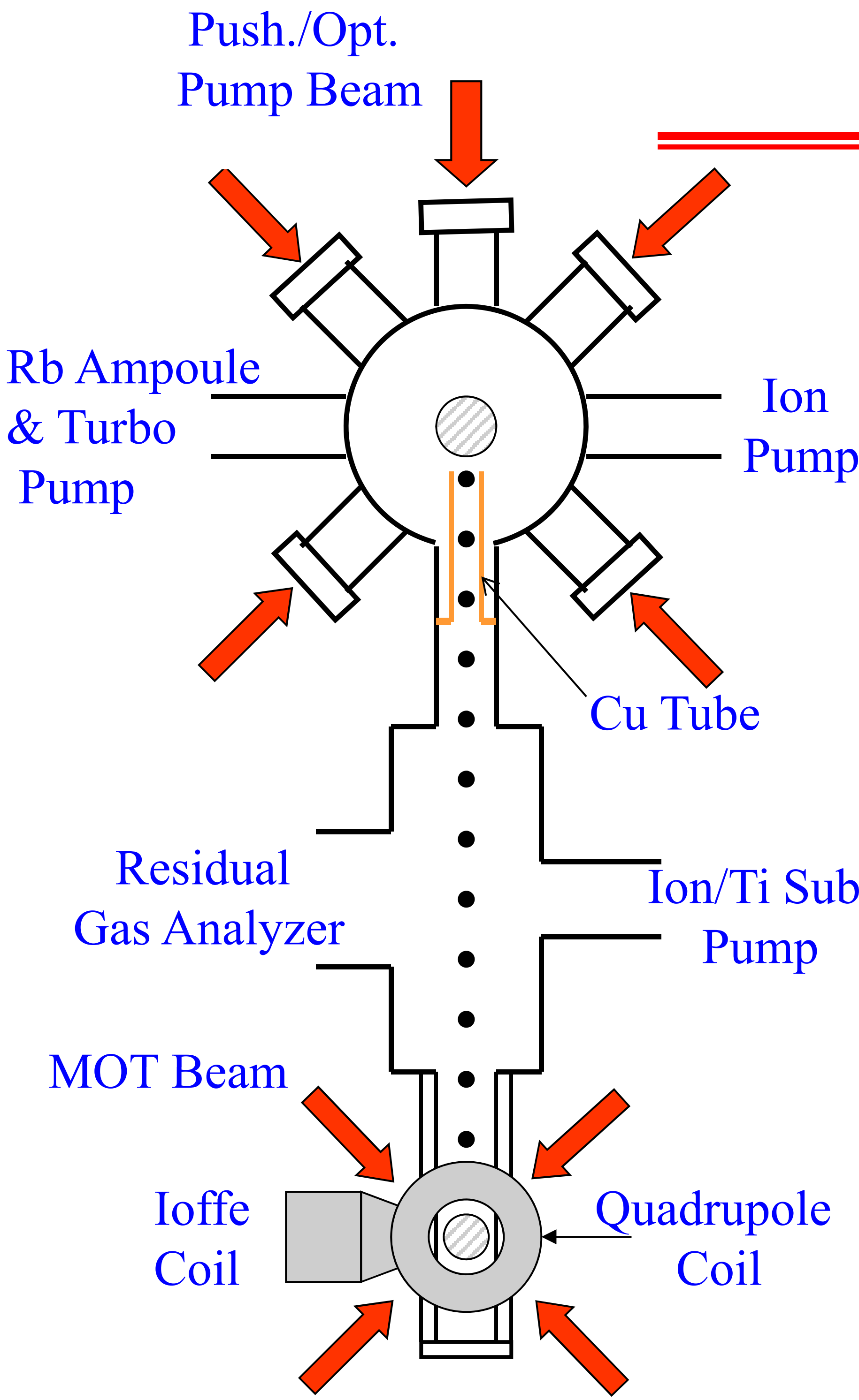
^{87}Rb MOT: Relevant Energy Levels



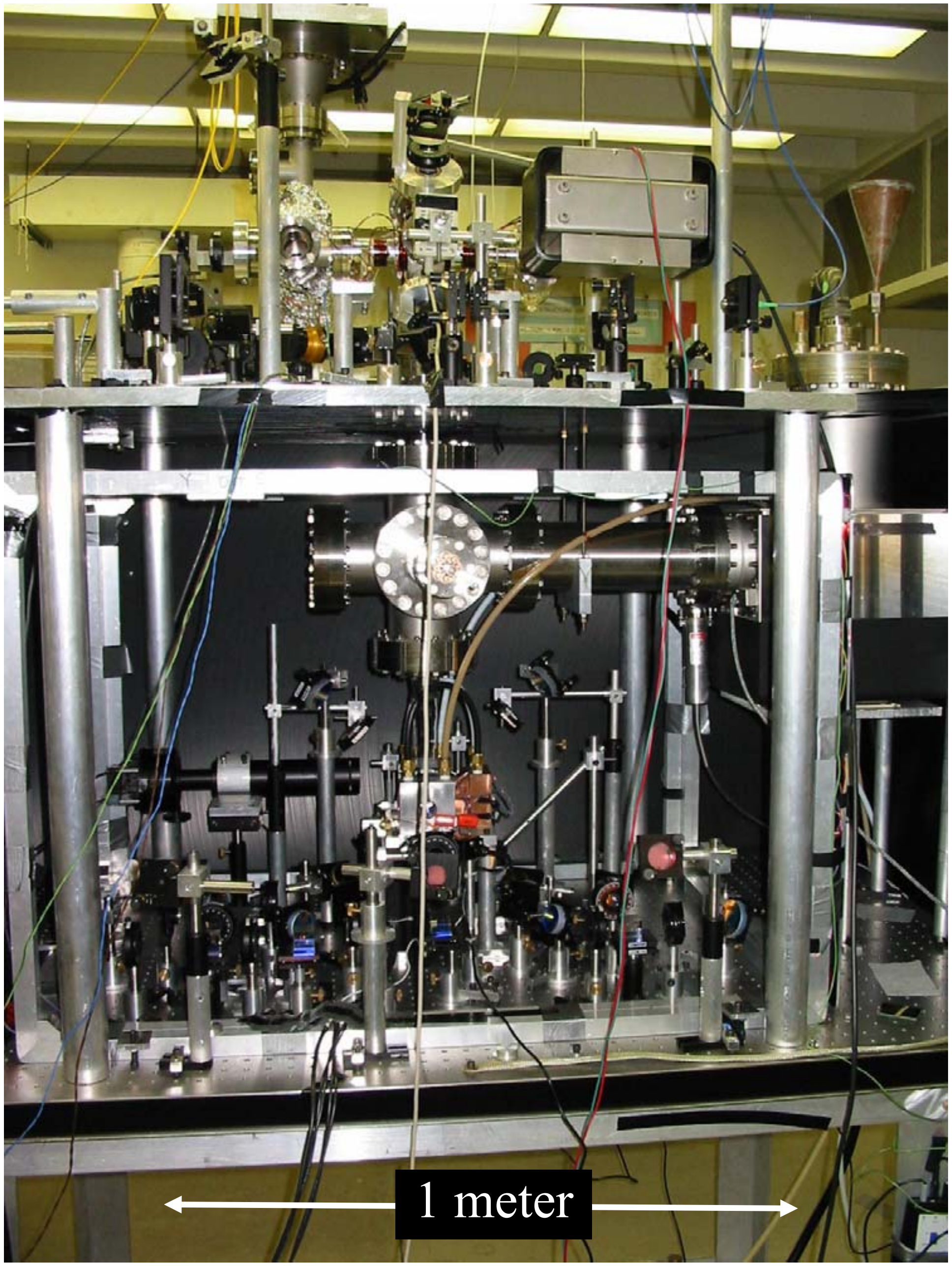
Layout of Laser Systems



Apparatus

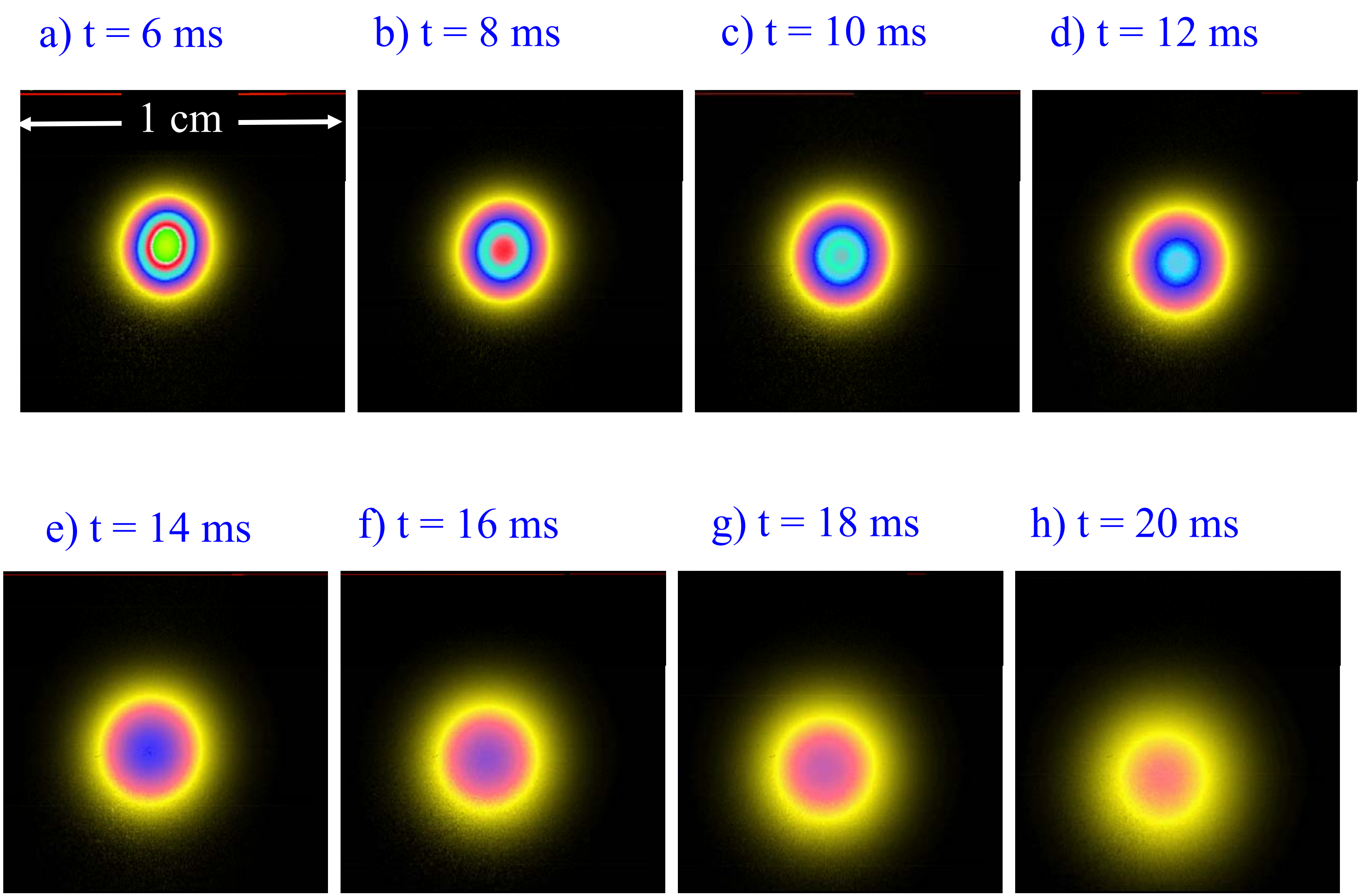


Push./Opt.
Pump Beam
Rb Ampoule
& Turbo
Pump
Ion
Pump
Cu Tube
Residual
Gas Analyzer
Ion/Ti Sub
Pump
MOT Beam
Ioffe
Coil
Quadrupole
Coil

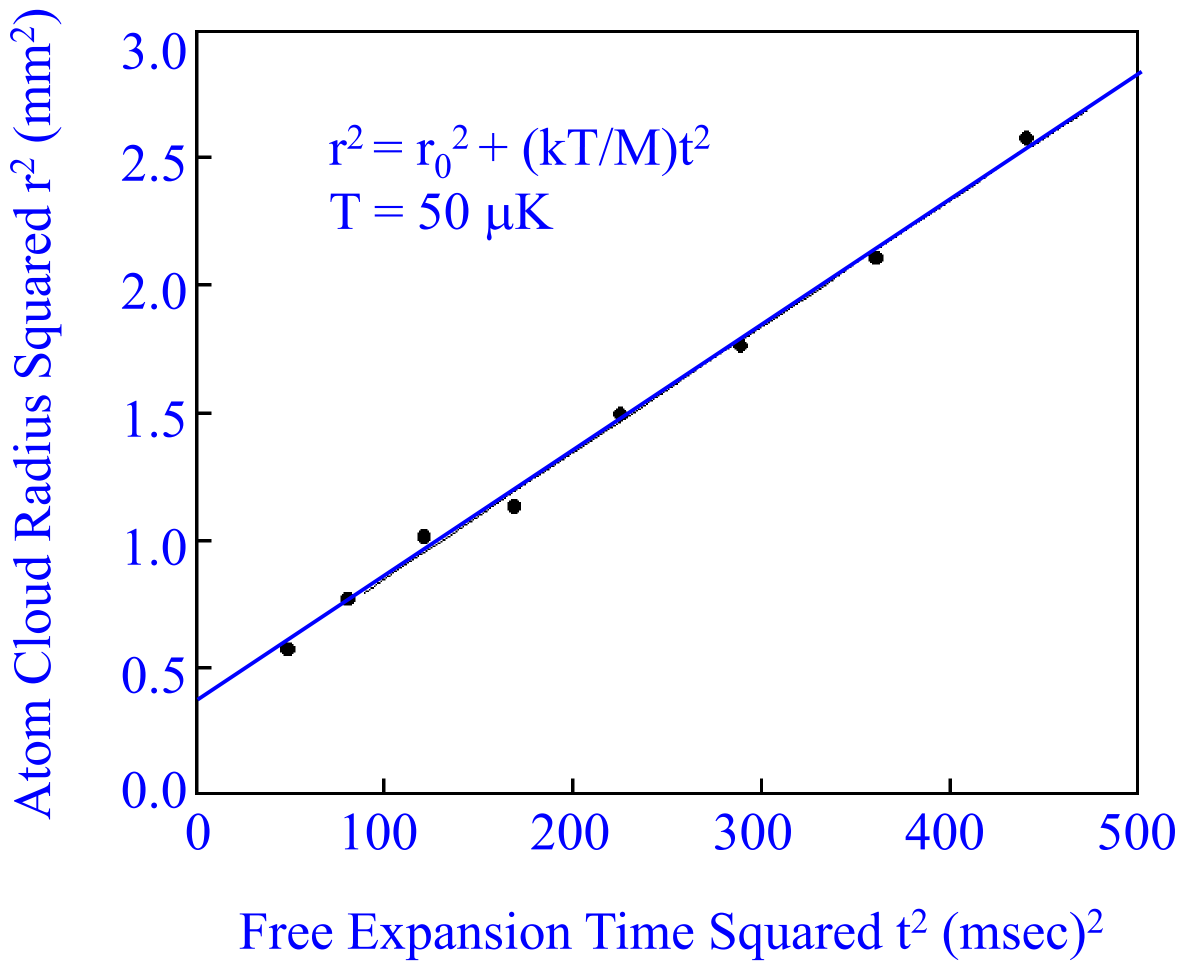


1 meter

Free Expansion of Atom Cloud



Temperature Determination

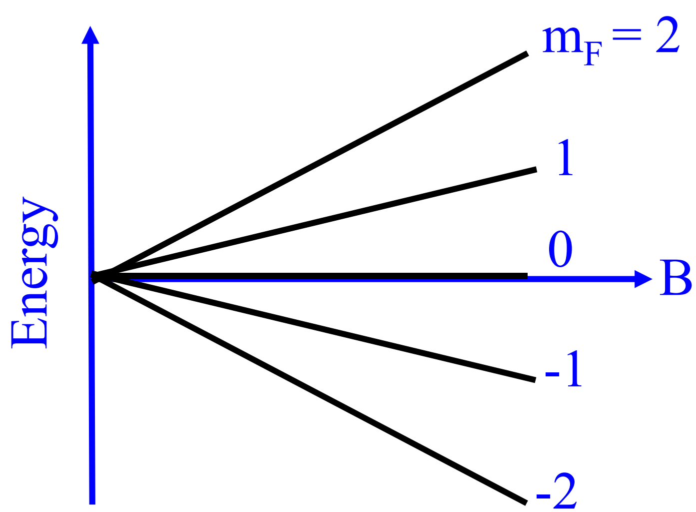


i) Magnetic Trap

Objective

- Accumulate high density of atoms
- Isolate atoms from hot chamber walls & lower temperature to achieve BEC

