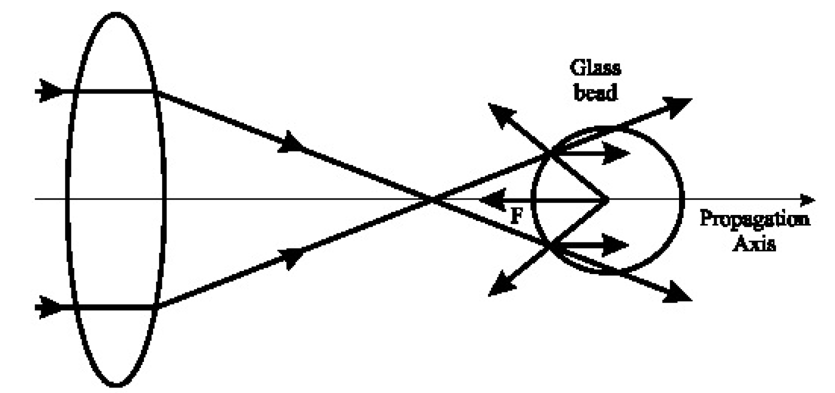
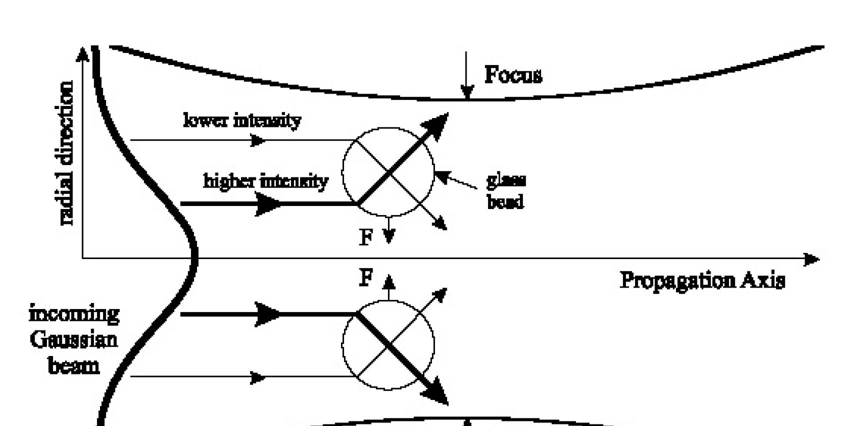
Course Format

- Two courses: PHYS 4061 (Laser Spectroscopy) and PHYS 4062 (Atom Trapping) introduced in 2007
- PHYS 4061 includes 11 experiments. Each experiment is completed in two 3-hour lab sessions. The experiments involve techniques in laser spectroscopy with a focus on atom trapping. Students submit weekly short-form lab reports that focus on data analysis.
- PHYS 4062 involves an identical format for 8 weeks. It takes students ~ 4-5 weeks to construct a magneto-optical trap. About 3 weeks are devoted to experiments with cold atoms. Students are required to submit a formal lab report at the end of the semester.
- Both courses are supported by one weekly lecture and tutorial. In PHYS 4061, lectures focus on theory of instrumentation such as lasers, Fabry-Perot interferometers, electro-optic and acousto-optic devices. In PHYS 4062, lectures focus on theory of the radiation pressure force and optical dipole force. Tutorials in both courses focus on experimental techniques relevant to the laboratory component.

