Atom trapping laboratory for upper level undergraduate students

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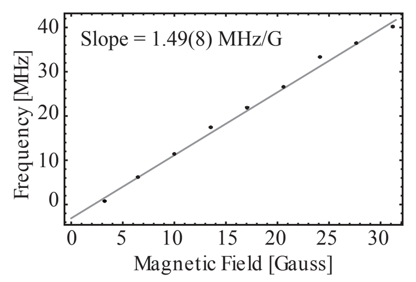
Course Format

Two courses introduced in 2007:
PHYS 4061 - Laser Spectroscopy
PHYS 4062 - Atom Trapping

– Laser spectroscopy course includes 9 experiments.
– Each experiment is completed in two 3-hour lab sessions.
– Experiments involve techniques in laser spectroscopy with focus on atom trapping.
– Weekly short-form lab reports focus on data analysis.

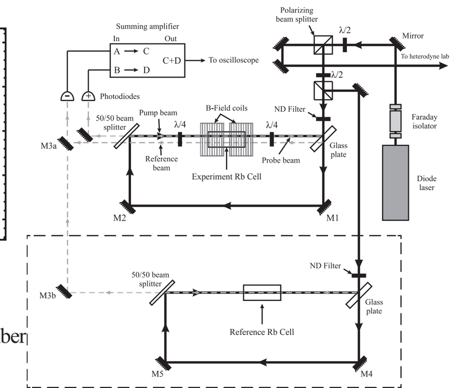
– Atom trapping course has two 3-hour lab sessions per week.
– Students typically take four to five weeks to obtain a MOT and spend an additional three weeks on cold atom experiments.
– Long-form lab report is completed during the last 3 weeks.

Zeeman Effect Experiment



$\Delta E = \mu_B B (g_F\, m_{F'} - g_F\, m_F)$

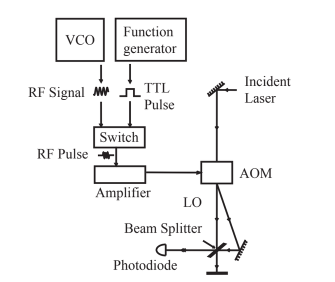
E = energy, m_F = magnetic quantum number
μ_B = Bohr magneton, g_F = Lande g factor

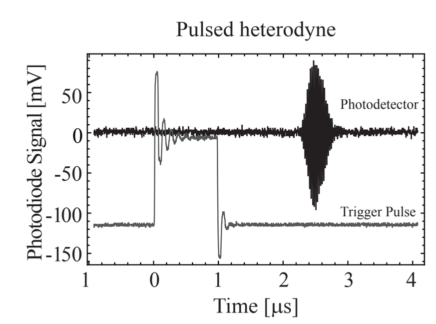


The spectral shift of a transition is measured with respect to a reference spectrum. Expected value for F = 3, m_F = 3→F' = 4, $m_{F'}$ = 4 sublevel transition is 1.4 MHz/G. The horizontal error bars are 5%, vertical error bars are comparable to the point size.

RF Circuitry and Heterodyne

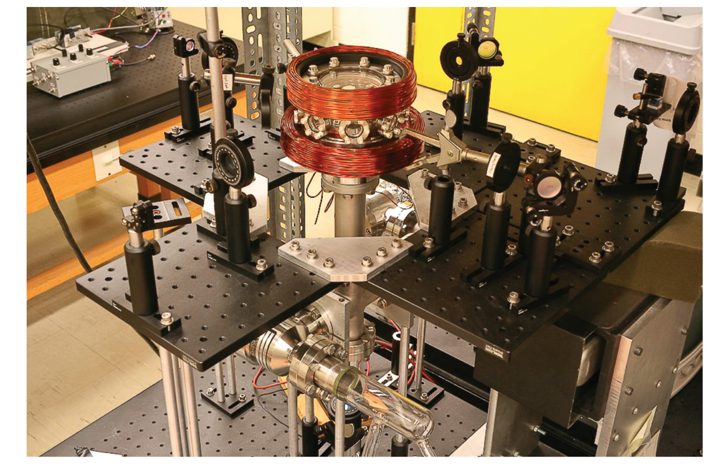
Analog RF components such as couplers, splitters, mixers, amplifiers, and attenuators are investigated. RF power measurements are taken.



