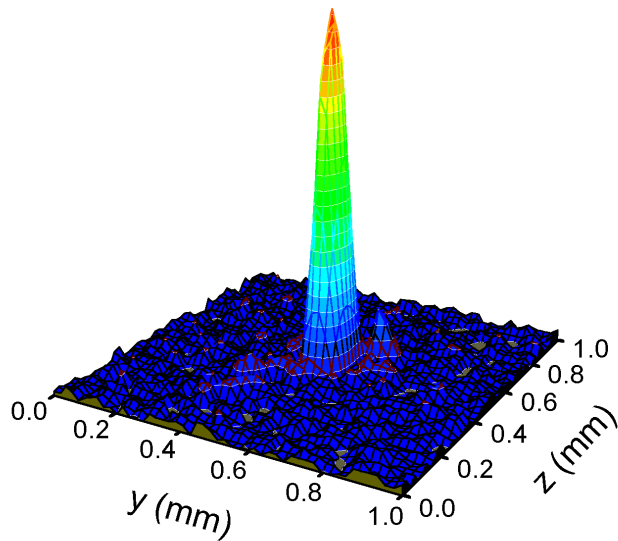


Fun with Ultracold Atoms

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

CAP Lecture Tour

2014

Statistical Mechanics Background

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

Fermions

Half integral spin (electron, proton, neutron)

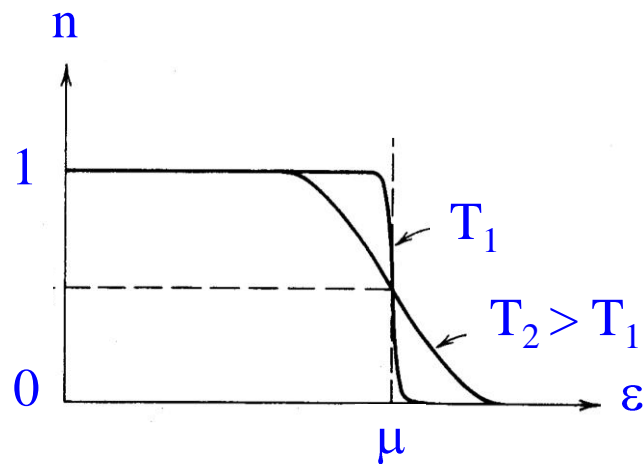
$$n = \{ \exp(\varepsilon - \mu)/kT + 1 \}^{-1}$$

where: n = # particles in state of energy ε

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

k = Boltzmann constant

T = temperature



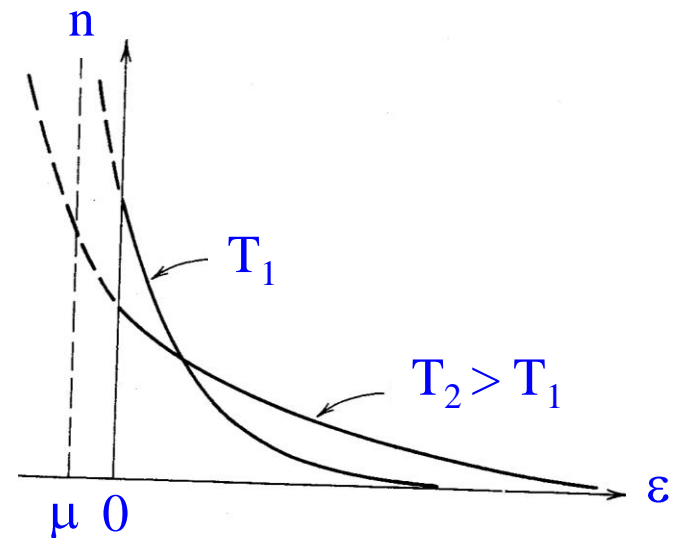
Paul Exclusion Principle:

Identical fermions can't occupy same state.

Bosons

Integral spin (photon, meson)

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



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 ≈ 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 ^4He in 3D Square Well

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

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

where: $n = \text{atom density}$

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

$h = \text{Planck's constant}$

$M = \text{atom mass}$

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

\Rightarrow Transition Temperature $T_c = 3 \text{ K}$

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

$N = \# \text{ trapped atoms}$

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

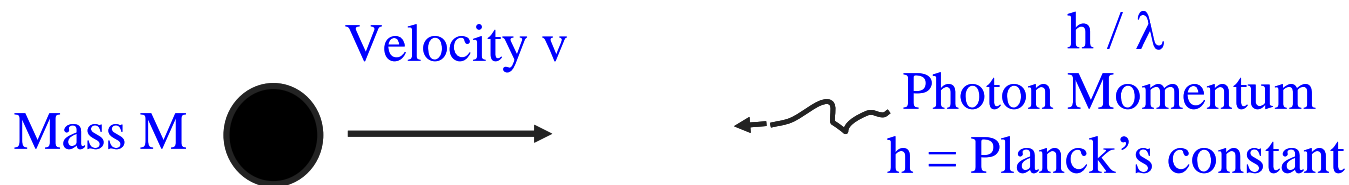
\Rightarrow Transition Temperature $T_c \approx 100 \text{ nK}$

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.



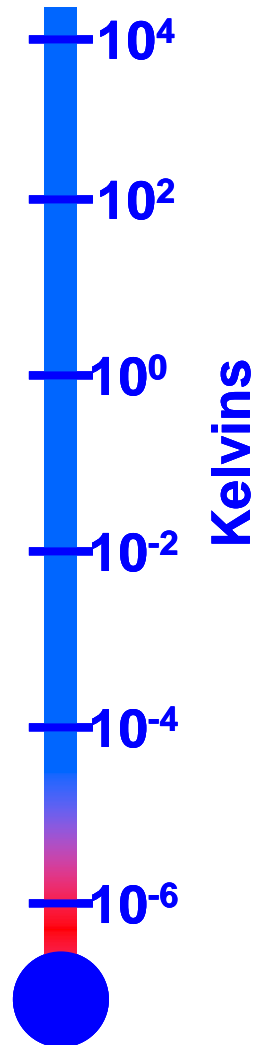
photons to stop thermal ^{87}Rb atom = $M v / (h / \lambda) = 50,000$ photons

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 = $10^9 \times 50,000 h v / T \approx 10$ mW

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

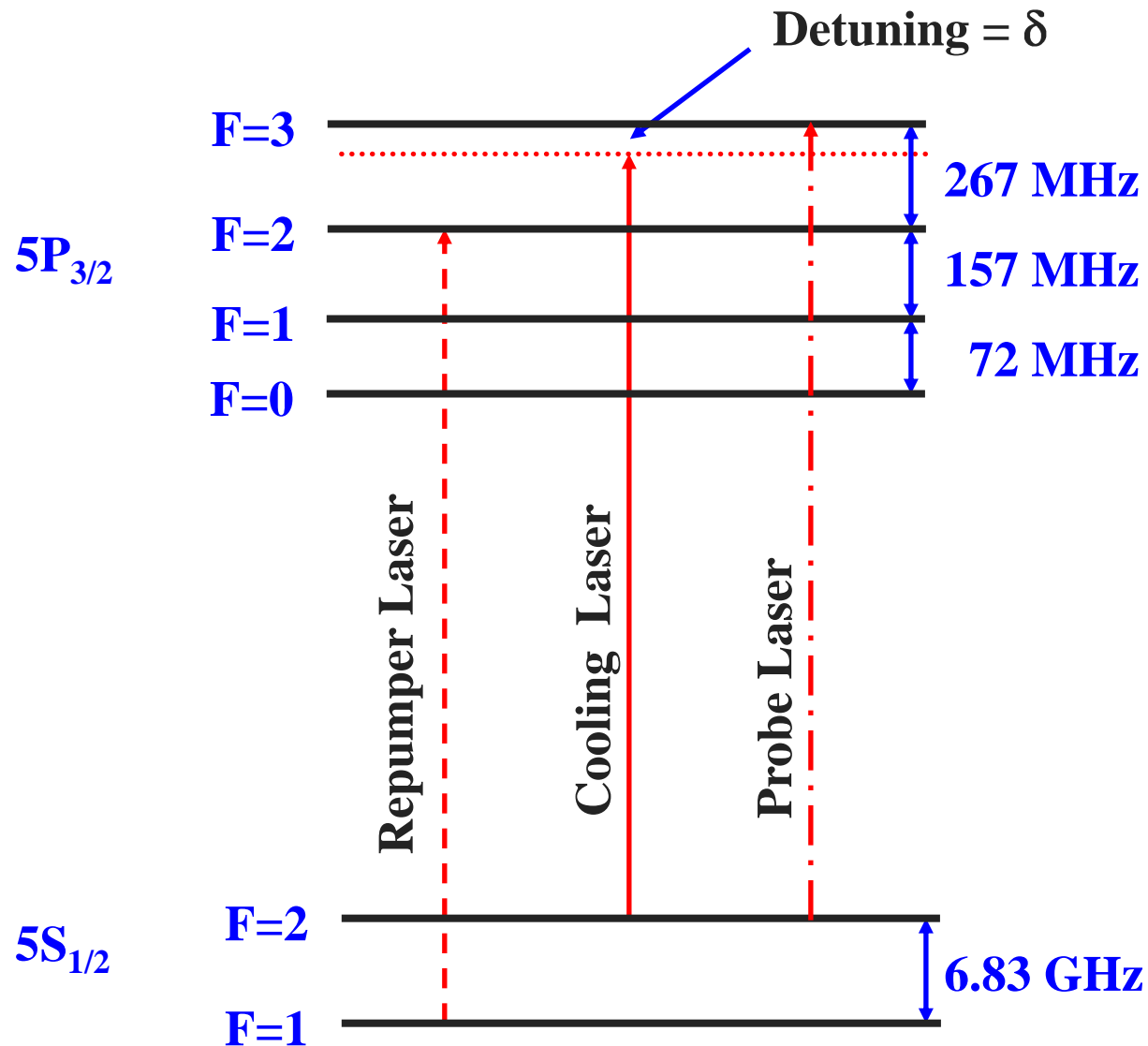


Experimental Requirements for BEC

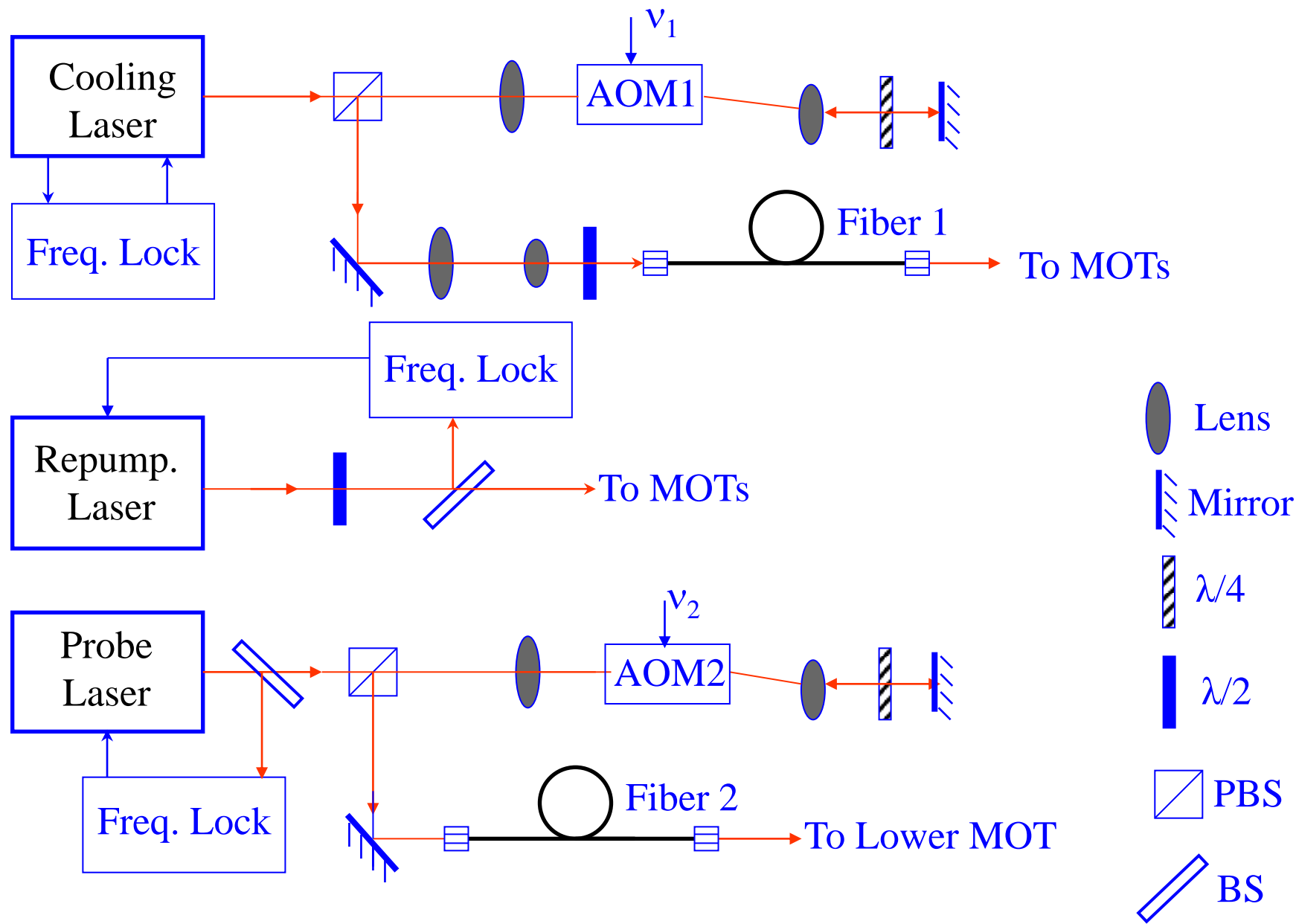
For detailed recipe see: B. Lu & WvW, *Can. J. Phys.* **82**, 81 (2004)