Optical Tweezers: Principle of Operation

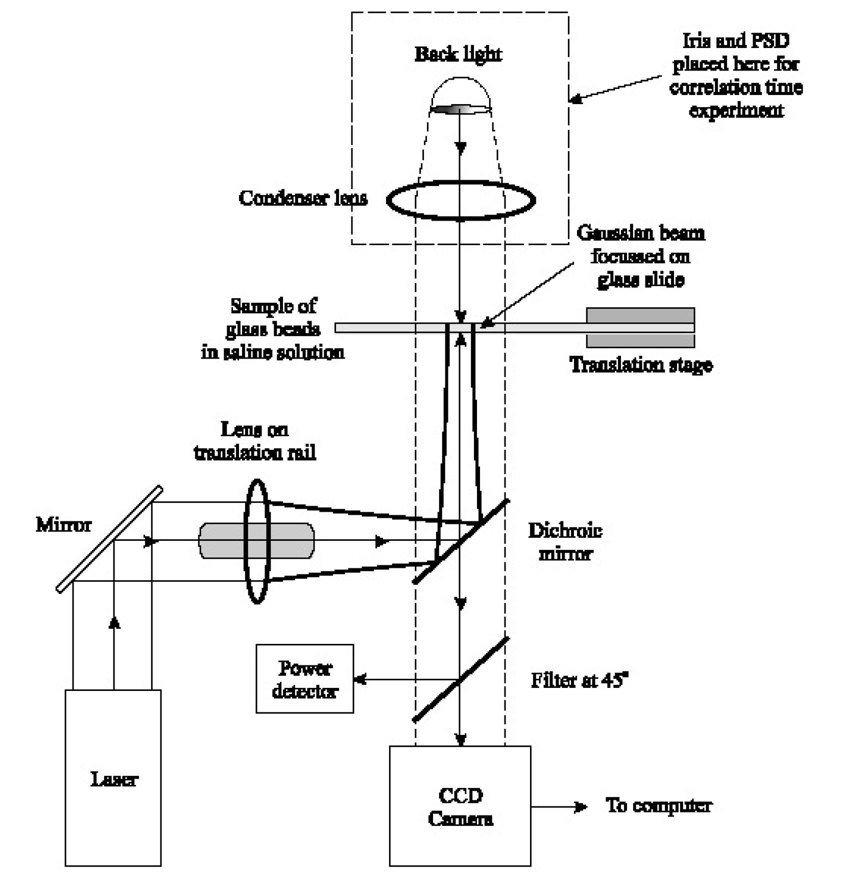


- Net force on bead toward focus



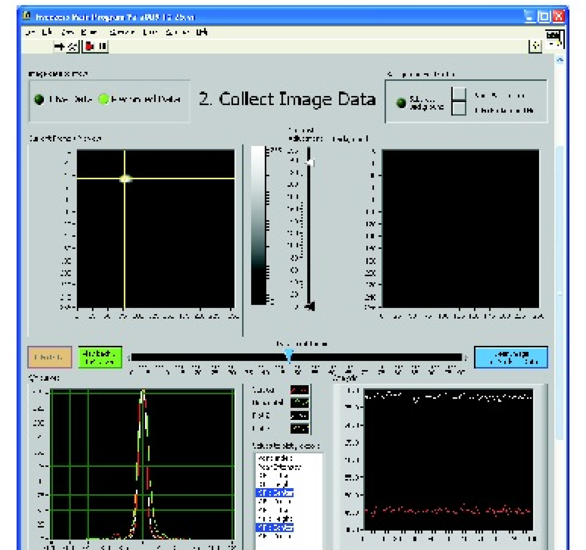
- Net force on bead toward symmetry axis

Optical Tweezers: Experimental Setup

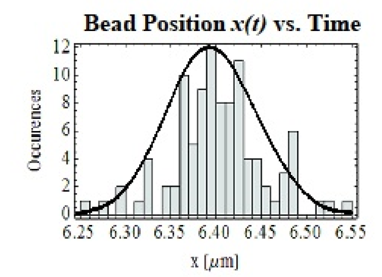


- Diameter of bead ~ 1 μm
- Dichroic mirror reflects green laser light and transmits backlight