Hamiltonian of Dipole Moment μ with Magnetic Field B: $H = -\mu \cdot B$



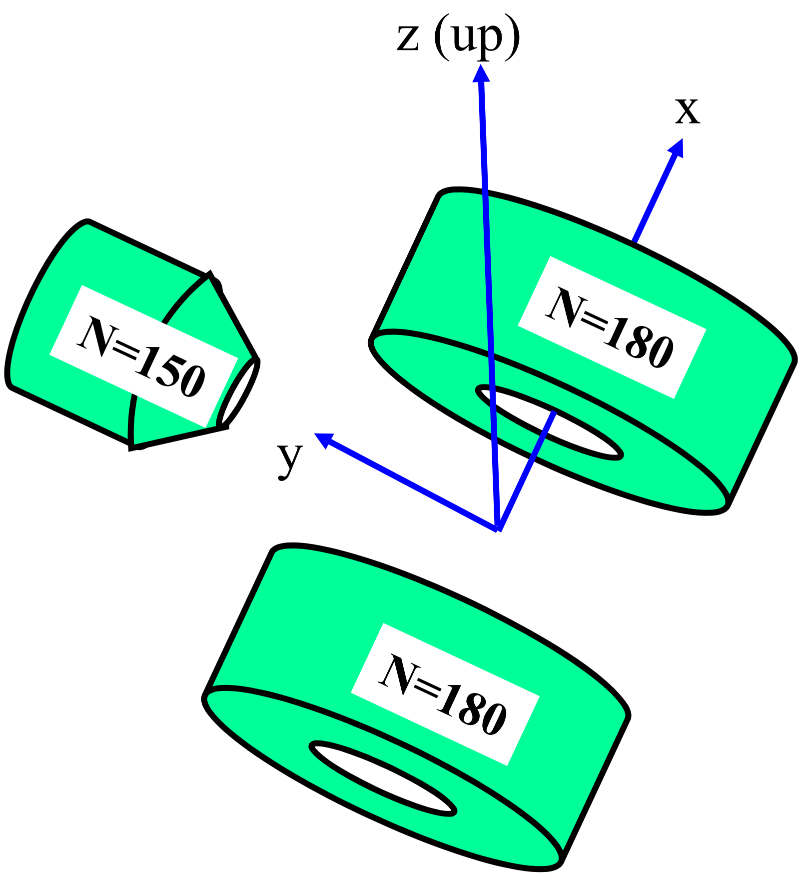
Quadrupole Trap

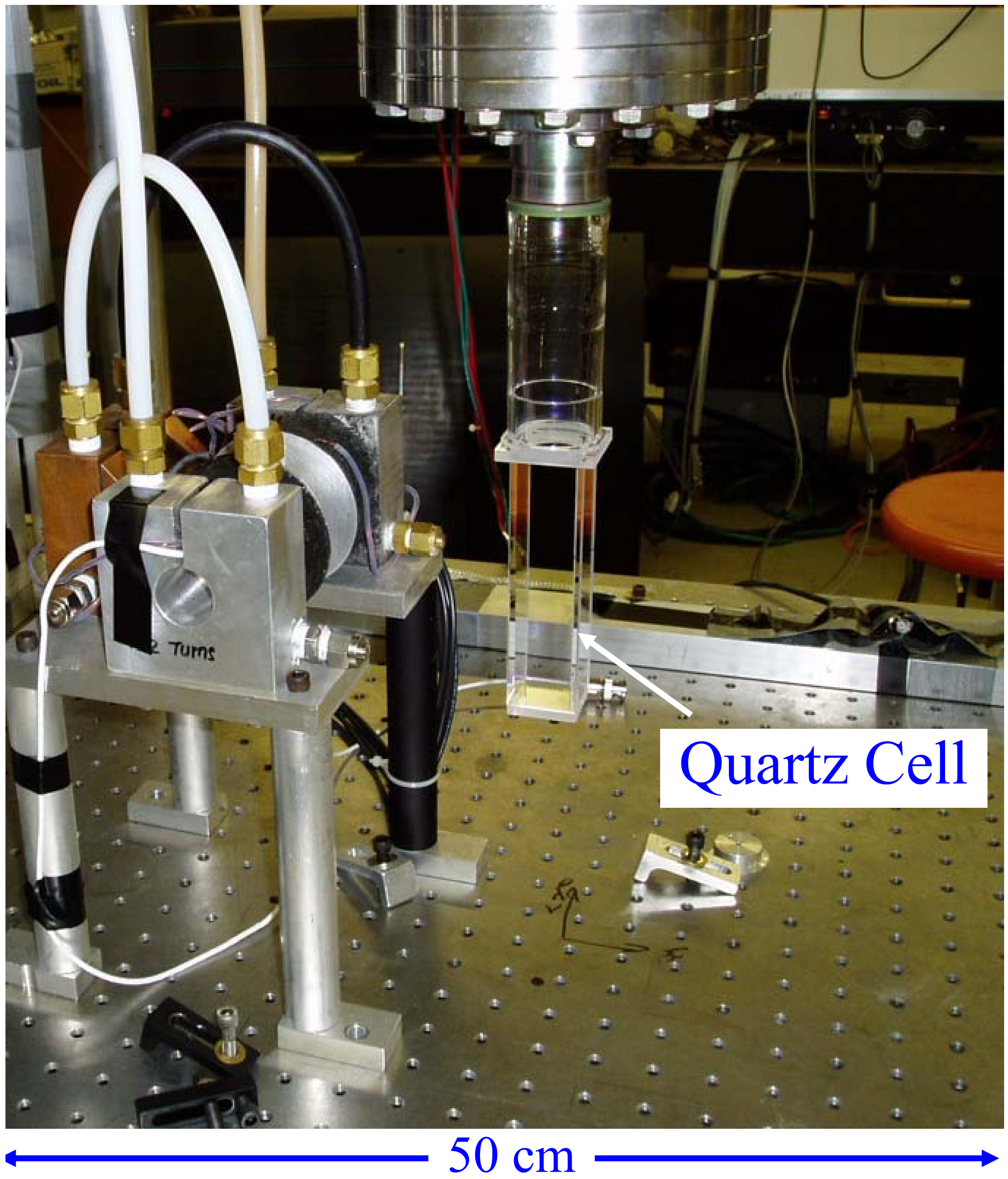
Pair of antiHelmholtz coils generate region having zero magnetic field to trap ^{87}Rb $5S_{1/2}$ (F=2) atoms occupying $m_F = +2,+1$ sublevels.

Problem: Spins flip when B = 0 and atom is no longer trapped.

