Cold atoms at the University of KwaZulu-Natal

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Abstract. The focus of this paper is based on the current experimental setup of a magneto-optical trap by the Quantum Research Group at University of KwaZulu-Natal (UKZN). In particular, presented are the details of the ultra-high vacuum system, optical system, and magnetic field generation that are implemented in the cold atom experiment. In addition to this, a fluorescence imaging system is described which can be used to determine the characteristics of the atom cloud.

1. Introduction

The concept of laser cooling was introduced in 1975 [1] and has since become an important part of experimental physics. These principles were utilised by Chu *et al*. in 1985 with the first creation of optical molasses, where atoms were cooled to a temperature of 240 μK using the radiation pressure of counter-propagating laser beams [2]. In the same year Migdall *et at*. expanded upon this idea even further where the laser-cooled atoms were trapped using a spherical quadrupole magnetic field at a temperature of 17 mK [3]. In 1987 Raab *et al* combined these two techniques of laser cooling and magnetic trapping to create a magneto-optical trap (MOT) [4]. This technique implied laser cooling to provide a velocity dependent force on the atoms reducing its temperature. The addition of the magnetic field, in combination with the circular polarisation of the beams, created a position dependent force allowing the cold atoms to be trapped in space.

The MOT has now become a standard tool by which to create a sample of cold atoms. Since its initial creation, cold atoms in a MOT have found applications in high precision metrology [5], atomic and molecular physics [6, 7], atom optics [8] as well as many other fields of research. The advancement of the cold atom and related fields has also lead to the creation of the first Bose-Einstein condensate (BEC) [9]. This has facilitated researchers to study the quantum mechanical nature of atoms on a macroscopic scale. It is the aim of the Quantum Research Group to develop Africa's first BEC experiment. However, the first step in achieving such a feat is to create a large number of laser-cooled atoms from which the BEC can be formed. Presented in this paper is the experimental setup that is currently implemented at UKZN for the creation of this cold atom reservoir. At a later stage techniques such as the compressed MOT and magnetic trapping will be implemented to increase the density of the atom cloud whereas techniques such as molasses and RF evaporative cooling will be implemented to reduce its temperature.

2. Experimental Setup

Cold atom physics is a multidisciplinary topic and therefore involves a wide range of experimental equipment; ultra-high vacuum (UHV) technology, laser frequency stabilisation, imaging systems, magnetic field coils, computer control system as well as the associated state-of-the-art electronics. Presented in this section will be the experimental setup currently at UKZN for the development of a cold atom experiment.

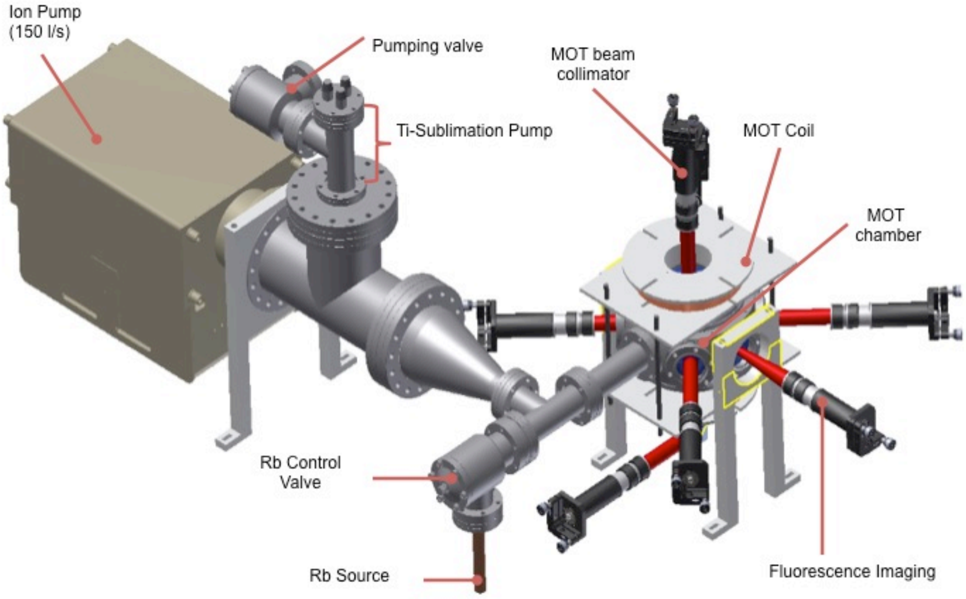

Figure 1: Illustration of the complete MOT system including the vacuum, magnetic coils and beam alignment systems.