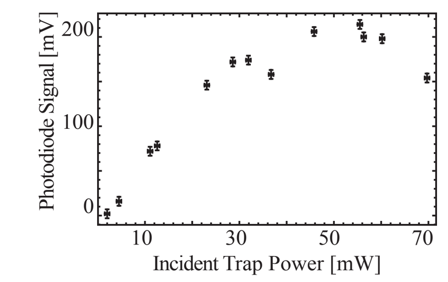


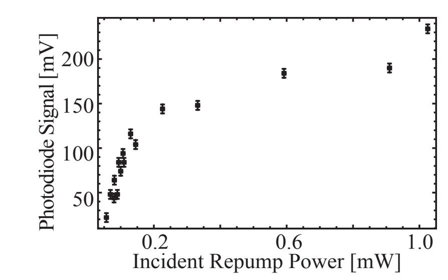
CW and pulsed Heterodyne detection are demonstrated using an AOM.

Mageto-Optical Trap Setup



Steady State Atom Number





Plots of the trapped atom number as a function of incident trapping and repump laser powers.

The trapped atom number is inferred from fluorescence.

200mV = 10^6 atoms

Impact

– Hands-on approach for teaching experimental physics.
– Students describe course as demanding, but rewarding.
– Highly popular because modern techniques and equipment used.
– Research environment flexibility and advanced data analysis skills are excellent preparation for graduate studies in AMO laboratories and industrial careers.

These courses are designed to be accessible for all undergraduate streams in physics and applied physics as well as incoming graduate students. PHYS 4061- Laser Spectroscopy has been expanded to two sections with a maximum of 20 students and is a mandatory course for all physics streams. PHYS 4062 - Atom Trapping can accomodate up to 10 students.

List of Experiments

PHYS 4061 - Laser Spectroscopy

– Absorption and Emission Spectroscopy
- EOM
– Zeeman Shift
– Lock-In
– Linewidth & Fabry Perot
– Optical Tweezers
– Gaussian Beams
– RF & Heterodyne
– Vacuum Systems
– Optical Detectors

PHYS 4062 - Atom Trapping

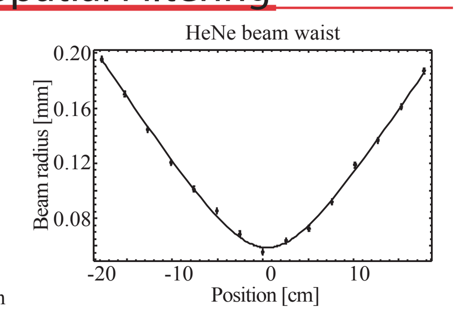
– Steady State Atom Number
– Trap Number Density
– Temperature
– Loading Rate
– Optical Pumping
– Magetic Gradients
– Beam Diameter

Gaussian Beams and Spatial Filtering

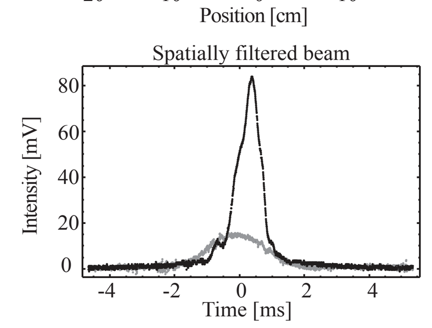
Properties of Gaussian beams such as divergence and Rayleigh range are measured with a scanning knife edge profiler.

$$w^2 = w_0^2\left(1 + \frac{z\lambda}{\pi n w_0^2}\right)$$

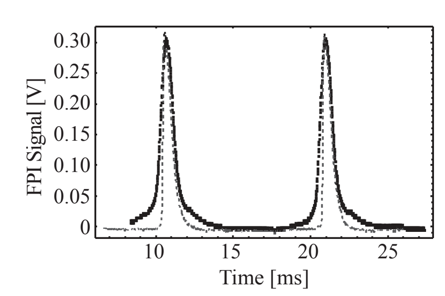
w = waist, w_0 = minimum waist
n = index of refraction, λ = laser wavelength



Spatial profile of a laser before (black) and after (grey) passing through an optical fiber.