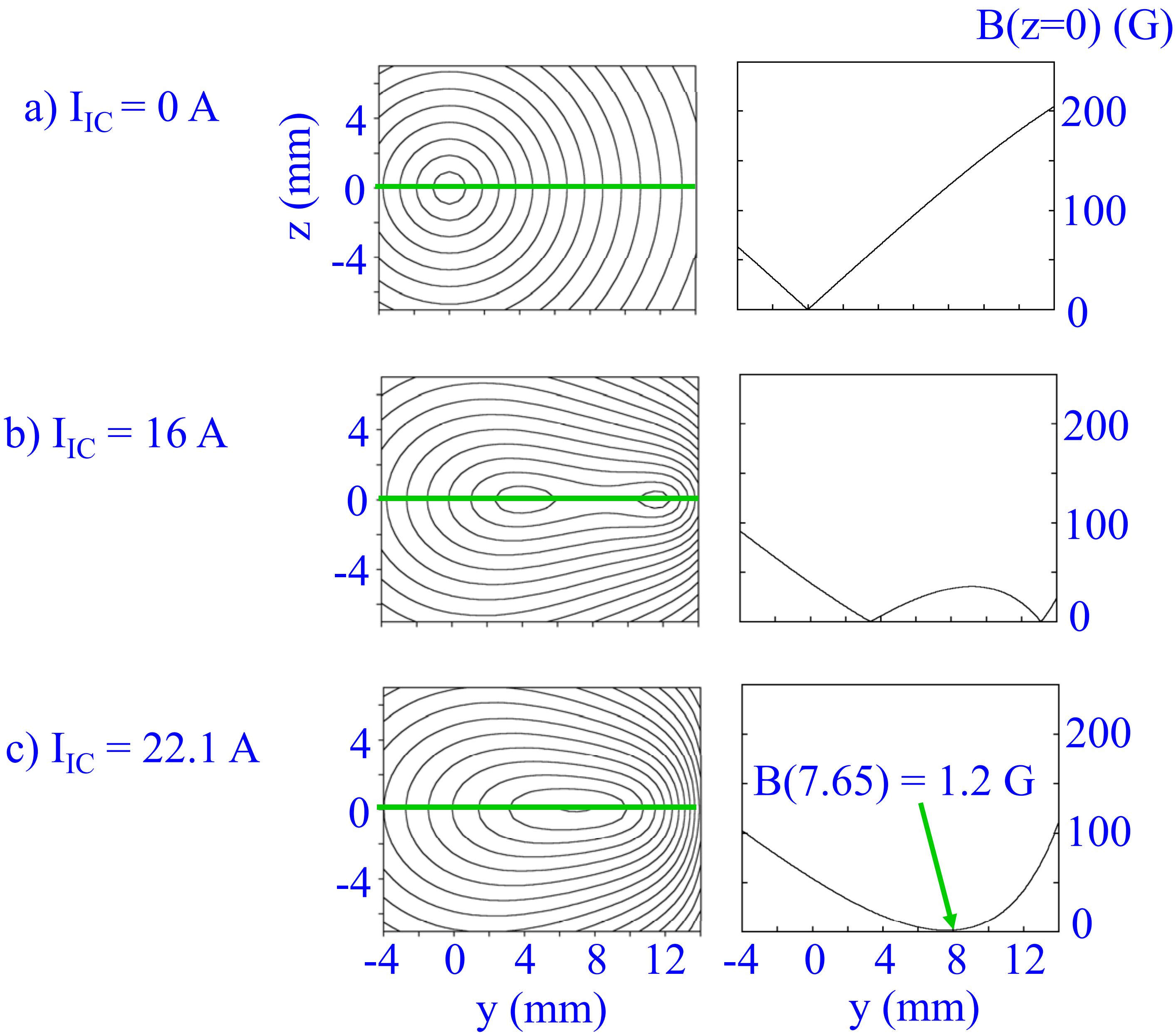
QUIC Trap

QUIC = 2 Quadrupole Coils + Ioffe Coil

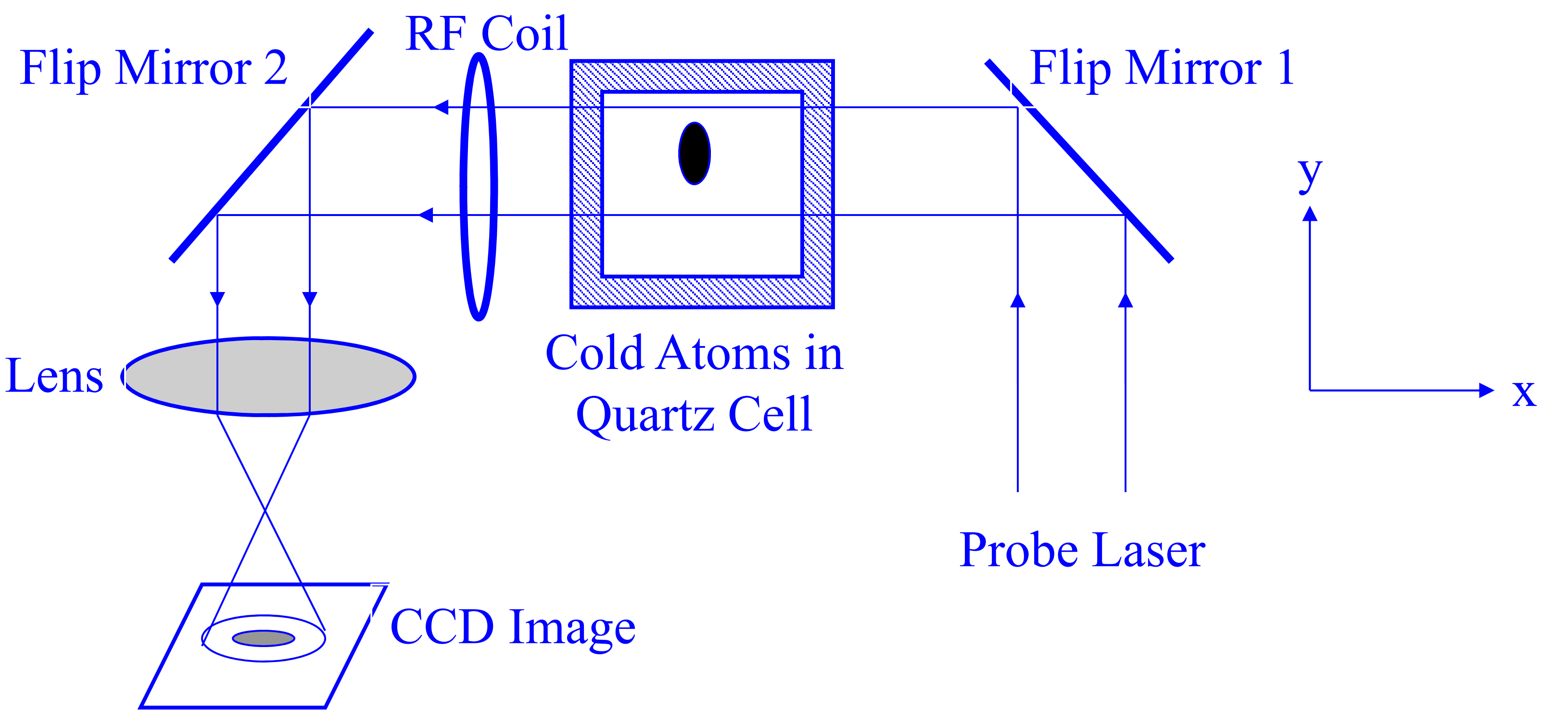


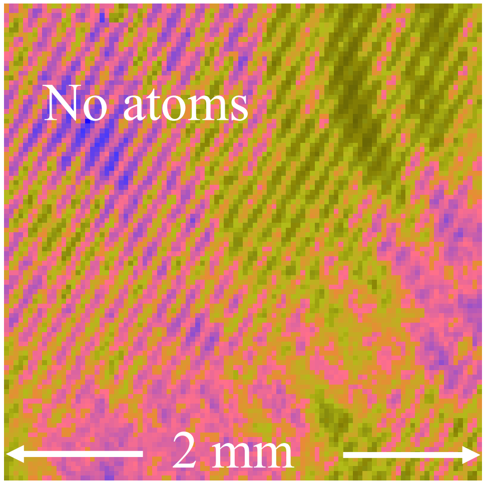


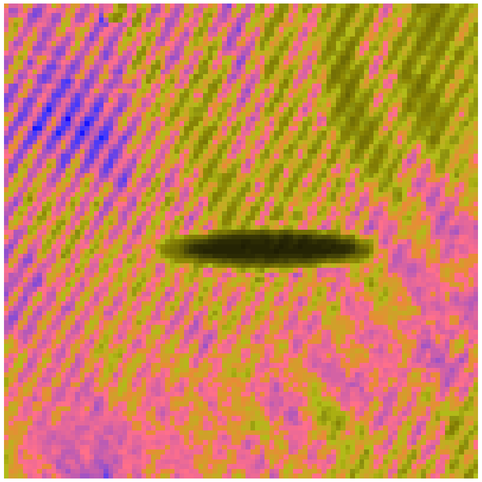
Effect of Ioffe Coil (I_{quad} = 25 A)

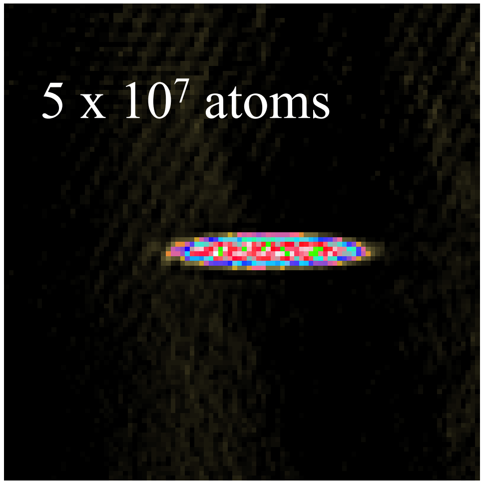


Imaging using Probe Laser Absorption



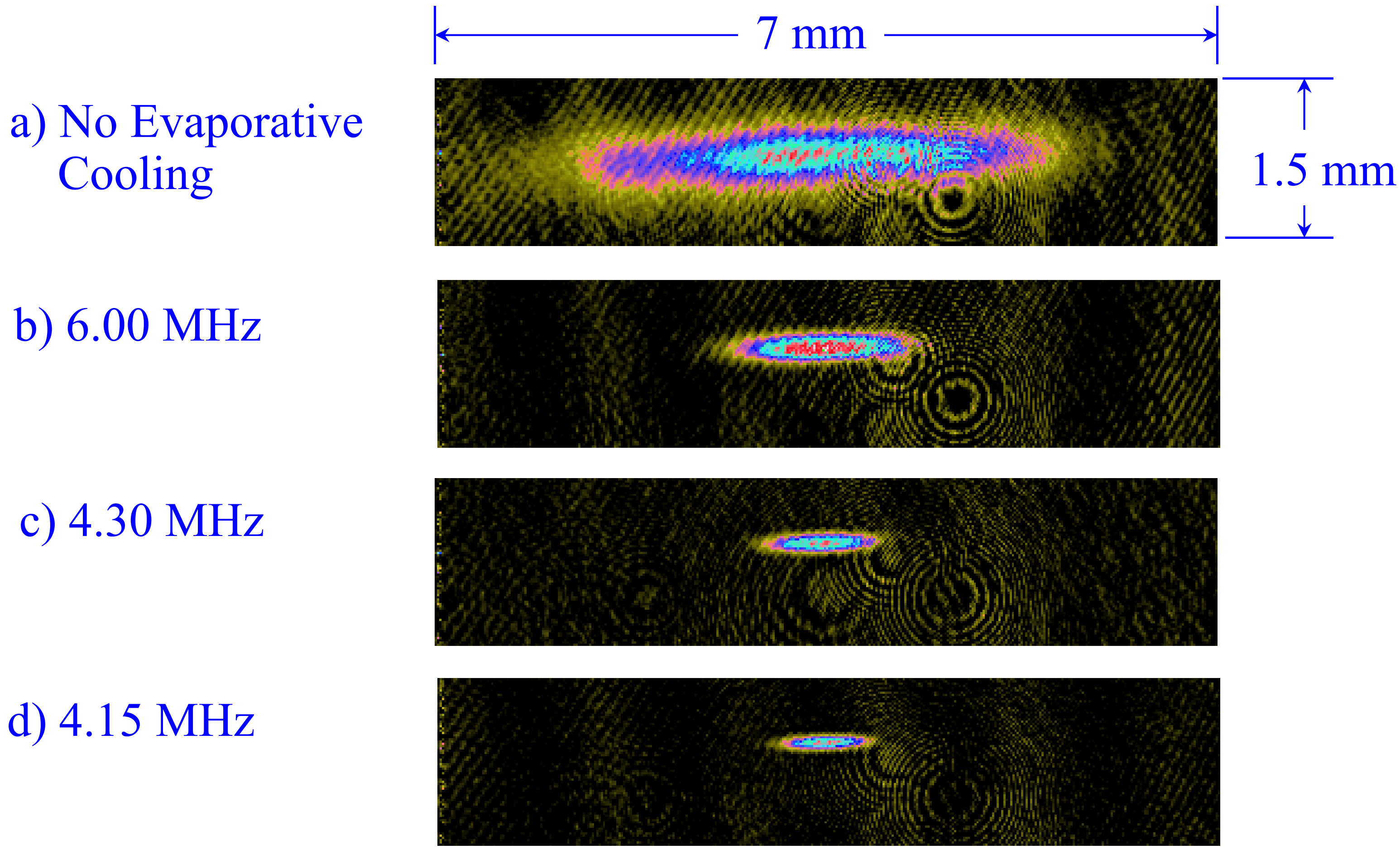






Evaporative Cooling

RF swept from 20 MHz to lower frequency over 40 sec. At high frequencies, only hottest atoms far from trap minimum experiencing high magnetic field are in resonance. Their spins are flipped and atoms become untrapped. Remaining atoms undergo collisions and rethermalize.



Transition to BEC

Absorption Images taken after 24 msec free expansion

a) Thermal cloud

$\nu_{stop} = 2.410$ MHz

$T = 449$ nK

$N = 1.9 \times 10^6$ atoms

b) Thermal cloud + Condensate

$\nu_{stop} = 2.406$ MHz

$T = 400$ nK

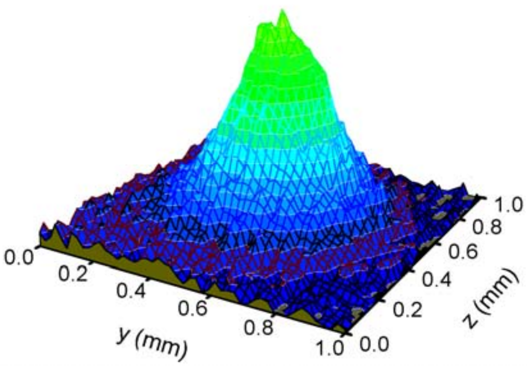
$N = 1.8 \times 10^6$ atoms

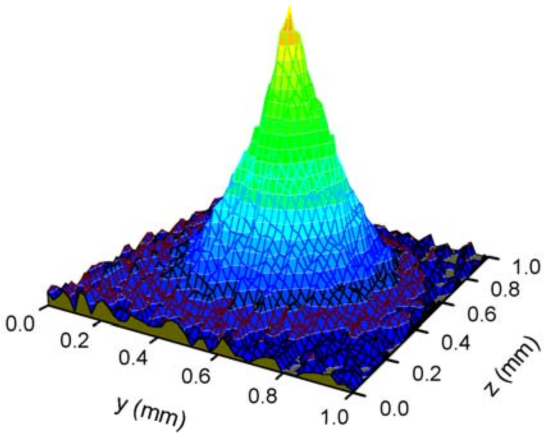
c) Pure Condensate

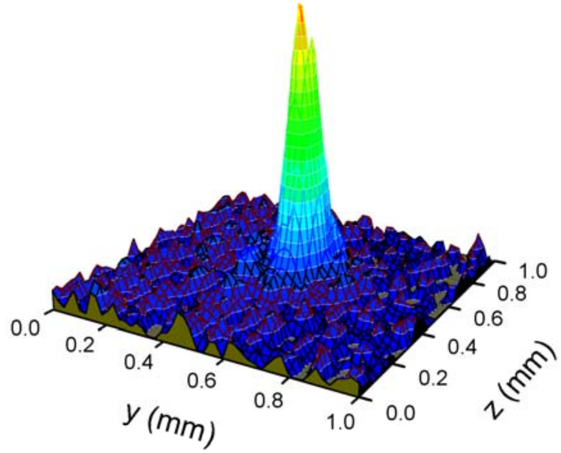
$\nu_{stop} = 2.402$ MHz

$T < 60$ nK

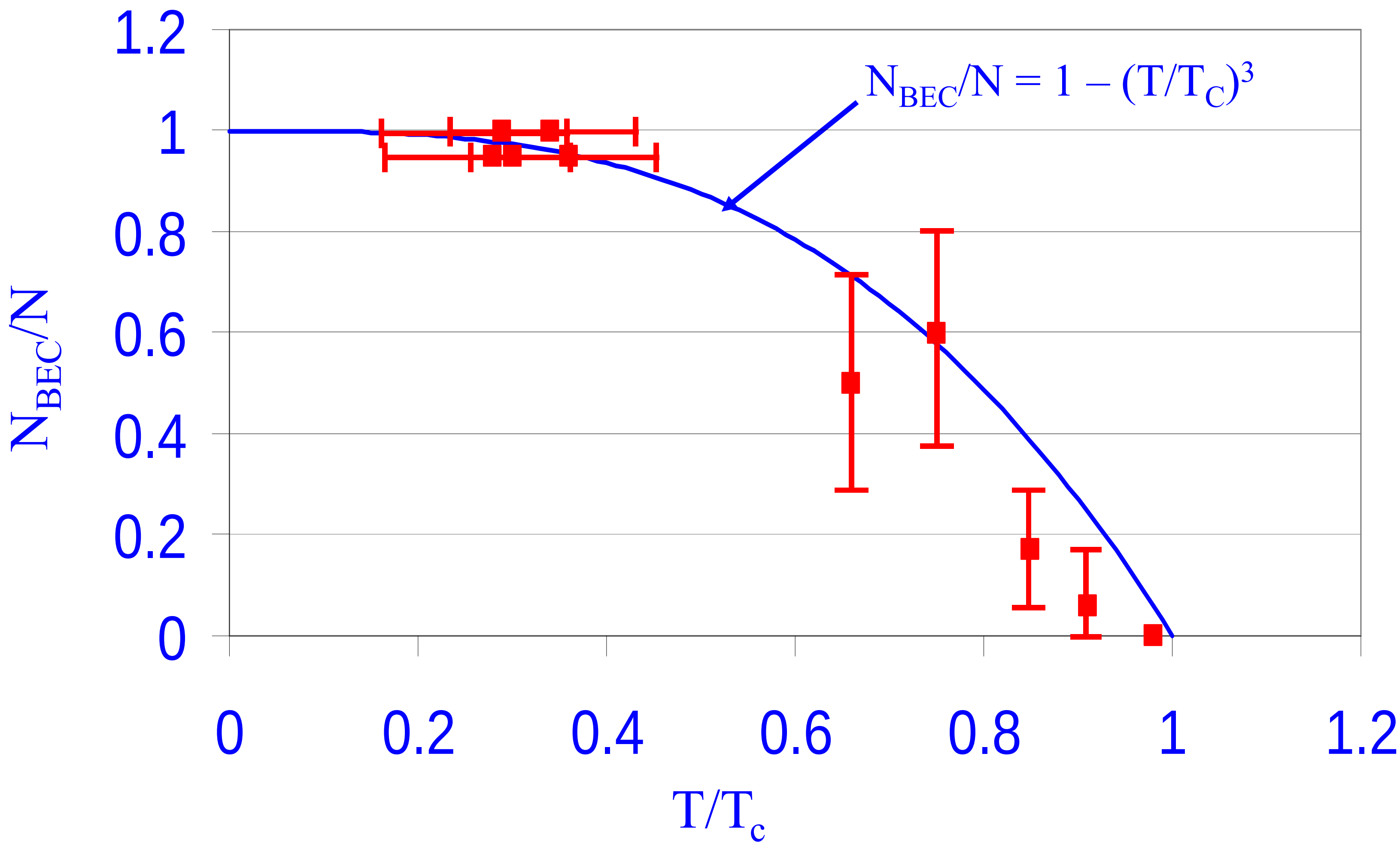
$N = 4.2 \times 10^5$ atoms







Fraction of Atoms in Condensate versus Temperature



BEC Time Evolution

<u>**Gross-Pitaevskii Equation**</u>

$$-\hbar^2/2m\ \nabla^2\ \Psi(r,t) + V\ (r)\ \Psi(r,t) + U_o\ |\Psi(r,t)|^2\ \Psi(r,t) = i\ \hbar\ \delta\Psi(r,t)/\delta t$$

where: $U_o = 4\pi\ \hbar^2\ a\ /\ M$

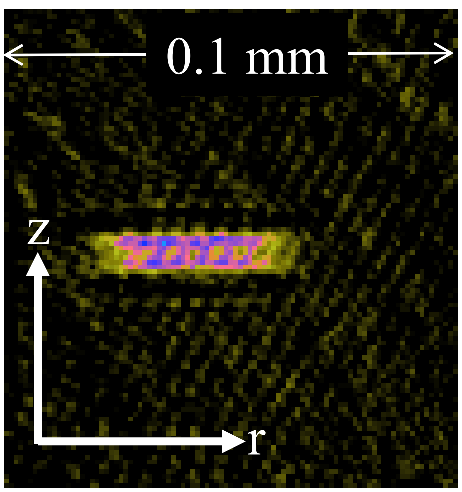
a = scattering length for lowest energy plane wave scattering

a>0 (a<0) if interaction between atoms is repulsive (attractive)