1. Excellent Vacuum $\approx 2 \times 10^{-11}$ 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

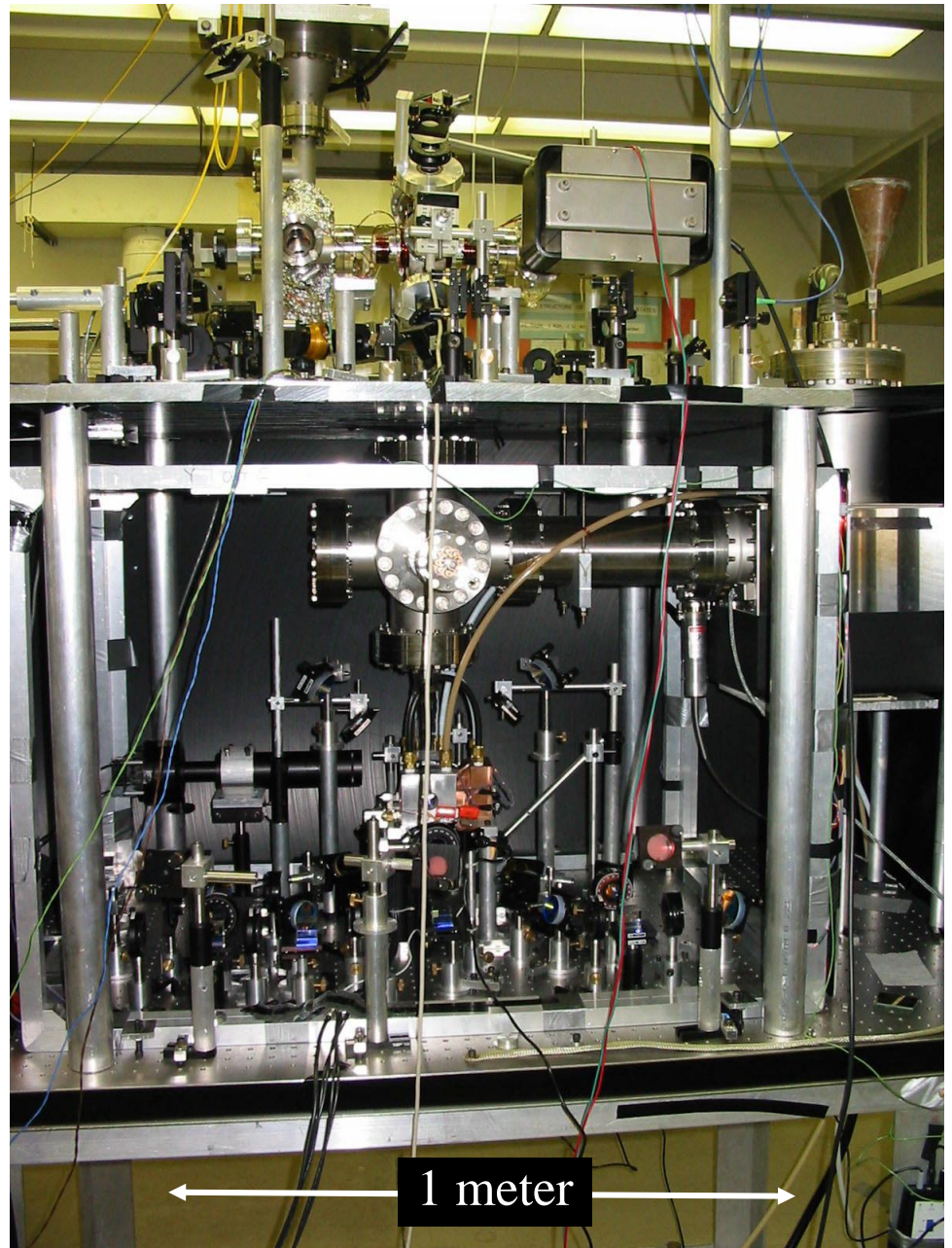
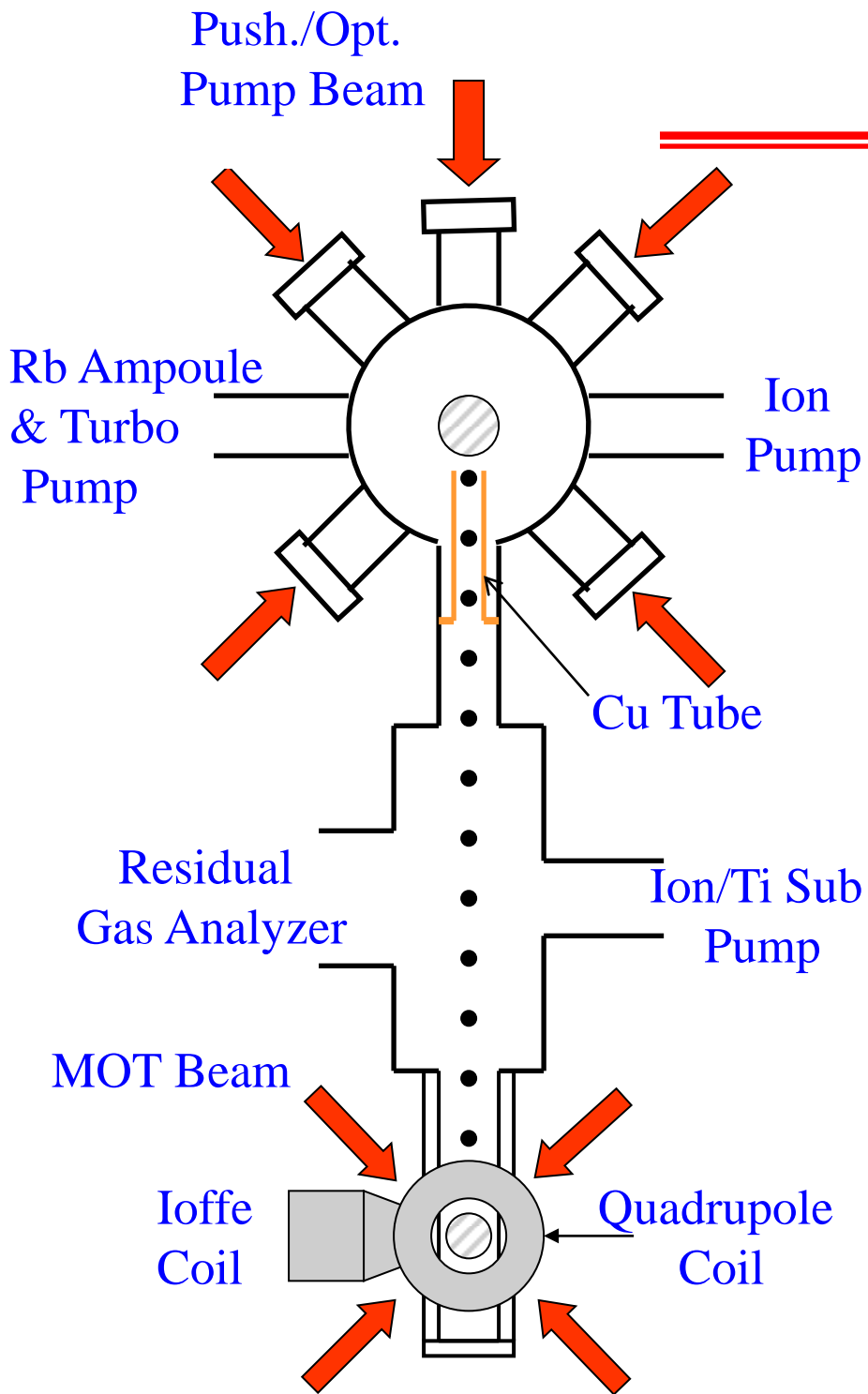
^{87}Rb MOT: Relevant Energy Levels



Layout of Laser Systems



Apparatus



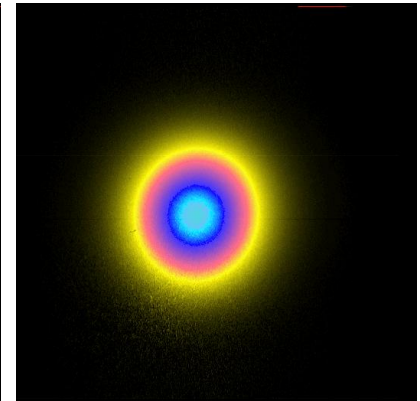
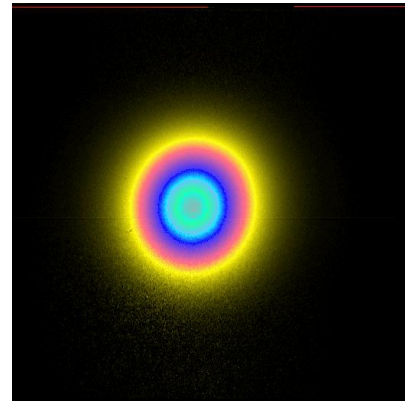
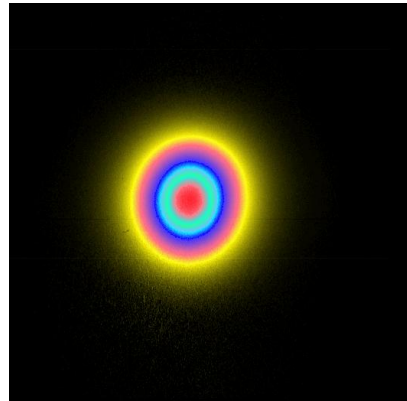
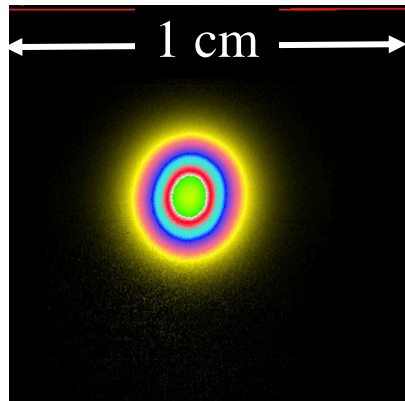
Free Expansion of Atom Cloud

a) $t = 6$ ms

b) $t = 8$ ms

c) $t = 10$ ms

d) $t = 12$ ms

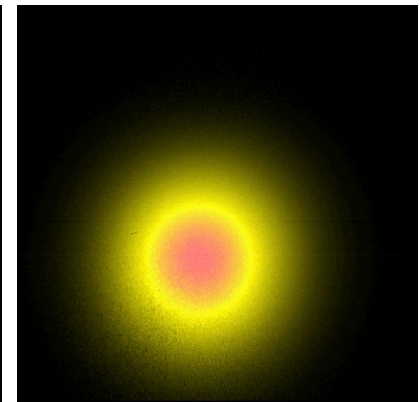
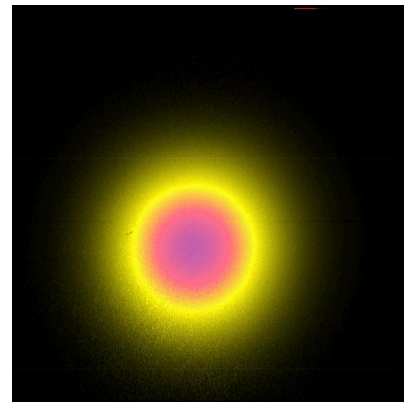
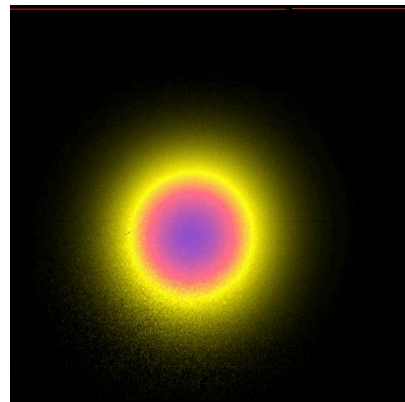
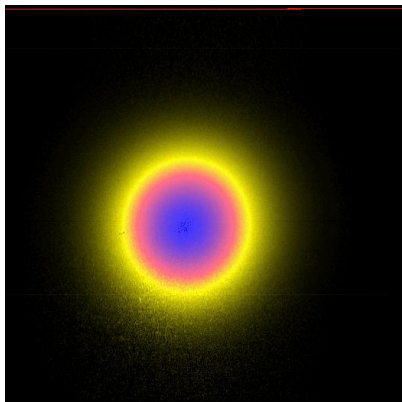