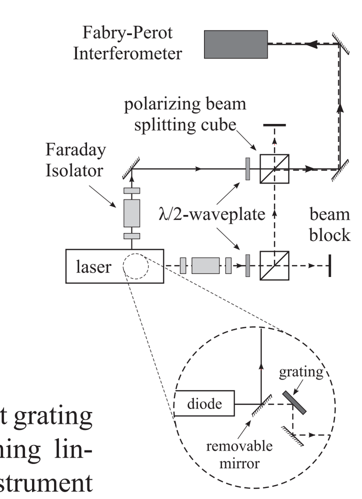


Fabry Perot Interferometry



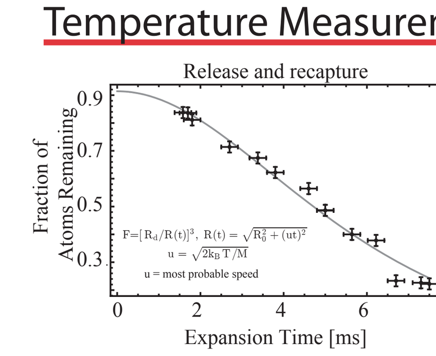
$$I(\delta) = \frac{I_0}{1 + F\sin^2(\delta/2)} \qquad F = \frac{4R}{(1-R)^2}$$

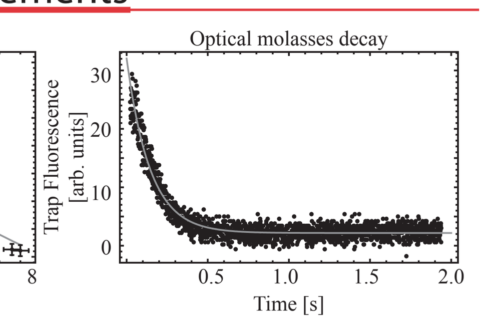
R = reflectance, F = Finesse, I = Intensity δ = phase



FPI peaks with (grey) and without grating feedback (black). The free running linewidth is 91(5) MHz. The instrument limited linewidth is 58(5) MHz.

Temperature Measurements



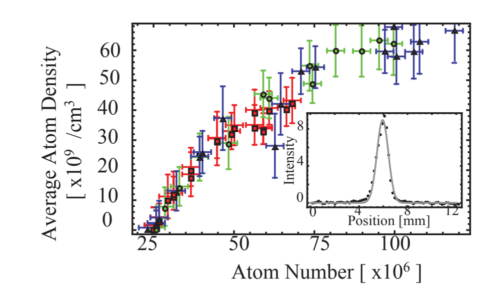


A measurement of the temperature of an atom trap using the release and re-capture method. The most probable speed from the fit gives a temperature of T = 420(20) µK.

A measurement of the optical molasses decay time. A fit to a decaying exponential gives a time constant of 0.165(2) s.

Atom Trap Density

Variation in average density as a function of atom number.
The atom number was varied by changing the trap laser power.



Repump laser powers
red squares: 0.60(6) mW
green circles: 1.0(1) mW
blue triangles: 50(5) mW

The cloud radius is determined from Gaussian fits along two dimensions that were summed in quadrature.

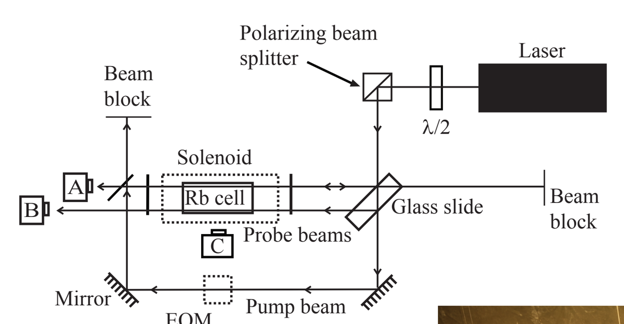
Inset: The integrated spatial profile of an atom cloud imaged by a CCD camera. A Gaussian fit gives a 1/e^2 cloud radius of 0.66(1) mm.