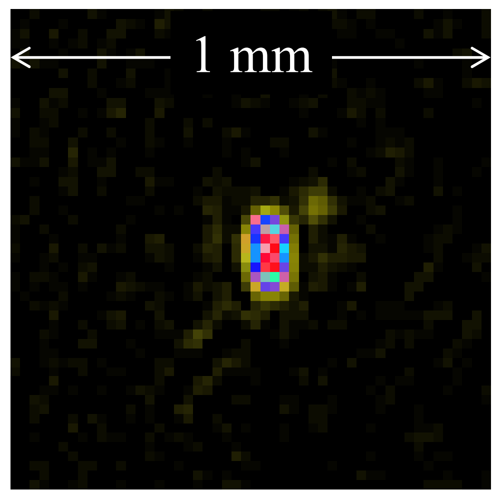
Ψ = condensate wavefunction, $|\Psi|^2$ = # atoms in condensate

$\Rightarrow$ predicts more rapid expansion in y than in z direction for harmonic potential

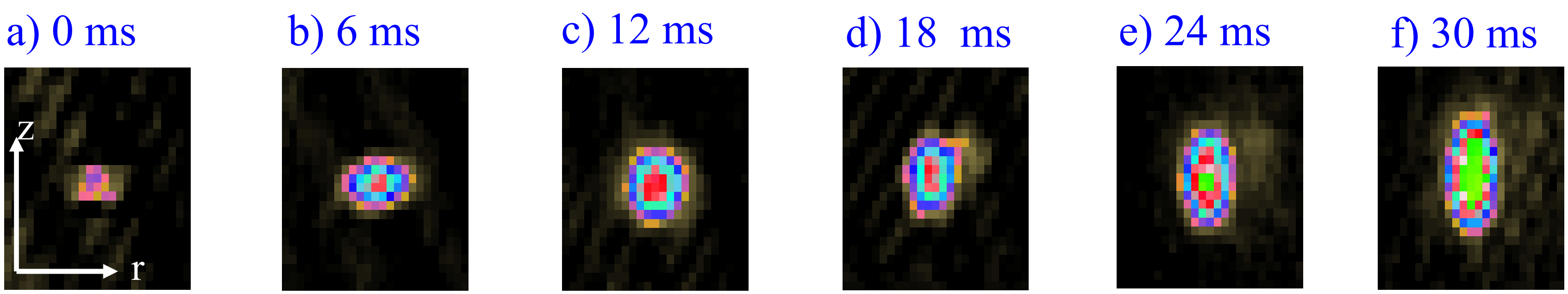
a) Before Free Expansion

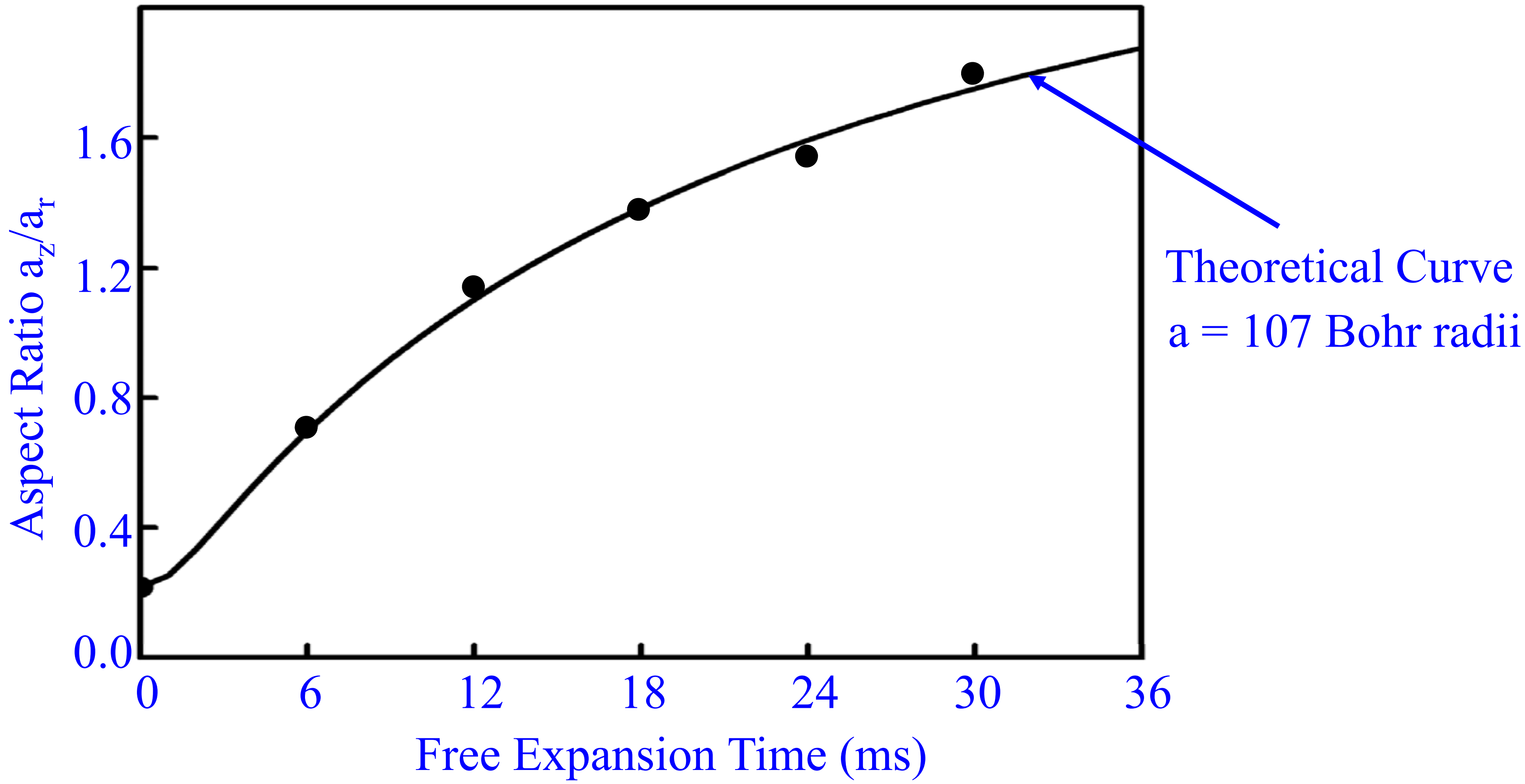


b) After 24 msec Free Expansion

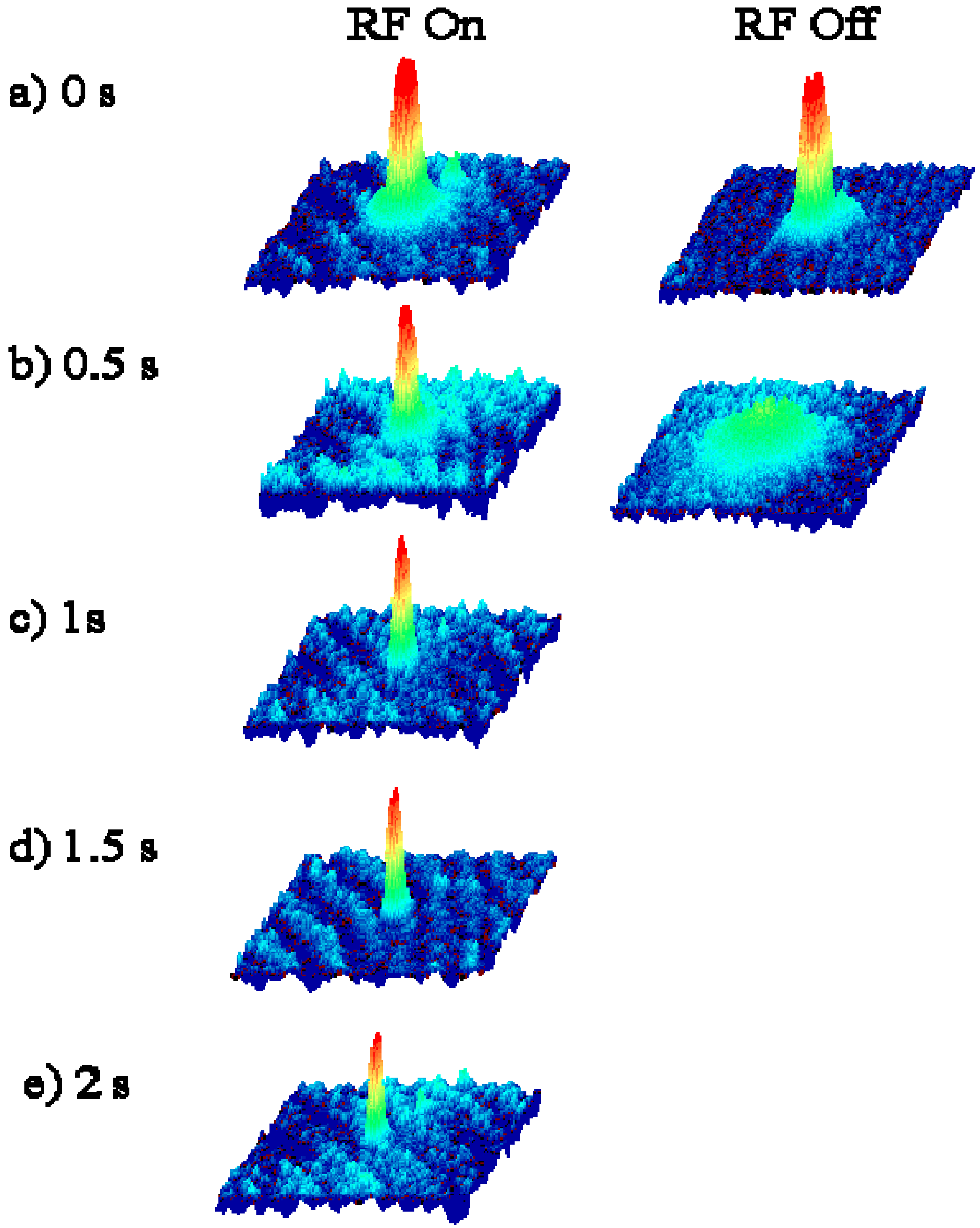


BEC Time Evolution





BEC Lifetime in QUIC Trap



ii) Optical Trap

H. Ming & WvW, CJP (2007)

Far **O**ff **R**esonance **T**rap **(FORT)** created by focusing laser detuned below resonance.

Trap Depth $U = \frac{\hbar}{4} \frac{I}{I_s} \frac{\Gamma^2}{\Delta}$ where Γ = natural linewidth

I = laser intensity

I_s = saturation intensity

Δ = detuning of laser from resonance

Heating Rate $H = \gamma \frac{\hbar^2 k^2}{M}$ where photon scatter rate $\gamma = \frac{3}{2} \frac{I}{I_s} \frac{\Gamma^3}{\Delta^2}$