Optical Tweezers: Computer Interface

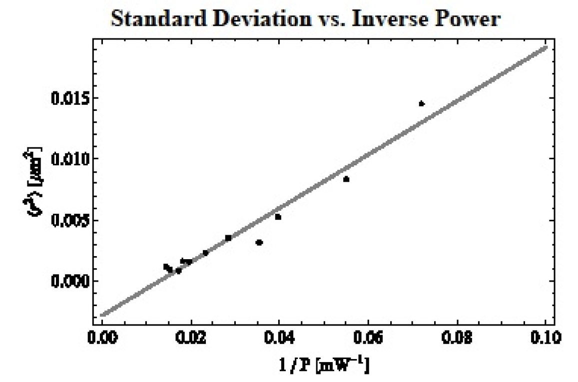


- Top left: trapped bead. Top right: background. Bottom left: instantaneous Gaussian spatial profile. Bottom right: position versus time.



- Mean squared deviation is 0.26 μm^2.

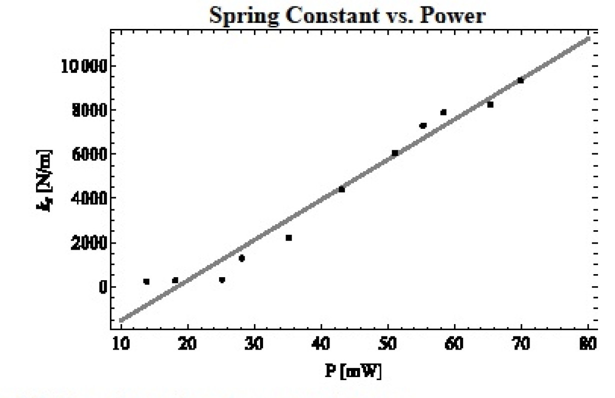
Optical Tweezers: Determination of k_s



$r^2 = x^2 + y^2$

- Slope of the fit line gives value of $0.22 \pm 0.02\ \mu m^2 W$

$$U_{OD} \propto I\ ;\ \text{since}\ U_{OD} = \frac{1}{2}k_s\langle r^2\rangle \Rightarrow \langle r^2\rangle \propto \frac{1}{P}$$



- Slope of fit line above is 182 ± 11 N/mW·m

$$U_{OD} = \frac{1}{2}k_s\langle r^2\rangle = \frac{1}{2}k_B T$$

Optical Tweezers: Correlation Theory

- First part of experiment (spring constant) used CCD exposure times of ~100 ms, thus images were uncorrelated
- The second part uses time scales of ~1 ms measure with a PSD to infer trap properties such as correlation time
- Laser field potential approximated by a parabola: $U(x) = \frac{1}{2}k_s x^2$
- Boltzmann distribution $\rho(x)$ gives particle position at room temperature, where Z is the partition function:

$$\rho(x) = \frac{e^{-\frac{U(x)}{k_B T}}}{Z};\quad Z = \int_{-\infty}^{\infty} e^{-\frac{U(x)}{k_B T}}dx,\quad \text{with}\ \langle x^2\rangle = \int_{-\infty}^{\infty} x^2\rho(x)dx = \frac{k_B T}{k_s}$$

- Following a formal proof, the time constant τ_0 is inferred:

$$\langle x(0)x(t)\rangle = \frac{M}{\gamma^2}e^{-\frac{\tau}{\tau_0}}\int_{-\infty}^{0} e^{\frac{2\tau''}{\tau_0}}d\tau'' = \frac{M}{2\gamma k_s}e^{-\frac{\tau}{\tau_0}}$$

- In the above formula, M is a measure of the amplitude of kick strength: $M = 2k_B T\gamma$
- Thus the above equations relate the time constant to the spring constant k_s and the damping constant γ of the solution:

