A novel 2-D$^+$ magneto-optical trap configuration for cold atoms

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Abstract. Presented in this paper is a proposed novel coil configuration for a 2-D$^+$ magneto-optical trap. The design is based on the cancellation of magnetic fields along a common radial axis of two pairs of coils positioned orthogonal to eachother in order to create a zero magnetic field along this axis while maintaining a sharp linear gradient along the other axes. This novel design is more compact than standard methods and achieves the same magnetic field properties with less electrical power consumption.

1. Introduction

The field of cold and ultra-cold quantum gases has lead to many significant breakthroughs in numerous fields of physics such as quantum optics, solid-state physics, precision measurement and metrology [1]. In order to create a Bose-Einstein Condensate (BEC) it is crucial to do so within an ultra-high vacuum environment to reduce the background collisions and thus extend the lifetime of the condensate. It is therefore common to create a double chamber system whereby atoms are first pre-cooled in a chamber with a high atomic background density and subsequently transferred into a separate chamber where there are no background atoms, and thus there is less loss of atoms due to thermal collisions. In this second chamber the atoms are again trapped and further cooled to form the Bose-Einstein condensate.

Many techniques have been experimentally implemented to transfer pre-cooled atoms between the chambers. Techniques such as Zeeman-slowers were initially implemented with great success. In this regime a thermal atom beam emerges from an ‘oven’ and is decelerated by a counter-propagating laser beam, while the changing Doppler shift, due to the reduced speed of the atoms, is compensated by an inhomogeneous magnetic field along the deceleration path [2]. More recently, techniques such as a low velocity intense source (LVIS), which rely on the optical cooling, have been used. In this method, a 3-D magneto-optical trap (MOT) is created with a small hole drilled on one of the retro-reflecting mirrors in order to produce a flux of low velocity atom beam [3]. Other techniques rely more on the magnetic transfer of atoms, which involves creating a 3-D MOT in the high-pressure chamber and magnetically guiding it into the low vacuum chamber. This can be performed by using moving coils [4], a series of fixed coils [5] or a magnetic wave-guide [6].

Today, the 2-D$^+$ MOT is the most popular technique to pre-cool and transfer atoms. It is compact, robust, relatively easy to setup and results in an intense flux of atoms entering the BEC chamber. In this paper we present a novel coil configuration for the 2-D$^+$ MOT which provides the same magnetic field as standard configurations but does so with less electrical power consumption. The novel coil configuration also leads to an overall more compact system and thus there are less stringent demands on the design of the vacuum system. This setup is an adaption of a previous MOT experiment which has been built in UKZN [7]. At this point it should be noted that this is a proposed setup and that it is not yet a reality. Also presented this paper is a brief overview of the entire experiment.

2. Experimental Setup

Bose-Einstein Condensation physics is one of the most multidisciplinary topics in physics. These experiments require ultra-high vacuum (UHV) technology, laser frequency stabilisation, high quantum efficiency imaging systems, high power magnetic coils, a sophisticated timing system as well as the associated state-of-the-art electronics. Given that the main focus of the paper is the 2-D$^+$ MOT, only the vacuum system, the laser system and the 2-D$^+$ itself will be presented.

2.1. Vacuum System

The final stage in creating a BEC is evaporative cooling which relies on elastic collisions between trapped atoms for re-thermalisation. Given that the process of magnetic trapping and evaporative cooling can take over 40 seconds, these procedures must be performed in very low vacuum environment to prevent large atom losses due to background collisions. On the other hand, to create a MOT with a large number of atoms, which is one of the first steps in creating a BEC, a relatively high background pressure of rubidium atoms is required. It is for this reason that our vacuum system is partitioned into two different chambers, which are separated by a differential pumping hole (DPH). The high-pressure side is referred to as the 2-D MOT section and is shown on the left-hand side of figure 1 whereas the low-pressure side is referred to as the BEC section and shown on the right-hand side of figure 1. The DPH that separates these two sections has a diameter of 2 mm and a length of 26 mm. This is large enough to allow the atom beam from the 2-D$^+$ MOT to pass through unobstructed with minimal atom loss and small enough to allow the two vacuum sections to maintain a differential pressure of three orders of magnitude. Both vacuum sections contain a chamber where optical access is provided by optical viewports, which allow the cooling, optical pumping and imaging beams to interact with the atom cloud.