Trap Lifetime $\tau = U / H$

FORT Laser

$\lambda = 852$ nm

$I = 100$ mW / π (30 μm)^2

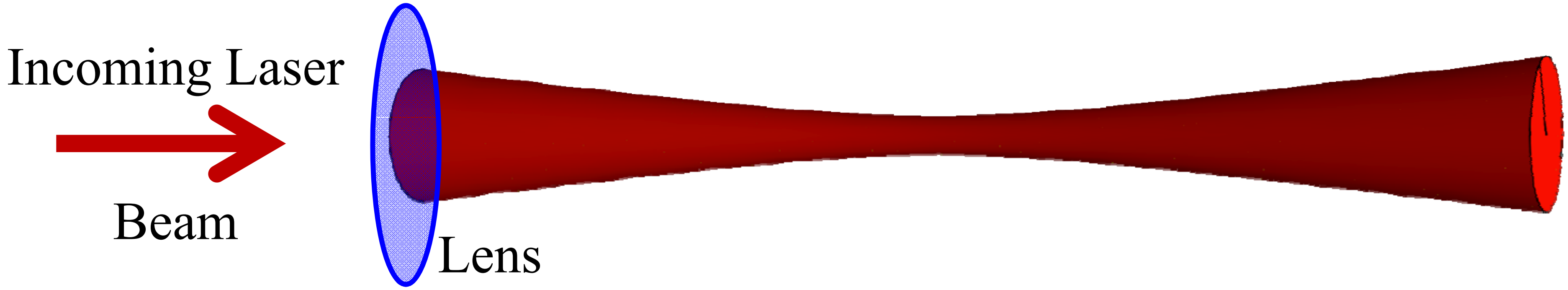
$\longrightarrow$

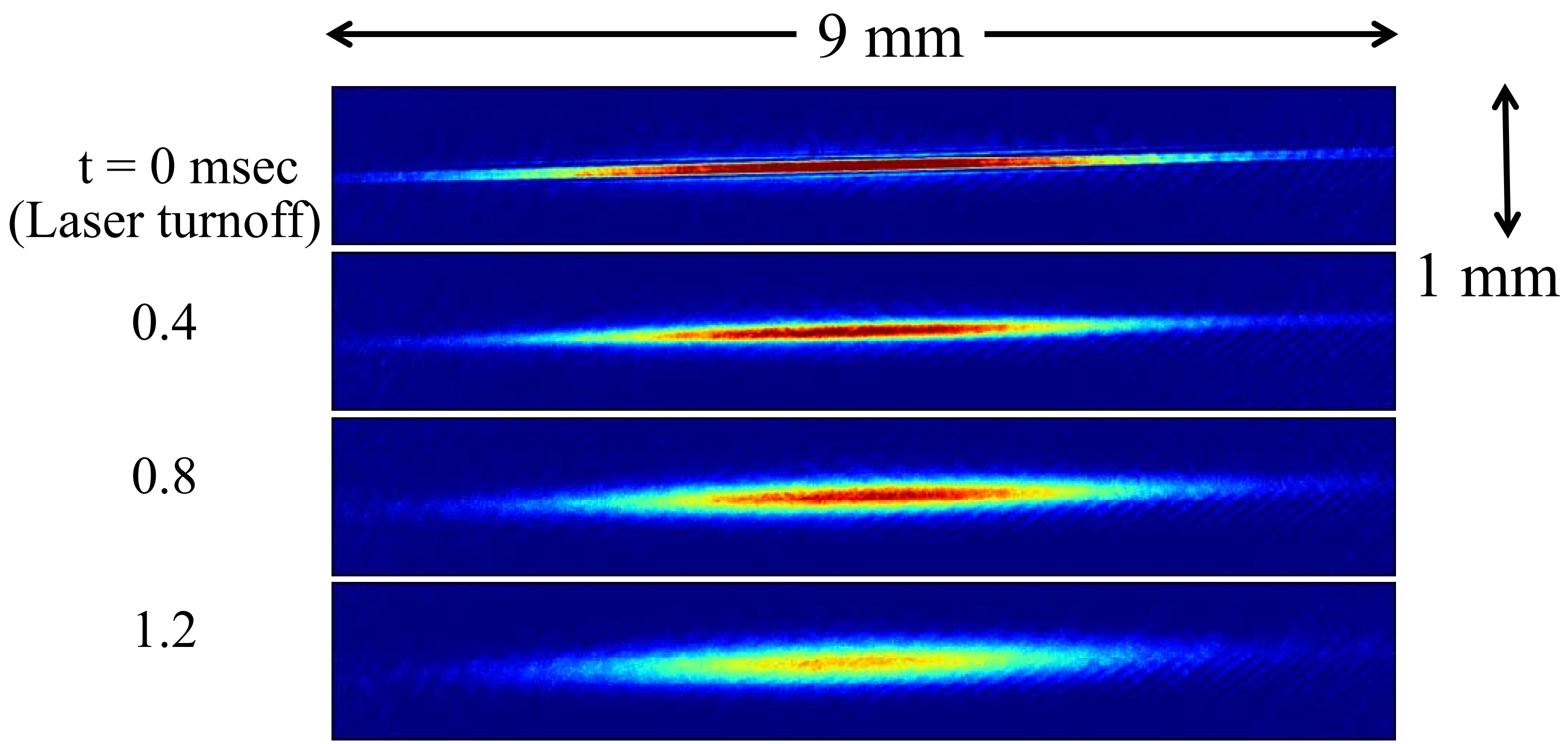
$U_{max} = 75$ μK

$H_{max} = 1$ μK/sec

$\tau = 75$ sec

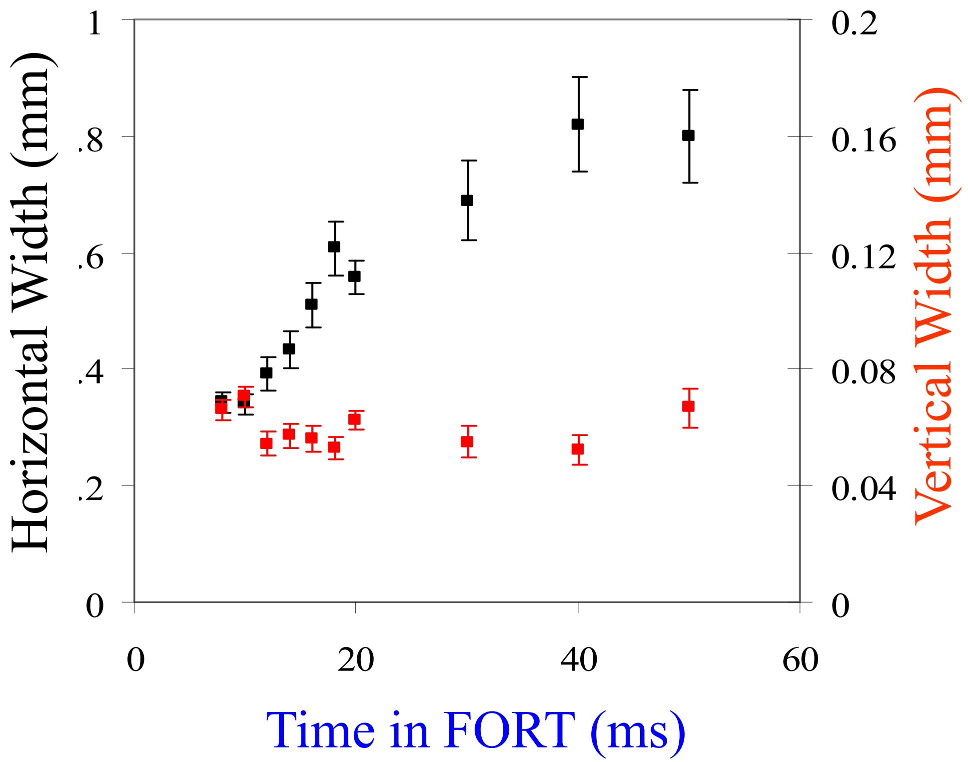
Optical Trap using focussed Infrared Laser

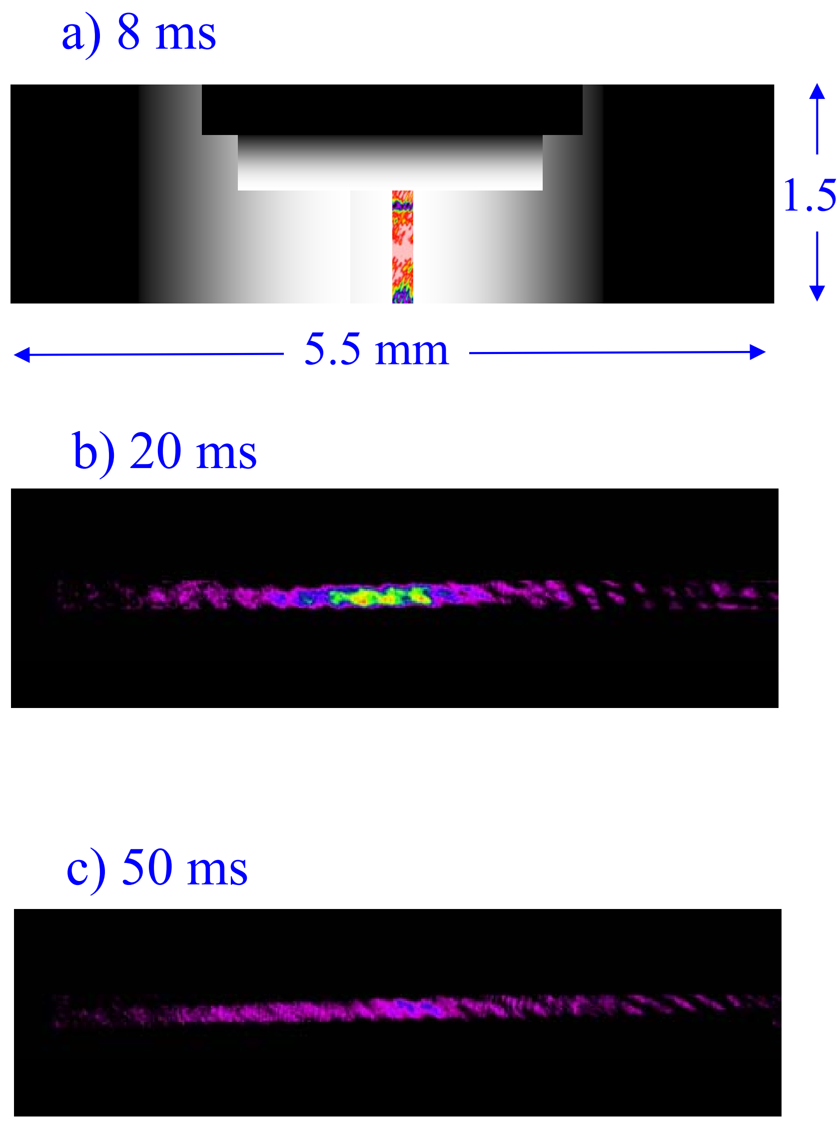




Evolution of Atoms in FORT

Time measured after QUIC trap turnoff H. Ming & WvW, CJP (2007)





