

Flux Limitations of Continuous Atom Lasers

Adele K. Morrison

**A thesis submitted for the degree of
Bachelor of Science with Honours in Physics of
The Australian National University**

12 May 2005

Declaration

This thesis is an account of research undertaken between July 2004 and May 2005 at the Department of Physics, Faculty of Science, The Australian National University, Canberra, Australia.

Except where acknowledged in the customary manner, the material presented in this thesis is, to the best of my knowledge, original and has not been submitted in whole or part for a degree in any university.

Adele K. Morrison
12 May 2005

Acknowledgements

First and foremost I would like to thank Nick for being such a truly wonderful person. I would have quit long ago if it hadn't been so enjoyable spending time in the lab with you. You're one of the kindest, most generous people I know. I would also like to thank John for providing help when needed and for understanding my dream of 'going to grow potatoes'. Hopefully one day (not too far in the future) you can both come and visit, wherever I may be, and spend some time chilling out in the garden.

Next I would like to thank Simon. Your help with physics has been much appreciated over the last year, but much more so, has been our friendship over the last few years.

My life has changed considerably during my honours year, not due to the physics, but due to my life at Raymond St. Thanks Francis, Clare, Sam, Jen, Gregory, Nat, Simon, the chickens and everyone else with whom I have enjoyed a sunny morning of pancakes, for making me realise that life can be a lot more random and interesting than I previously imagined possible.

I would like to thank Stu for believing in me back in the old days and convincing me to move to Canberra.

Thanks to Andy for all the years of doing physics with me. Despite my early protestations, you, along with Nick, are one of the main reasons I stayed and enjoyed physics for this long. It's a shame we weren't able to do honours together.

Thanks Tam for our many crazy adventures away from civilisation over the last few years. They've been great fun.

Thanks to Mum and Dad for the financial help during my undergraduate degree. Also, thanks to Mum for supporting whatever I want to do, even if it isn't the 'normal' thing.

Thanks to Schnozzle for your little cosy presence in the lab. I hope you're warm and cosy somewhere else now.

Finally, thanks to Sam for stopping me from turning into a newt by spending fourteen hours a day in the lab. It's been much nicer playing with the chickens and the compost. You're lovely; I'll miss you.

Abstract

If atom lasers are to transform many fields of physics, as well as find applications in industry, the most essential development needed is increased atom flux. In this thesis we report on the experimental observation of fundamental limits on the flux of continuous atom lasers.

The flux produced by the commonly used radio frequency outcoupler, can not be arbitrarily increased by increasing the strength of the outcoupling. Above a critical Rabi frequency, the atom laser shows large classical density fluctuations, due to coupling between the multiple Zeeman states. In our system this critical Rabi frequency is ~ 1 kHz. Furthermore, at large coupling strengths (> 4 kHz for our experimental parameters), the continuous atom laser output completely switches off, as a result of the atoms remaining trapped in a bound state.

In addition to the investigations of the radio frequency outcoupler, we have demonstrated the first continuous Raman outcoupled atom laser. Preliminary data indicates that the Raman outcoupler will be flux limited in a similar way to the radio frequency outcoupler.

Contents

Declaration	iii
Acknowledgements	v
Abstract	vii
1 Introduction	1
2 Bose-Einstein Condensation	5
2.1 Introductory Theory	5
2.2 Atomic Structure of ^{87}Rb	6
2.3 Atom Manipulation	7
2.4 Laser Cooling	7
2.4.1 Doppler Cooling	7
2.4.2 Magneto-Optical Traps	7
2.4.3 Polarisation Gradient Cooling	8
2.5 Optical Pumping	9
2.6 Magnetic Trapping	9
2.7 Evaporative Cooling	10
2.8 Calculation of Atom Numbers	11
3 The Third Incarnation of the ANU BEC Machine	13
3.1 Upper MOT and Push Sequence	13
3.2 Lower MOT and Optics	14
3.3 Magnetic Trap	15
4 Atom Lasers	17
4.1 An Analogy with Optical Lasers	17
4.1.1 Definition of an ‘Atom Laser’	17
4.1.2 A Simple Physical Comparison	18
4.2 The Pumped Atom Laser	19
4.2.1 Continuous Loading of a Trap for BEC	20
4.2.2 Continuous Evaporation in a Magnetic Guide	21
4.2.3 An Alternative Method	22
4.3 Non-State Changing Outcoupling	23
4.4 The Resonant Width of the Condensate	23
4.5 Radio Frequency Outcoupling	25
4.6 Raman Outcoupling	27

5	Flux Limitations of Continuous Rf Atom Lasers	31
5.1	Introduction	31
5.2	Experimental Setup	32
5.2.1	Calibration of the Outcoupling Magnetic Field	33
5.3	Results	34
5.3.1	Weak Coupling Regime	34
5.3.2	Strong Coupling Regime and the Bound State	35
5.3.3	3 ms Outcoupling	36
5.3.4	Computational Simulations	37
5.4	Conclusion	39
6	A Continuous Raman Atom Laser	41
6.1	Experimental Setup	41
6.2	Results	43
6.2.1	Dependence on Detuning and Polarisation	43
6.2.2	Pulsed Outcoupling	45
6.2.3	Indications of Flux Limitations and the Bound State	46
6.3	Derivation of the Suppression of Two Photon $\Delta m_F = 2$ Transitions	48
6.4	Conclusion	49
7	Conclusions and Future Directions	51
	Bibliography	53

Introduction

Since optical lasers were first demonstrated in 1960 [1], not only have they revolutionised many fields of physics, but they have reached the stage where hundreds of millions of people consider technology which is reliant on lasers to be an integral part of their lives. Whereas previously only thermal light sources, such as light globes, were available, the advent of optical lasers introduced a bright, highly directional beam of coherent, monochromatic photons. Atom lasers, such as the one shown in Figure 1.1, have a similar potential to transform the study of physics, in particular within the new field of quantum atom optics. Atom lasers will find use in precision measurement, where they have the potential to outperform optical techniques by many orders of magnitude.