e) $t = 14$ ms

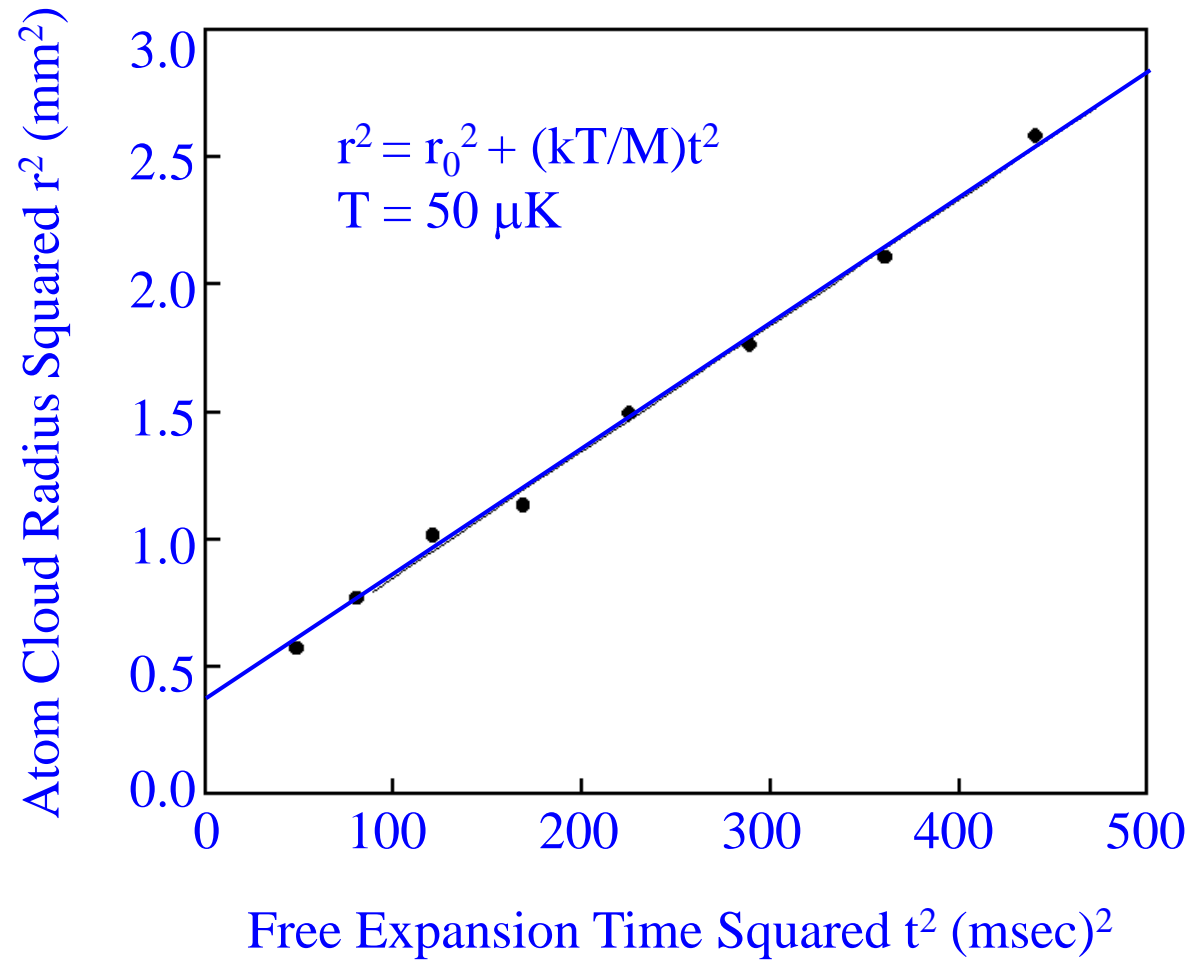
f) $t = 16$ ms

g) $t = 18$ ms

h) $t = 20$ ms



Temperature Determination

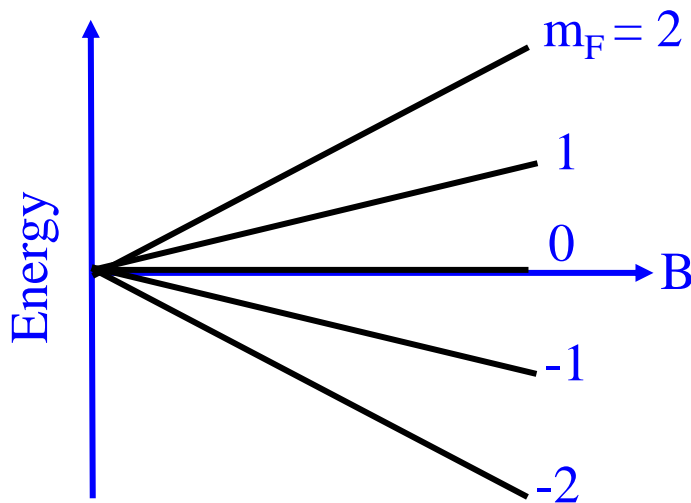


i) Magnetic Trap

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 : $H = -\mu \cdot B$



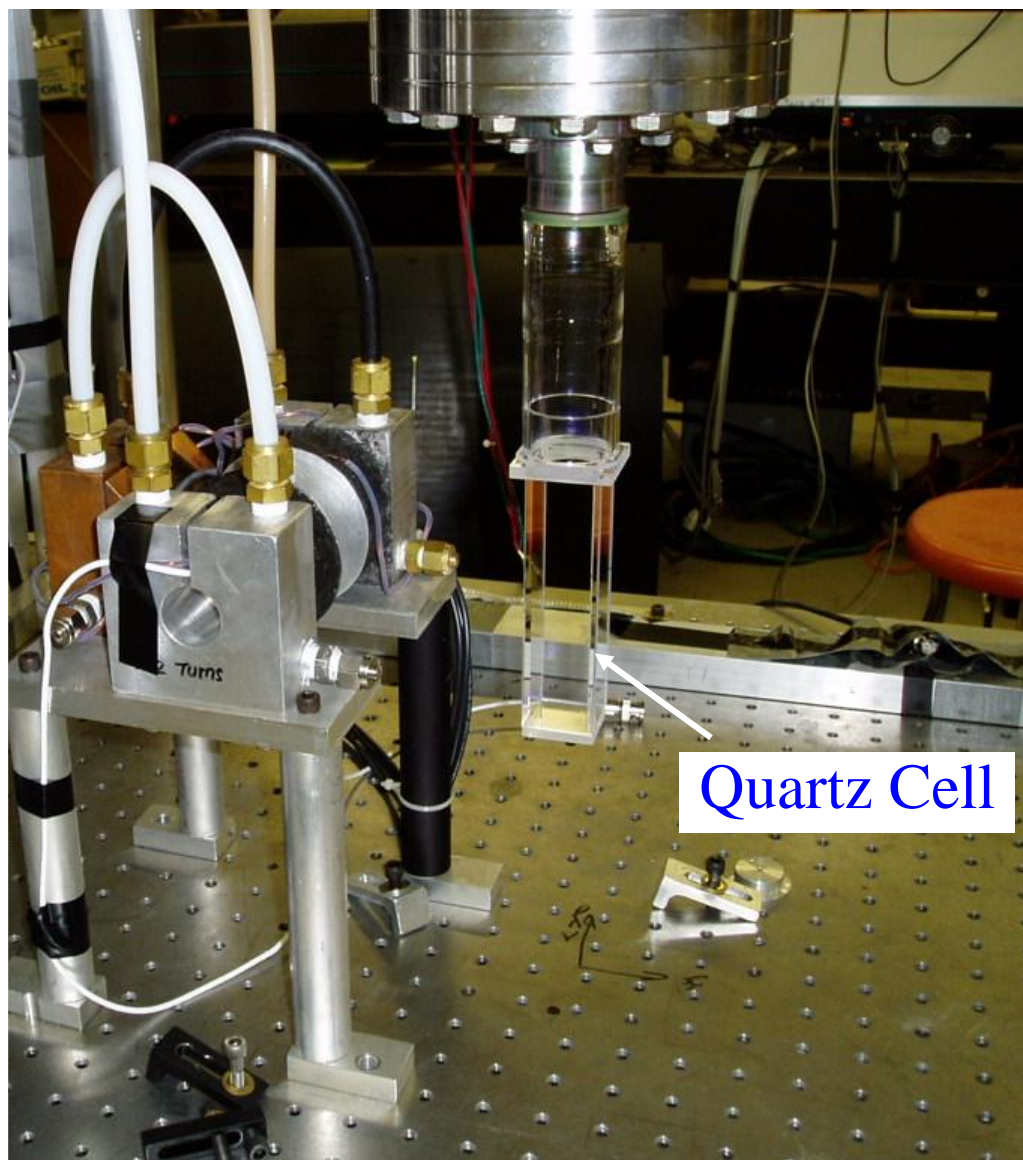
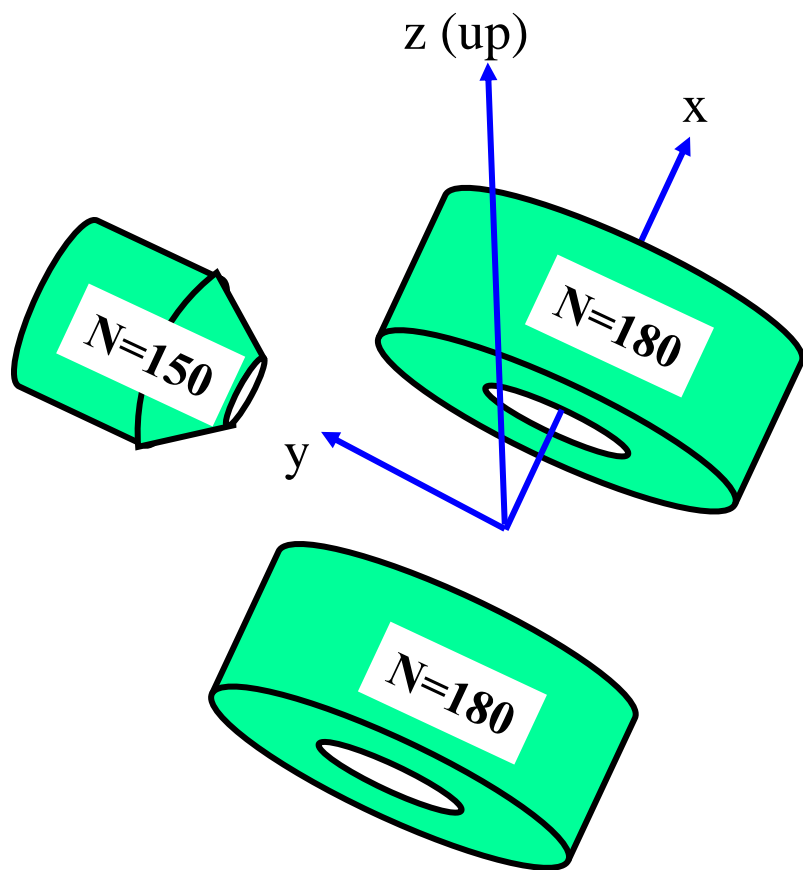
Quadrupole Trap

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.