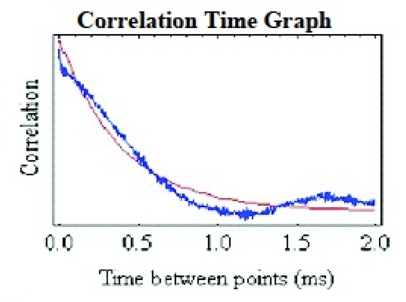
$$\tau_0 = \frac{\gamma}{k_s}$$

Optical Tweezers: Correlation vs. Laser Power

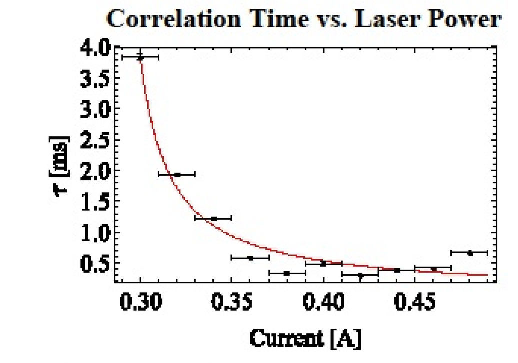
- For a correlated pair of images, exposure time must be less than:

$$\tau_0 = \frac{\gamma}{k_s},\ \text{where}\ k_s \propto P$$

- Correlation function constructed from $x(t)$ is fit to the exponential and gives $\tau_0 = 0.40 \pm 0.01$ ms

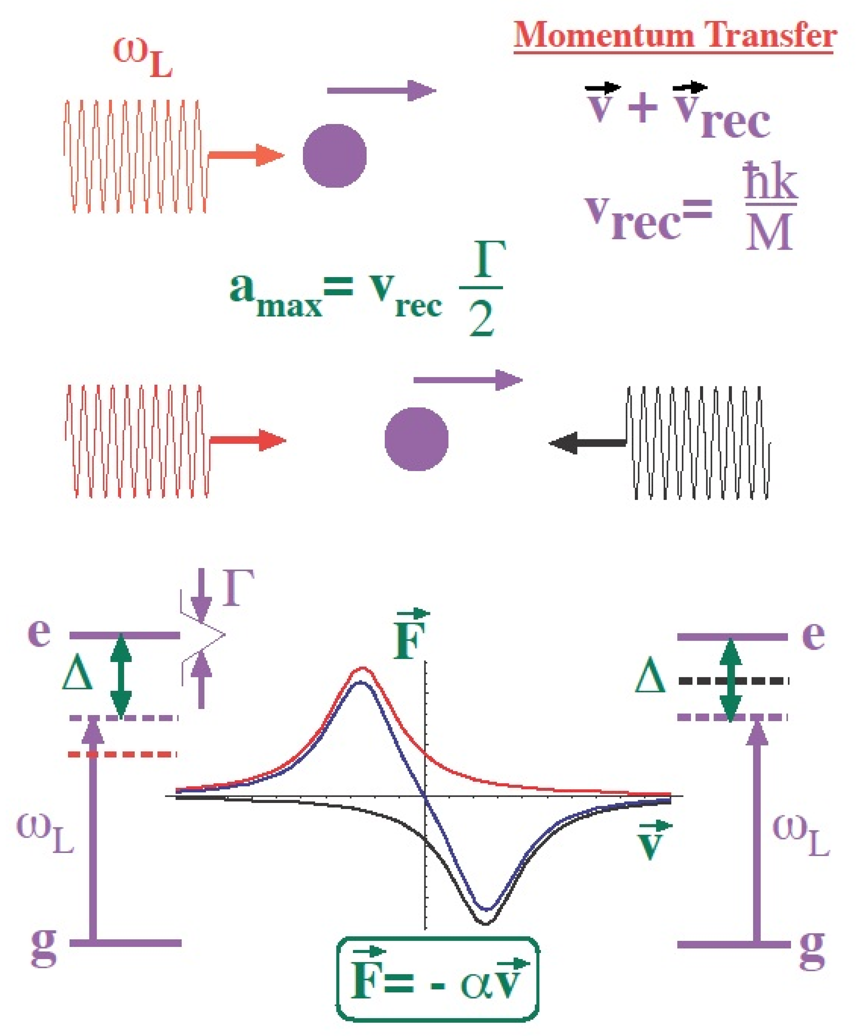


- Bead diameter of ~1 μm
- 1:14 concentration ratio (7 drops of saline for 0.5 drops of bead solution)

