Chapter 4

Non-destructive measurement of the temperature of the cold atoms in a MOT

4.1 Introduction

To measure the temperature of the laser cooled atoms in a Magneto Optical Trap (MOT) the most commonly used technique is Time-Of-Flight (TOF) [1, 2, 3, 4], which has been discussed in some detail in chapter I of this thesis. In TOF the magnetic field and the laser beams have to be switched off in a very short time so that the cold atoms fall under gravity. TOF is a destructive method, as the sample of cold atoms used to measure the temperature is completely lost. There are a few reports on alternative ways of finding the temperature of the laser cooled atoms in a MOT.

One interesting alternative method is that by Khons et al [5]. These authors performed an on-line measurement of sub-Doppler temperature for rubidium atoms using oscillations of the trapped cloud about the center of the trap. This measures the mechanical restoring force and the damping coefficient of the MOT. We have used this method to determine the temperature of the cold atoms in our MOT. By applying an external periodic force in the form of a weak a.c. magnetic field, the cloud of atoms was set into forced oscillations. The frequency response of the phase of this oscillation was determined from which the force constant and damping constant were obtained. Knowing the size of the cloud and the force constant one can use the equipartition theorem to get the temperature of the cloud.

4.2 The technique

In a MOT, the atoms have low velocities. Near the trap centre the magnetic field with the light beams provides a harmonic potential in which the atoms move. The Doppler shift of the resonance frequency of the atoms coupled with the scattering force of the light beams provides a damping force as discussed in chapter I. The atoms execute a damped harmonic motion in the trap.

Consider the cloud centre as the origin. An atom displaced by y moving with a velocity v will experience a force $F(v, y) = - \alpha v - \kappa y$ (neglecting stochastic heating) where α is the damping coefficient and κ is the spring constant. The equation of motion of the atom in a MOT is

$$\ddot{y} + (\frac{\alpha}{m})\dot{y} + \omega_{trap}^2 y = 0, \tag{4.1}$$

where m is the mass of the atom in the MOT and $\omega_{trap} = \sqrt{\frac{\kappa}{m}}$ is the natural frequency of the atom in the MOT. In thermal equilibrium

$$k_B T = \kappa < y^2 >= m < v^2 > . \tag{4.2}$$

Therefore, the temperature of the cold atoms in a MOT can be obtained by measuring the spring constant κ and trap extension -i.e. the FWHM of the Gaussian distribution of atoms in the cloud. The damped oscillation of the atoms was first demonstrated by Steane and Foot [2]. They used the radiation force of an auxiliary laser beam to push the trapped cold atoms out of the trap centre. However, the calculation of the pushing force is somewhat complicated and use of the additional laser beam may produce other disturbing effects.

The cloud may also be set into a forced periodic motion with the help of an external periodic force and the spring constant measured. This was the technique adopted by Kohns et al [5]. We have followed this technique.

A pair of Helmhotz coils is introduced near the UHV chamber along the y axis of the MOT. A small a.c. current sent into the coils produces a spatially uniform but temporally sinusoidal bias field at the position of the cloud. This superimposes in the y direction onto the temporally constant spherical quadrupole (trapping) field. The oscillating magnetic field causes the minimum of the potential in the trap to oscillate about the center of the trap $y = 0$ as

$$y(t) = \xi_0 * \cos(\omega t) \tag{4.3}$$

where ξ_0 is the amplitude of the oscillation of the potential minimum. ξ_0 is made small so that the restoring force is linear. This maintains the shape and size of the cloud.

The displacement of the trap center gives rise to a periodic restoring force

$$f(t) = \kappa y(t) = m\omega_{trap}^2 y(t) \tag{4.4}$$

where ω_{trap} is the natural frequency of oscillation of the atom in the trap. The random motion of the atom is superimposed on the forced harmonic oscillation. The equation of motion for the forced oscillation of the atom in the MOT is

$$\ddot{y} + (\frac{\alpha}{m})\dot{y} + \omega_{trap}^2 y = \frac{f(t)}{m} + \frac{f_{random}}{m}. \tag{4.5}$$