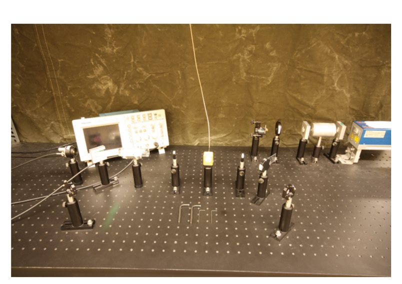
Budget

The cost of equipment based on commercially available components is \$150,000. This budget is dominated by the cost of four diode laser systems (total \$80,000). The laser budget can be substantially reduced to ~\$30k by using home-built external cavity diode lasers and master oscillator-power amplifier systems. Student training opportunities could include building Faraday isolators, lock-in circuits, and Rb reference cells. The laboratory manual containing a list of equipment relating to the individual experiments is available upon request.

The California Institute of Technology, University of Michigan and State University of New York: Stony Brook as well as several liberal arts colleges have developed courses in related areas. An alternative format to this work can involve a small subset of these experiments.

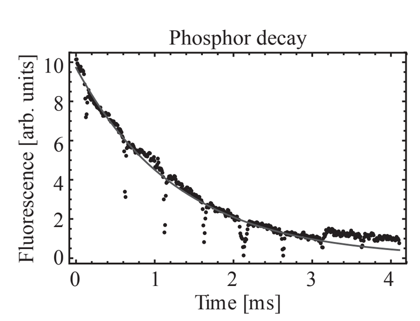
Spectroscopy Setup





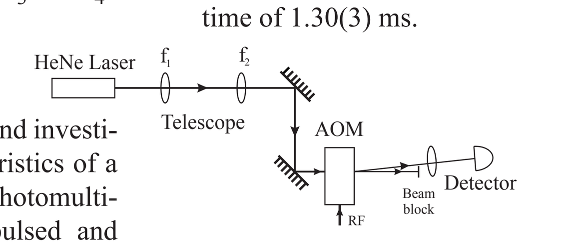
Saturated absorption setup used in three experiments: EOM, Zeeman Shift, and Lock-in Detection

Optical Detectors

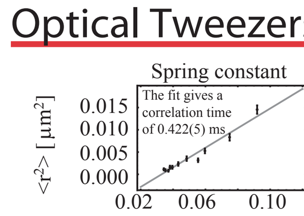


Phosphor fluorescence from an oscilloscope electron beam sweep is recorded by a triggered CCD camera. The dips correspond to grid lines on the oscilloscope screen. An exponential fit gives a 1/e decay time of 1.30(3) ms.

Students calibrate and investigate noise characteristics of a photodiode and a photomultiplier tube using pulsed and CW light.

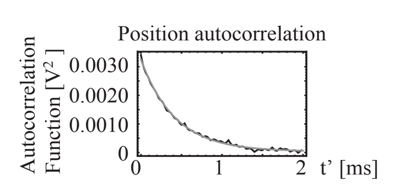


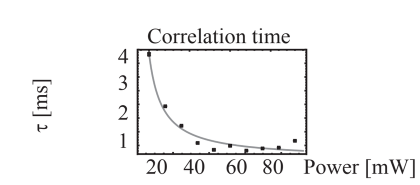
Optical Tweezers

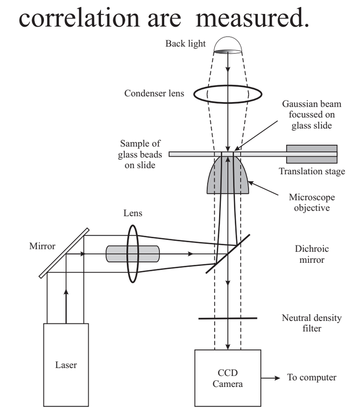


The optical dipole force is used to trap 3.14 µm polystyrene beads.