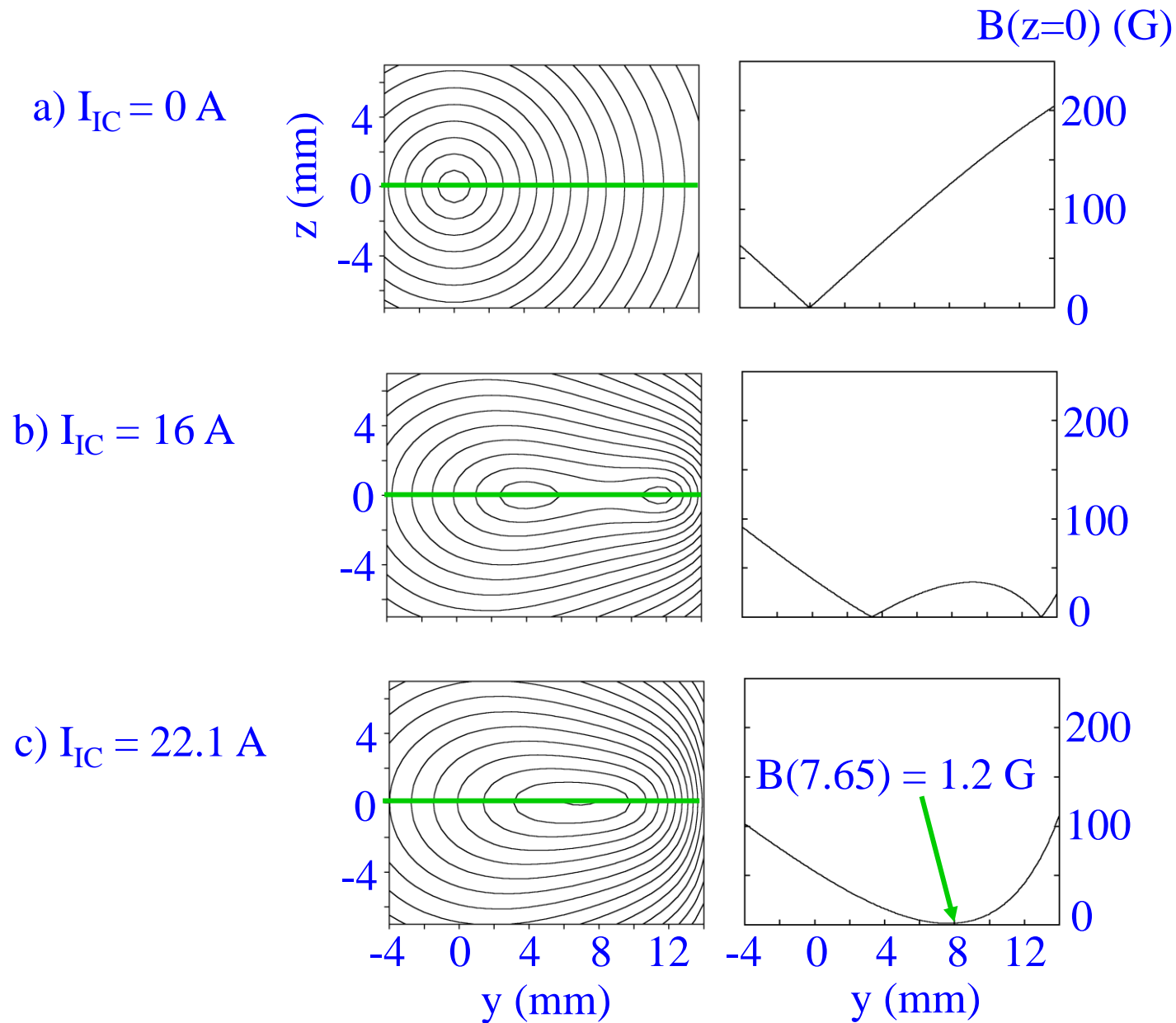
QUIC Trap

QUIC = 2 **Q**uadrupole Coils + **I**offe **C**oil

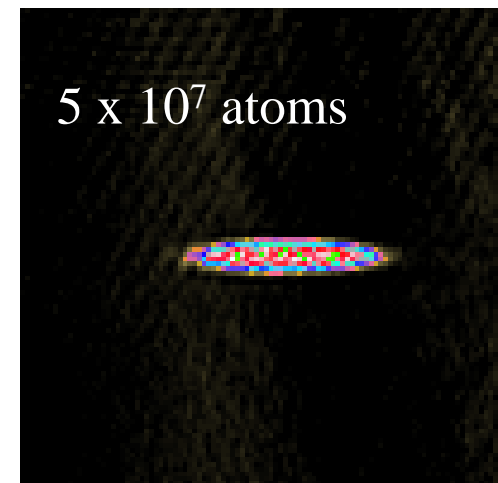
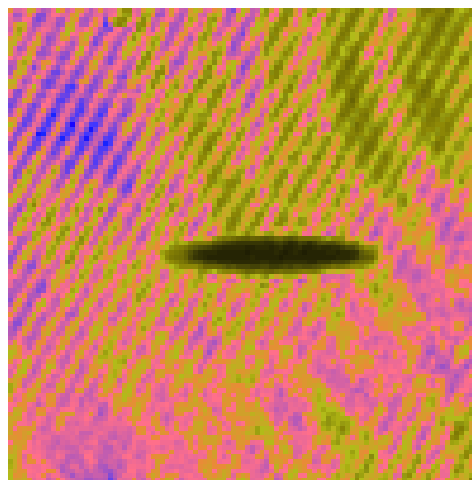
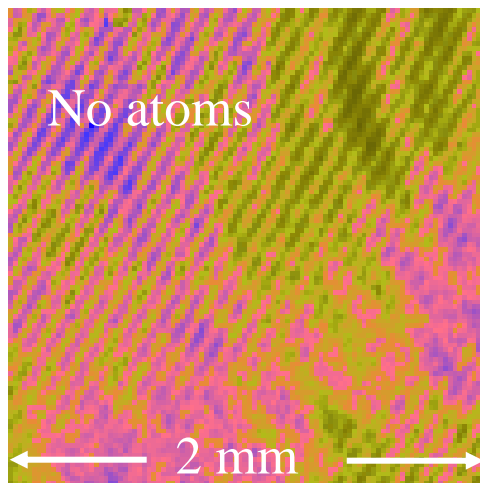
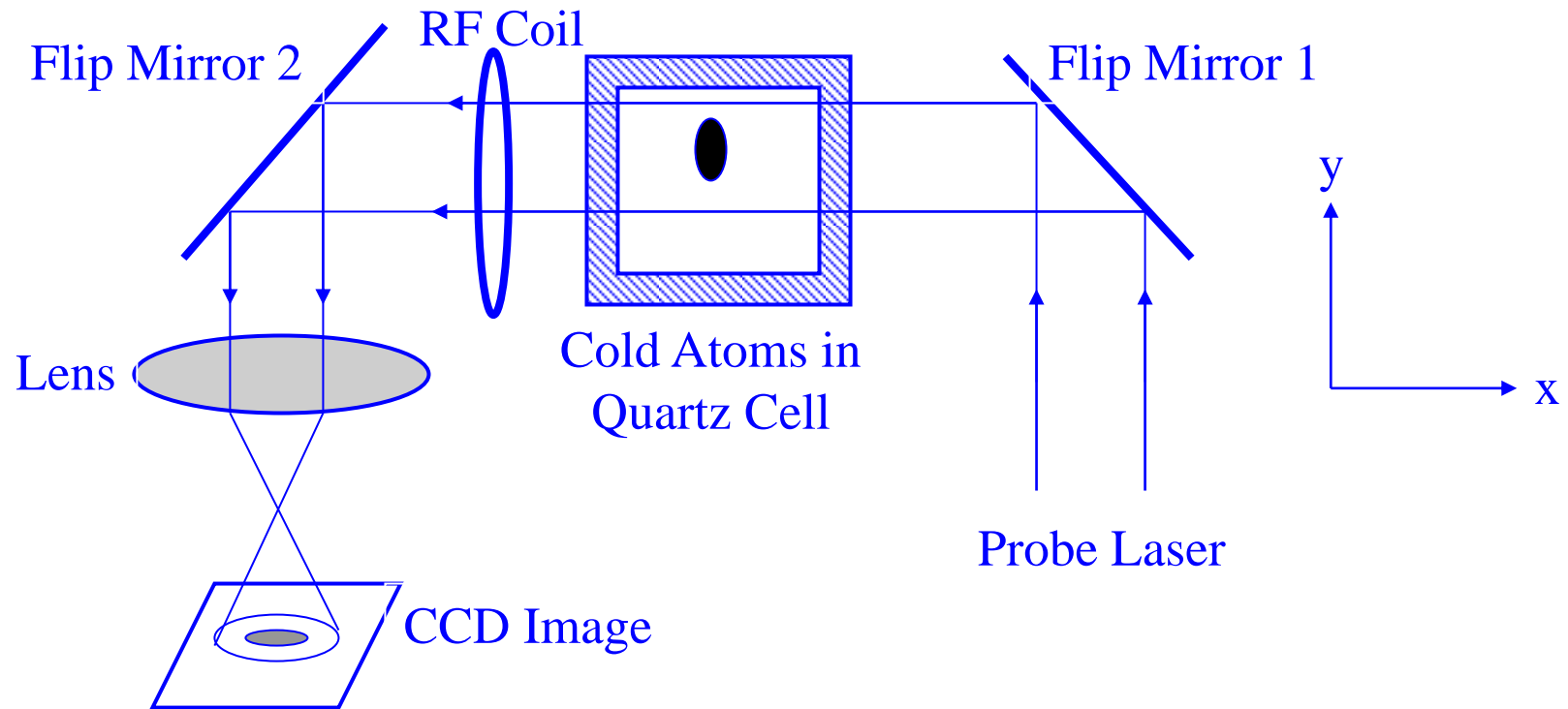


50 cm

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



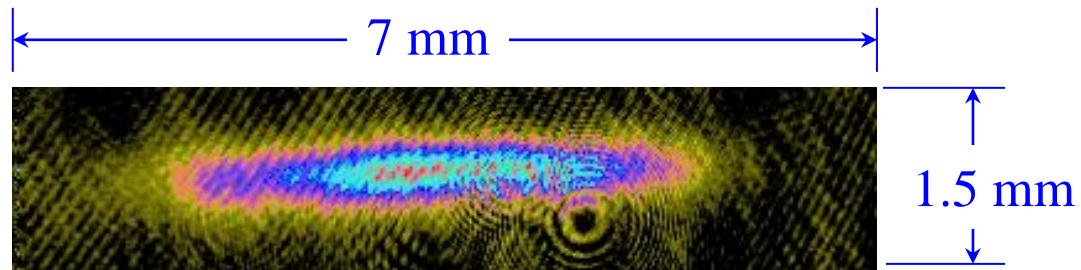
Imaging using Probe Laser Absorption



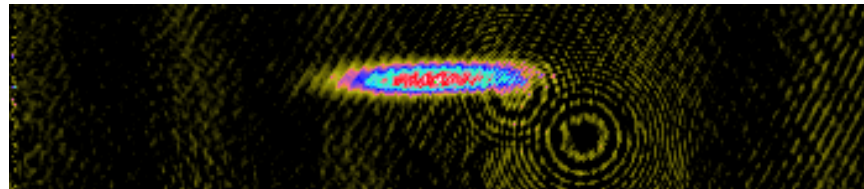
Evaporative Cooling

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.

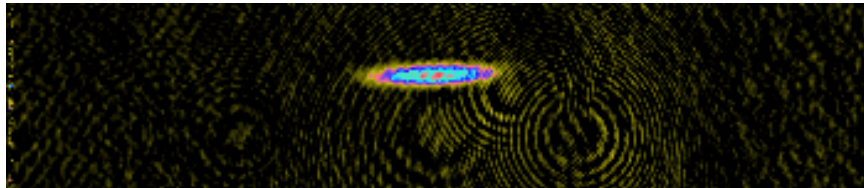
a) No Evaporative Cooling



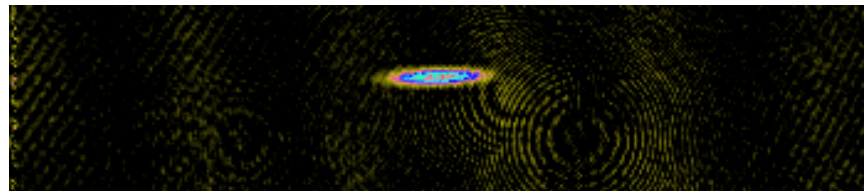
b) 6.00 MHz



c) 4.30 MHz



d) 4.15 MHz



Transition to BEC

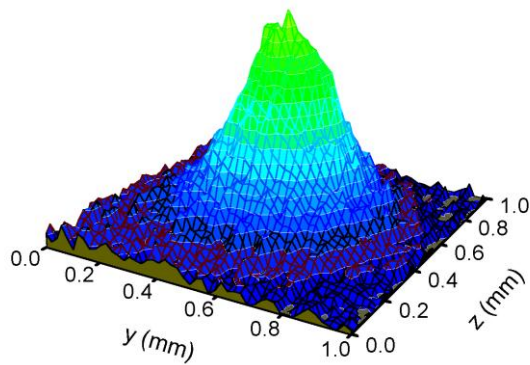
Absorption Images taken after 24 msec free expansion

a) Thermal cloud

$$\nu_{\text{stop}} = 2.410 \text{ MHz}$$

$$T = 449 \text{ nK}$$

$$N = 1.9 \times 10^6 \text{ atoms}$$

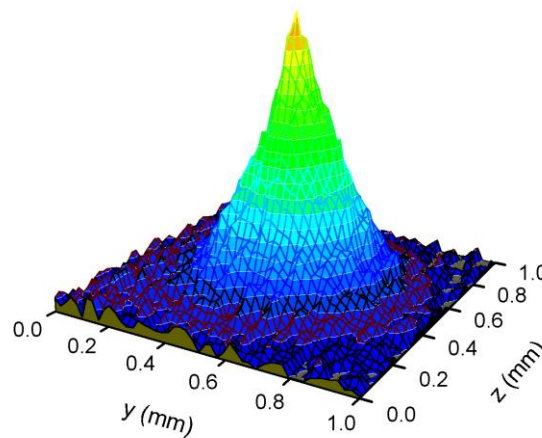


b) Thermal cloud + Condensate

$$\nu_{\text{stop}} = 2.406 \text{ MHz}$$

$$T = 400 \text{ nK}$$

$$N = 1.8 \times 10^6 \text{ atoms}$$

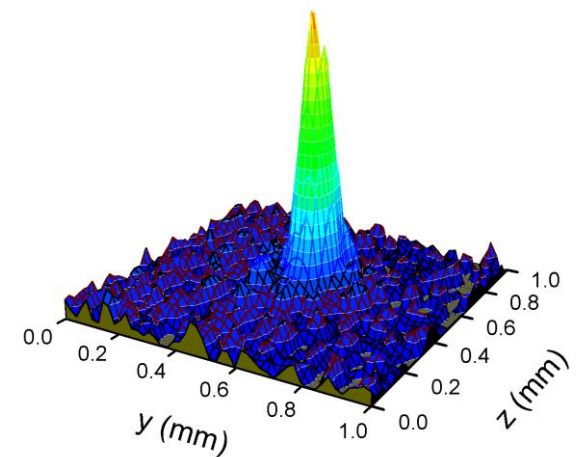


c) Pure Condensate

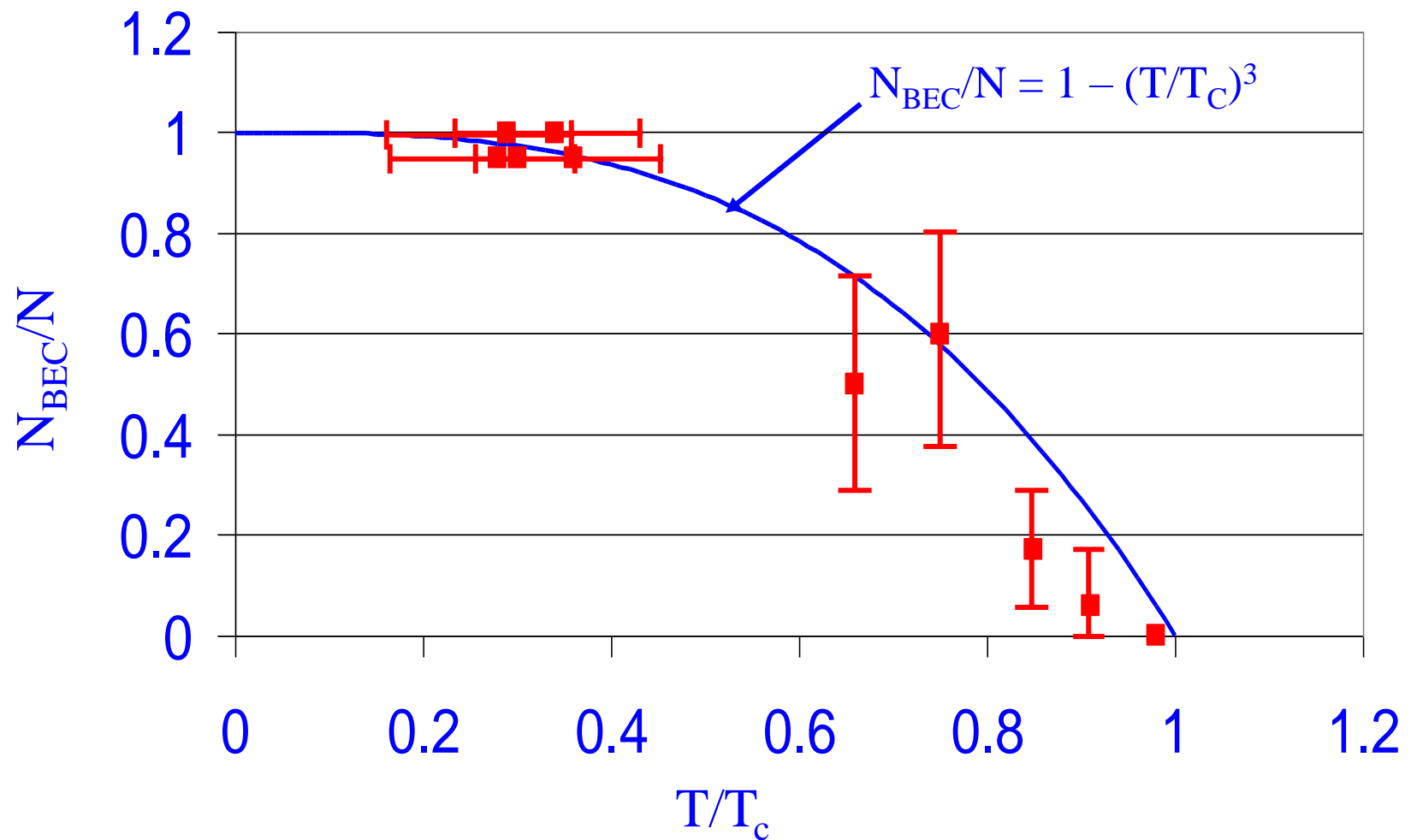
$$\nu_{\text{stop}} = 2.402 \text{ MHz}$$

$$T < 60 \text{ nK}$$

$$N = 4.2 \times 10^5 \text{ atoms}$$



Fraction of Atoms in Condensate versus Temperature



BEC Time Evolution

Gross-Pitaevskii Equation

$$-\hbar^2/2m \nabla^2 \Psi(r,t) + V(r) \Psi(r,t) + U_0 |\Psi(r,t)|^2 \Psi(r,t) = i \hbar \delta \Psi(r,t)/\delta t$$

where: $U_0 = 4\pi \hbar^2 a / M$

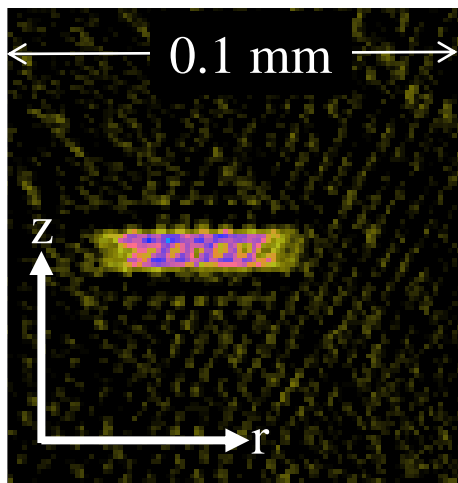
a = scattering length for lowest energy plane wave scattering

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

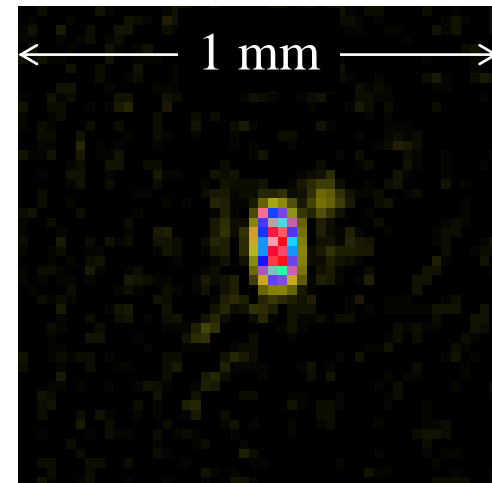
Ψ = condensate wavefunction, $|\Psi|^2 = \#$ atoms in condensate