Here α is the damping constant and f_{random} is the stochastic force arising from absorption-emission, collision etc. By summing the above equation for all atoms we get the equation of motion of cloud as

$$\ddot{Y} + (\frac{\alpha}{m})\dot{Y} + \omega_{trap}^2 Y = \frac{f(t)}{m} \tag{4.6}$$

where Y is the displacement of the center of mass of the cloud and the random force drops out of the equation. The solution to this equation can be written as

$$Y(t) = A(\omega) * cos(\omega t - \varphi(\omega)). \tag{4.7}$$

where

$$A(\omega) = \frac{\kappa.\xi_0}{\sqrt{(\kappa - m\omega^2)^2 + \alpha^2\omega^2}} \tag{4.8}$$

$$\begin{aligned} \varphi(\omega) &= tan^{-1}(\frac{\alpha.\omega}{\kappa - m\omega^2}) \\ &= tan^{-1}(\frac{\alpha_0.\omega}{\omega_{trap}^2 - \omega^2}) \end{aligned} \tag{4.9}$$

where $\alpha_0 = \alpha/m$. Measuring the phase φ and/or the amplitude A as a function of ω the value of the constants α and κ can be obtained.

4.3 Experiment

A pair of anti-Helmholtz coils (MOT coils) (9 cm diameter, 140 turns each) are placed outside the chamber along the Z- axis. This produces a spherical quadrupolar magnetic field, which superimposes on the intersection region of the beams where the field is zero and the cloud is formed. The field gradient at the center can be varied from 5 to 15 G/cm by varying the current through the coils in the range of 5 to 15 A. To avoid heating and burning the coils are contained in a water jacket.

The a.c coils (9 cm diameter, 200 turns) are placed outside the UHV chamber along the y axis of the MOT. The coil is driven by a LM1875 chip which, is an audio amplifier, can give a maximum power output of 20 W in a matched load. The audio amplifier in turn is driven by a signal generator.

The fluorescence from the trapped cloud of atoms is imaged on to both a charge -couple device(CCD) camera for viewing, and a photodiode(PD) for quantitative measurements. If one wishes to measure the amplitude a video recorder can be used to film the motion of the cloud. However we preferred to measure the phase of the oscillation of the cloud as a function of the frequency. A schematic of the experimental set-up is shown in figure 4.1. Photograph of the actual set-up is shown in figure 4.2. The fluorescent light from the cloud is collected by a lens and focused onto a photo detector. In order to see a modulation of the photo current propotional to the motion of the cloud, a razor blade was positioned in front of the photo detector covering half the cloud when the a.c field is switched off. As the cloud oscillates more light or less light falls on the photo detector depending on whether the cloud is displaced away from the edge of the blade or towards the edge of the blade. This produces an oscillating output from the photo detector which will be out of phase with the driving current through the coils. The phase shift is detected using SR850 DSP lock-in amplifier made by Stanford Research Systems. A voltage derived from the coil current is used as the reference signal input to the lock-in-amplifier. The lock-in amplifier measures directly the amplitude and phase of the signal from the photo detector.

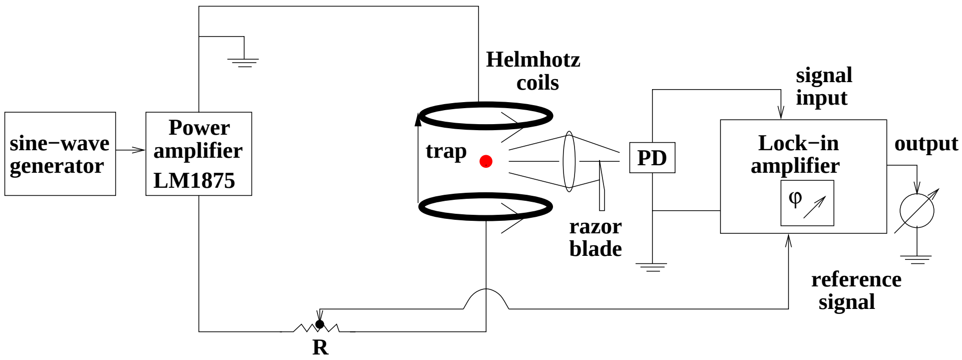

Figure 4.1: Schematic experimental set-up for measuring the frequency response (laser beams and quadrupole coils not shown). PD is the photo detector.