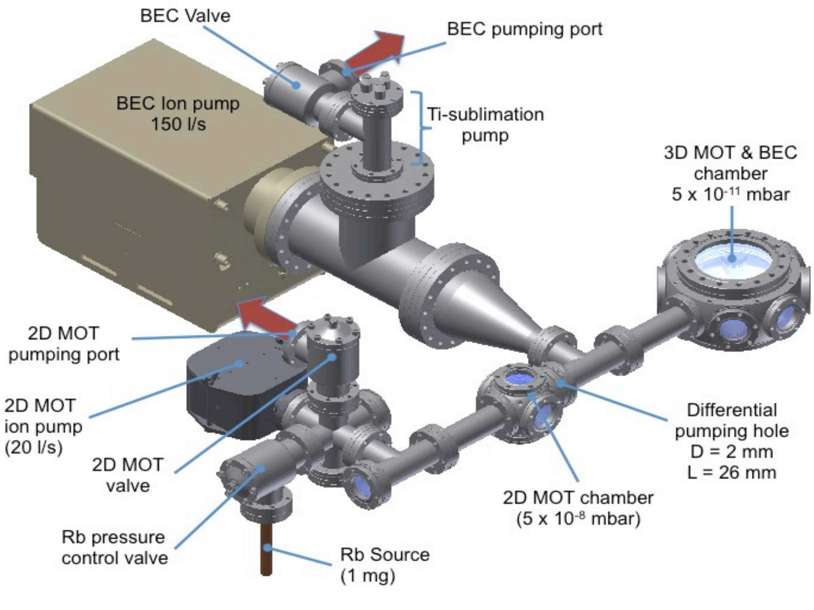

Figure 1: Illustration of the current vacuum system at UKZN.

An ion pump in each vacuum section maintains the UHV that is achieved during the bake-out procedure where the vacuum is heated to ~350°C for two weeks. During this process the out-gassed materials are removed using two turbo-molecular pumps which are backed-up by a single rotary vain pump. There is also a titanium sublimation pump which can be used to decrease the base pressure if it rises due to continuous use. This pump creates a very thin porous layer of titanium on the vacuum internal surface which absorbs background gases and thus reduces the vacuum pressure.

The 2-D MOT section contains a 1 mg ampule of rubidium which constantly out-gases and thus fills this side of the vacuum system with rubidium vapour resulting in the pressure of ~5x10^{-8} mbar. This pressure can be controlled using the 'Rb pressure control valve' as indicated in figure 1. These thermal background atoms are cooled using the laser cooling beams and a novel coil configuration combined together in the form of a 2-D^{+} MOT. The atoms are then optically pushed through the DPH into the low pressure section of ~5x10^{-11} mbar where they enter the BEC chamber and are again cooled in the form of a 3-D MOT and will eventually form the BEC.

2.2. Laser System

Figure 2 (a) shows the hyperfine structure of the $5^2S_{1/2} \rightarrow 5^2P_{3/2}$ Rb-87 transition as well as the required laser frequencies necessary to build a BEC experiment. There are four main frequencies necessary in such an experiment, namely, the cooling, imaging, optical pumping, and repumping frequencies. Figure 2 (b) gives the general schematic implemented to derive and distribute these beams. As can be seen, the various sections are coupled together using polarisation maintaining (PM) optical fibres which allow the beams to be easily transported around the experiment.

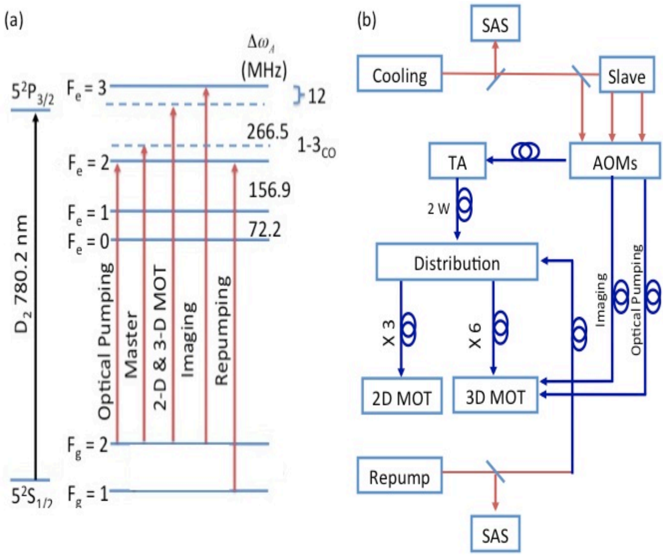

Figure 2: (a) The hyperfine structure of ^{87}Rb with all the necessary optical transitions and corresponding frequencies shown. (b) A block diagram showing an overview of the laser system layout.