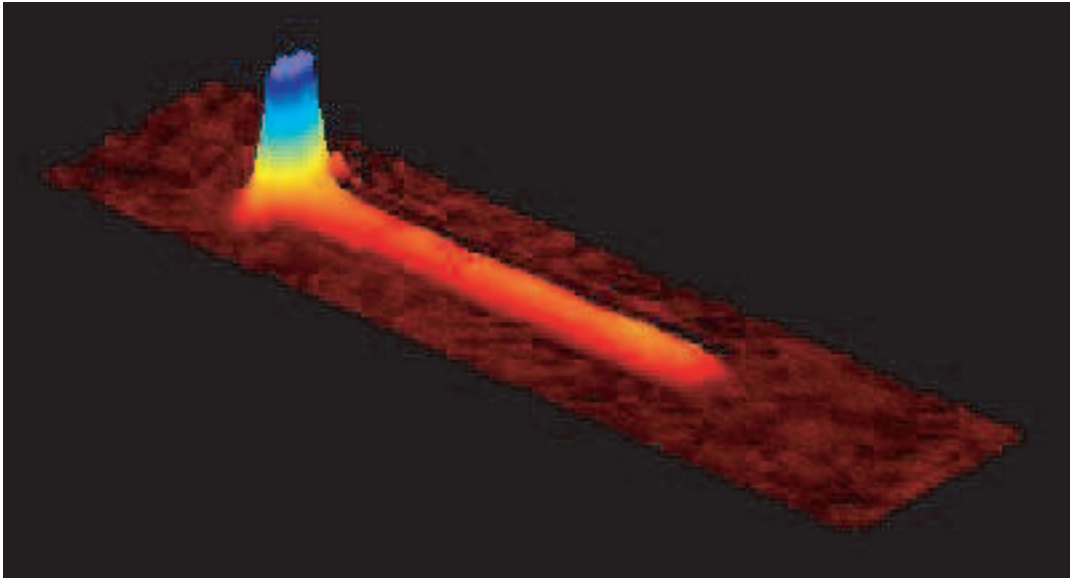


Figure 1.1: An atom laser produced with 10 ms of radio frequency outcoupling in our laboratory. The atom laser has fallen under gravity and has a total length of 0.5 mm. The top of the BEC has been removed from the figure, in order to better show the atom laser.

There are many applications for atom lasers in fundamental research. They may be used in atom optics as sensitive probes of Bose-Einstein condensates. In the new field of quantum atom optics, atom lasers may be used for such schemes as entanglement and teleportation and also as a squeezed source of atoms, just as optical lasers are used in quantum optics. Atom lasers will provide an ultra-cold source of atoms for high precision spectroscopy, with applications to precision measurements of fundamental constants. As

a test of general relativity, atom lasers may be used to study a sonic analog of Hawking radiation [2].

The current proposals for applications of atom lasers in industry are mostly speculative, due to the infancy of the field. Due to the slow speed and small wavelength of atom lasers, it is likely that they will find uses in interferometry for extremely sensitive measurements of gravitational acceleration and rotational motion [3]. For example, in a Mach-Zehnder gyroscope rotating at frequency Ω_r , the phase shift is given by

$$\Delta\phi = \frac{4\pi\Omega_r A}{v\lambda} \quad (1.1)$$

where A is the area enclosed by the interferometer, v is the velocity of the particles (either photons or atoms) and λ is the particle wavelength. For photons, $v\lambda = c\lambda$, while for atoms, $v\lambda = \frac{h}{m}$, where h is Planck's constant and m is the mass of the atom. Therefore for an interferometer of fixed area, there results a large difference between the phase shift for atoms and photons. For alkali atoms, the phase shift is roughly eleven orders of magnitude larger than that resulting from visible light. Atom lasers also have the potential to provide significantly greater accuracy for atomic clocks in time and frequency standards. The smaller wavelength of atom lasers, as compared with optical lasers, suggests their use in atomic microscopes [4], atom holography and more generally in nanotechnology.

The source, from which an atom laser is extracted, is a Bose-Einstein condensate (BEC). Having been theoretically predicted by Einstein in 1925 [5], it was another seventy years until BEC was first experimentally realised in a dilute atomic gas [6]. The field of Bose-Einstein condensation is an exciting one, with two Nobel prizes being given in the area within four years of each other. In 1997, the Nobel prize was awarded to Steve Chu, Bill Phillips and Claude Cohen-Tannoudji for the development of methods to cool and trap atoms with laser light, as a lead up to the achievement of BEC. In 2001, Eric Cornell, Wolfgang Ketterle and Carl Wieman received the Nobel prize for the achievement of Bose-Einstein condensation in dilute gases of alkali atoms, and for early fundamental studies of the properties of the condensates.

In BEC, a large number ($\sim 10^6$) of extremely cold atoms undergo a dramatic transition to quantum degeneracy. This is achieved by trapping a dilute gas of neutral, bosonic atoms in a harmonic magnetic potential. The atoms are cooled until a macroscopic fraction of the atoms occupy the ground state of the trap. As a result of the cooling process, the atomic de Broglie wavelength becomes comparable to the interparticle separation and the individual wavefunctions of the atoms overlap. Figure 1.2 shows the formation of a BEC. The succession of images were taken at different stages during the evaporative cooling.

To form an atom laser beam, atoms are coupled out of the condensate with apparently no loss of coherence. Due to gravitational acceleration, the outcoupled atoms form a quasi-collimated beam, with the divergence determined by the repulsive interactions between the condensate and atomic beam. By analogy with an optical laser, an atom laser is a stream of coherent atoms in a single, highly populated mode. Atom lasers have been demonstrated experimentally in both pulsed and continuous modes. Outcoupling mechanisms demonstrated to date fall into two distinct categories: those that use state changing and those that do not. State changing mechanisms couple atoms from the magnetically trapped BEC state to a magnetically insensitive untrapped state, which falls away from the trapping region due to gravitational acceleration. Whereas non-state changing outcoupling mechanisms utilise optical methods and are not reliant on the Zeeman splittings of the ground state.

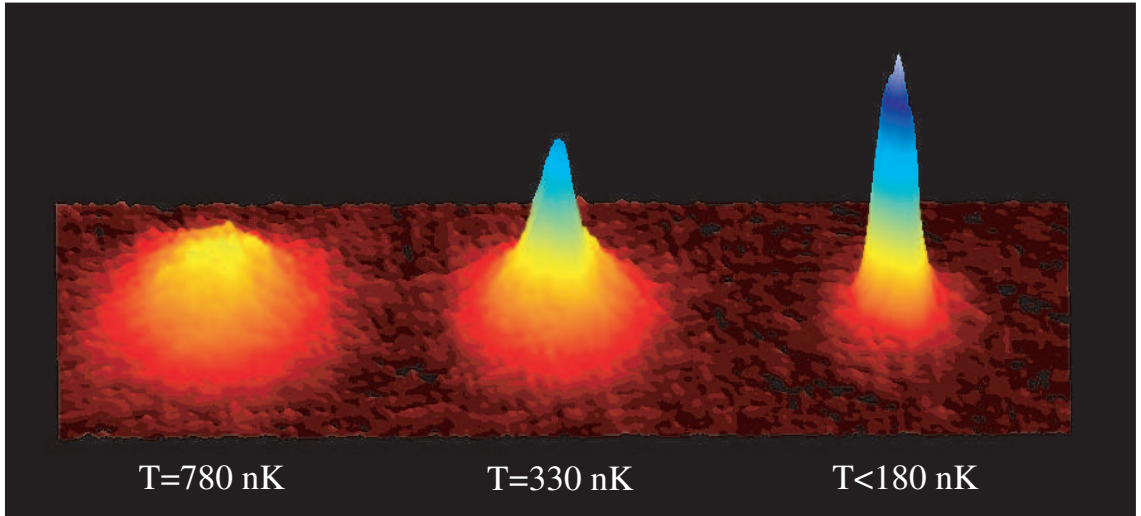


Figure 1.2: Successive images, from our laboratory, showing the formation of a Bose-Einstein condensate, as the evaporation frequency is gradually reduced. The temperature of the atom cloud is given under each of the images. The first image depicts a thermal cloud. In the second image, the BEC has started to form and the cloud is bimodal. The third image shows a pure BEC. The width of the expanded condensate in the final image is roughly $100\ \mu\text{m}$.