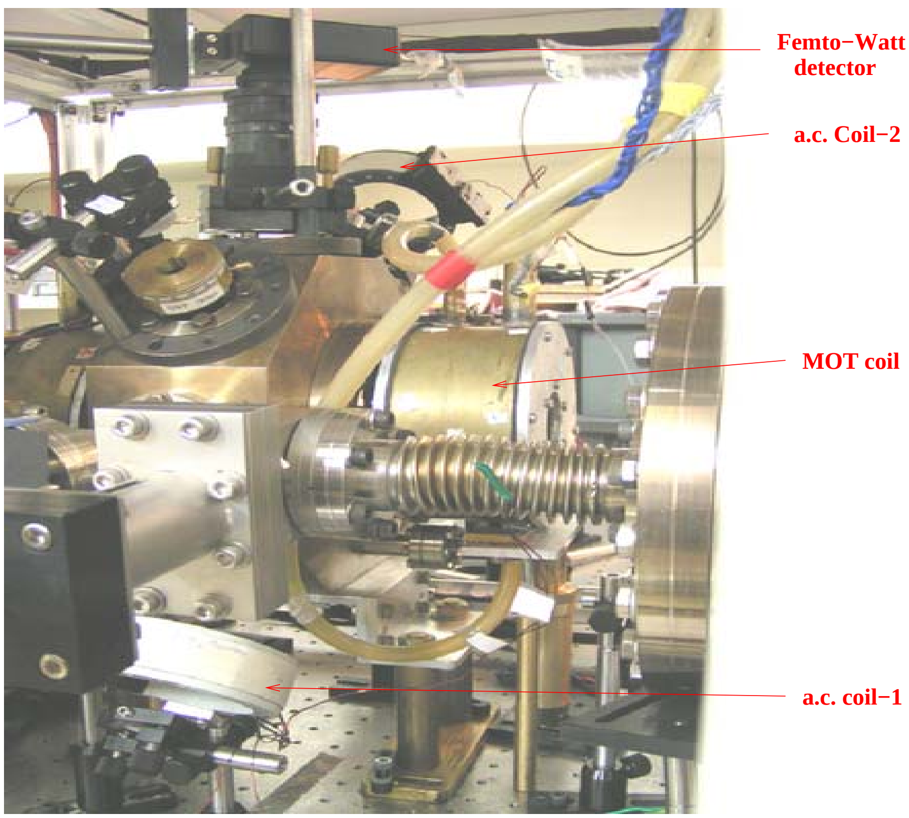

Figure 4.2: Experimental set-up used in the lab

Measurements were made of the phase of the signal in the range of the driving frequencies from 6 Hz to 60 Hz for four different quadrupolar field gradients. Resonance was observed around 30 Hz. This is signalled by the phase reaching a value 90^o and the amplitude reaching a maximum. We measured only the phase and not the amplitude of the cloud for the following reason. The FPG (frame grabber) card in our laboratory has a frame grab rate of 30 frames/sec. Therefore it does not allow us to apply a frequency greater than 15 Hz for a.c. field (according to the Nyquist theorem). But with the photo detector the phase could be determined continuously to higher frequencies using the lock-in amplifier.

The value of the phase as a function of the driving frequency was fitted to the equation 4.9. The fits are shown in figure 4.3.

Least square fitting to the data (see figure 4.3) gives us four sets of α_0 and ω_{trap} values(see table 4.1).

Trapping field current (A)	ω_{trap} in Hz	α_0 (10^{-23}) kg s
8.2	191	4.7
9.1	216	5.0
9.95	224	5.3
10.8	237	5.4

Table 4.1: Parameters of the fit to the curves in figure 4.3.

ω_{trap} is proportional to the square root of the spring constant κ, and therefore, to the square root of the trapping field current. Figure 4.4 is the plot to verify the same.

To get the temperature of the cloud we need the Gaussian full width at half maximum (FWHM) of the profile of the cloud. A CCD image of the cloud at zero bias field for each quadrupolar field current is taken to measure the actual size of the cloud for each set of data. We take a line profile of the cloud and fit a Gaussian (see figure 4.5). FWHM is taken as indicative of the size of the cloud. This is the size of the image recorded by the CCD camera, this has to be divided by the magnification of the camera (≈ 5.6) to get the FWHM of the cloud. This gives the diameter of the cloud. Half of this value will give the radius of the cloud. The radius of the cloud is estimated to be about 0.6 mm. This estimate will have a considerable error. But it can be still used to get the approximate value of the temperature.