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

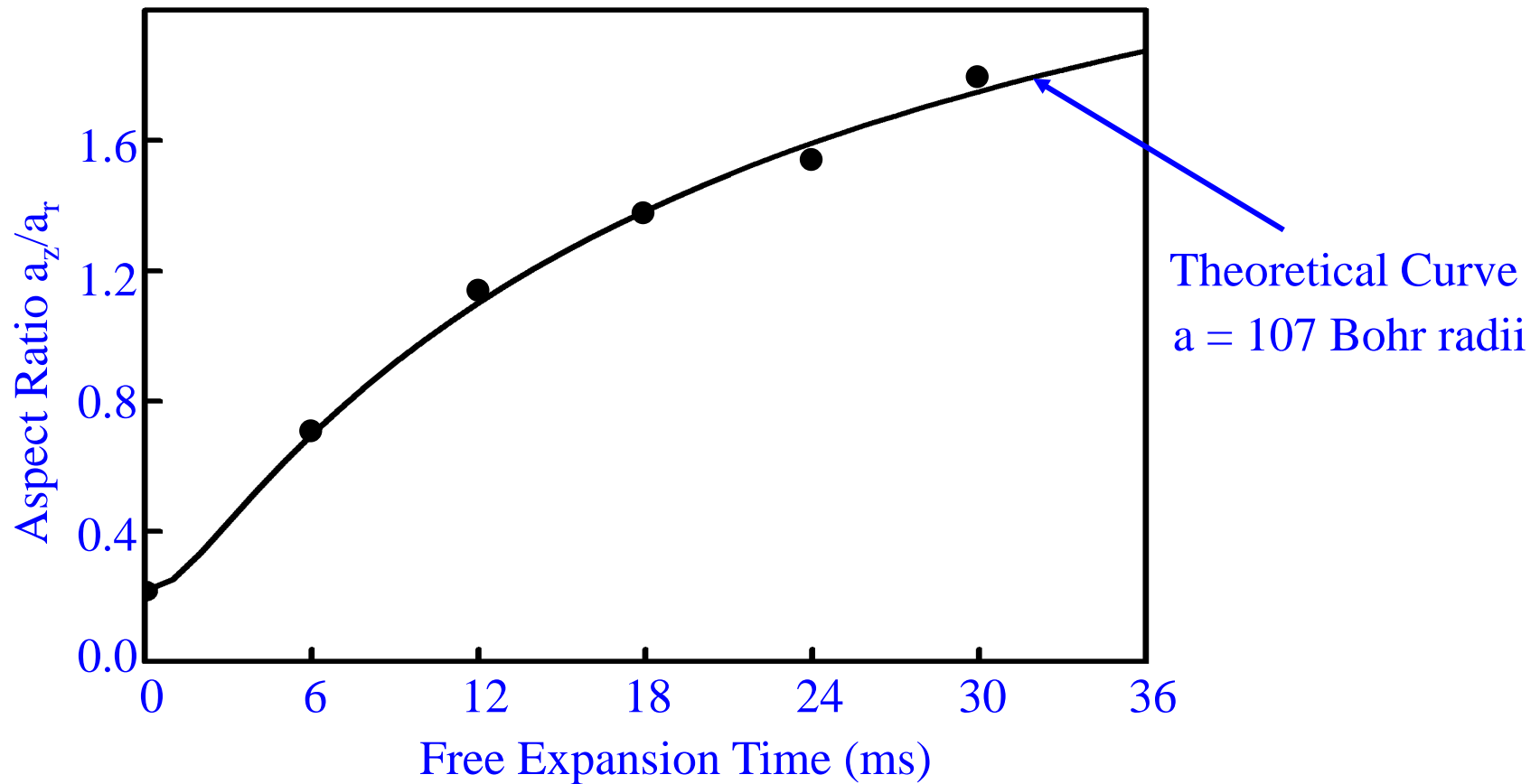
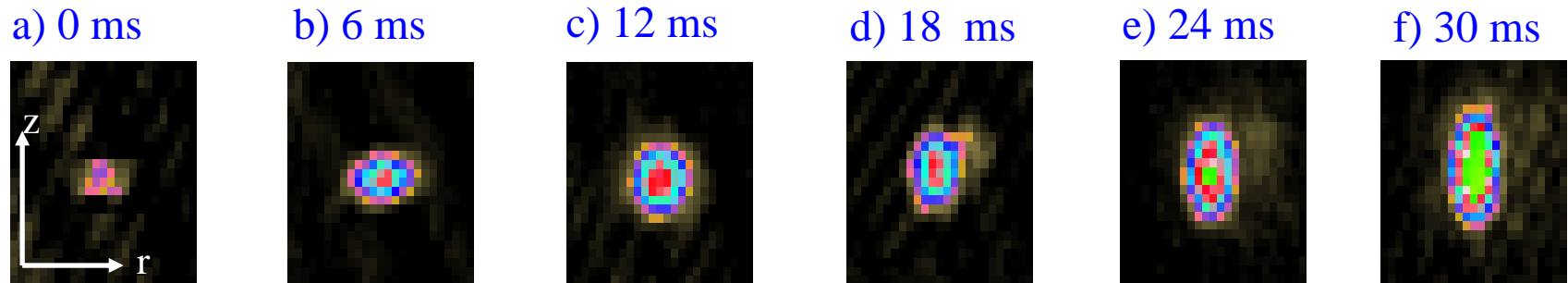
a) Before Free Expansion



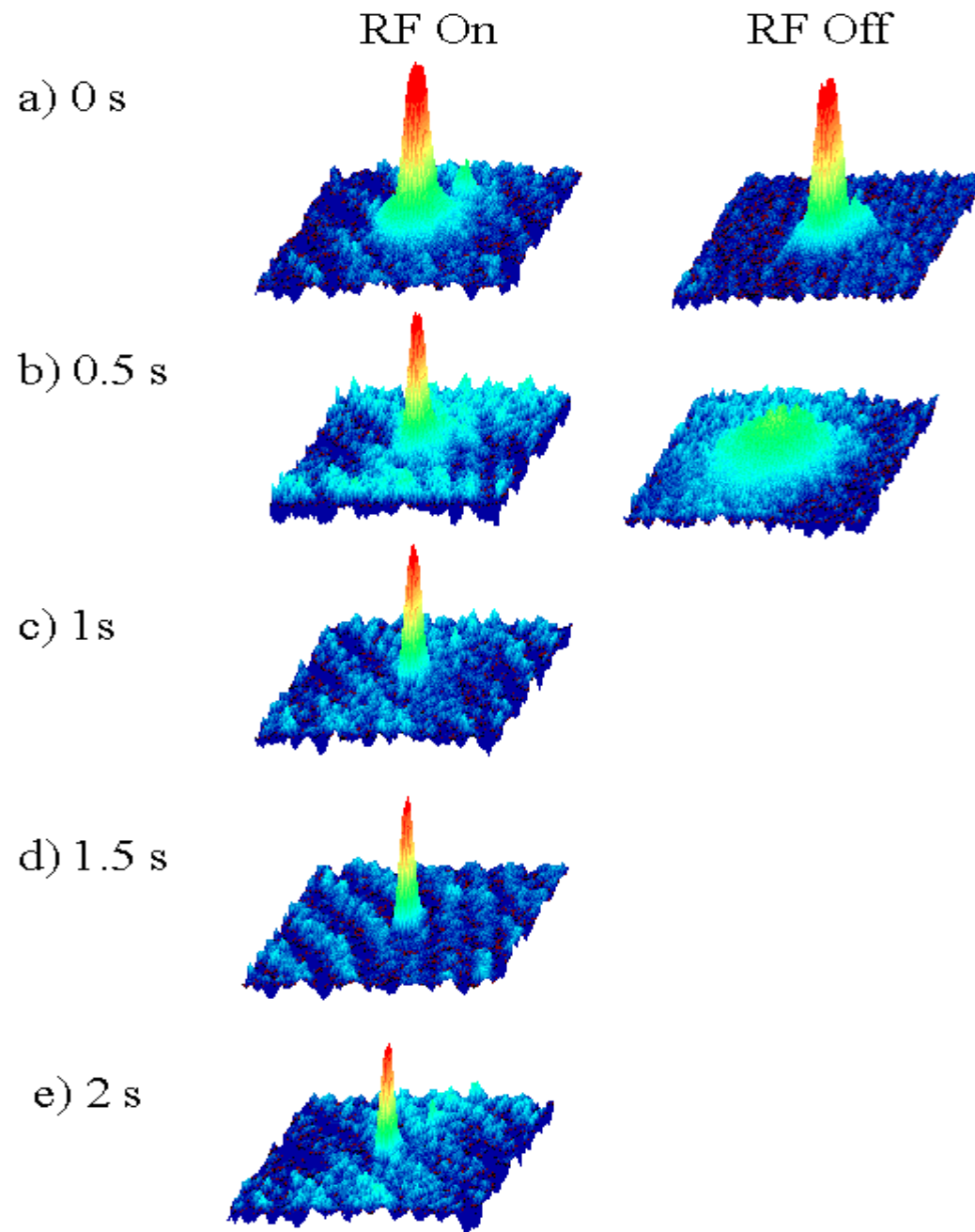
b) After 24 msec Free Expansion



BEC Time Evolution



BEC Lifetime in QUIC Trap



ii) Optical Trap

H. Ming & WvW, CJP (2007)

Far Off Resonance Trap (FORT) created by focusing laser detuned below resonance.

Trap Depth $U = \frac{\hbar I}{4 I_s} \frac{\Gamma^2}{\Delta}$ where $\Gamma =$ natural linewidth
 $I =$ laser intensity
 $I_s =$ saturation intensity
 $\Delta =$ detuning of laser from resonance

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

Trap Lifetime $\tau = U / H$

FORT Laser

$$\lambda = 852 \text{ nm}$$

$$I = 100 \text{ mW} / \pi (30 \text{ } \mu\text{m})^2$$

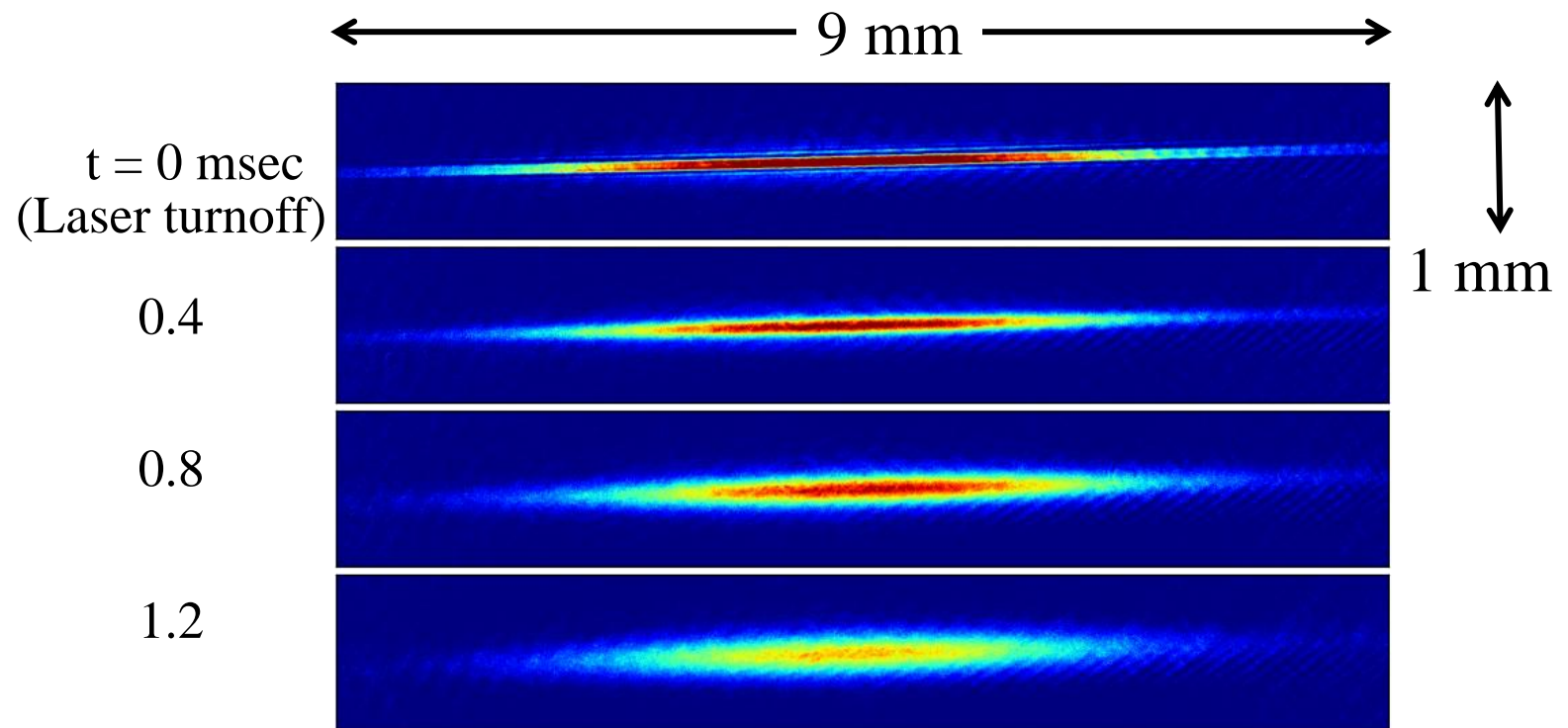
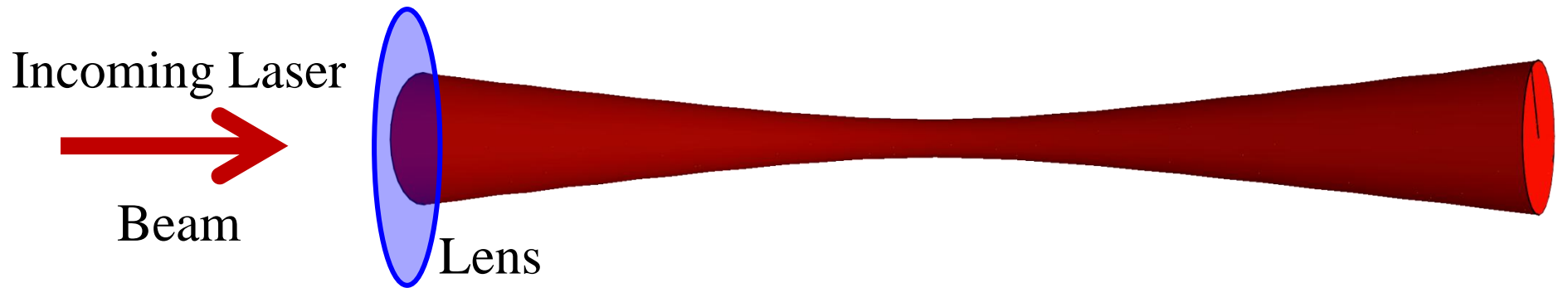