There have been two demonstrations of atom lasers without state changing. The first was based on tunneling between a vertical array of optical traps [7]. Atoms confined in an optical lattice were induced to tunnel downwards into different lattice sites by gravity, forming a kind of pulsed atom laser. The second outcoupling method without state changing was based on all-optical techniques [8]. Atoms were extracted from the condensate by continuously lowering the dipole trapping potential until atoms spilled over the edge.

However, most research (more than 90%) has focused on state changing outcoupling mechanisms, as these are the most adaptable and controllable. There are two types of outcoupling based on state changing: radio frequency (rf) outcoupling [9, 10] and Raman outcoupling [11]. The rf transition is used to couple directly between the magnetic sublevels of the ground state, whereas Raman outcoupling uses two highly detuned optical fields to couple the trapped BEC state to the atom laser state via a higher intermediary state.

In order for atom lasers to find useful applications in both research and industry, it is essential that atom lasers are developed with constant, high flux. Current state of the art atom lasers, such as that shown in Figure 1.1 are often barely detectable above the background noise level and can display large intensity fluctuations. One way to greatly improve atom laser flux is to continuously pump the condensate. All atom lasers produced to date have been unpumped. This is the equivalent of an optical laser, which has had the power switched off and is merely draining the reservoir of photons. Pumping an atom laser by replenishing the outcoupled atoms with new atoms from a surrounding thermal cloud will have a significant effect on the peak flux. However, as presented in this thesis, we have found that the common outcoupling mechanisms (rf and Raman) impose limits on the peak homogeneous flux achievable in a continuous atom laser. Therefore, even a pumped atom laser, produced with these outcoupling mechanisms, will be flux limited.

Overview of Thesis

Following this introduction, we begin with a detailed introduction to the experimental aspects of creating Bose-Einstein condensates and the techniques necessary for the manipulation of cold atoms. In Chapter 2 the experimental path to degeneracy followed by our group is described. This consists of laser cooling in a double MOT setup, followed by evaporative cooling in a magnetic trap. The construction of the third generation ANU BEC machine is outlined in Chapter 3.

An introduction to atom lasers is given in Chapter 4. In particular, the definition of an atom laser is discussed and previous atom laser experiments are reviewed. We also describe the basic theory of rf and Raman outcoupling methods.

The results of this thesis are presented in Chapters 5 and 6. In Chapter 5 we show that an rf outcoupler is not suitable for the production of a high flux continuous atom laser. In the weak coupling regime, it is shown that the atom laser begins to switch off as the Rabi frequency is increased above a critical value, due to interactions between multiple Zeeman states. The existence of a bound state is demonstrated for strong rf coupling. Chapter 6 presents the results of the first continuous Raman outcoupled atom laser. Possible indications that the Raman atom laser is flux limited in the same way as the rf atom laser are discussed. It is also shown here that it is not possible to drive two photon $\Delta m = 2$ transitions with large detuning.

Finally, Chapter 7 concludes this thesis with a summary of the results and suggestions for future work in this field.

Publications and Conference Presentations

The results presented in Chapter 5 have been submitted to *Physical Review Letters*. The submitted paper is available at <http://arxiv.org/abs/cond-mat/0501747>. This material has also been presented at the Australian and International Workshop on Quantum and Atom Optics in December 2004 and at the Australian Institute of Physics National Congress in January 2005.

The results of Chapter 6 are currently being written up for publication. The results of both Chapters 5 and 6 have been accepted for presentation at the Conference on Lasers and Electro-Optics (CLEO) and also as an invited talk at the International Conference on Laser Spectroscopy (ICOLS) in June 2005.

Bose-Einstein Condensation

Since BEC is an integral component in the production of atom lasers and also since the first two months of my honours project were spent creating a functioning, stable BEC machine, this section gives some introductory BEC theory as well as an overview of the experimental path to BEC, which is followed by most groups in the world.

BEC is achieved by a two step process: laser cooling followed by evaporation in a confining magnetic potential. Laser cooling collects and cools the atoms to around $50 \mu K$. The atoms are then evaporatively cooled to the BEC transition using a radio frequency (rf) cut in the trapping magnetic field.

2.1 Introductory Theory

For indistinguishable massive bosons in an external potential, the Bose-Einstein distribution function gives the number of particles in the k^{th} energy state as

$$N_k = \frac{1}{e^{(\epsilon_k - \mu)/k_B T} - 1} \quad (2.1)$$

where ϵ_k is the energy of a particle in the k^{th} state, μ is the chemical potential, k_B is Boltzmann's constant and T is the temperature [12]. So that N_k always remains positive, the restraint $\mu < \epsilon_0$ is placed on the chemical potential, where $k = 0$ denotes the ground state. Below a critical finite temperature, macroscopic occupation of the ground state occurs. This is known as Bose-Einstein condensation. The critical temperature for non-interacting particles depends on the form of the confining potential. For a three dimensional harmonic oscillator, the critical temperature is given by

$$T_c = \frac{\hbar \bar{\omega}}{k_B} \left(\frac{N}{\zeta(3)} \right)^{1/3} \quad (2.2)$$

where $2\pi\hbar$ is Planck's constant, $\bar{\omega}$ is the mean of the three trapping frequencies, N is the total number of particles and ζ denotes the Riemann Zeta function [13].

The number of particles in the ground state at a given temperature T is

$$N_0 = N \left(1 - \left(\frac{T}{T_c} \right)^3 \right). \quad (2.3)$$

A quantitative value for the chemical potential is determined by considering the con-

straint on the total number of particles:

$$N = \int n d^3x \quad (2.4)$$

where n is the density of particles. Including the effects of interactions and trap confinement gives

$$\mu = \frac{1}{2}(15a\hbar^2\sqrt{m\omega}^3N)^{2/5} \quad (2.5)$$

where a is the scattering length and m is the mass of a particle.