2.1. Vacuum System

Although it is possible to achieve cold atoms in a MOT with a pressure of 10^{-6} mbar, the performance of the experiment in terms of steady state number of atoms, lifetime, and density, is dramatically limited by the atomic collision rate with the thermal background vapour. It is thus desirable to achieve an UHV system with a base pressure of $\sim 10^{-9}$ mbar which allows the isolation of the atom cloud from the surrounding environment. The current vacuum system at UKZN is illustrated in Figure 1, along with other experimental components, and is based upon the industrial standard ConFlat (C.F.) flange technology for ultrahigh vacuum. The MOT chamber is a stainless steel octagonal chamber with seven 2.75" C.F. viewports around the octagonal surfaces and two 6" C.F. viewports on the top and bottom faces for optical access of laser beams.

In order to create the required vacuum pressure, a turbo-molecular pump (TMP), which is backed up by a scroll pump (Agilent Technologies, TPS Compact), is attached to the pumping valve. The scroll pump is initially used alone to decrease the pressure to approximately 2×10^{-2} mbar. The TMP is then initiated and a pressure of $\sim 1 \times 10^{-7}$ mbar is achieved within a few hours. This is the limit of the TMP and therefore to decrease the pressure even further a bakeout procedure is used. This is where the entire vacuum system is slowly heated to ~300 ºC causing the internal contaminants to evaporate and be removed via the TMP. This temperature is maintained for approximately two days after which time the temperature is decreased slowly. At approximately 120 °C the pumping port is closed and both the TMP and the scroll pumps are switched off. The ion pump is switched on and thus the entire vacuum system is being pumped solely by the ion pump. Using this technique a base pressure of 2×10^{-9} mbar has been achieved.

The Rb dispenser comes in the form of a vacuum-sealed capsule which contains 1 mg of rubidium. The capsule is housed in a copper tube which is squeezed once the UHV environment is created thus breaking the capsule and exposing the rubidium to the vacuum environment. Due to the UHV, the rubidium metal constantly evaporates and thus the Rb vapour pressure can be controlled by varying the position of the control valve. The titanium sublimation pump is used after some period of time to decrease the base pressure if it has increased due to continuous diffusion of rubidium into the system.