The master cooling laser provides the initial seed power for the cooling, imaging and optical pumping beams as shown in figure 2 (b). A small percentage of the laser output is directed to a saturated absorption spectroscopy setup where the lasers is locked to the $F_g= 2 \rightarrow F_e=(1\text{-}3)_{CO}$ crossover peak of the Rb-87 D_2 line. A detuning of 12 MHz from the $F_g= 2 \rightarrow F_e= 3$ cooling transition, which compensates for the Doppler shift, is provided via an acousto-optical modulator (AOM) in a double pass configuration. Given that the correct frequency has been generated for the cooling process, 10 - 20 mW of optical power is injected into a tapered amplifier (TA) which generates a up to 2 W output beam at this frequency. This beam is then sent to a distribution board where a series of waveplates and polarisation beam-splitters divide the beam into its various beam components. Three beams are required for the 2-D^{+} MOT and six beams are required for the 3-D MOT. These are coupled to polarisation maintaining (PM) optical fibre and sent directly to the experiment. In addition to the cooling beams, we require a repumping beam in order to keep the atom resonant with the cooling laser. This is performed using a separate ECDL locked to the $F_g= 1 \rightarrow F_e=2$ transition. The repump beam is then sent to the beam distribution section where it is coupled to the MOT fibres.

To perform the tasks of absorption imaging and optical pumping, an additional two frequencies are derived from the master cooling laser. Given that our cooling laser has a low output power we use a slave laser to provide power for these beams. The slave laser is injected with 2 mW of master power and thus its output is of the same frequency. Two separate AOMs are used to shift the imaging and optical pumping frequencies to their relevant transition. The imaging beam is shifted on resonance with the $F_g= 2 \rightarrow F_e= 3$ cooling transition and the optica pumping beam is shifted to the $F_g= 2 \rightarrow F_e= 2$ transition. These beams are coupled to fibre and then sent directly to the experiment.

3. A Novel 2-D Magneto-Optical trap

A 2-D MOT cools and traps atoms in two spatial dimensions allowing atoms to move freely along the remaining axis. This is done by using elliptical beams, which perform laser cooling in two spatial dimensions, in combination with a magnetic field which traps the atoms in the same two spatial dimensions. Thus atoms are trapped in two dimensions but are free to move along the third spatial dimension. A 2-D$^+$ MOT is an extension of this where a low powered push beam is used to preferentially push the atoms in one particular direction along the untrapped axis. This creates a high flux of cold atoms in this axis, which enter the BEC chamber.

3.1. The 2-D MOT Magnetic Fields

The magnetic field required to create a 2-D MOT is a linear quadrupole field. This field can be produced using four equally spaced straight current carring bars in a rectangular arrangement with currents flowing in alternate directions for neighbouring bars. In practice this is can be performed using either one or two pairs [8] of rectangular coils in anti-Helmholtz configuration as shown on figure 3 (a) and (b). These coils create a linear gradient on the x- and y- axis but a zero magnetic flied along the z-axis. In the case where one coil pair is used, the short end bars of the rectangular coils create a magnetic field that can disrupt or shorten the length of the zero magnetic field along the z-axis. This effect can be eliminated by increasing the length of the coils along the z-axis, but this results in an increase in electrical power consumption. In the case of two coil pairs, again there is an increase in electrical consumption due to the addition of two extra coils, but the magnetic field gradient is double that of a single pair and the field generated by the end bars cancel each other allowing the length of the coils to be shorter. The magnetic field created by the rectangular coils, B_{rect}, can be written as $B_{rect} = \alpha_{rect}(x,-y,0)$ where α_{rect} is the over all axial gradients in the x- and y-axis.