iii) Microtrap on Atom Chip

B. Jian & WvW, JOSA *B* **30**, No. 2, 238 (2013)

Trap Parameters

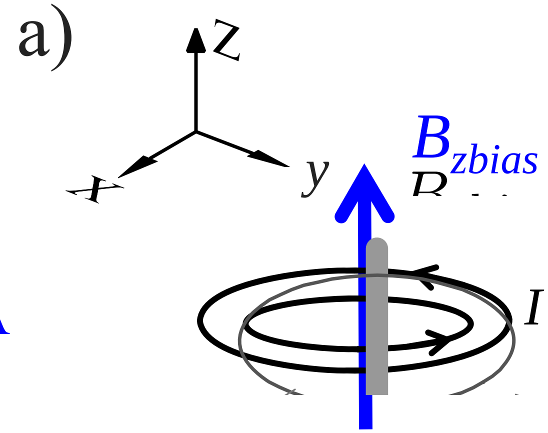
Inner Loop Radius = 300 μm

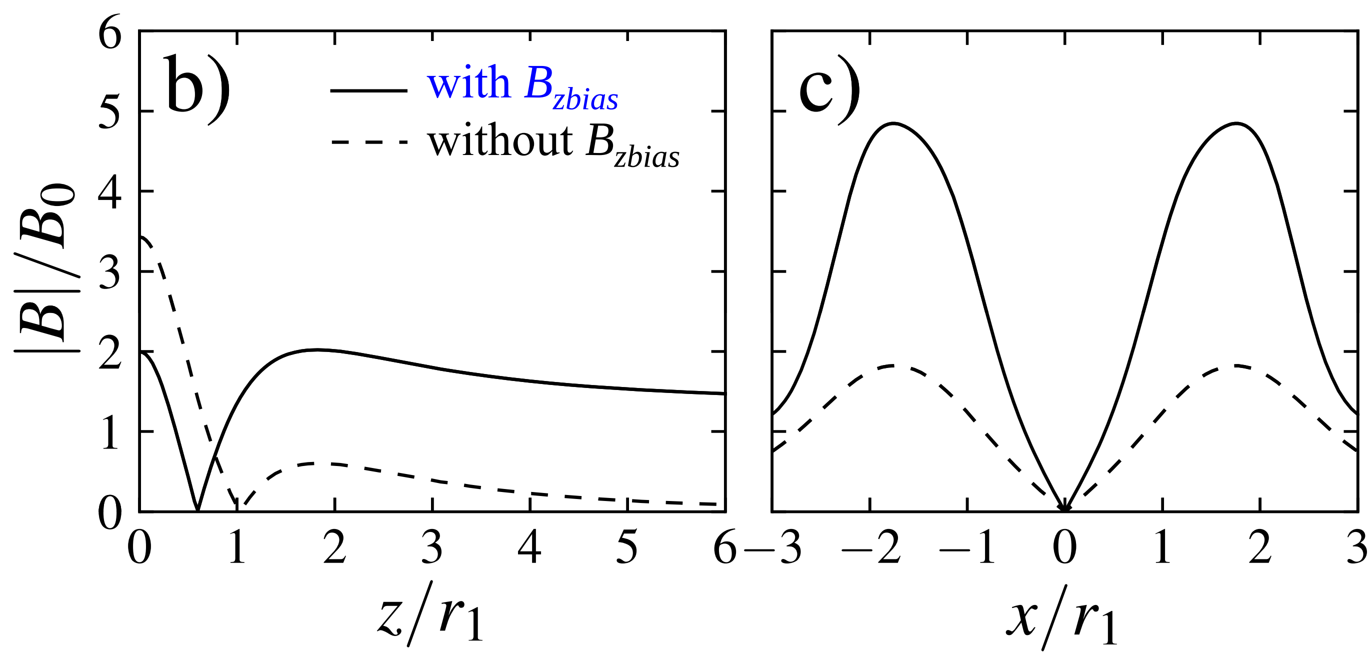
Outer Loop Radius = 660

Current = 2.6 Amp

^{87}Rb Trap Depth~1 mK at I=2.6 A

& $B_{zbias} = B_o = \mu_o/4\pi\ I/r_1 = 10$ G

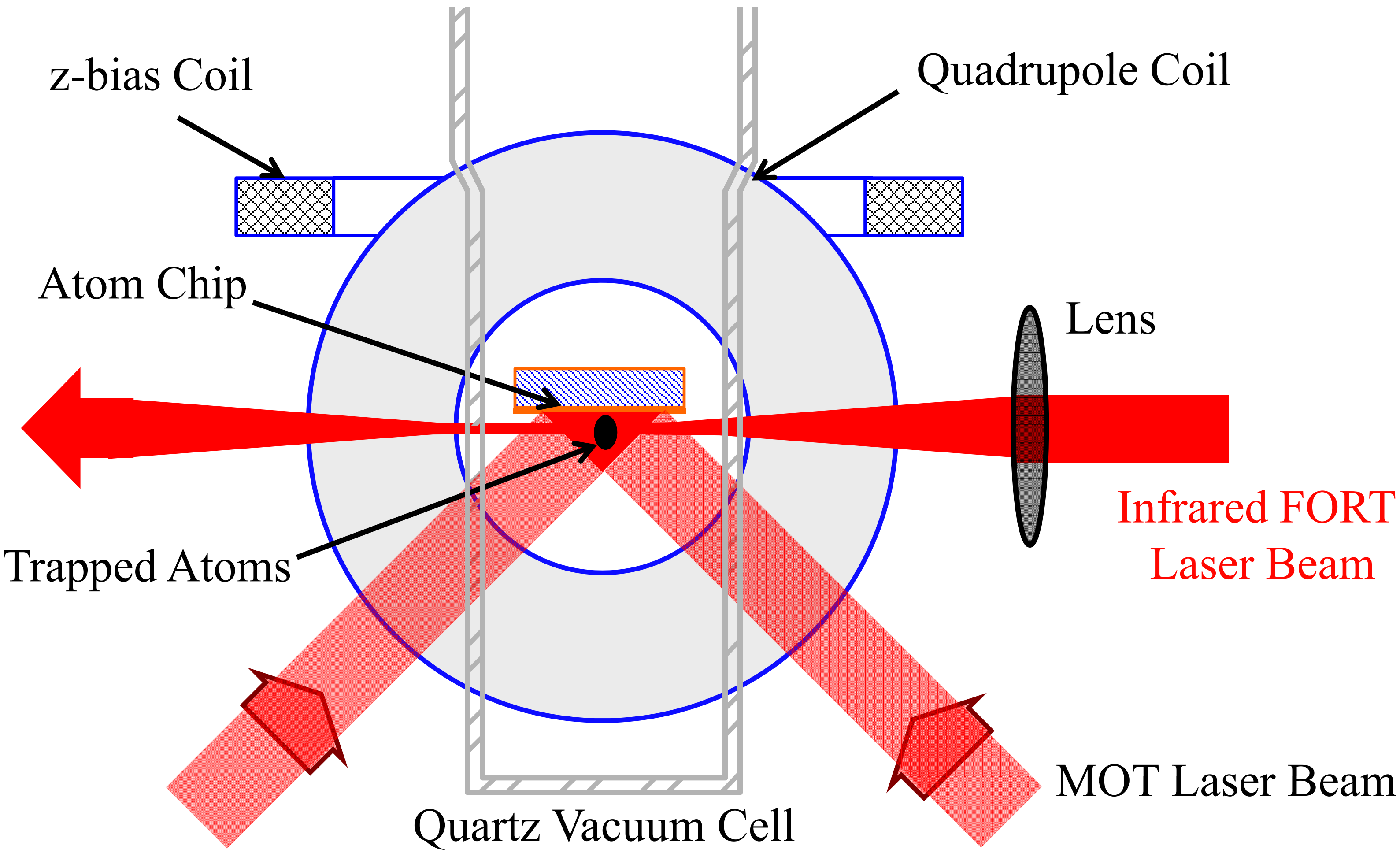




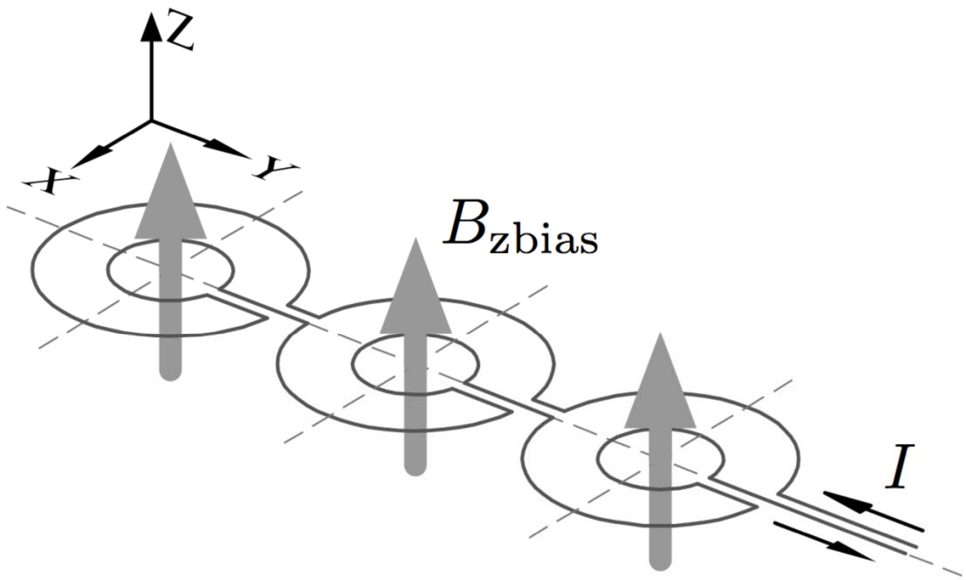
Microtrap Loading

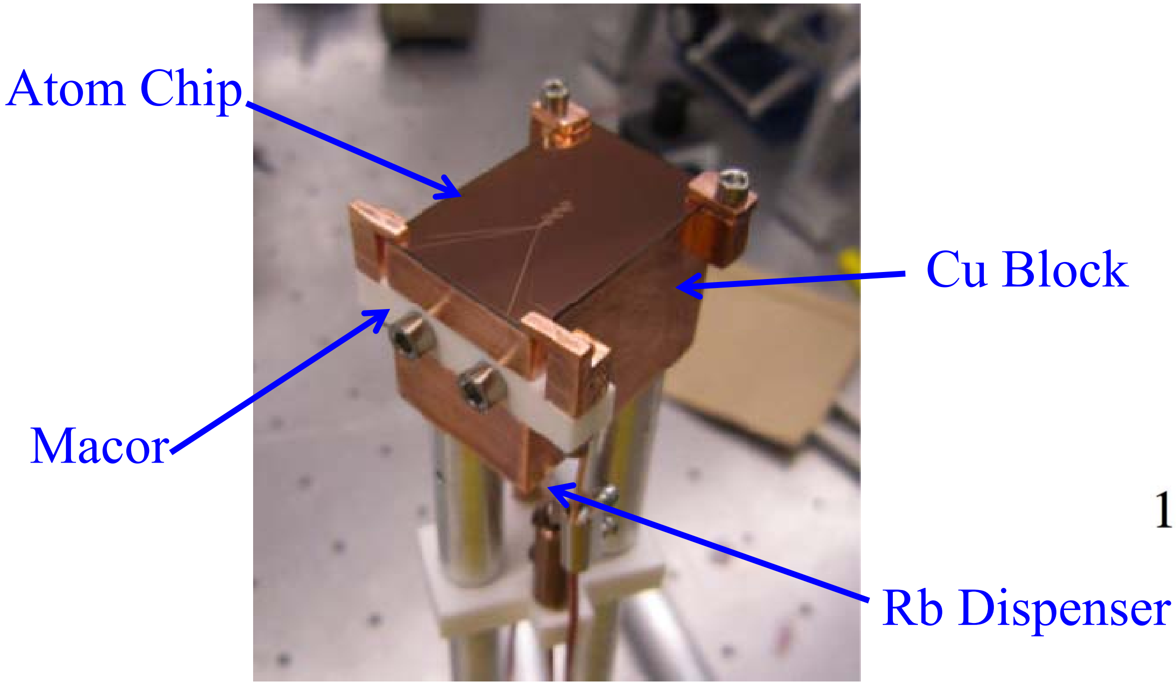
B. Jian & WvW, *Appl. Phys. B*, DOI 10.1007/s00340-013-5573-4 (2013)

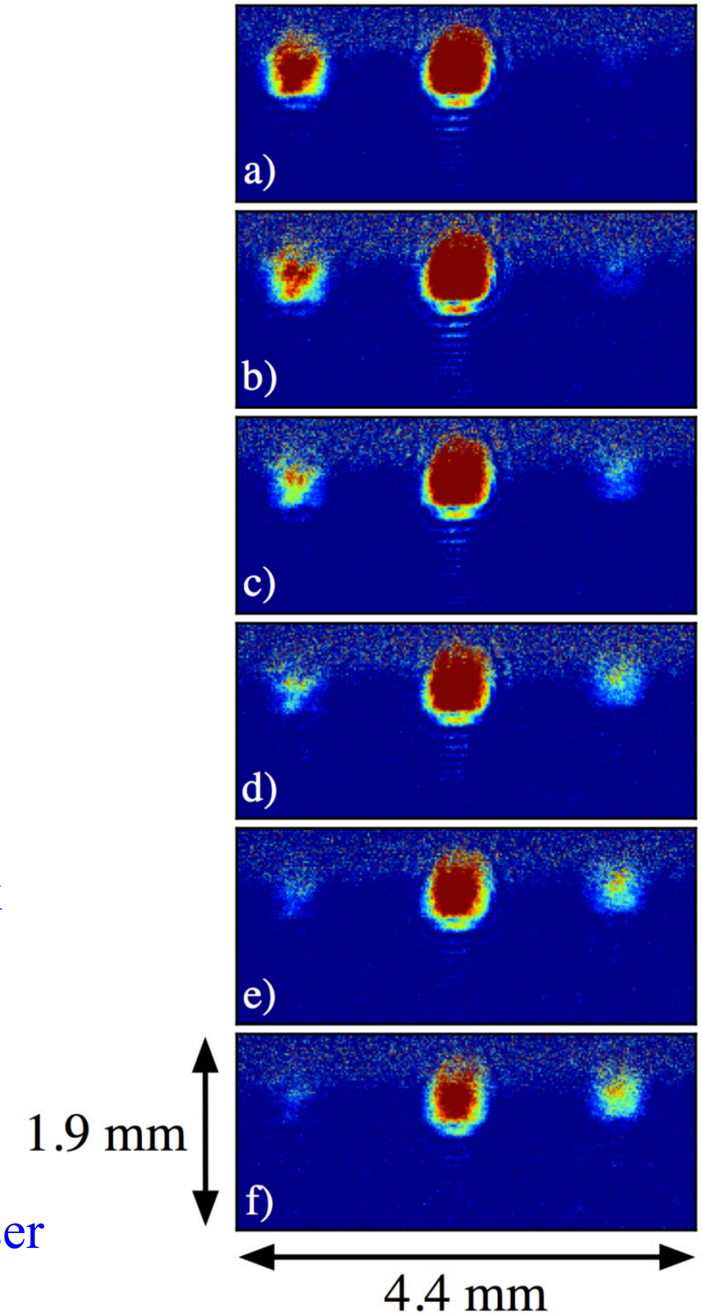
Methods: **1)** Move MOT toward microtrap, 2) Surface MOT, 3) FORT