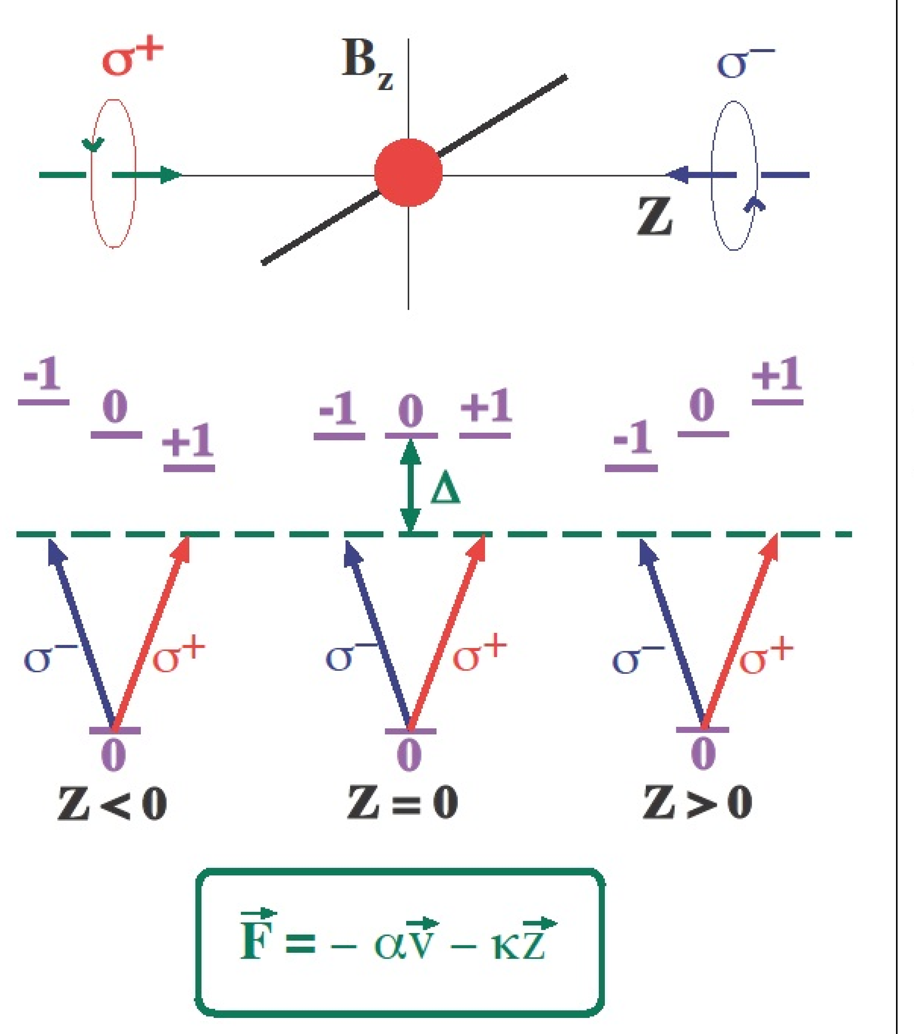


- *Note:* Power scales linearly with current
- The data follows expected inverse trend: increasing the power decreases the spring constant