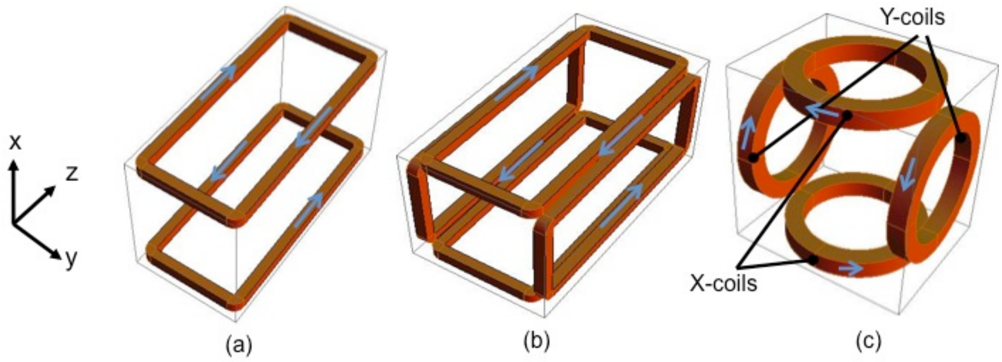

Figure 3: Illustrations of coil configurations for the 2-D MOT.

Figure 3(c) illustrates our novel coil configuration for generating the same magnetic field. This consists of two pairs of circular coils in anti-Helmholtz configuration. A single pair of circular coils in anti-Helmholtz configuration creates a spherical quadrupole field where the gradient in the axial direction is twice that of the radial axes. Thus the magnetic field, B, created by each individual pair of coils, is given by $B_{x-coil} = \alpha_x(x,-y/2,-z/2)$ and $B_{y-coil} = \alpha_y(x/2,-y,z/2)$, where α represents the axial gradient of that specific coil pair. The total magnetic field generated by the two pairs of coils, B_{tot}, is the sum of each of the individual coil pairs and is thus given by

$$B_{tot} = \left[\left(\alpha_x + \alpha_y/2\right)x, \left(-\alpha_x/2 - \alpha_y\right)y, \left(\alpha_x/2 - \alpha_y/2\right)z\right] \tag{1}$$

From this equation it is clear that the axial gradient of one coil pair adds with the radial gradient of the other coil pairs in both the x- and y-axis. However, in the z-axis, both radial fields generated by the individual pair subtract from each other. Thus, if both coils are the same and have identical gradients, $1.5\alpha_x = 1.5\alpha_y = \alpha_{tot}$, a zero magnetic field is created along the z-axis. The individual and combined effect of the coils for all spatial dimensions can be clearly seen on examination of figure 4(a). In this case equation 1 becomes B_{tot} $B_{tot} = \alpha_{tot}\left(x, y, 0\right)$ which is of the same format as the standard 2-D MOT coils. Contour plots of the magnetic field can be seen in figure 4 (b), where the zero magnetic field along the z-axis can be clearly seen in the z-x plot and the spherical quadrupole field can be seen in the x-y plot.

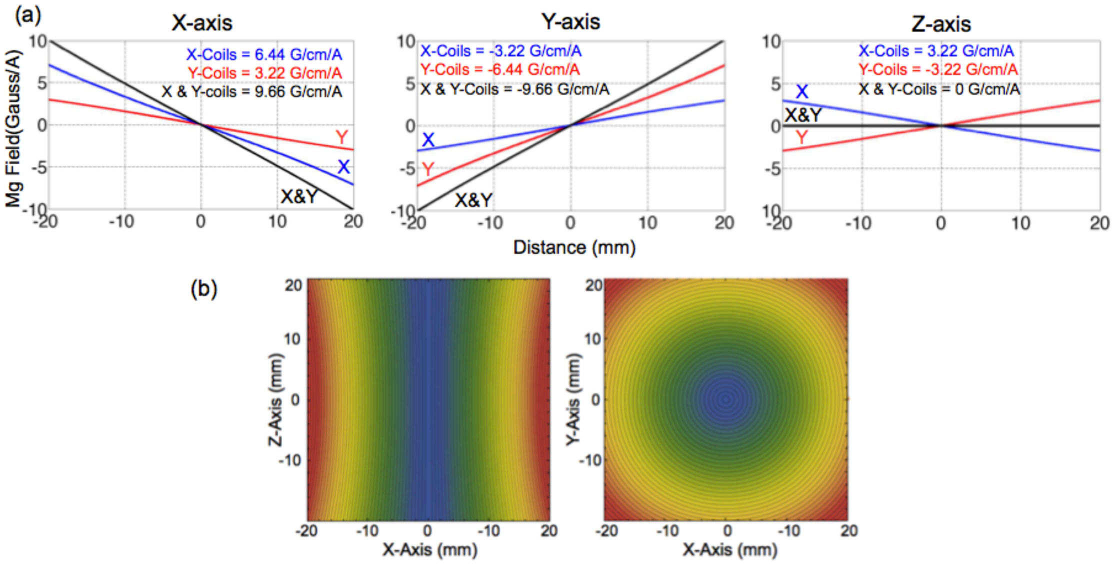

Figure 4: (a) Line plots and (b) contour plots of the magnetic fields created by the circular 2-D MOT coils in the respective axes.