2.2 Atomic Structure of ^{87}Rb

Typically alkali atoms are used in cooling and trapping experiments, due to their advantageous atomic properties. In particular, alkalis have large elastic cross-sections at low temperatures, which allows efficient evaporative cooling. The ANU BEC lab makes ^{87}Rb condensates, as this is one of the easiest species to Bose condense and there are relatively cheap lasers available at the appropriate wavelength. The optical transitions from the ground state of ^{87}Rb are depicted in Figure 2.1. The states are split first due to the hyperfine effect and may be split further by the Zeeman effect in the presence of a magnetic field.

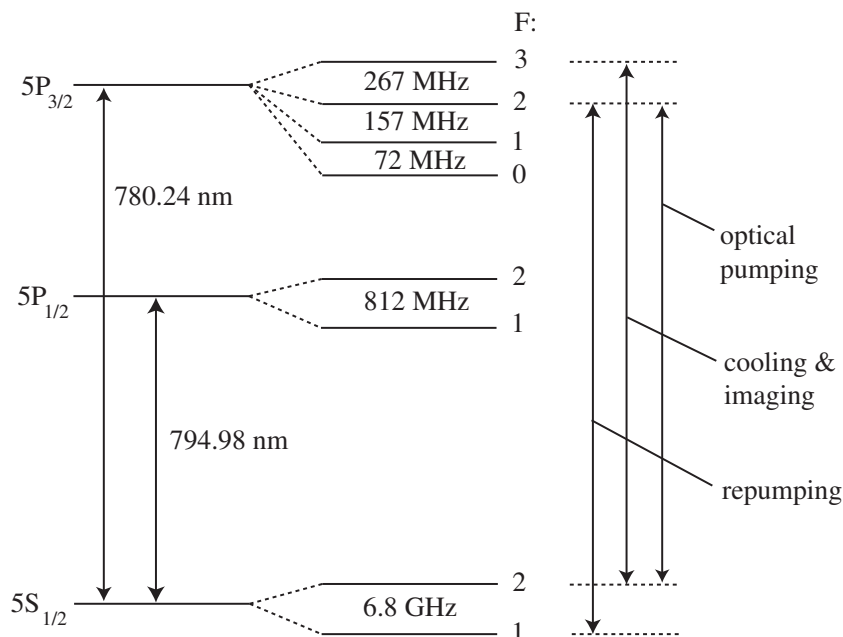


Figure 2.1: Hyperfine structure of ^{87}Rb and the optical transitions from the ground state. The different optical transitions, used to make BEC, are shown on the right.

Various optical frequencies are required to cool the atoms and manipulate the atomic state on the path to BEC. These frequencies are depicted on the right of Figure 2.1. The cooling transition is $5S_{1/2}, F=2 \rightarrow 5P_{3/2}, F=3$. However, roughly one in every thousand atoms will be excited to the $5P_{3/2}, F=2$ state and one in every two of these atoms will decay from there to the $5S_{1/2}, F=1$ state, taking the atom out of resonance with the

cooling laser. In order to avoid this, a second laser, known as the repump, is employed to repopulate the $5S_{1/2}, F = 2$ state via the $5P_{3/2}, F = 2$ state. The optical pumping light is used to create atomic samples in a single magnetic state.

2.3 Atom Manipulation

The cooling and trapping methods described in the following sections are based on two main forces. The first is the radiation pressure force. This arises when an atom absorbs multiple photons from a laser beam. Although the atom emits spontaneously in random directions, the atom receives a momentum kick in the direction of the laser beam upon each absorption event. After many absorption and emission events, the atom experiences a net force in the direction of the laser beam. The radiation pressure force is the basis of laser cooling. The second force, which is used to manipulate atoms, arises due to the interaction of the atomic spin with an external inhomogeneous magnetic field. This magnetic force allows neutral atoms to be trapped and guided.

2.4 Laser Cooling

2.4.1 Doppler Cooling

Laser cooling [14] is a very important step on the path to BEC, as it allows atoms to be collected from a room temperature gas and cooled to a few hundred microKelvin in a matter of seconds. The 1997 Nobel Prize was given for developments in laser cooling and trapping. The cooling force arises from the momentum imparted to the atoms during scattering events. A simple model is gained by considering a two level atom, which scatters photons from two red detuned, counter-propagating laser beams of equal intensity. As the atom moves towards one of the laser beams, the opposing photons will be Doppler shifted into resonance and the atom will absorb and spontaneously emit a large number of photons. The photons in the other laser beam, which are co-propagating with the atom, will be shifted further away from resonance and few of these photons will be scattered. As a result of many scattering events, the atom's kinetic energy will be reduced. Cooling in three dimensions is achieved by the use of three orthogonal pairs of counter-propagating laser beams. The temperature, which may be achieved by laser cooling, is limited since the atoms will emit spontaneously in random directions. The spontaneous nature of the scattering leads to the Doppler cooling limit, $T_D = \hbar\Gamma/2k_B$, where Γ is the linewidth of the atom and k_B is Boltzmann's constant. For a ^{87}Rb transition with linewidth $\Gamma = 2\pi \times 6$ MHz, the Doppler limit is $120 \mu\text{K}$.

2.4.2 Magneto-Optical Traps

Although laser cooling, as described above, will reduce the velocity of the atoms, it will not trap them, due to the lack of position dependence. One method of introducing position dependence is known as a magneto-optical trap (MOT). A MOT uses circularly polarised beams to limit excitations to certain Zeeman levels in the presence of a position dependent magnetic field. By controlling the rate at which an atom in a particular position scatters photons from the various beams, the atom may be pushed to the centre of the trapping region.

The basic principle of a MOT is illustrated in one dimension by considering an atom with a total angular momentum $J=0$ ground state and $J=1$ excited state. In a linear, zero crossing magnetic field, the excited state will be split into three Zeeman sublevels, as depicted in Figure 2.2. The atom is illuminated by two counter-propagating beams of opposite circular polarisation. Due to angular momentum restrictions, the σ^+ beam from the left can only excite to the $m = +1$ state, while the σ^- beam from the right can only excite to the $m = -1$ state. So for an atom in the negative field region, the σ^+ beam is close to resonance, while the σ^- beam is far from resonance. The atom therefore absorbs strongly from the σ^+ beam and experiences a force towards the centre of the trap. For an atom in the positive field region, the opposite scenario occurs and the atom absorbs photons from the σ^- beam, which once more pushes it towards the centre of the trap. In this way the lasers, in the presence of a magnetic field gradient, provide both cooling and trapping forces. Although this is a simplified one dimensional model, it gives results which are qualitatively very similar to a more complicated three dimensional calculation, which includes the actual angular momentum states [15].