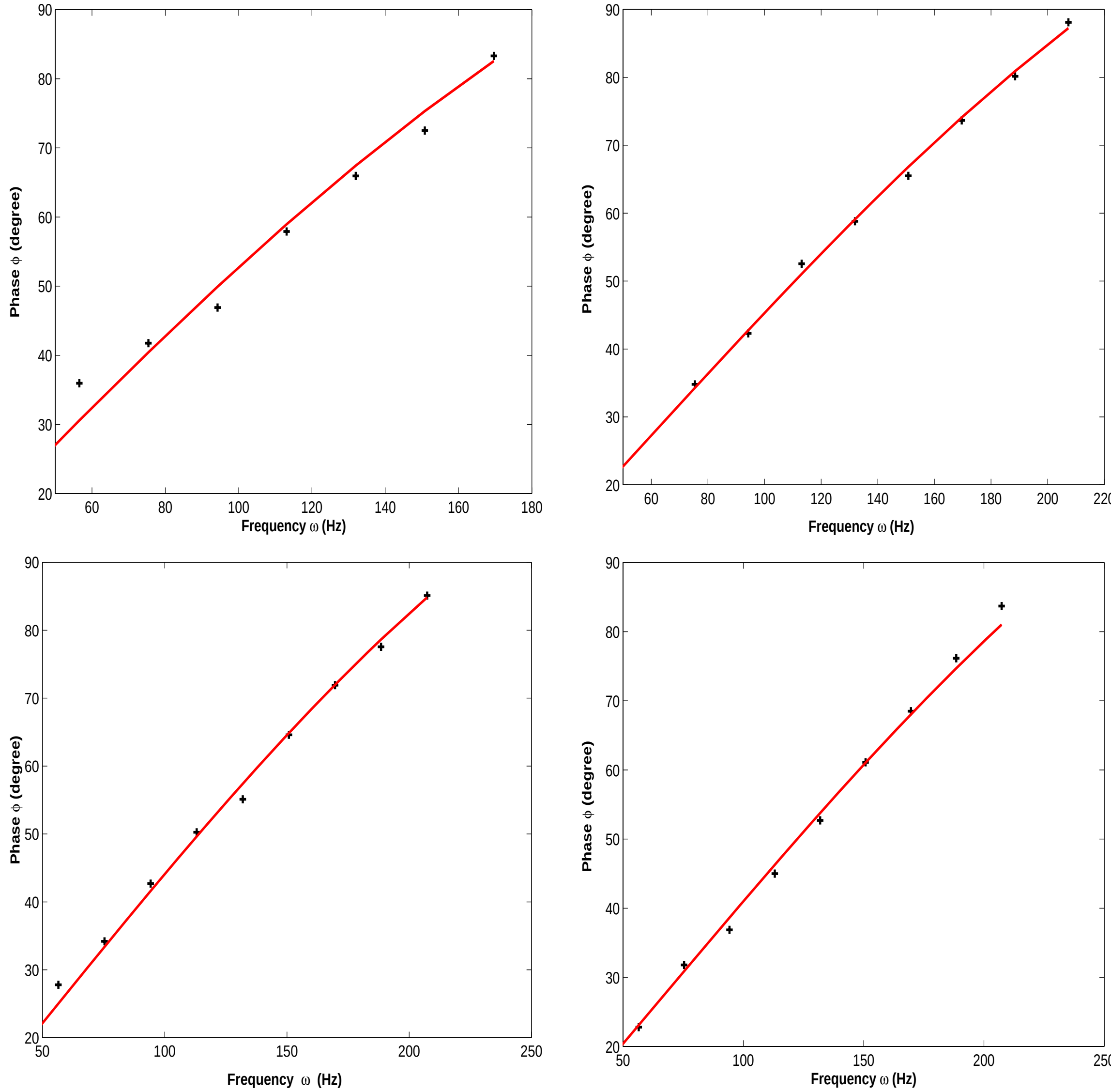

Figure 4.3: Frequency response of $\varphi(\omega)$. The MOT parameters, namely trap coil current, detuning of cooling laser, intensity of cooling beam were- top left: 8.2 A, $\delta = -1.63\Gamma$, I= $0.5I_s$ ($I_s = 1.67\ mW/cm^2$); top right: 9.1 A, $\delta = -1.63\Gamma$, I= $0.5I_s$; bottom left: 9.95 A, $\delta = -1.63\Gamma$, I= $0.5I_s$; bottom right: 10.8 A, $\delta = -1.63\Gamma$, I= $0.5I_s$, in each case the solid line is a fit to the data.