$$U_{max} = 75 \text{ } \mu\text{K}$$

$$H_{max} = 1 \text{ } \mu\text{K/sec}$$

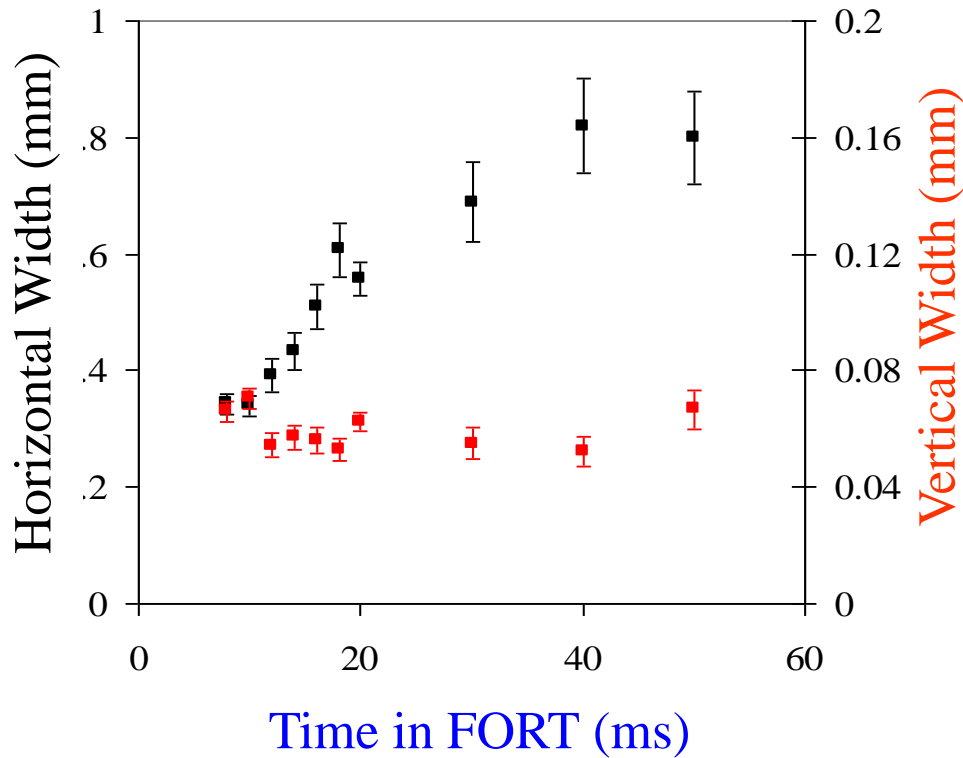
$$\tau = 75 \text{ sec}$$

Optical Trap using focussed Infrared Laser

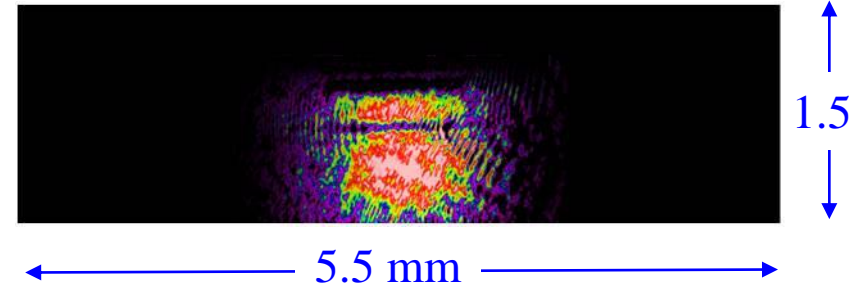


Evolution of Atoms in FORT

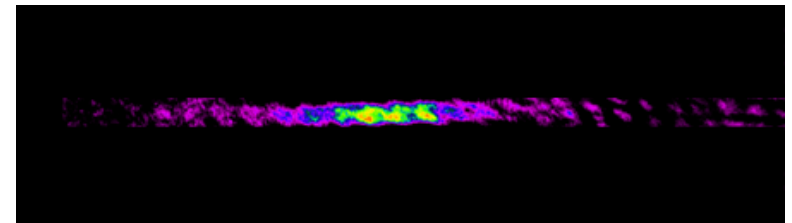
Time measured after QUIC trap turnoff H. Ming & WvW, CJP (2007)



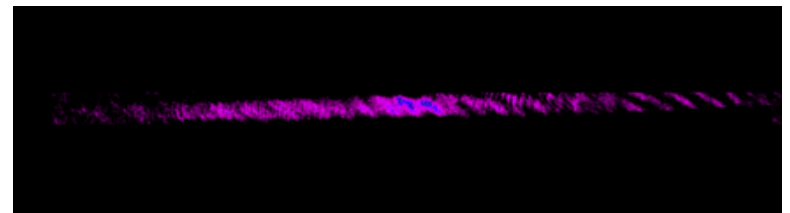
a) 8 ms



b) 20 ms



c) 50 ms



iii) Microtrap on Atom Chip

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

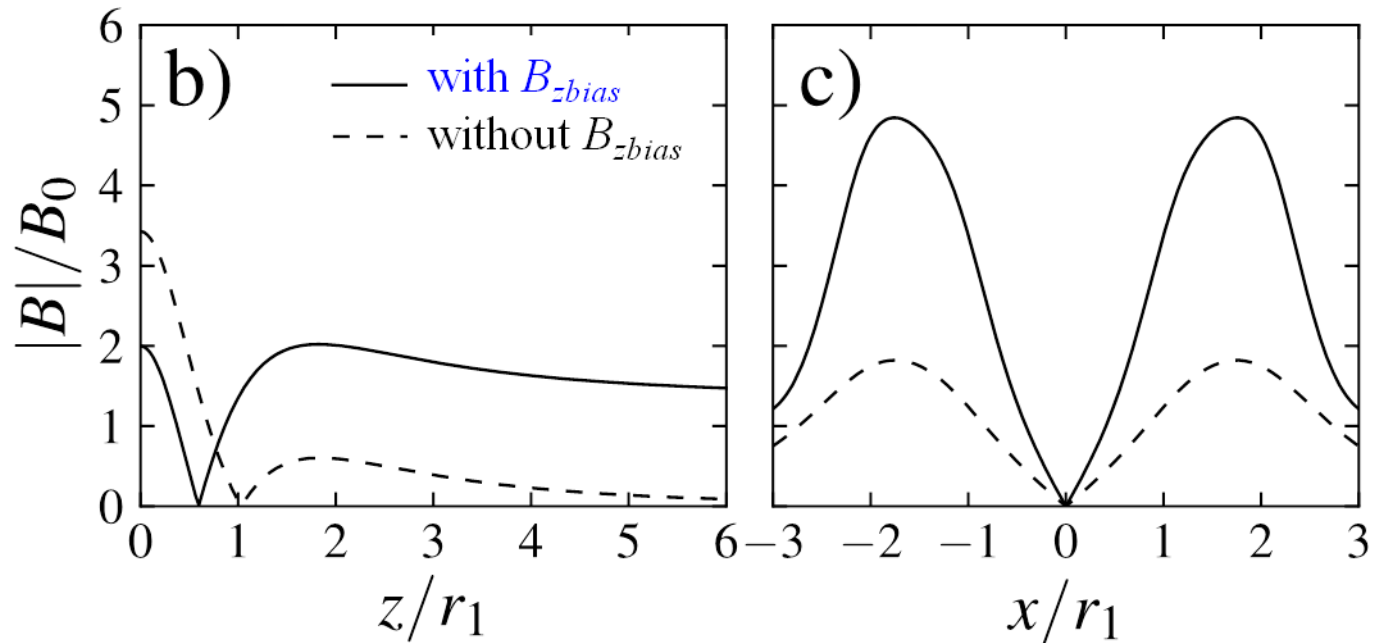
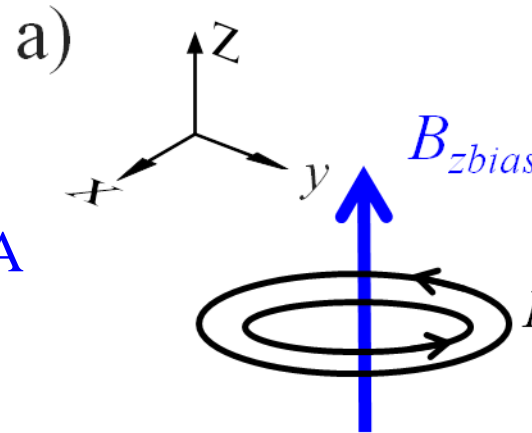
Trap Parameters

Inner Loop Radius = 300 μm

Outer Loop Radius = 660 μm

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

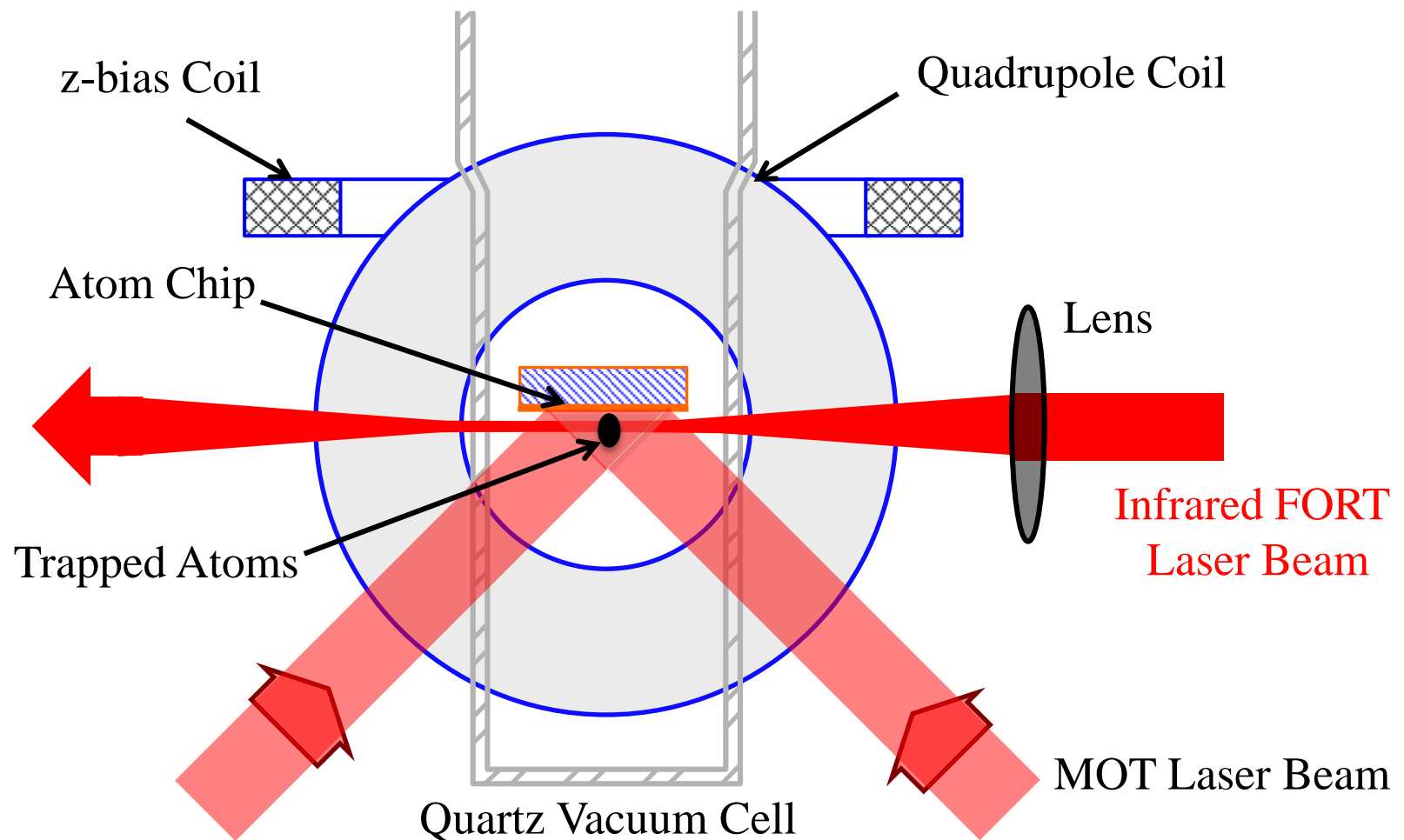
& $B_{z\text{bias}} = B_0 = \mu_0/4\pi I/r_1 = 10$ G