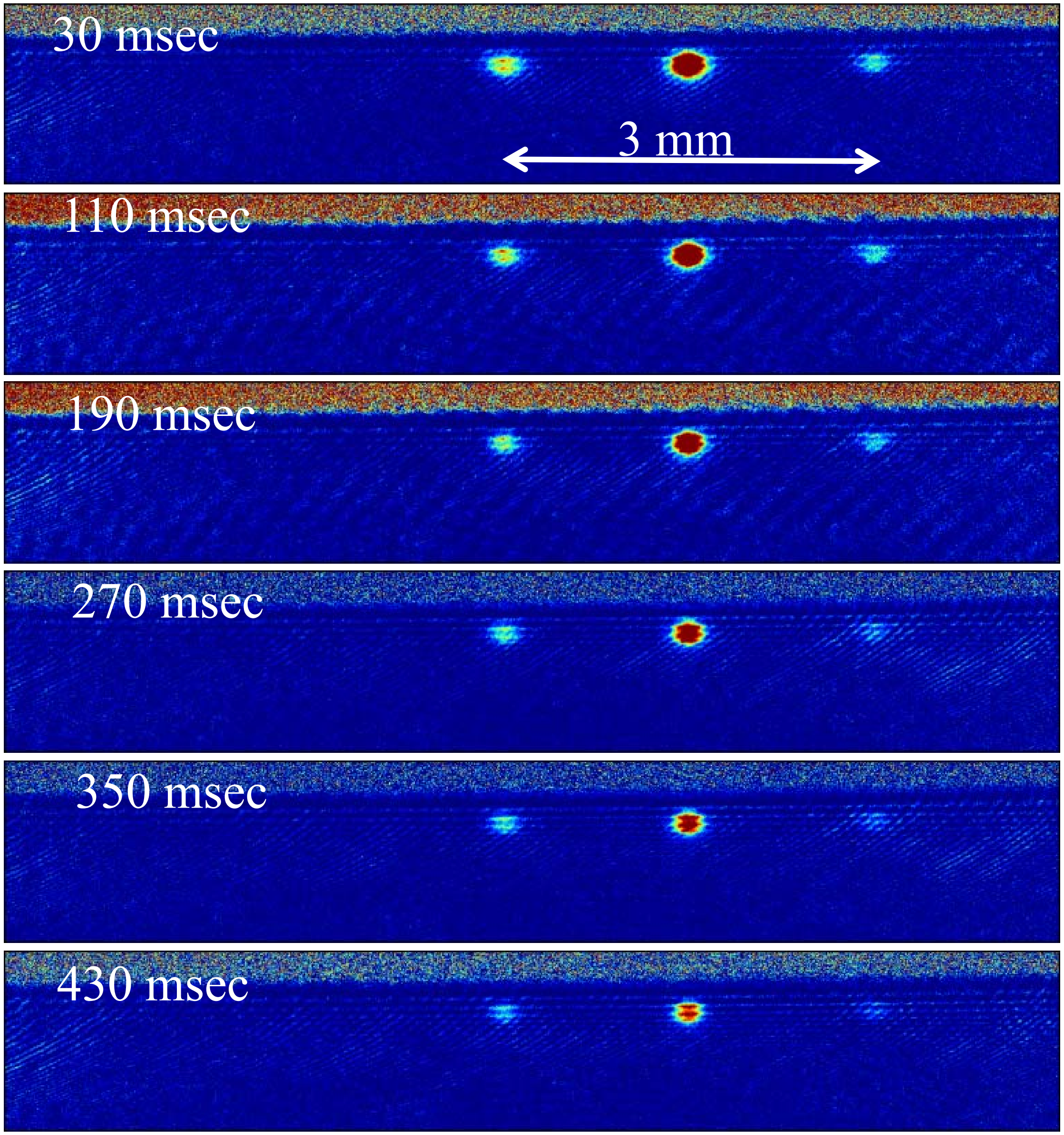
Microtrap Array



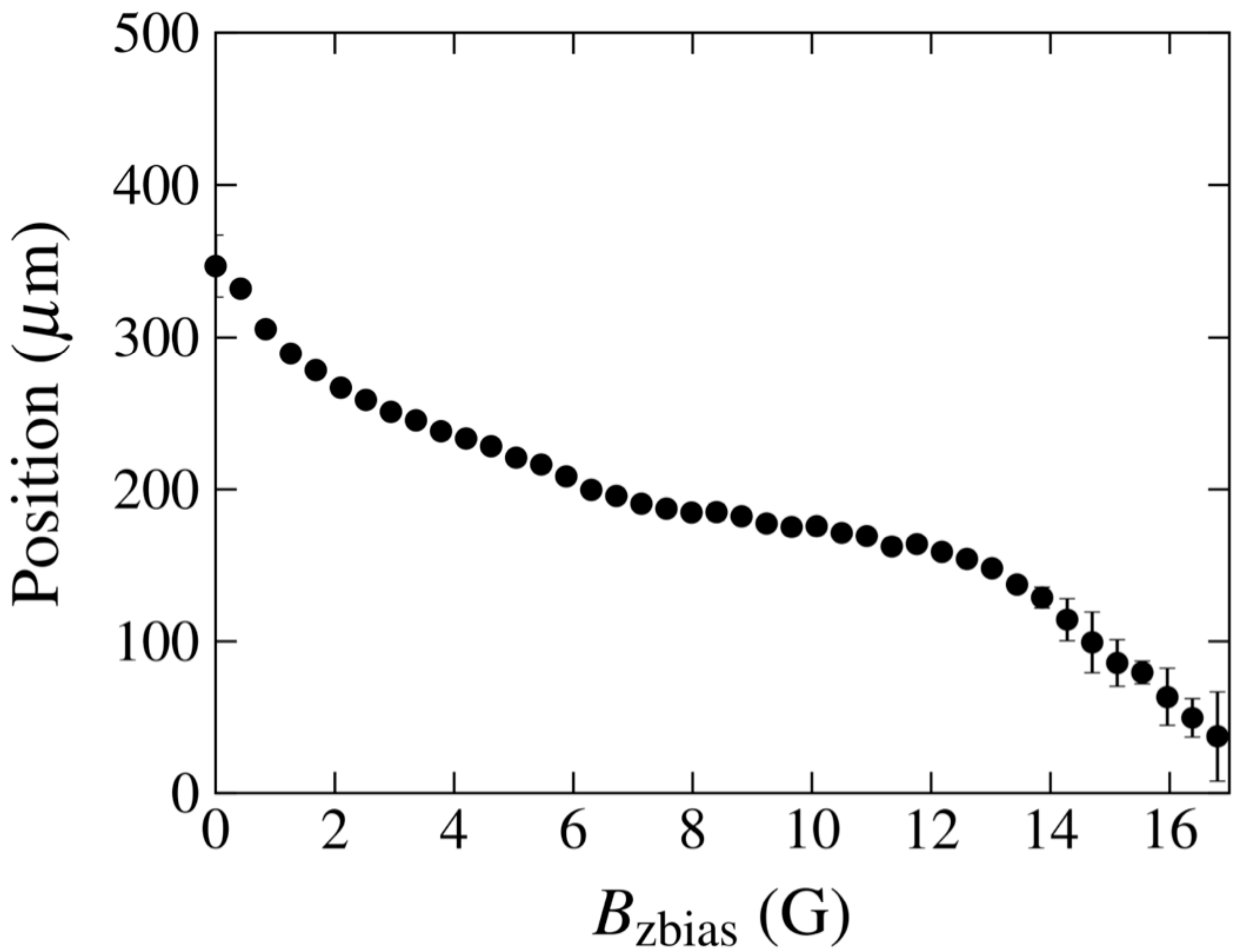




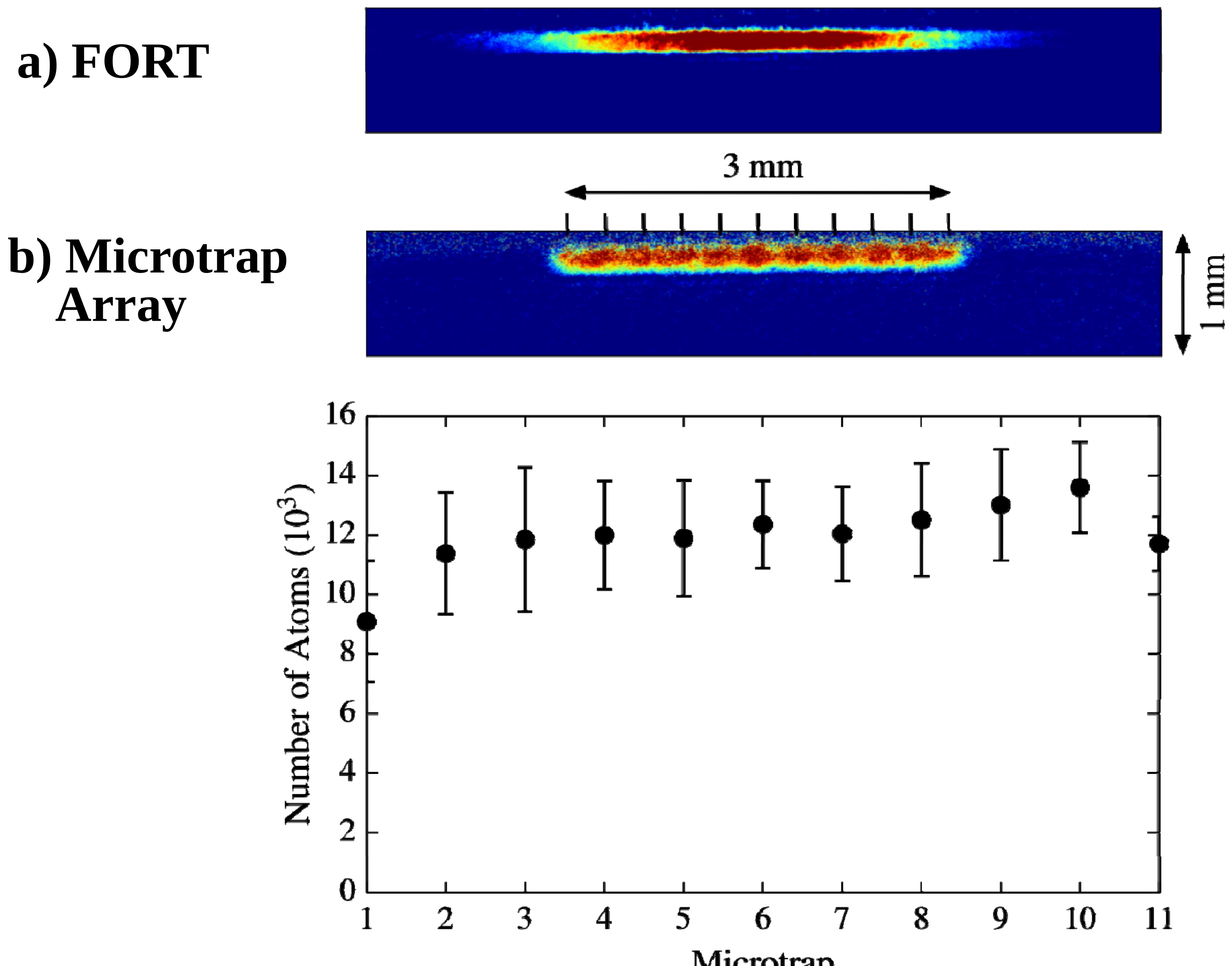
Temporal Evolution of Microtrap Array Loaded from Optical Trap (Lifetime = 350 ms)



Precise Positioning of Atom Cloud above Chip Surface

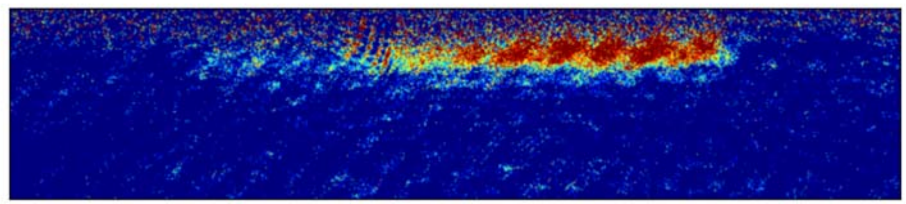


Loading 11 Microtrap Array from a FORT

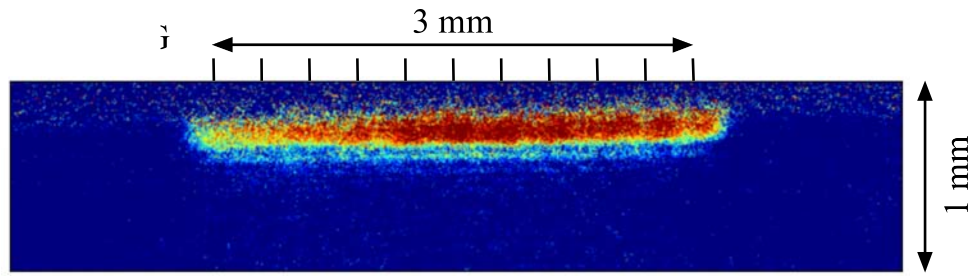


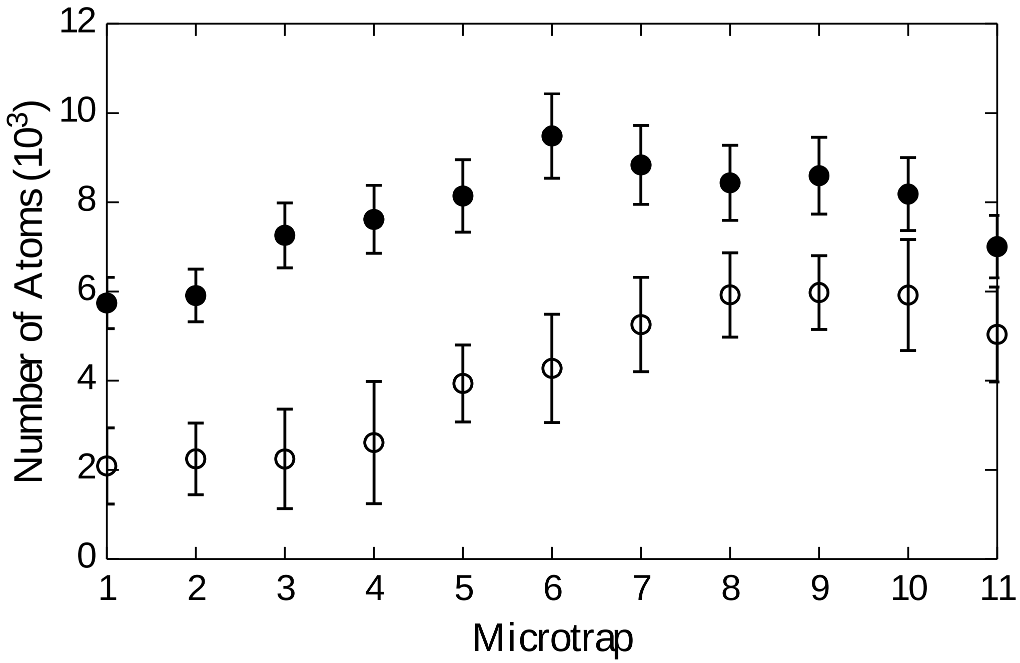
Loading 11 Microtrap Array from a Surface MOT

a) $B_{yshift} = 0$ G



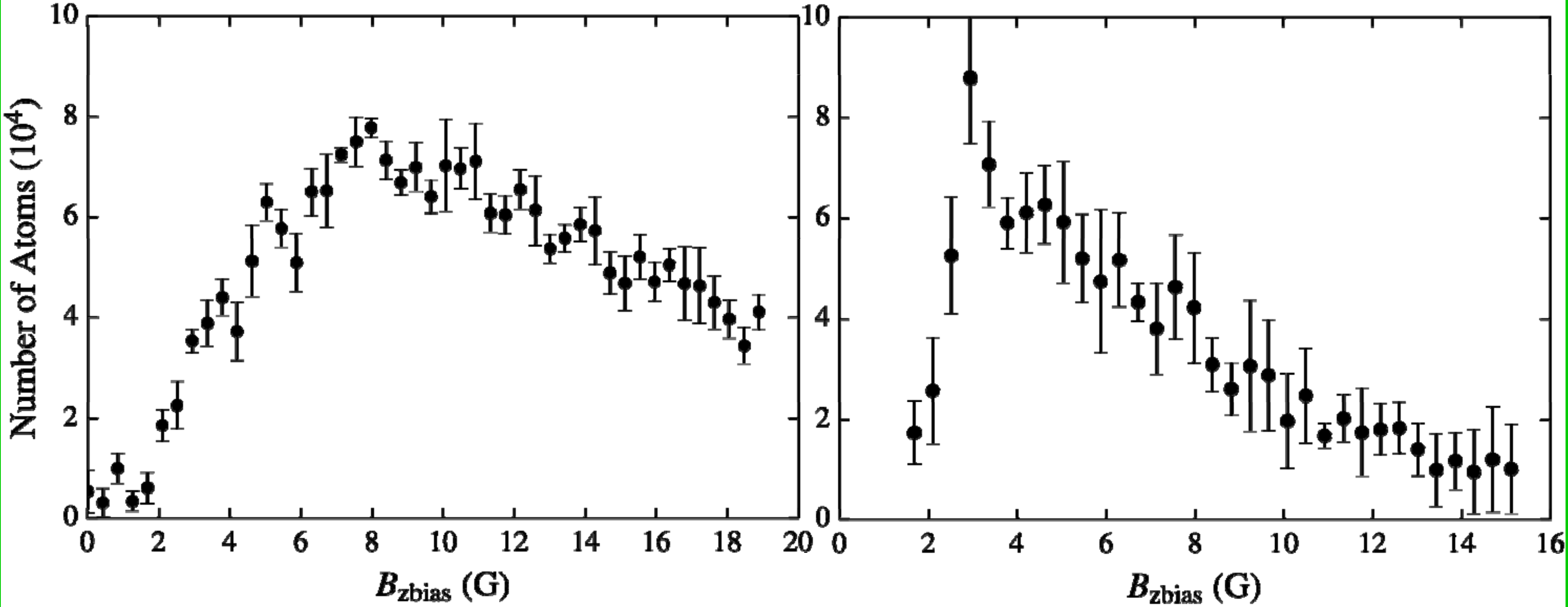
b) $B_{yshift} = 0.5$ G





Effect of Bias Field on Microtrap

a) Surface MOT Loading **b) FORT Loading**

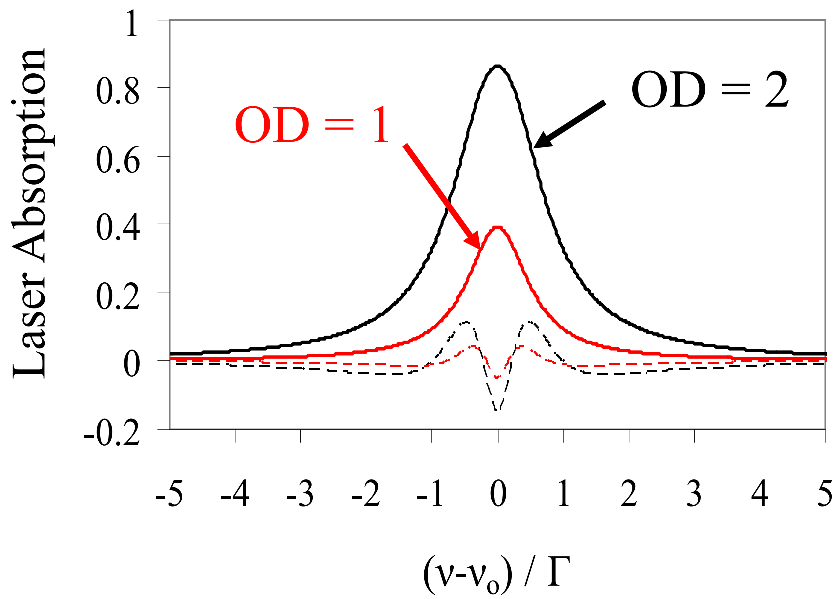


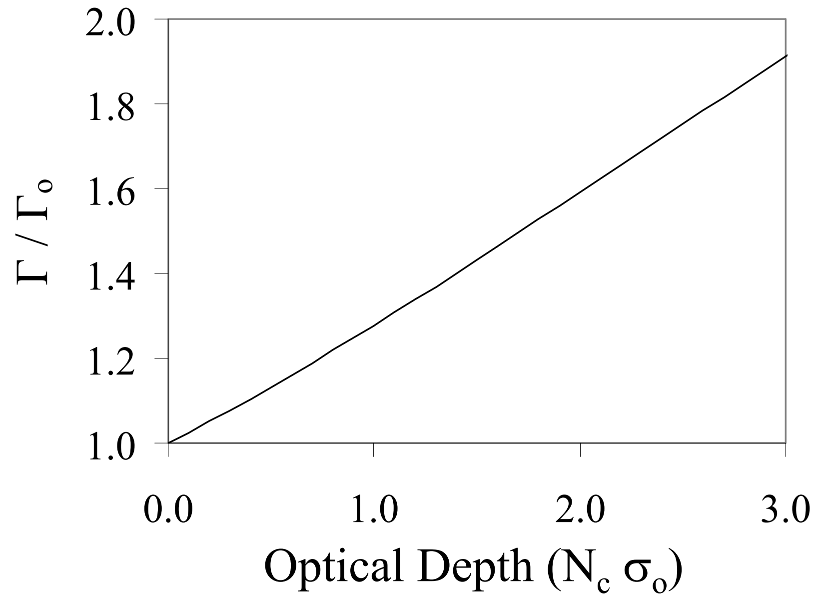
b) Precision Spectroscopy Rb D2 Linewidth