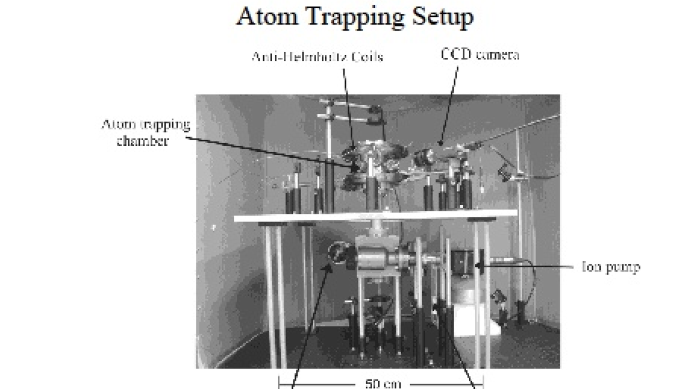
Laser Cooling



Mageneto-Optical Traps



Atom Trapping Setup



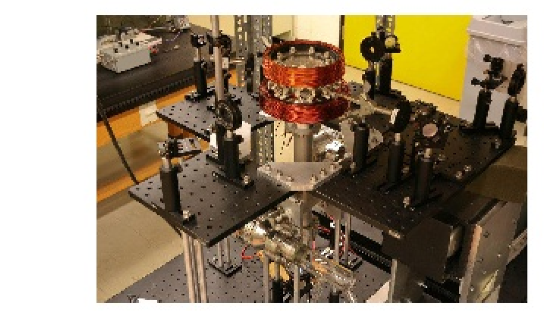
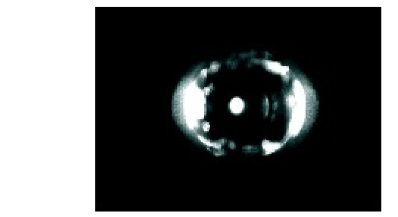
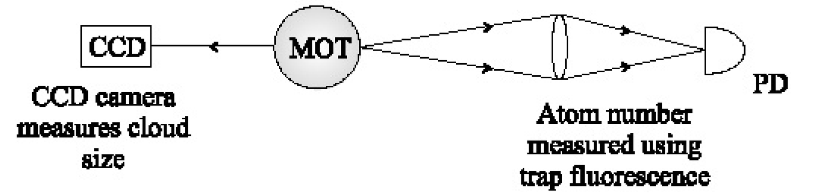
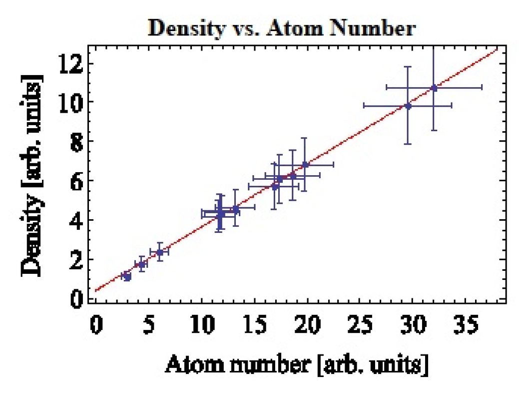