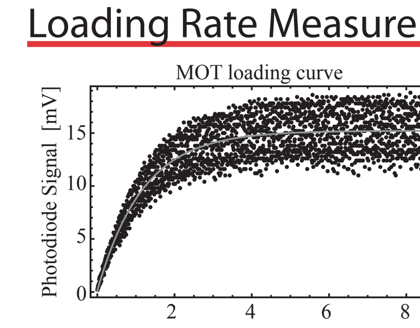
The spring constant and autocorrelation are measured.







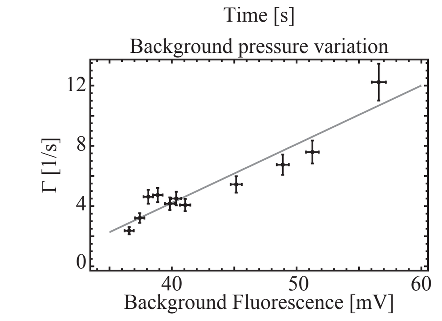
Loading Rate Measurements



A fit to the form (1-$e^{-\Gamma t}$) gives 1/Γ = 1.17(3) s.

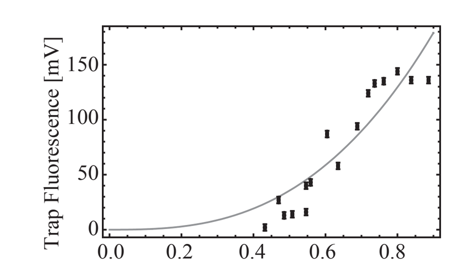
$$\frac{dN}{dt} = R - \Gamma N$$

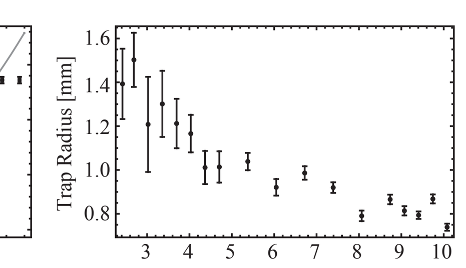
R = loading rate, Γ = collisional rate
N = atom number



Variation of the collisional rate with background density.

Effect of Beam Diameter and B Gradient





The atom number has a sensitive dependence on the trap beam size. A power law fit is shown by the solid line.

The atom 1/e cloud radius as a function of magnetic field gradient along the vertical axis of the MOT.

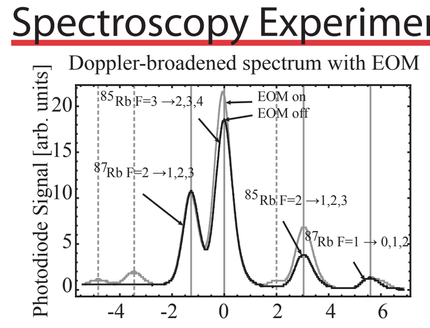
Maintenance

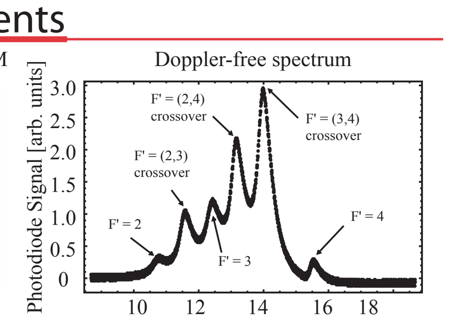
At York University, these courses have been in operation for more than five years.

The average operational maintenance budget is \$3,000/year. This is sufficient to cover minor equipment failure. Items that typically require replacement are laser diodes, (\$1,000 commercial) and control electronics. Ion pumps (\$1,000) may need to be replaced on a timescale of 10 years. The maintenance budget is comparable to the budget for other upper-year laboratory courses.