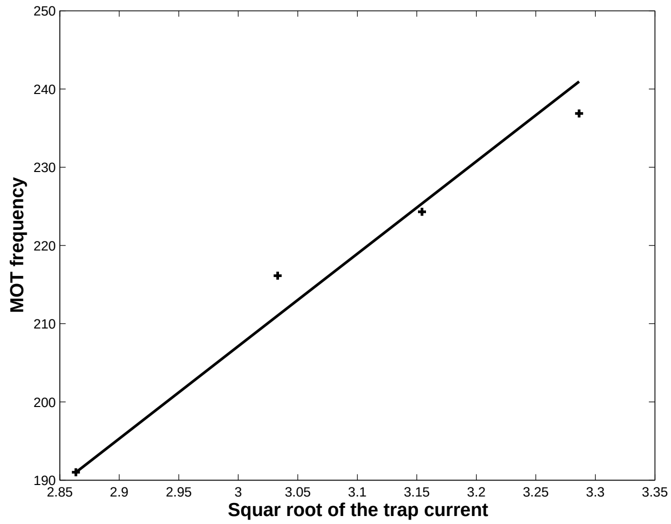

Figure 4.4: Variation of MOT frequency ω_{trap} with the trapping field current. Solid line is a fit to the data.

The estimated temperature using the force constant values taken from the Table 4.1 varies from 180 μK to 220 μK. So the average temperature of the cloud is 200 ± 20 μK.

This temperature value indicates that we are in the Doppler cooling regime. In this regime the damping constant can be calculated from

$$\alpha = 16(\hbar k^2)(-\delta/\Gamma)\frac{I/I_s}{[1+2(I/I_s)+4(\delta/\Gamma)^2]^2}. \tag{4.10}$$

The intensity of our beams is 800 $\mu W/cm^2$ and $\Gamma = 2\pi \times 6$ MHz. I_s is 1.67 mW/cm^2. The detuning δ is -1.63 Γ. Using these values α comes out to be 5.3×10^{-22} Kg s. The value of α should be independent of the magnetic field gradient. Our experimental data in Table 4.1 shows an average value of α of 5.1×10^{-23} Kg s with a 10% variation. We see the measured value is one order of magnitude smaller than the theoretically expected value. One possible explanation is the following. The retro-reflected beams along X, Y and Z have a smaller intensity than the forward beams since we do not use anti-reflection coated optics. This will give an unbalanced force on the atom and push it away from the center. We did observe that the cloud is pushed to one edge of the overlapping beams. At such a point the intensity of

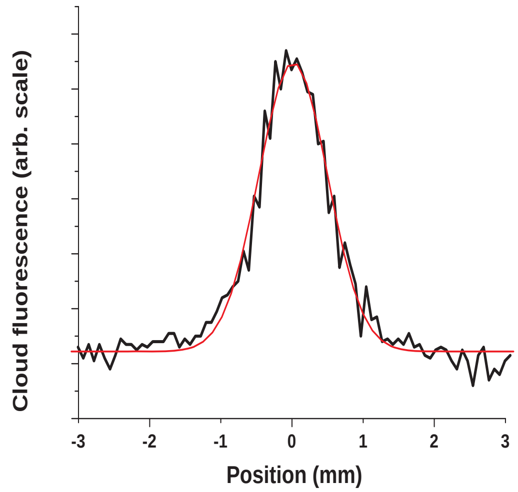

Figure 4.5: Line profile of the cloud (black line) and a gaussian fit to the profile (red line), to mesure the radius of the cloud.

the beam will be low resulting in a lower value of α. However this will have no effect on the temperature. So the temperature mesured from the resonant frequency will be valid.

4.4 Summary

We have measured the temperature of the cold cloud in our MOT by measuring the mechanical properties -i.e., spring constant of the MOT and damping coefficient. We have bounced the cloud using an a.c. magnetic field, a technique first used by Kohns et al. The phase of the oscillation of the cloud is measured as a function of the driving frequency and the results are fitted to a damped harmonic oscillator model. We get a good fit for the data. The resonance frequency is found to be proportional to the square root of the current as expected. From the measured FWHM of the density profile of the cloud we estimate a temperature of about 200 μK for the cloud.

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