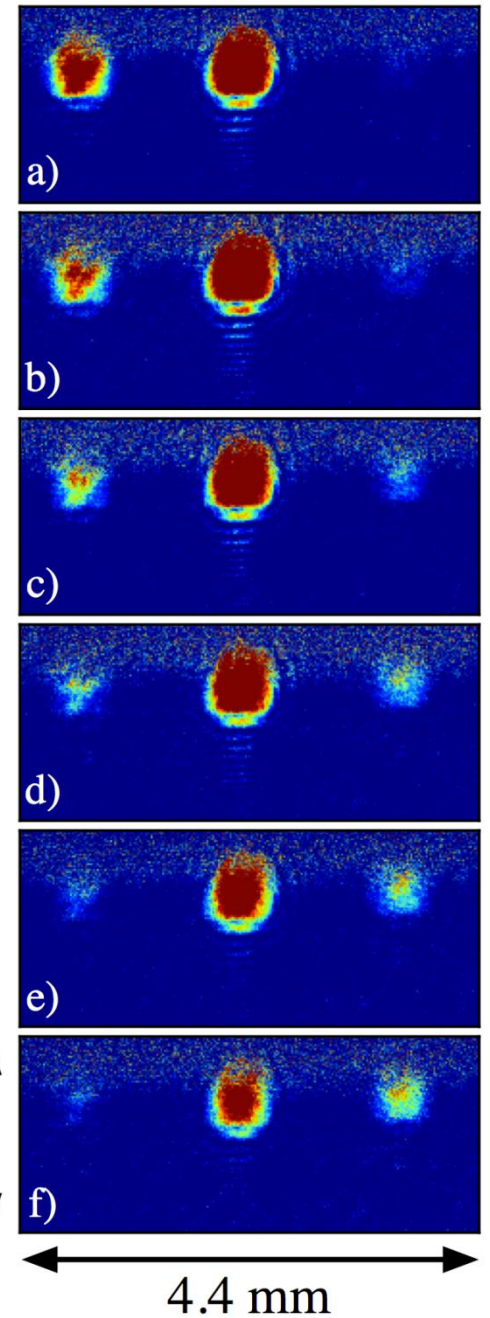
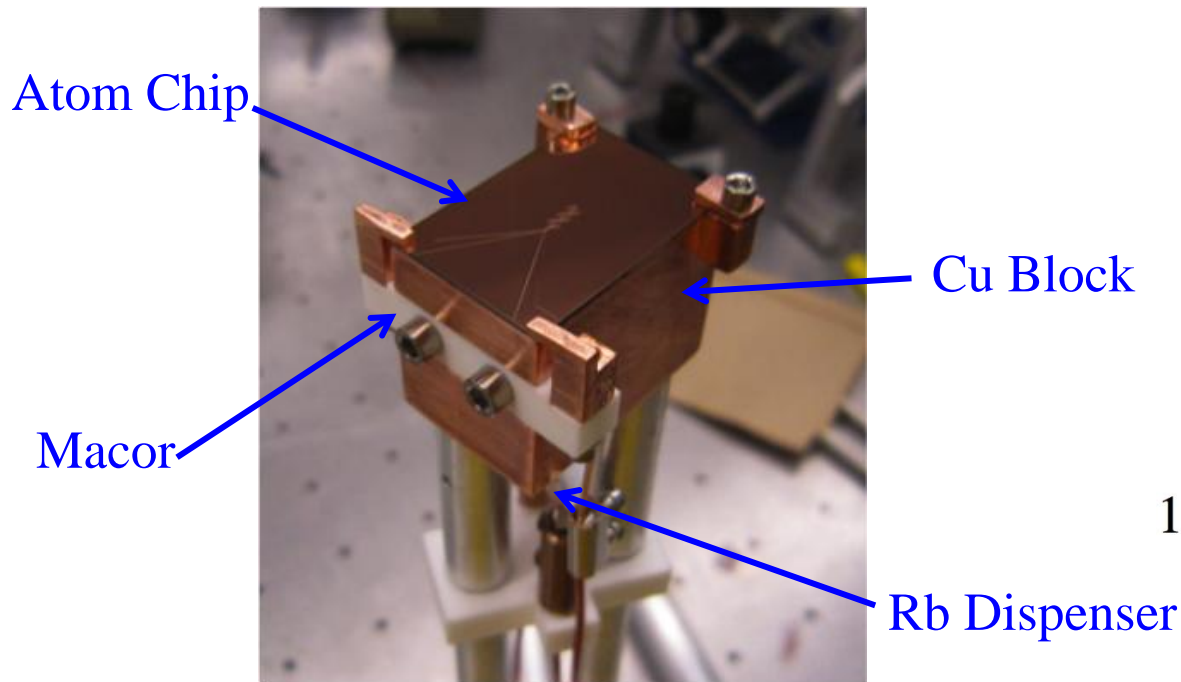
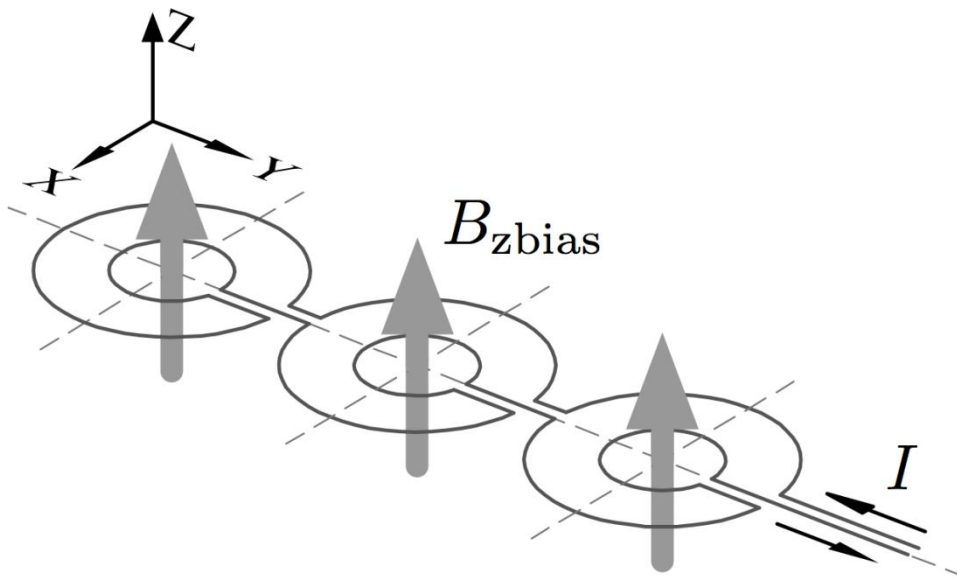
Microtrap Loading

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

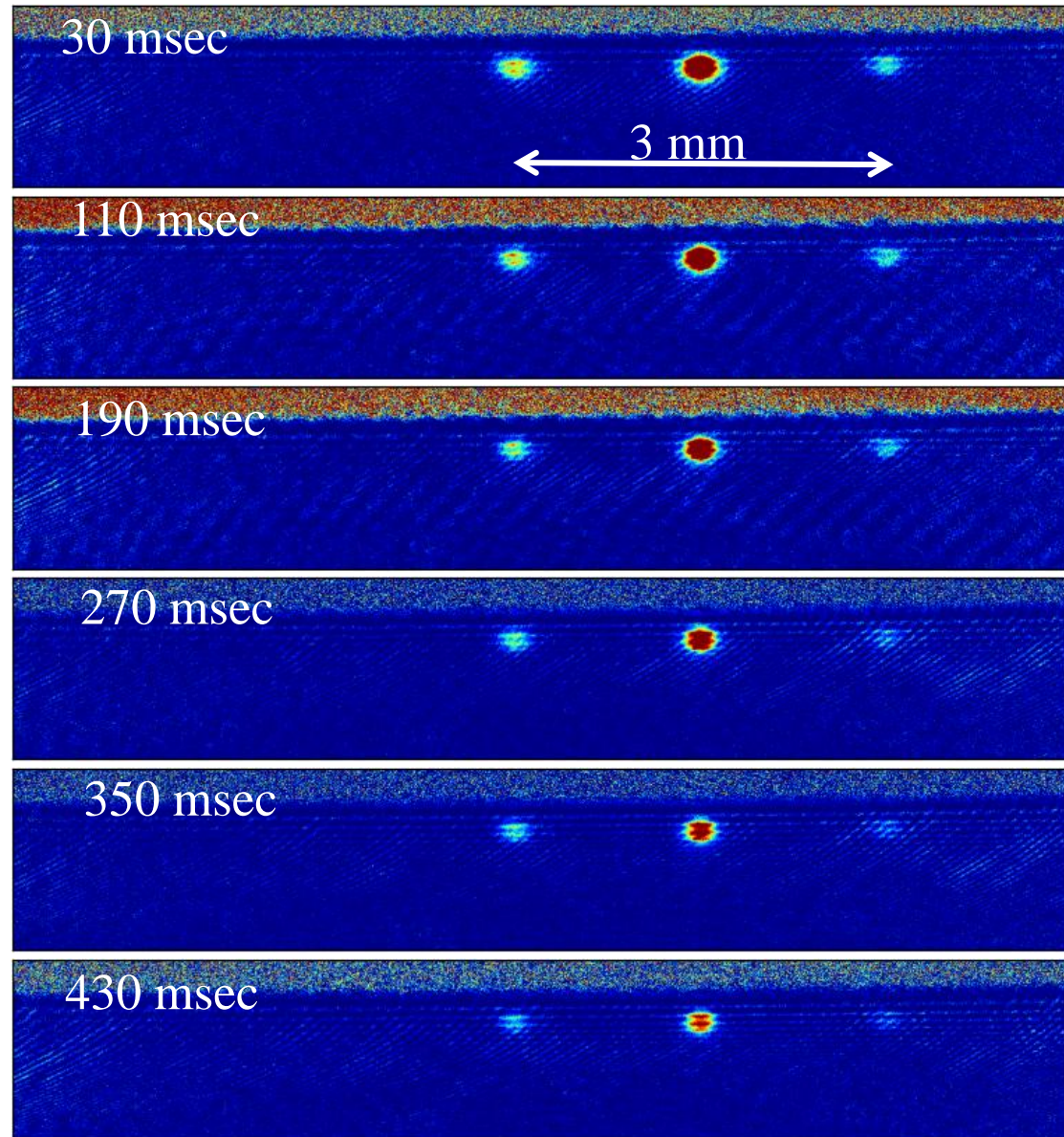
Methods: 1) Move MOT toward microtrap, 2) Surface MOT, 3) FORT



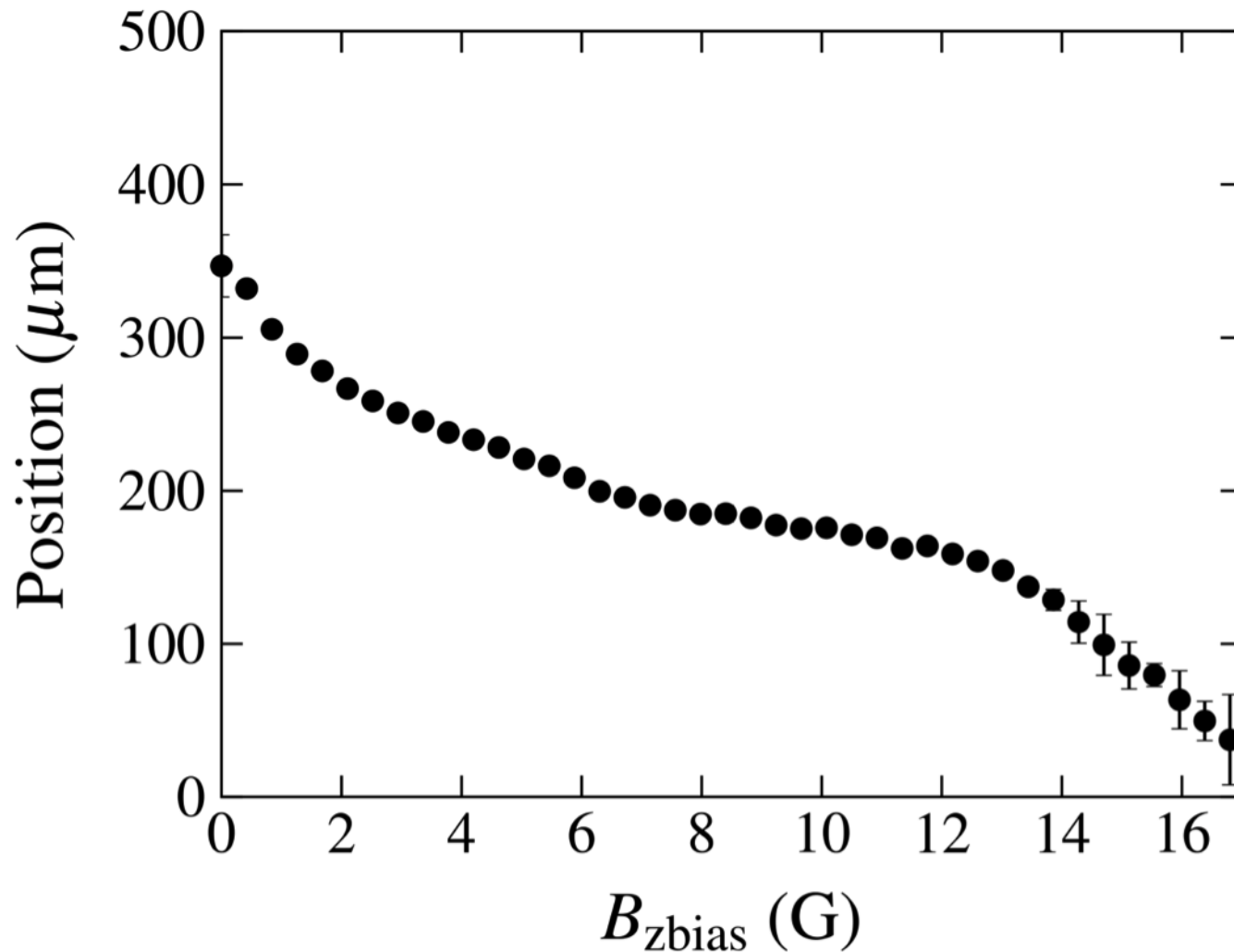
Microtrap Array



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



Precise Positioning of Atom Cloud above Chip Surface

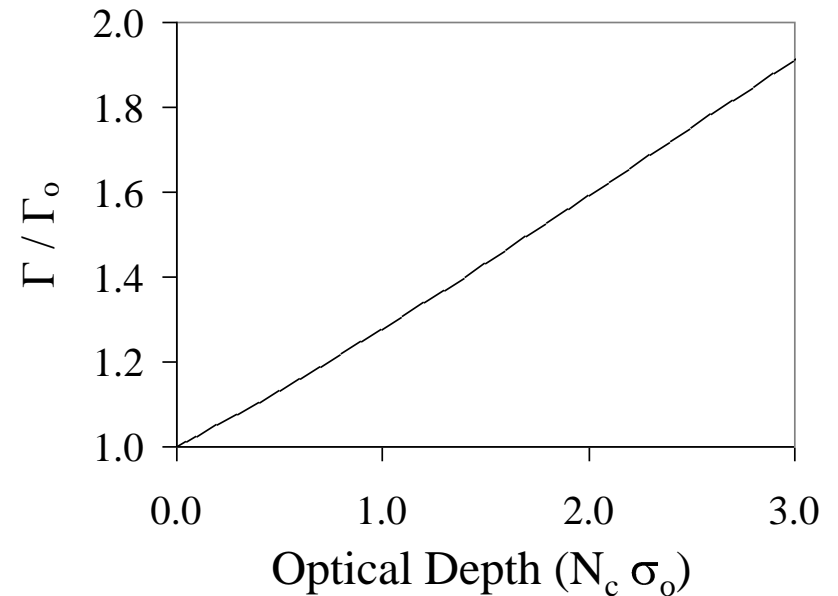
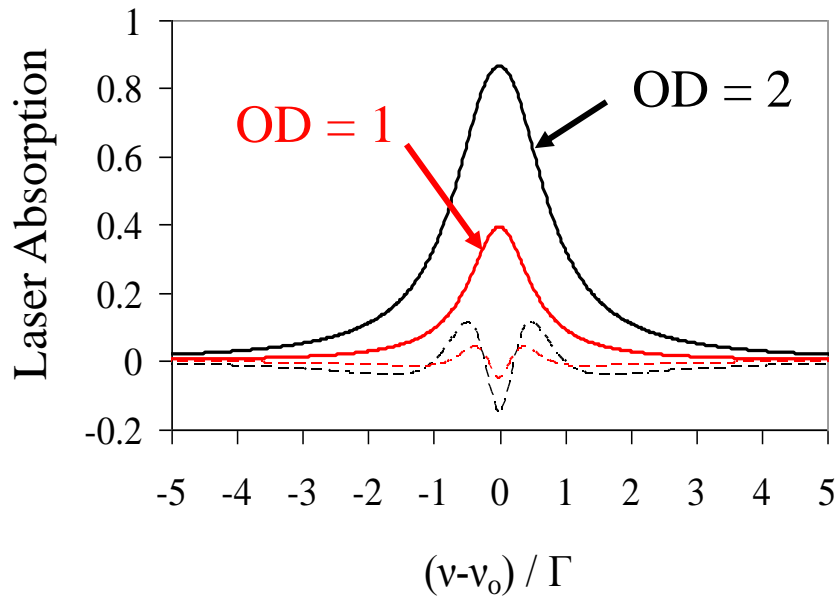