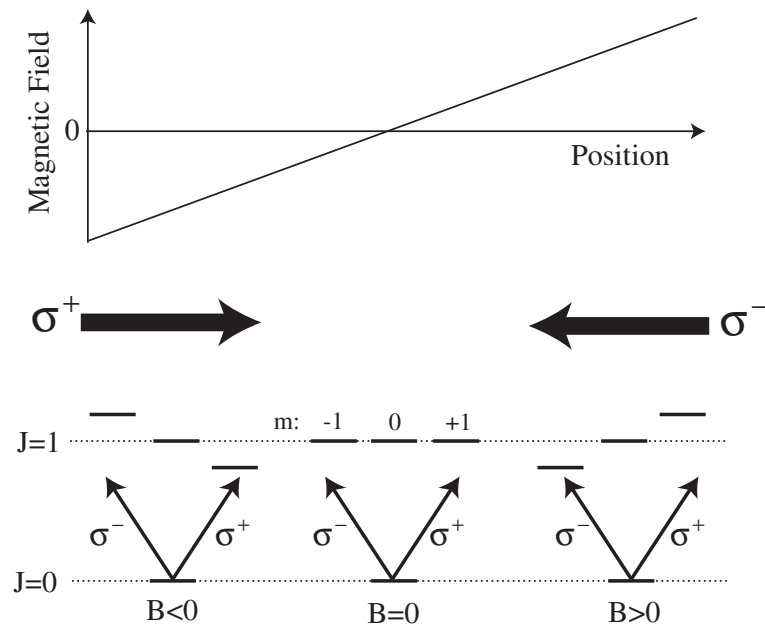


Figure 2.2: A one dimensional model of a MOT. The upper portion of the figure shows the spatially dependent magnetic field. The laser polarisations and directions are shown in the middle portion. The lower portion shows the splittings of the Zeeman levels in the presence of the magnetic field.

2.4.3 Polarisation Gradient Cooling

It is actually possible to laser cool well below the Doppler limit using a mechanism based on polarisation gradients [16]. Sub-Doppler cooling works at low laser powers when the optical pumping time between the ground state sublevels is long. In each orthogonal direction of a MOT, there is a pair of counter-propagating, oppositely circularly polarised lasers. At any given point, the resulting light field is always linear and rotates helically along the axis of the beams. This polarisation gradient causes atoms to be optically pumped into

certain Zeeman levels, depending on the velocity of the atoms. The population imbalance causes preferential absorption from either the right or left circularly polarised beam. If we consider an atom with $J = 1$ ground state, then atoms moving towards the σ^+ beam will have a greater population in the $m_F = 1$ state. The scattering probability for these atoms from the σ^+ beam is six times greater than from the σ^- beam, which results in the atoms scattering more light from the counter-propagating laser and an overall cooling force. Polarisation gradient cooling can reduce the temperature of the atoms to tens of microKelvin, which is an order of magnitude below the Doppler cooling limit.

2.5 Optical Pumping

Before transfer to the magnetic trap, atoms are optically pumped into the trappable $m_F = +2$ magnetic sublevel of the ground state by applying a laser resonant with the $5S_{1/2}, F = 2, m_F = x \rightarrow 5P_{3/2}, F = 2, m_F = x + 1$ transition. Due to angular momentum restrictions, the atoms can decay only to the $5S_{1/2}, F = 2, m_F = x, x + 1$ or $x + 2$ states. Therefore on average, the atoms will shuffle up to higher m_F states. Once the atoms are in the $m_F = +2$ state, they are no longer in resonance with the pumping laser and remain in a dark state.

2.6 Magnetic Trapping

Neutral atoms can be trapped in inhomogeneous magnetic fields due the Zeeman effect. The atomic magnetic moment, which is dominated largely by the electronic contribution, interacts with external magnetic fields according to the Hamiltonian,

$$H = -\mu \cdot B \quad (2.6)$$

where μ is the atomic magnetic moment operator and B is the applied magnetic field. This causes splittings of the hyperfine energy levels, as shown in Figure 2.3. The full form of the Zeeman energy plotted here, including the second order contribution, is given in [13].

For weak magnetic fields, in which the Zeeman effect is small and may be treated as a perturbation, the splittings may be approximated as linear solutions of the form

$$E = g_F m_F \mu_B |B| \quad (2.7)$$

where g_F is the Landé g factor (equal to $+\frac{1}{2}$ for the $F = 2$ manifold and $-\frac{1}{2}$ for the $F = 1$ manifold), m_F is the projection of the total angular momentum, μ_B is the Bohr magneton and $|B|$ is the magnetic field magnitude. The ground state splittings are 700 kHz/G between adjacent m_F states for both the $F=1$ and $F=2$ manifolds of ^{87}Rb . Depending on the sign of $g_F m_F$, the atoms will seek either high or low magnetic fields, in order to minimise their energy. Maxwell's equations do not allow localised magnetic field maxima in free space. However, it is possible to produce magnetic field minima and hence to trap weak field seeking atoms. We create condensates in the $F = 2, m_F = +2$ level of the ground state, since it is most strongly coupled to the magnetic field and allows for easy optical pumping and imaging. Condensates with ^{87}Rb are also commonly made in the $F = 1$ manifold.

Atomic confinement in a linear quadrupole magnetic trap fails at low kinetic temperatures due to Majorana spin flip losses [17]. The atoms can not adiabatically follow

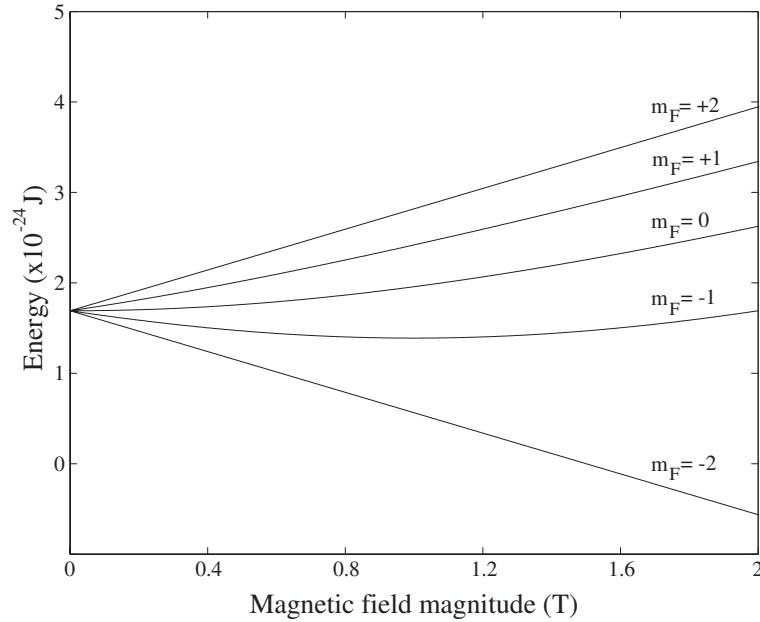


Figure 2.3: The energy levels of ^{87}Rb in the hyperfine state $5S_{1/2}, F = 2$ in the presence of an external magnetic field.

through the zero field point and as a result spin flip to an untrapped state. There are a number of solutions to this problem, the most popular being the time orbiting potential (TOP) trap [18] and the Ioffe-Pritchard (IP) trap [19]. In our laboratory, we use the quadrupole-Ioffe-configuration (QUIC) trap [20], as it is the simplest type of IP trap, consisting of only three coils.