Image of ^{85}Rb Atom Cloud



Atom Trapping: Density

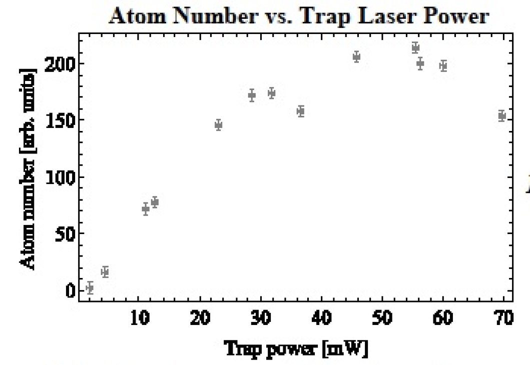




$N = 5 \equiv 1 \times 10^5$ atoms
Density $= 2 \equiv 3 \times 10^8$ atoms/cm^3

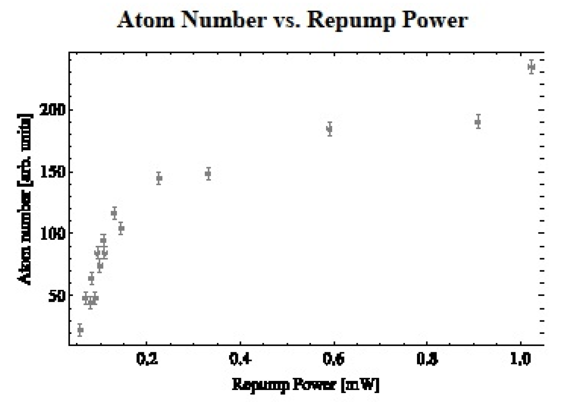
- The slope of the fit line above is 0.322 ± 0.004
- $n = N/V$
- Atom number is varied by changing the laser power
- With no radiation trapping, a linear fit is expected; i.e., cloud density increases since the cloud size is unchanged

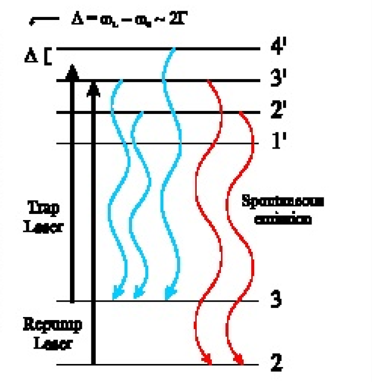
Atom Trapping: Atom Number Variation



$N = 200 \equiv 4 \times 10^6$ atoms

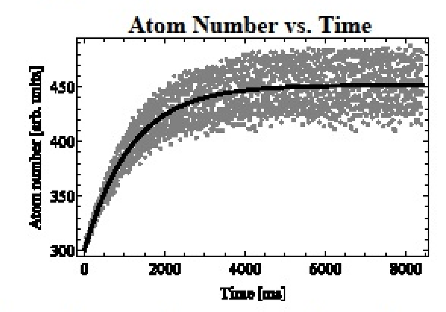
- Net force F on atoms depends on the power P
- As I increases, we expect an increase in atom number
- At low intensity there is a linear trend; as I increases, saturation is reached, i.e. all atoms up to the capture velocity have been slowed and trapped





- Repump laser is needed to pump atoms out of $F = 2$ level
- Atom number is not limited by the repump power

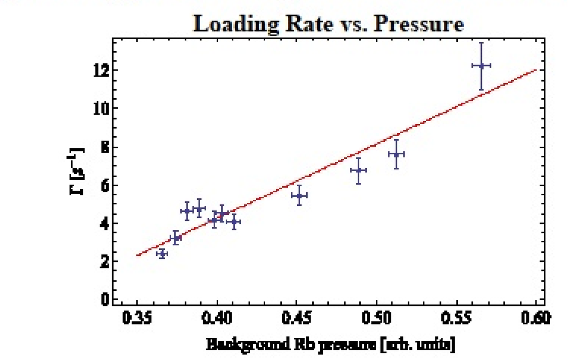
Atom Trapping: Loading Time of Trap



- Atoms loaded into the trap after turn on of trap laser at $t = 0$. The laser is turned on a long time after atoms have escaped the trapping volume.
- Collision rate Γ given by:

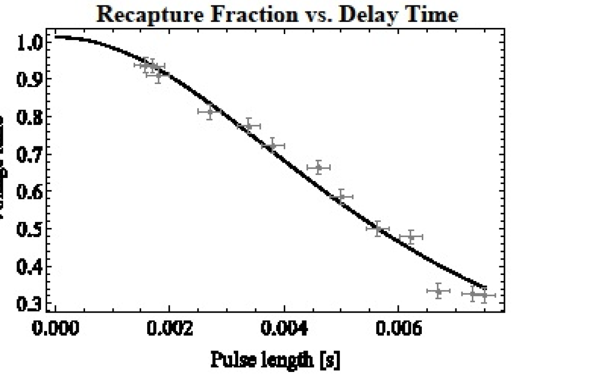
$$\frac{dN}{dt} = l - \Gamma N \Rightarrow N = N_{ss}(1 - e^{-\Gamma t})\ ,\ \text{where}\ l\ \text{is loading rate}$$