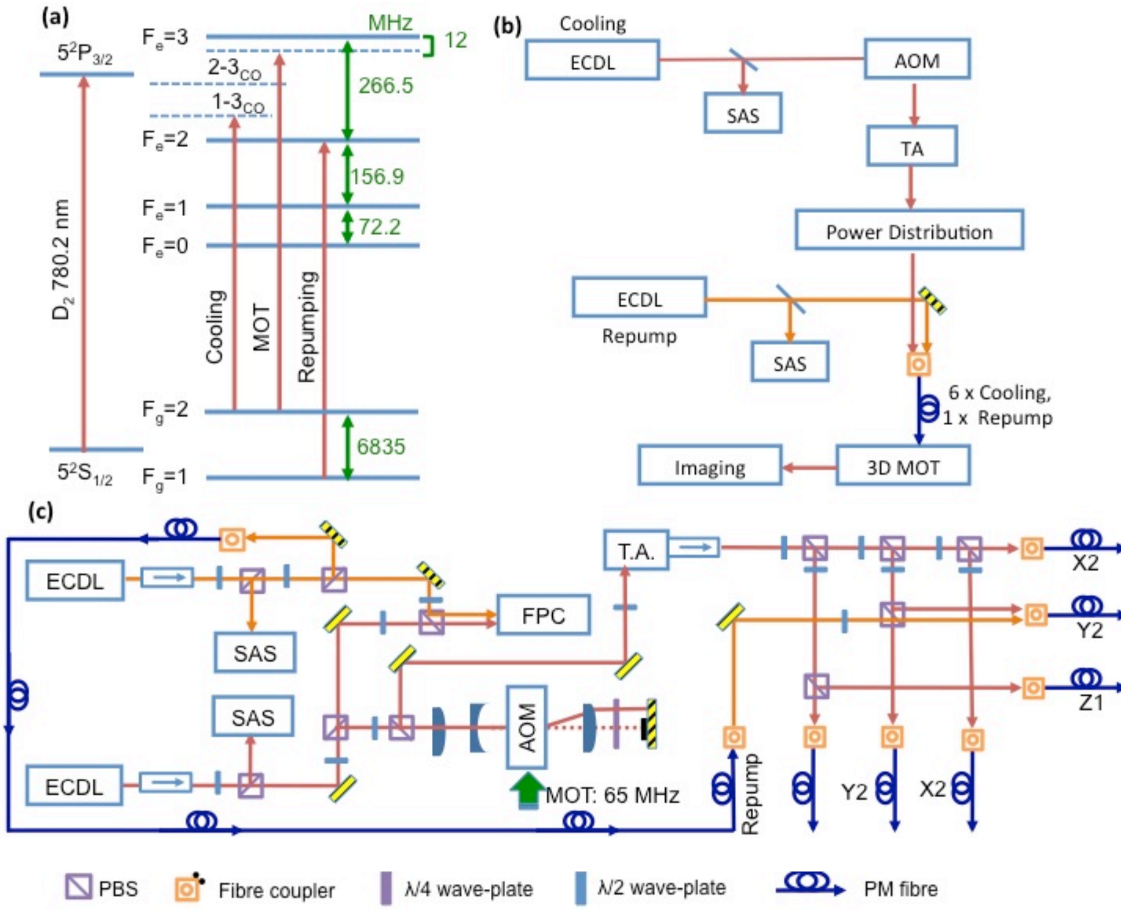

Figure 2: (a) The hyperfine structure of ^{87}Rb with all the necessary optical transitions used for the MOT and corresponding frequencies shown. (b) A block diagram showing an overview of the laser system layout. (c) Full schematic of laser system.

2.2. Laser System

Figure 2(a) shows the hyperfine structure of the $5^2S_{1/2} \rightarrow 5^2P_{3/2}$ ^{87}Rb transition as well as the required laser frequencies necessary to create a MOT. The closed $F_g = 2 \rightarrow F_e = 3$ transition is used as the cooling cycle. However, due to inaccuracies in the degree of circular polarisation in the cooling beam, a small percentage of atoms can decay down to $F_g = 1$ ground state. Once the atoms are in this atomic state, they are out of resonance with the cooling cycle and thus will no longer be cooled. To prevent this from occurring a second repumping laser is used to excite the atom to the $F_e = 2$ state from where it can decay to the $F_g = 2$ state and rejoin the cooling cycle. Therefore two separate extended cavity diode lasers (ECDL) are used to generate these frequencies (MOGLabs, ECD001). The ECDL configuration provides an output with a reduced linewidth and improved control of the laser at the expense of a slightly reduced output power. A schematic overview of the laser system can be seen in

Figure 2(b) and a more detailed version is illustrated in Figure 2(c). A small portion of the cooling laser output power (1 mW) is sent to a Doppler-free saturated absorption spectroscopy (SAS) setup [10] where it is locked to the $F_g = 2 \rightarrow F_e = (1\text{-}3)$ crossover transition. The majority of the laser power is passed through an acousto-optical modulator (AOM) (InterAction Corp, ATM Series) in a double pass configuration [11] shifting the frequency by a total of 120 MHz. The resultant laser frequency (labelled "MOT" in Figure 2(a)) is thus 12 MHz red-detuned from the cooling transition which compensates for the Doppler shift experienced in the atoms frame of reference. Approximately 15 mW of this laser beam is then injected into a tapered amplifier (TA) (Sacher Lasertechnik) creating an output power of up to 2 W. This power is split into the six cooling beams using a series of half wave-plates and polarisation beam splitters (PBS) as can be seen in Figure 2(c). These are coupled to polarisation maintaining (PM) optical fibres (Thorlabs, P3-780PM-FC-5) and sent directly to the vacuum chamber. By adjusting the half wave-plates the powers coupled to each fibre can be varied. The repumping frequency is provided by a separate ECDL laser locked directly to the $F_g = 1 \rightarrow F_e = 2$ repumping transition using a Doppler-free SAS setup. The repumping power is also coupled to one of the MOT fibres and thus coproprogates with this beam. A small portion of both the cooling and repumping beams are sent to a Fabry-Perot cavity (FPC) for analysis of their relative frequencies and laser locking status.