Bolpasi *et al* [9] use a similar coil configuration to create a linear quadrupole magnetic field as part of an Ioffe Pritchard trap replacing the usual race-track shaped Ioffe bars with the two pairs of circular coils. In this case the authors present a plot of the magnetic field gradient per unit power as a function of varying coil length which is a direct measure of the efficiency of the coil configuration. From this analysis it is clear that the higher gradients per unit power are achieved for the smaller coil length. In fact, compared to the circular configuration, coils of typical length can lose up to 60% of its gradient per unit power. This also applies for the above mentioned novel configuration for the 2-D MOT.

3.2 The Complete 2-D⁺ MOT

The derivation of the optical power for the 2-D$^+$ MOT, as well its associated frequency relative to an atomic transition is briefly explained in section 2.2. This optical power arrives to the vacuum chamber via PM fibres. On exiting the fibre the beam expands freely and is then collimated using a convex lens creating a beam with a circular cross-section. This beam is then polarised using a quarter wave-plate to create the σ^+/σ^- polarised light necessary for laser cooling. The polarised beam is expanded in one dimension using a spherical cylindrical concave lens and collimated again using a large cylindrical convex lens. This results in a 68 x 17 mm beam which is cut to 40 x 17 mm (which is the optical access limitation of the vacuum view-ports) which gives a more even power distribution along the larger dimension. The expansion of both the 2-D$^+$ MOT beams can be seen in figure 5(a). Also shown is the mechanical housing of the optics which makes the entire beam system easy to align. With the aid of standard optical components these beams are aligned to intersect perpendicular to each other at the geometrical centre of the 2-D MOT chamber. The complete optical and magnetic coil combination is illustrated in figure 5(b).

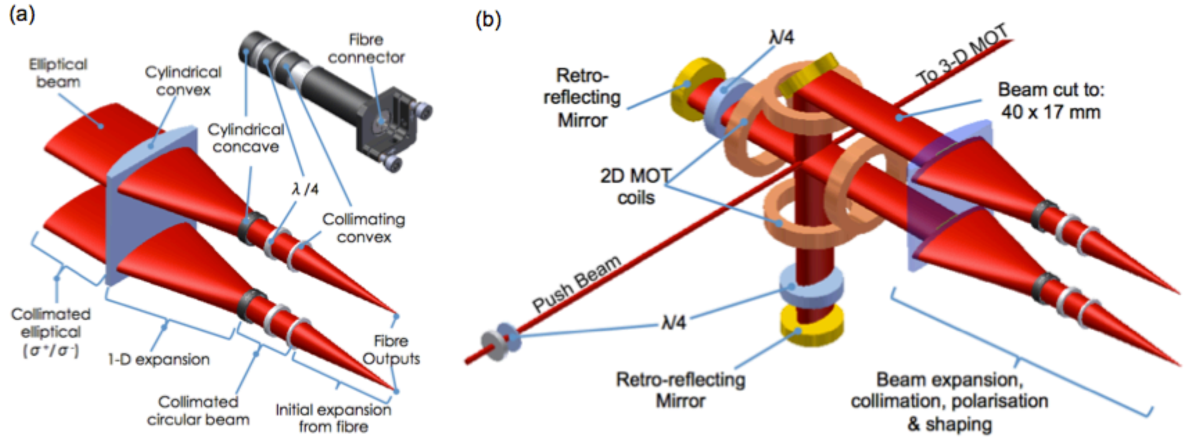

Figure 5: (a) the expansion of the 2-D MOT beam. (b) Illustration showing the magnetic coils and the 2-D$^+$ MOT beam configuration.

4. Conclusion and Outlook

Presented here is a novel coil configuration of a 2-D MOT. We have given a mathematical description of the magnetic field showing that it is of the same format as the more traditional rectangular coils. Also presented are the vacuum and laser system in order to give a clearer overview of the entire setup. This coil configuration allows the 2-D MOT to be compact and efficient in terms of creating an adequate magnetic field gradient with low power consumption. The atomic flux created by the 2-D$^+$ MOT will serve as a supply for a 3-D MOT whose atoms will eventually form Africa's first BEC.

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