Designing a trap of any type for BEC experiments is a formidable task as many parameters must be balanced and fine tuned in order to obtain a workable system. Considerations such as power dissipation, mechanical stability, optical access and switching times must be combined with the requirement to achieve high geometric trapping frequencies for optimal evaporative cooling and a stable bias field. Stability of the trap bias is especially critical for atom laser studies.

2.7 Evaporative Cooling

Evaporative cooling is carried out by applying rf radiation, resonant with the $m_F = x \rightarrow m_F = x \pm 1$ transitions, to cold atoms in the magnetic trap [21]. The rf radiation follows a frequency sweep to remove the most energetic atoms first. The atoms are coupled to the untrapped and antitrapped states and escape the trapping region. The remaining trapped atoms rethermalise through elastic collisions, thus lowering the temperature of the cloud. The rf frequency is gradually reduced until the temperature drops to the BEC transition temperature. There are several factors which affect the efficiency of the evaporation through heating and loss of atoms. These factors include: 2-body collisions with background atoms, depending on the quality of the vacuum; 2- and 3-body inelastic collisions between the cold atoms, which are dependent on the density and square of the density respectively; and absorption of stray resonant photons. Therefore ultra-high

vacuum and much baffling is needed to create BEC. The amplitude and length of the evaporation sweep, as well as the magnetic trap confinement are adjusted to operate in a regime in which the 2-body elastic collision rate is greater than the inelastic collision rates. In our experiment, the rf radiation followed a 50 s logarithmic sweep from 30 MHz to ~ 200 kHz, depending on the magnetic field bias.

2.8 Calculation of Atom Numbers

Atom numbers N are calculated from absorption images by assuming a closed imaging transition $F = 2, m_F = 2 \rightarrow F = 3, m_F = 3$ and using

$$N = \frac{2\pi}{3\lambda^2} \frac{(\Delta\omega)^2 + (\gamma/2)^2}{(\gamma/2)^2} \left(\frac{p}{M}\right)^2 \Sigma\Phi(x, y) \quad (2.8)$$

where λ is the wavelength of the imaging light, $\Delta\omega$ is the detuning of this light from resonance, γ is the natural linewidth of the imaging transition in angular frequency, p is the pixel size on the CCD camera, M is the magnification factor of the imaging system and $\Sigma\Phi(x, y)$ is the optical depth summed over all pixels [22]. The optical depth for a pixel (x, y) is determined using the Beer-Lambert law

$$I(x, y) = I_o(x, y)e^{-\Phi(x, y)} \quad (2.9)$$

where $I(x, y)$ and $I_o(x, y)$ are the intensities of the detection beam at (x, y) following and before absorption respectively [23].

This calculation assumes a spin polarised sample in the $F = 2, m_F = 2$ state. This is not the case for MOT clouds, for which the actual number is closer to three times that calculated using the equations above.

The Third Incarnation of the ANU BEC Machine

Our laboratory first achieved BEC in 2001. This first machine is described in Jessica Lye's thesis [24]. A major overhaul was undertaken by Nick Robins in 2002 [25]. Among the improvements were a simplified optics setup and a more stable magnetic trap. In order to carry out the experiments described in this thesis, it was necessary to once again significantly overhaul the machine. The main improvement criteria were: to repeatably produce condensates with the same number of atoms at the same temperature; to push the bias field stability into the mG regime; and to improve the computer control system to provide better stability and temporal resolution.

As the first two months of my honours were spent building the aforementioned BEC machine, this chapter outlines the improvements and changes that were made to the system in that time. The machine described in this chapter no longer exists, as the vacuum system broke in late January 2005. However, the design of the new machine, which was still under construction at the time of writing, does not vary greatly from the third incarnation, so most of the improvements described here are still relevant. The style of this chapter is somewhat less formal than the rest of the work contained in this thesis. It is more in the nature of a laboratory journal, as that is the most natural way to communicate the accomplishments of the period of time spent building the machine.

The third generation BEC machine, shown in Figure 3.1, was a double MOT system. The upper MOT had a relatively high background pressure of $\sim 10^{-7}$ torr, controlled by a Rb dispenser. Cold atoms were then transferred to the lower MOT by a push beam. The lower MOT had a background pressure of 8×10^{-11} torr, as obtained from a MOT lifetime measurement. Following polarisation gradient cooling and optical pumping into the ^{87}Rb $F = 2, m_F = 2$ state, roughly 10^9 atoms were transferred into a 144 W QUIC trap with a bias of approximately 0.25 G and trapping frequencies of 20 Hz and 260 Hz in the axial and radial directions respectively. Evaporation was carried out for 50 s, resulting in pure condensates of $\sim 10^5$ atoms.

3.1 Upper MOT and Push Sequence

When I began honours, Nick had already been working on the machine for a few months. In this time he rebuilt the upper MOT using polarising beam splitter cubes instead of plate beamsplitters, instituted a new laser locking scheme and wrote a new Labview interface for the machine.

In order to make BEC, we began optimising the machine from the first point of atom

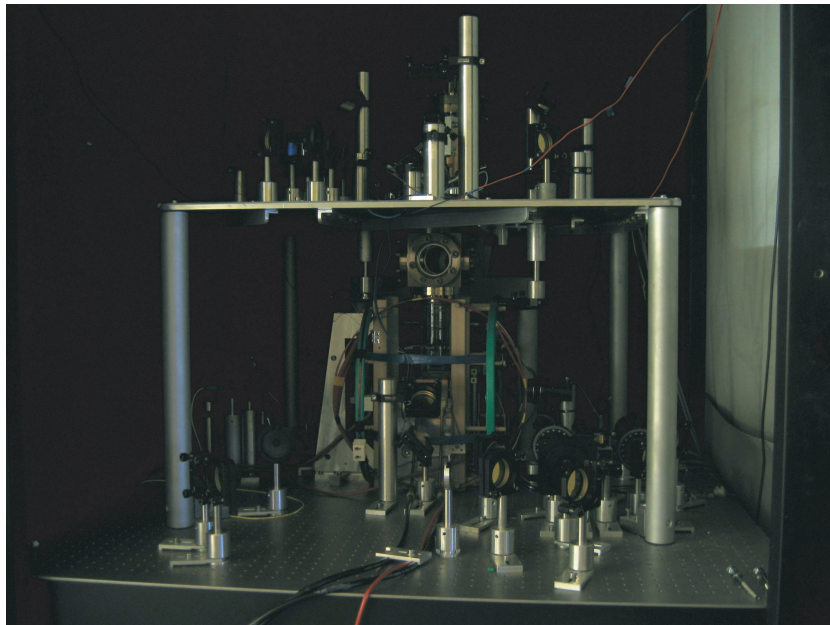


Figure 3.1: The third generation ANU BEC machine.