b) Precision Spectroscopy Rb D2 Linewidth

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

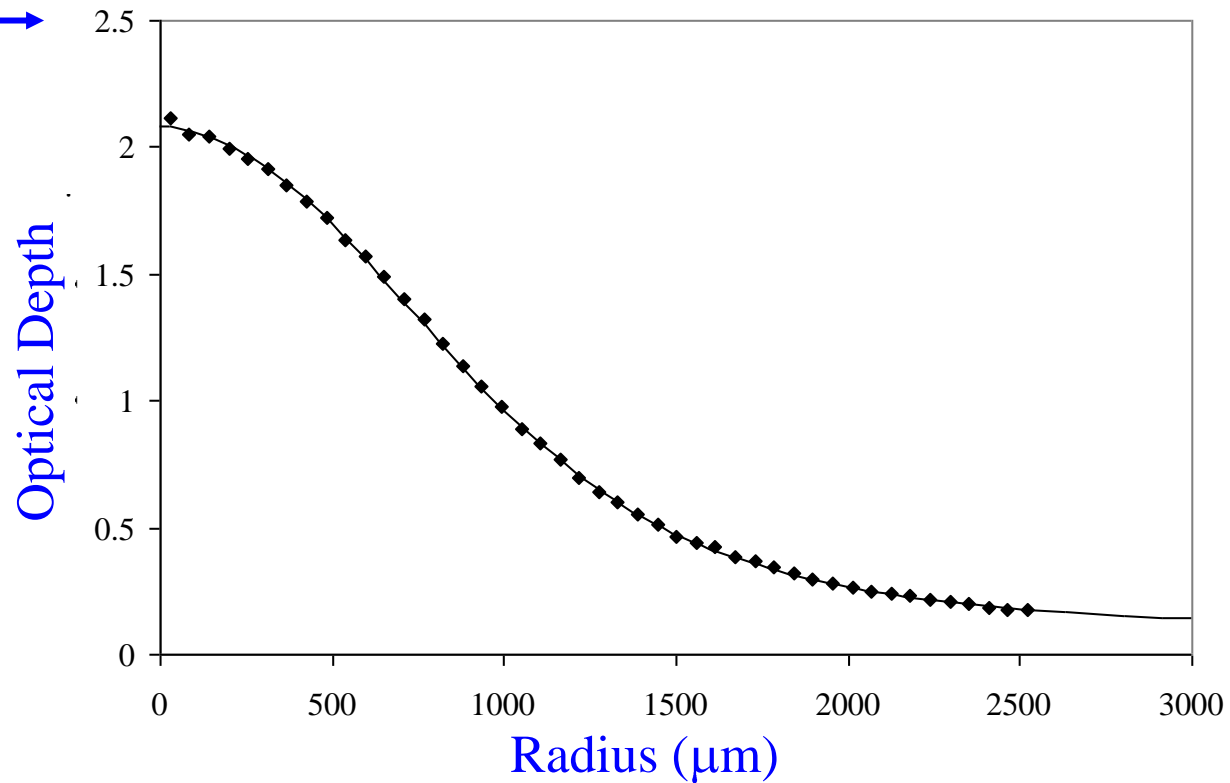
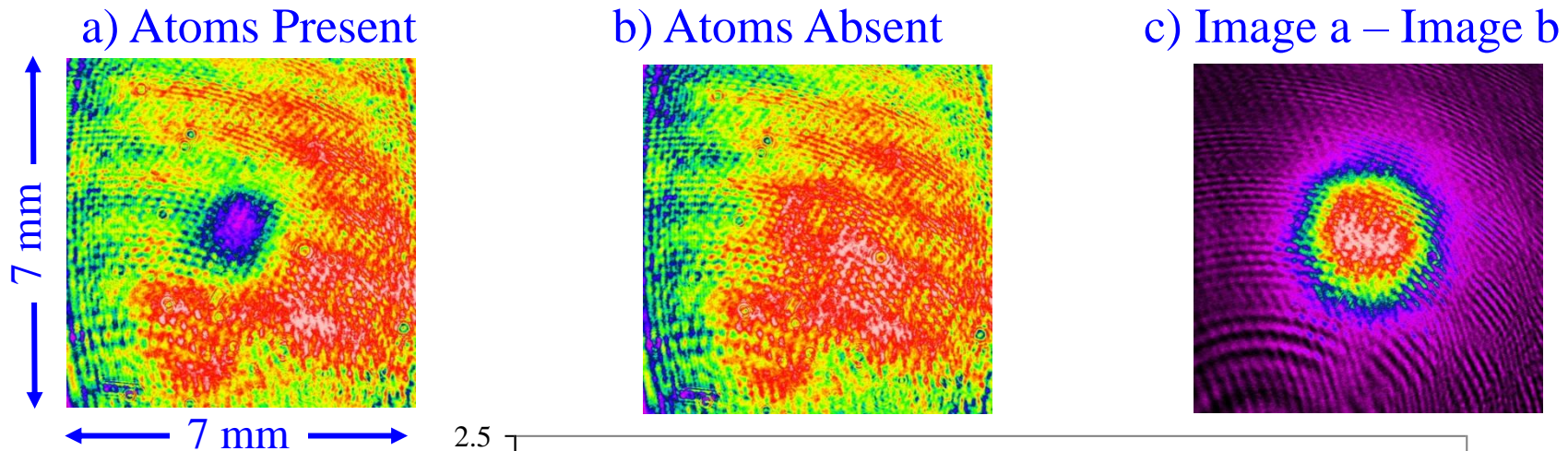
Laser intensity transmitted through atom cloud: $I = I_o e^{-N_c \sigma}$

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

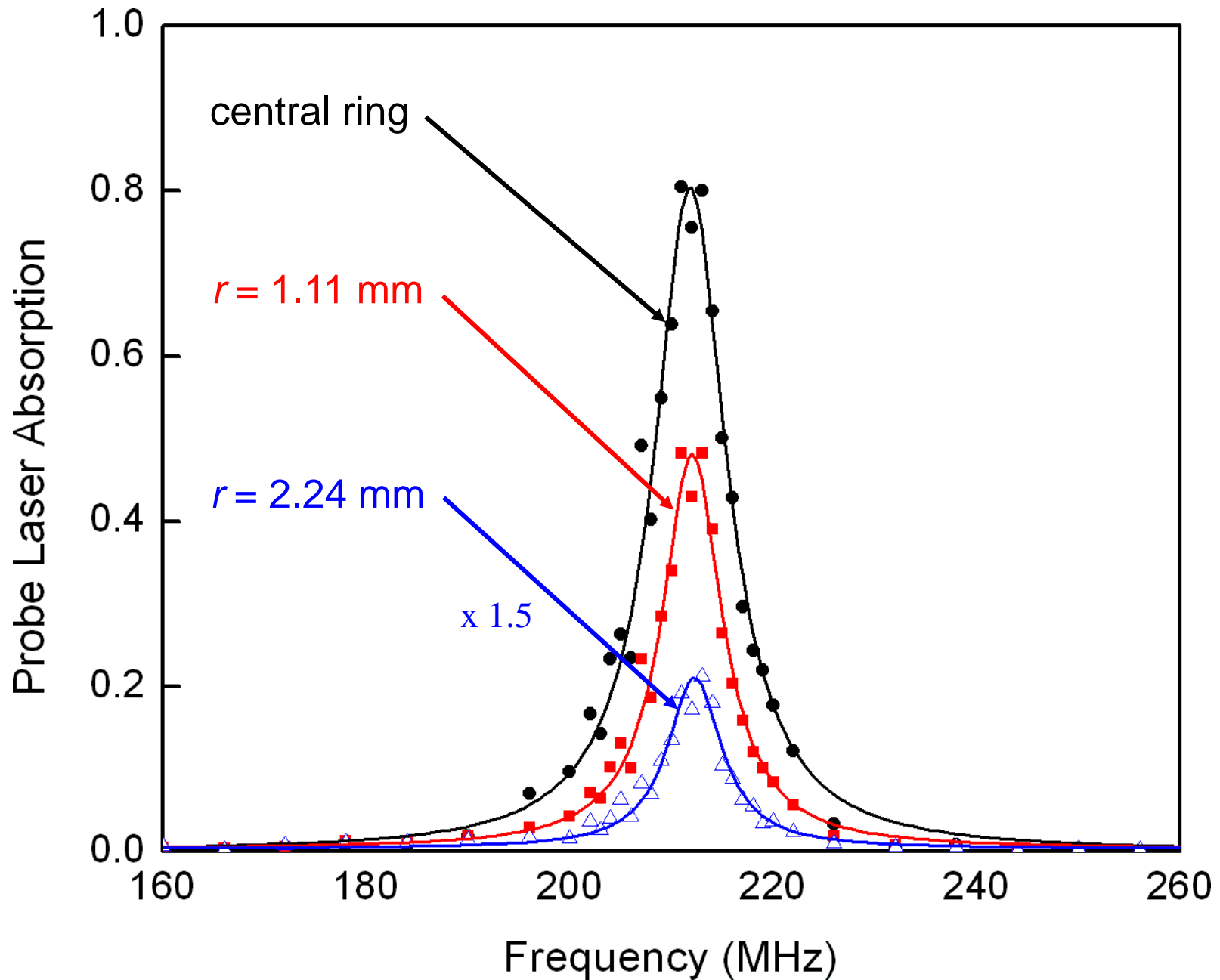


----- (Signal – Lorentzian fit) x 10
----- (Signal – Lorentzian fit) x 100

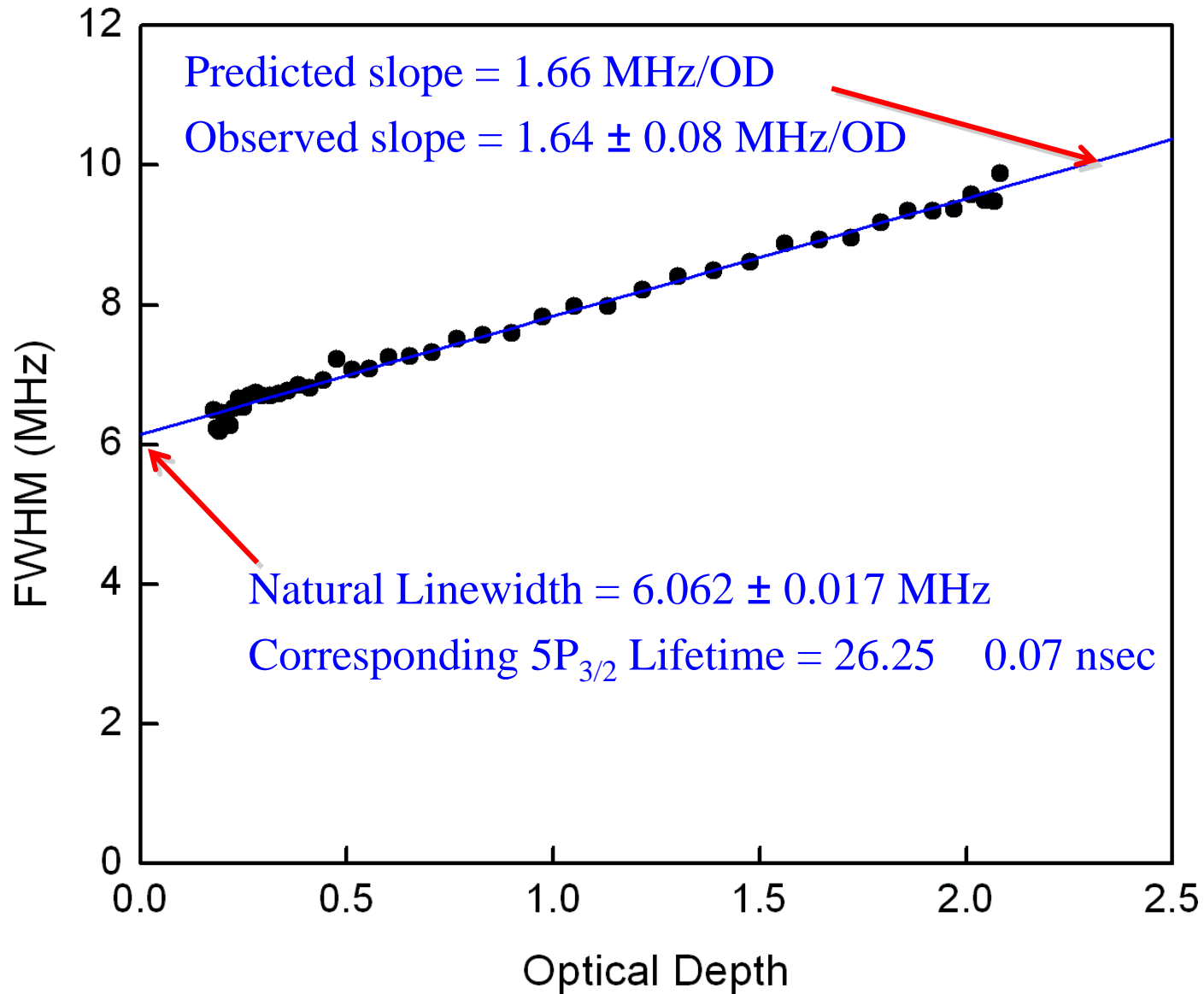
CCD Images of Probe Laser Transmitted through Atom Cloud



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