2.3 Magnetic Field Generation

The MOT operates with a spherical quadrupole magnetic field created by a pair of coils in anti-Helmholtz configuration where the current through the individual coils flow in opposite directions as shown in Figure 3(a). The magnetic field, B, along the axial direction can be determined using the Biot-Savart law:

$$B = \frac{\mu_0 N I a}{2}\left(\frac{1}{\left[1+(r_{coil}-x)\right]^{3/2}} - \frac{1}{\left[1+(r_{coil}+x)\right]^{3/2}}\right) \quad (1)$$

where r_{coil} is half the separation of the coils, a is the average radius of the coils, N is the number of loops per coil, I is the current passed through the coils and x represents the distance from the field point to the geometrical centre of the coils. The coils have a diameter of 125 mm, 700 loops of enameled wire of 1 mm diameter and are separated by a distance of 137 mm from centre-to-centre. Figure 3(b) shows the calculated magnetic field along the axial direction for each individual coil (green and blue) as well as the resultant magnetic field created by the coil pair (red) for an applied current of 1A. This creates an axial gradient of 10.7 (Gauss/cm)/A and a gradient of half this value along both of the radial axes. Figure 3(c) shows the contour plot of the spherical quadrupole field at the centre of the coils. The elongation of the contour plot along in the y-axis is due to the fact that its magnitude of the magnetic field gradient is half of that in the x-axis.

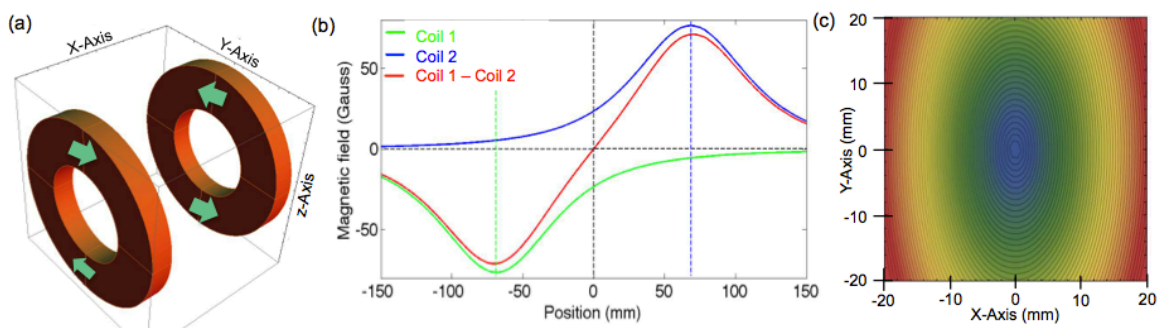

Figure 3: (a) MOT coils in anti-Helmholtz configuration. (b) Magnetic field generated by the MOT coils for a current of 1 A (c) contour plot of the spherical quadrupole field created by the MOT coils.

2.4 The Magneto-Optical Trap

The laser light is transported from the laser setup to the vacuum chamber via PM fibre as explained in Section 2.3. On exiting the fibre the beam freely expands and is subsequently collimated to a diameter of ~25 mm as is illustrated in figure 4. The circular polarisation is set with the aid of a quarter wave-plate. Three of the expanded beams are aligned mutually orthogonal to each other through the viewports of the MOT chamber. The three remaining laser beams are aligned to counter-propagate against these beams with orthogonal circular polarisations. Each beam is operated with a central intensity of approximately 3 mW/cm^2. The magnetic coils are place on the top and bottom view ports with the geometrical centre of the coils overlapping with the beam intersection. During normal operation of the MOT, the coils will generate an axial gradient of between 10 – 15 Gauss/cm.