Ideally, the course can be maintained by two trained graduate teaching assistants with a research concentration in AMO physics and one technical staff member.

Spectroscopy Experiments





Doppler-broadened data is fit to a Gaussian curve obtaining typical FWHM of 750 MHz. This is compared with theory. The effect of EOM sidebands is studied.

$$I(v) = I_0 \exp\left[-\frac{M_{Rb}c^2}{2k_BT}\left(\frac{\Delta v}{v_0}\right)^2\right]$$

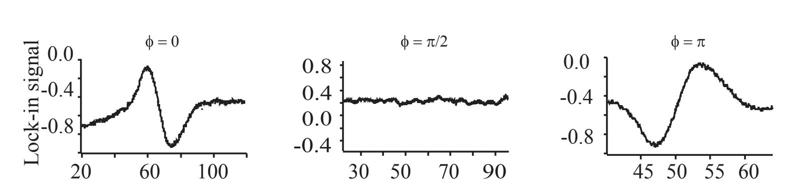
Doppler-free data is fit to a Lorentzian lineshape to obtain a typical FWHM of 15 MHz. This is compared to the natural linewidth.

$$\alpha(v) = \frac{\alpha_0 \Gamma_v}{(v - v_0)^2 + (\Gamma_v/2)^2}$$

Lock-In Amplifier

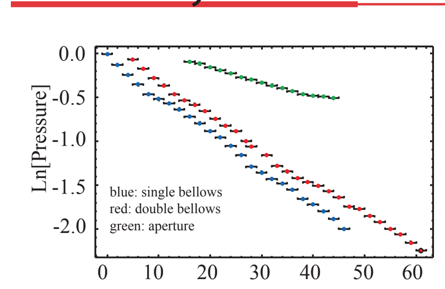
Performance of lock-in components: mixers, filters, and phase shifters are investigated.

Laser is locked using commercial lock-in module for durations of 10-15mins. The frequency stability is measured.



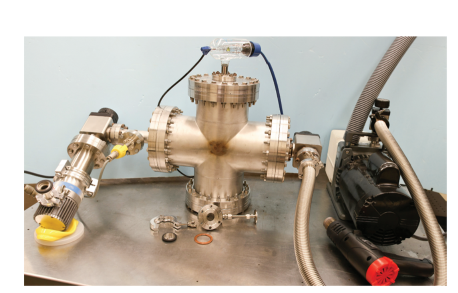
Lock-in error signals obtained by scanning a laser across an atomic resonance for different phase shifts ϕ.

Vacuum Systems



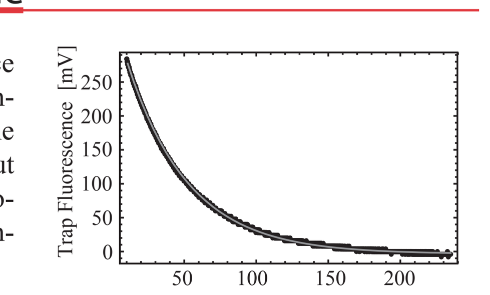
The pressure insdie a vacuum system as a function of time is measured during pump down. The pumping speed is varied by adding bellows lengths and apertures.

The conductances of the components are found from the slope. Leaks are demonstrated by loosening seals and outgassing is demonstrated by heating the chamber.



Optical Pumping Time

A plot of the fluorescence from the F' = 4 → F = 3 transition as a function of time after the repump laser is shut off using an AOM. An exponential fit gives a time constant of 42.42(5) µs.



Other possible experiments include:
– Absorption spectroscopy of cold atoms
– Transition probability measurements
– Trapping [85]Rb or [87]Rb

Laboratory Environment

– Data analysis skills are emphasized in Mathematica
– Mathematica tutorial during first two weeks of PHYS 4061
– Mandatory Laser Safety tutorial and training
– LabVIEW tutorial included

Students are exposed to an actual laboratory environment. They must calibrate equipment for absolute measurements.

Teamwork is necessary to optimize data taking and to prepare a long-form lab report.

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