collection in the upper MOT. In the upper MOT vacuum chamber there were two Rb dispensers. One of these had been in use since 1998, when Jess and the others first began to work towards BEC. We found that by using the other dispenser, we increased the number of atoms in the upper MOT substantially. It is surprising that the first dispenser was still able to produce BEC six years after it was first used, as usually the lifetime of a dispenser is only a few years.

Atoms were transferred from the upper MOT to the lower MOT by switching off the upper MOT (magnetic coils and trapping beams) and switching on a push beam. The combined forces of gravity and absorption from the push beam guided the atoms to the lower MOT. The push beam was misaligned from the centre of the MOT, so as not to blast away the atoms, which had already been established in the lower MOT. After allowing the upper MOT to refill for a short time, this process was repeated. We empirically found that the optimum catch rate occurred for a 1 ms push, followed by a 300 ms load time. This push time is shorter than previously used in our lab (5 ms). The number of atoms in the lower MOT began to plateau after ~ 20 s of loading. This plateau occurs due to the finite lower MOT trap depth, as well as the balance between the loading and loss rates in the lower MOT. We therefore loaded the lower MOT for 100 push cycles.

3.2 Lower MOT and Optics

In order to achieve a high transfer efficiency from the lower MOT to the magnetic trap, we found it was necessary to align the MOT beams very precisely with the magnetic field zero. This was not an easy task, as the three beams and their retroreflected beams had to be aligned to intersect perpendicularly to within less than a mm of each other inside the vacuum system. Two of these beams were diagonally vertical, which means they could not be referenced against the glass cell or table. The only guide was the number of atoms in

the MOT. We tried adding a bias coil, in order to shift the magnetic field zero. However, the bias coil displaced the MOT centre from the quadrupole trap centre and therefore reduced the catch efficiency following polarisation gradient cooling. After spending many days attempting and failing to increase the MOT number by any significant amount, we finally came up with a useful alignment tool. We sent a design to the workshop for a fixed mount for the two diagonal retroreflection mirrors. This mount ensured that these mirrors were at 45° to the table. So long as we aligned both of the diagonal beams so that they bounced back directly overlapping, we knew that they were as close as we could get to 45° and it was simply a matter of shifting the beams back and forth until the MOT number was maximised. We repeatedly measured MOT numbers of 6×10^9 , as compared to 2×10^9 atoms in the second generation machine. Both of these numbers are three times those calculated using Equations 2.8 and 2.9, in order to account for the distribution of atoms across all five Zeeman states, as explained in Section 2.8.

3.3 Magnetic Trap

Magnetic trap switching times must be short so that the catch, following polarisation gradient cooling, into the quadrupole trap is efficient and also so that the atoms do not spin flip during the switch off before imaging, as was the case in the second generation BEC machine. Due to an unclear switch off, all BEC pictures from the old machine had two clouds of atoms - an $m_F = 2$ cloud, as well as an $m_F = 1$ cloud. It is best if the switching time is a lot less than the time scale of the trap.

Originally we had been planning to use a recently purchased Kepco BOP 20-20M (20 A / 20 V) power supply to run the magnetic trap with orders of magnitude improvement in switching times. However, brief testing and a more thorough reading of the manual revealed that the Kepco was not designed to power inductive loads. It switches very quickly ($\sim 25 \mu\text{s}$), but in the steady state regime has noise at 10 kHz, up to 500 mV in amplitude. We tried smoothing the signal with a capacitor in parallel with the power supply, but this added noise to the switching, as well as slowing the switching times considerably.

With no other choice but to use the old power supply (a F.u.G. Elektronik NLN 1400M-35), we spent some time attempting to improve the switching times. We came up with a circuit involving insulated gate bipolar transistors (IGBTs) to ramp different coils in and out of the circuit. Figure 3.2 shows the final magnetic trap circuit, which is also used in the current machine.

The IGBTs are effectively variable resistors. With a high voltage input, they allow current to flow through them with very little resistance. With a low voltage input, they have very high resistance and no current flows. At the start of an experimental run, IGBT A is high and IGBT B is low, allowing current to flow through the quadrupoles, but not the ioffe coil. After the MOT is loaded, the solid state switch is used to switch the quadrupoles off for optical pumping and on again for the transfer to the QUIC trap. The transfer sequence consists of a slow sinusoidal ramp on of IGBT B, followed by a slow sinusoidal ramp off of IGBT A. This process takes about 1 s in total. The diodes allow for a fast switch off by reducing the eddy currents in the coils. The zener diodes across the two sets of coils have been adjusted so that the coils switch off with approximately the same time scales. The switch on time for the quadrupoles is < 1 ms with no significant oscillations. This is a large improvement on the previous trapping circuit, which had a switch on time of ~ 5 ms with oscillations up to 100 ms later. The switch off time of the ioffe trap is the same as previously ($\sim 500 \mu\text{s}$) and is limited by the diodes.

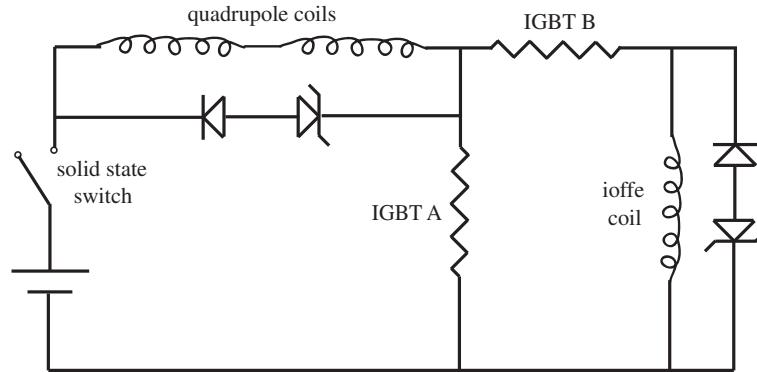


Figure 3.2: The magnetic trap circuit.