- The fit (solid line) gives a loading rate Γ of $0.268 \pm 0.005\ s^{-1}$



- Γ is the inverse of loading time.
- Collision rate is measured as a function of background Rb density n
- Linear trend is consistent with $\Gamma = n\sigma v$, where v is relative velocity of collisions between background and trapped atoms, and σ is the collision cross-section

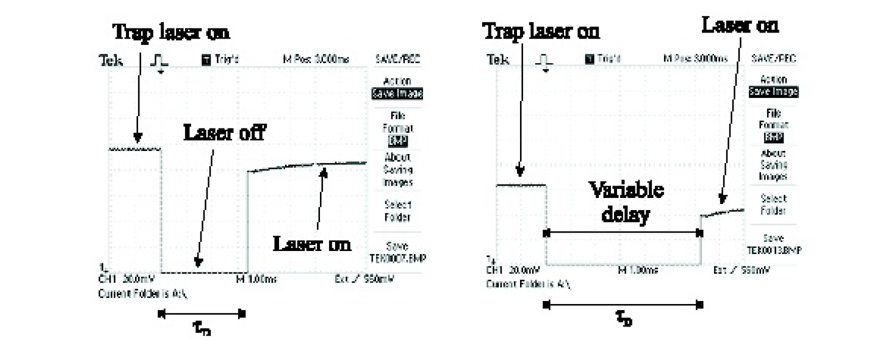
Atom Trapping: Temperature Measurement



- Release/recapture method: turning trap laser on and off by pulsing AOM

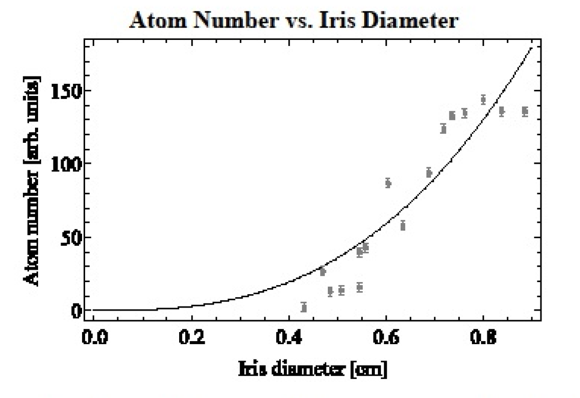
$$f(t_D) = \frac{r_0^3}{\left(r_0^2 + (v_0 t_D)^2\right)^{3/2}}\ ,\ \text{where}\ r_0 = 5.37\ \text{mm and}\ v_0 = 35 \pm 1\ \text{mm/s}$$

- Temperature of 420 ± 20 μK inferred by fit using: $v_0 = \sqrt{\frac{2k_B T}{m}}$



- Increasing off time corresponds to smaller recaptured fraction

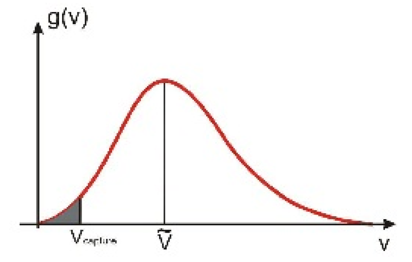
Atom Trapping: Atom Number vs. Beam Size



$N \propto D^{2.8}$

- As beam diameter D increases, transit time through trap laser beam increases
- Increasing the capture velocity v increases the atom number N

Speed Distribution of Atoms Inside Vacuum Chamber



Conclusions

Atom Trapping

- We have presented an outline of typical data obtained by students in the atom trapping course PHYS 4062

Optical Tweezers

- Followed tweezers experiment by Bechhoffer et. al, AJP 70, 393 (2002), for spring constant measurements
- Extended experiment to measure the correlation time
- Experiment has been introduced in PHYS 4061 and works reliably using a green laser pointer