B. Schultz, H. Ming, G. Noble & WvW, *Eur. Phys. J. D*, **48**, 171 (2008)

Laser intensity transmitted through atom cloud: $I = I_o e^{-N_c \sigma}$

Absorption cross section: $\sigma = \dfrac{\sigma_o}{1+\left(\dfrac{\nu-\nu_o}{\Gamma_o/2}\right)^2}$ where $\Gamma_o^{-1} = 2\pi\tau$



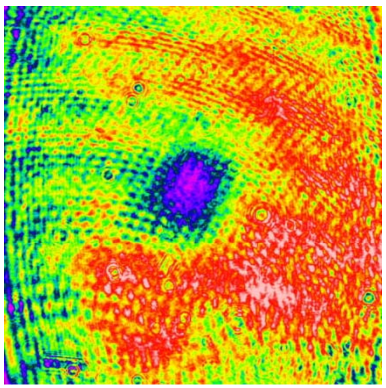


------- (Signal – Lorentzian fit) x 10

------- (Signal – Lorentzian fit) x 100

CCD Images of Probe Laser Transmitted through Atom Cloud

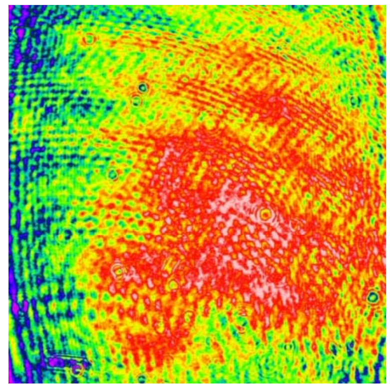
a) Atoms Present



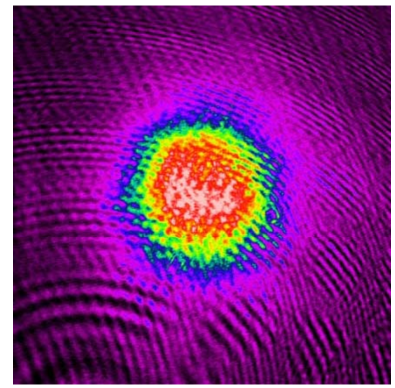
7 mm

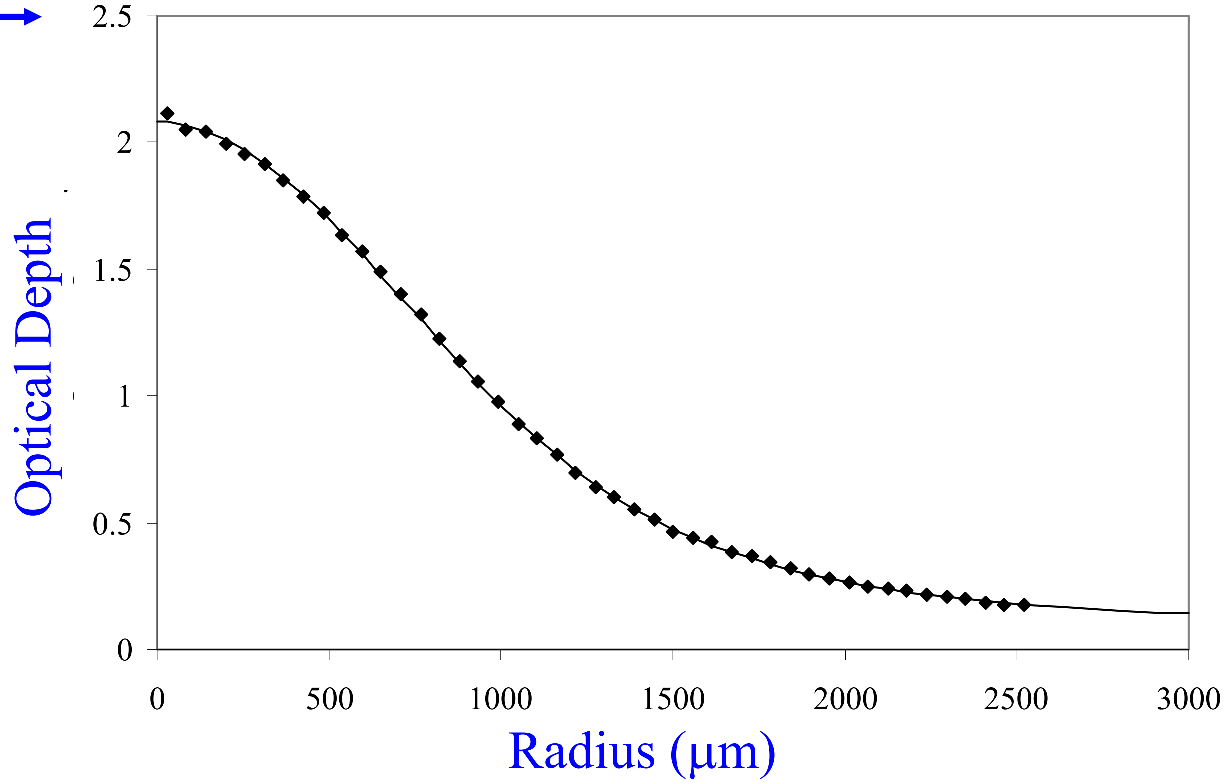
7 mm

b) Atoms Absent

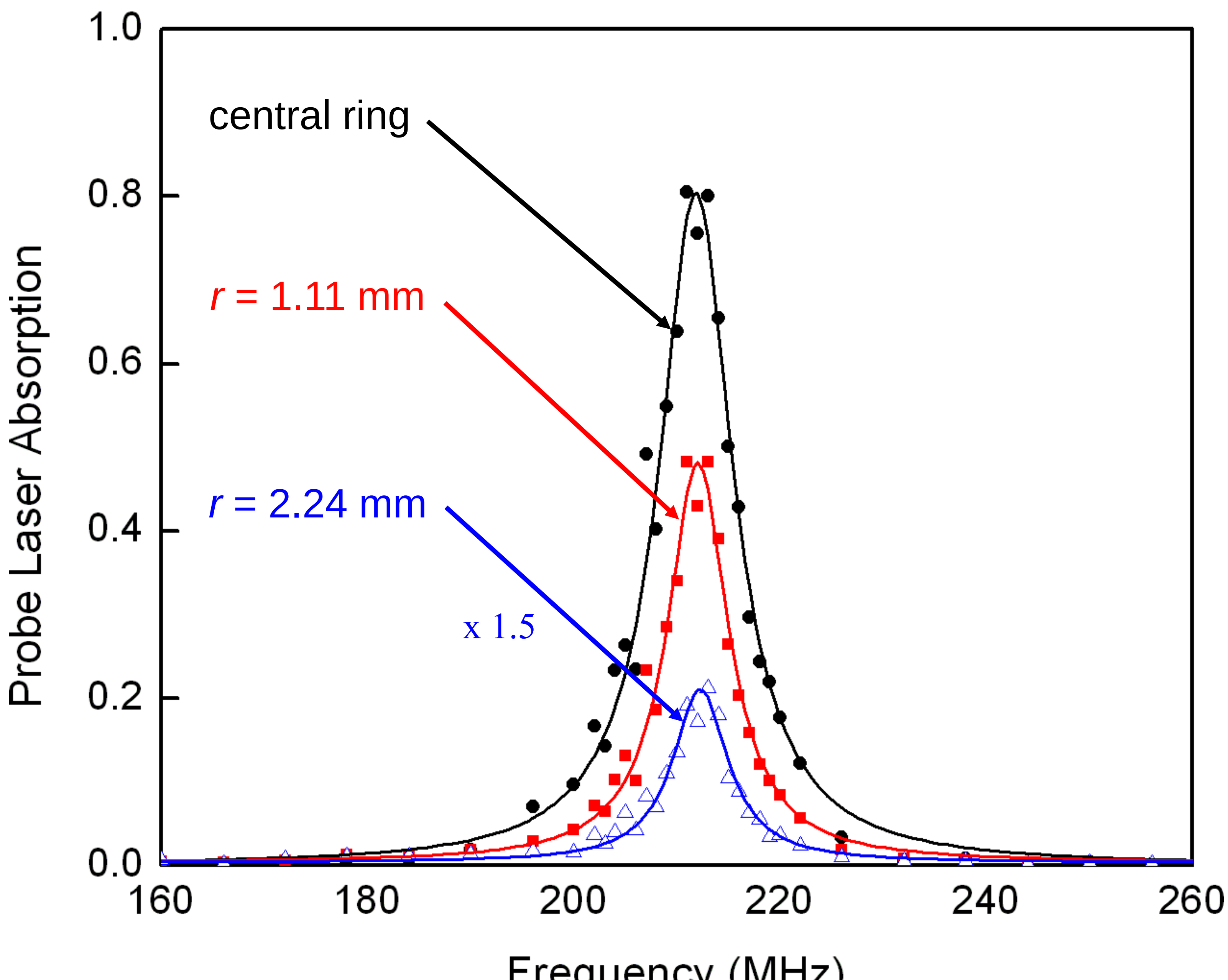


c) Image a – Image b

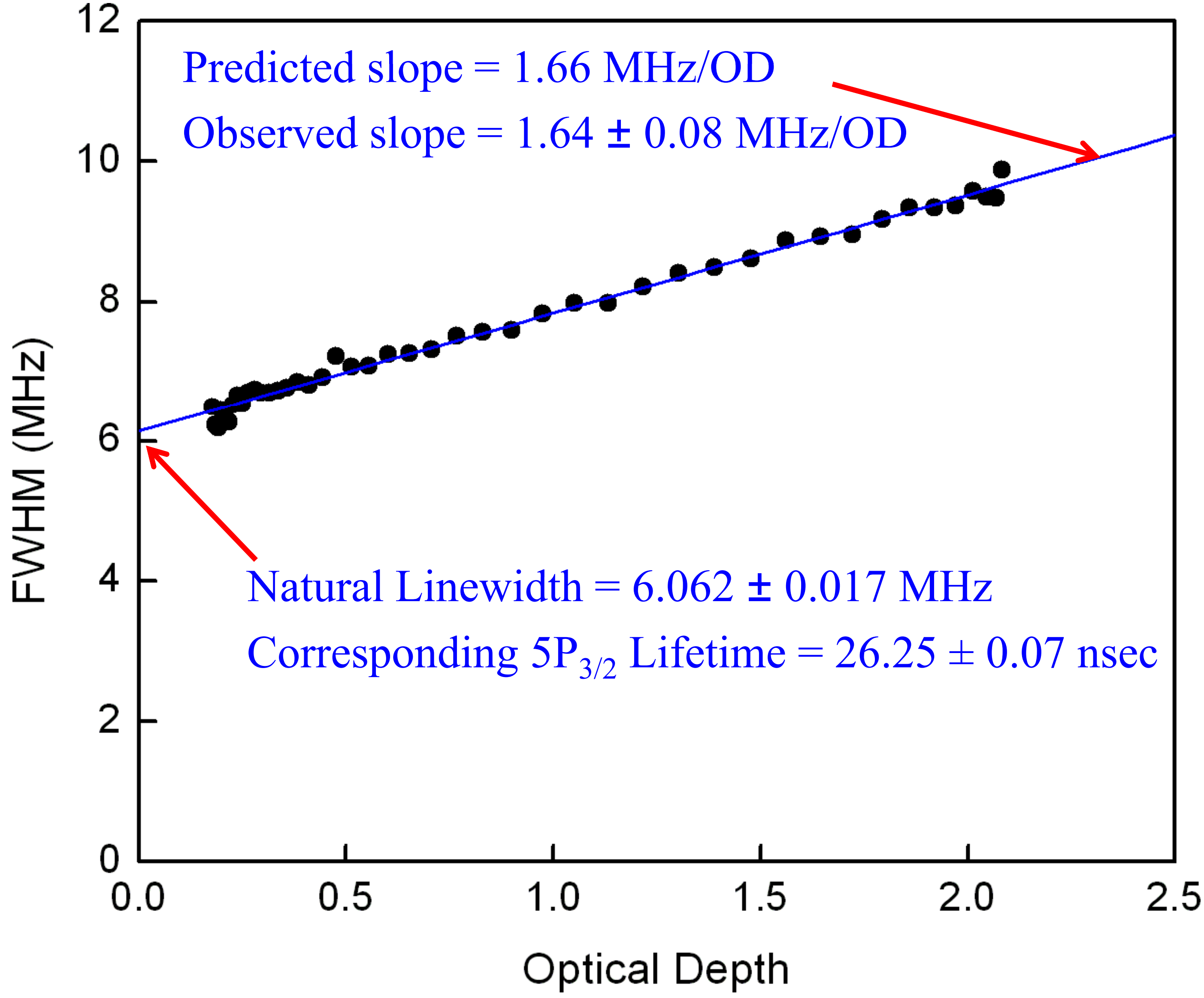




Signal Dependence vs. Radius of Atom Cloud



FWHM Linewidth vs. Optical Depth



Summary & Future Outlook

QUIC Trap

- operates reliably to generate BEC generating temperatures as low as 7 nK

Optical Trap

- 10^6 atoms transferred from magnetic trap into FORT with 50% efficiency
- Atom cloud tightly trapped along radial direction but freely expands along laser propagation direction

Microtraps

- Linear array of 3 microtraps populated. – extendable to 2 dimensional array
- Atom position can be controlled to within microns of chip – interesting for surface studies

Precision Spectroscopy

- Doppler width negligible for ultracold atoms, ideal for linewidth studies
- Rb $5P_{3/2}$ lifetime determined from natural linewidth at 0.3% level

YORK UNIVERSITÉ UNIVERSITY redefine THE POSSIBLE.

Graduate Openings: wvanwijngaarden.info.yorku.ca