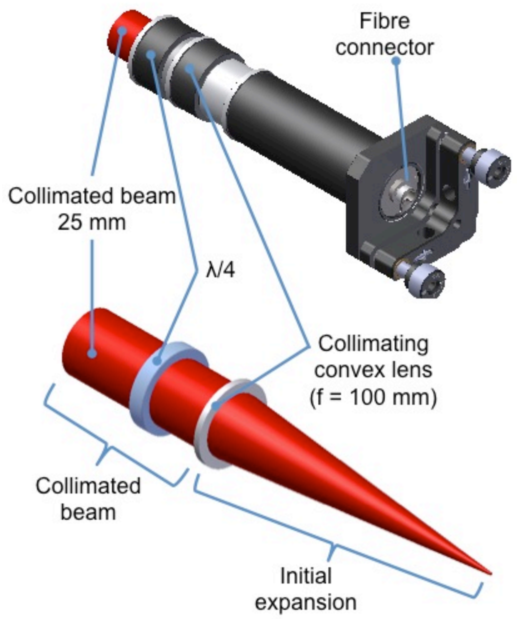

Figure 4: Expansion of the MOT beams

3. Fluorescence Imaging

In order to determine the parameters and characteristic of the cold atom cloud a fluorescence imaging system will be implemented. This is where the spontaneous emission from atoms within the MOT is focused onto the detection device. This is illustrated in Figure 5 where the fluorescence from laser cooled atoms is captured by a collimating lens and subsequently focused on to the detection device which will either be a CCD camera or a photodiode (PD). When the fluorescence is captured and focused onto a PD, the intensity of fluorescence is being directly measured. This is directly proportional to the number of trapped atoms and thus the real-time number of atoms in the MOT can be determined. This number of atoms, N, can be determined by:

$$N = \frac{4\pi P}{\Omega_{\text{Im}} R_{sc}} \tag{2}$$

where P is the power falling onto the PD and Rsc is the scattering rate which depends on experimental parameters such as laser power and detuning of the cooling laser beams. The solid angle $\Omega_{\text{Im}} = \pi D_{lens}^2 / 4d_{\text{Im}}^2$ is the angle subtended by the collimating lens of the imaging system where d_{Im} is the distance between the MOT and the first lens and D_{lens} is the diameter of the first lens. This detection device also allows the detection of dynamic properties such as the loading time as well as lifetime. By measuring such characteristics, the MOT experimental parameter such as magnetic field gradient, laser power and detuning can be adjusted to optimise the performance of the atom cloud.

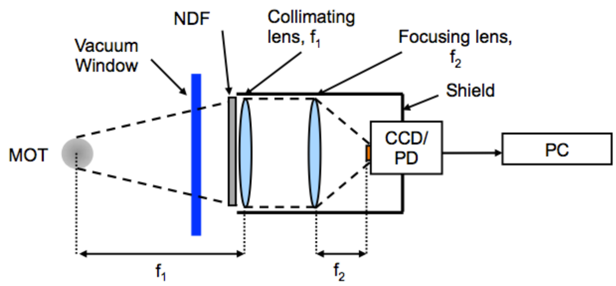

Figure 5: Fluorescence imaging apparatus used for the analysis of cold atom in a MOT.

When the cold atom fluorescence is focussed onto a CCD camera an image of the atom cloud can be taken. Through the analysis of this image a 2-D density profile can be determined. By applying Gaussian fits to the intensity profile of the image, the size and shape of the cloud is acquired.

4. Conclusion and Outlook

Presented here is the design and implementation of the cold atom setup in UKZN. The experiment is broken up into three different sections; the vacuum chamber, laser system and magnetic field generation. The details of each section are described as well as how they are combined to create a cold atom experiment.

The overall goal of the experiment is to create Africa’s first Bose-Einstein condensation experiment. The cold atom experiment described here is a first step in creating this ultra-cold quantum gas. This will allow researcher to study the quantum mechanical nature of atoms and develop quantum technologies for future quantum information science.

5. Acknowledgements

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6. References

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