One significant problem with the magnetic trap in the second generation machine was heating. Heating causes the bias field to drift, reducing the stability of the trap for outcoupling. The coils in our experiment, which are still being used in the current machine, are mounted on water cooled copper blocks. Unfortunately, due to a mistake by the workshop, the coil mounts were glued to the copper blocks with *insulating* glue, instead of being welded. In the old machine and for the first two months of running the third generation machine, the copper blocks were cooled with the Physics Department water system. The temperature and pressure of this water supply fluctuate wildly throughout daytime hours, changing the temperature of the trap coils. We noticed a strong correlation between machine stability and local water use. For this reason, Nick could only operate the old machine between 2 am and 9 am and for the first two months of the third generation machine, we could only run experiments before 11am or at night. Therefore one of the most important changes we made to the third generation machine was the installation of recirculating water chillers. With the trap no longer reliant on the external water pressure, we found that we could run the machine at any hour of the day. In addition, there are the obvious environmental benefits of recirculating the water.

Another major improvement, which we made to reduce the heating, was to reduce the trap current from 25 A (700 W) to 12 A (144 W). High currents have traditionally been used in magnetic traps for making BEC, in order to increase the density sufficiently for efficient evaporative cooling. Running at high current at one stage, before the purchase of the water chillers, the ioffe coil heated up to such an extent that it began to burn and cracks formed between the wires. Following this incident and failed attempts at reducing the temperature of the coil in a cost efficient manner (we tried various air cooling techniques), we had no choice but to reduce the current. We were able to do this by shifting the ioffe coil away from the trap centre and extending the evaporation length to 50 s. The resultant trap has trapping frequencies nearly identical to those of the old trap: 20 Hz in the axial direction and 260 Hz in the radial direction. The bias is only 0.25 G. We measure a drift of significantly less than 0.7 mG over 8 hours.

Atom Lasers

4.1 An Analogy with Optical Lasers

4.1.1 Definition of an ‘Atom Laser’

The term ‘atom laser’ has become widely used in the last decade and it is therefore important to have a rigorous definition of what actually constitutes an atom laser. Such a definition was given by Wiseman in 1997 [26]. A generalised ‘laser’ is a device containing a highly populated mode of a boson field, known as the laser mode. The laser mode is continuously replenished, so that the output continues indefinitely. Damping (via some outcoupling mechanism) forms an output beam, which is well approximated by a classical wave of fixed amplitude and phase. This definition leads to four conditions on the output beam; it must be highly directional and monochromatic, as well as having well defined phase and intensity.

The directionality of a laser clearly defines a longitudinal direction, along which dispersion may occur, and two transverse directions, along which diffraction may occur. The directionality condition does not imply that the laser output must travel in free space. Waveguides, such as fibres, are often used for optical lasers. A waveguide may prove to be useful for atom lasers to prevent spreading due to diffraction and also to support against gravity [27].

Wiseman’s second condition is that of monochromaticity. This condition imposes a limit on the spread of the longitudinal spatial frequency of the output such that $\delta k \ll \bar{k}$, where k is the wave vector of a boson in the output. This can also be expressed in terms of the coherence length $\ell_{coh} = (\delta k)^{-1}$, as $\ell_{coh} \gg \lambda$, where λ is the wavelength of the bosons.

Well defined phase implies that the phase fluctuations in the output beam must be small. This condition can be expressed quantitatively using Glauber’s normalised coherence functions [28]. The n^{th} order coherence function is a measure of difference between $2n$ points in spacetime of a field. The normalised first order coherence function is defined as

$$g^{(1)}(\tau) = \frac{\langle a^\dagger(t+\tau)a(t) \rangle}{\langle a^\dagger(t)a(t) \rangle} \quad (4.1)$$

where $a(t)$ is the complex amplitude of the field. It is related to the linewidth, Γ , by

$$\frac{1}{\Gamma} = \int_0^\infty |g^{(1)}(\tau)| d\tau. \quad (4.2)$$

An ideal first order coherent source has $g^{(1)}(\tau) = 1$ and therefore an infinitely narrow linewidth. Wiseman’s condition of well defined phase can therefore be reformulated as requiring approximately first order coherence.

The final condition, which a laser beam must satisfy, is that of well defined intensity. Like the last condition, this can also be expressed in terms of coherence functions. The second order normalised coherence function is given by

$$g^{(2)}(\tau) = \frac{\langle : I(t + \tau) I(t) : \rangle}{\langle I \rangle^2} \quad (4.3)$$

where I is the intensity of the field and $\langle : \rangle$ denotes normal ordering (i.e. all creation operators to the left of all annihilation operators). For fields that are second order coherent, $g^{(2)}(\tau) = 1$ and the only intensity noise contribution is quantum noise (ie. shot noise).

It has been shown that atom lasers have well defined phase, ie. that $g^{(1)} \approx 1$ [29]. This experiment is described later in Section 4.5. Second order coherence has not yet been demonstrated for atom lasers. However, Bose-Einstein condensates have been shown to be second order coherent [30] and therefore there is a strong indication that, even without pumping, atom lasers will have second order coherence. However pumping is needed to make atom lasers useful. A pumped atom laser will have higher flux, reduced linewidth and will be truly continuous.

Note that the definition given above excludes pulsed lasers. However, the creation of a pulsed atom laser is relatively simple, requiring only that a number of separately formed condensates be released from a trap in succession. The usage of the term atom laser in the literature, since Wiseman's article, has not followed his definition. Instead, the term has been widely used for beams outcoupled from condensates, which may or may not be pulsed and for which the condensate (ie. the lasing mode) is not continuously replenished. For consistency with the literature, I use the term 'atom laser' for any atom beam which satisfies Wiseman's four conditions above, but which is not necessarily extracted from a replenished BEC. I interchangeably use the terms 'pumped atom laser' and 'truly continuous atom laser' to refer to atom lasers which are outcoupled indefinitely from a replenished condensate source.

4.1.2 A Simple Physical Comparison

An optical laser is easily understood on the simplest level by considering its physical components. A generalised optical laser is shown in Figure 4.1.

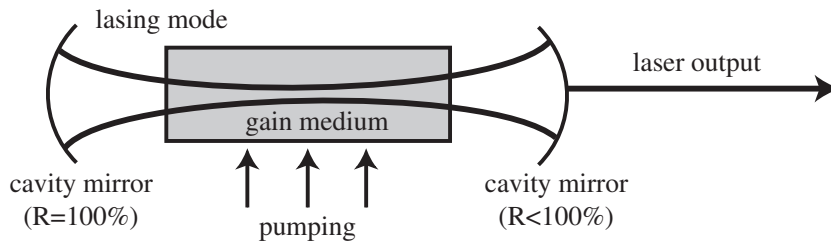


Figure 4.1: The mechanical components of an optical laser.

An optical laser consists of a cavity with one or more resonant modes. Within this cavity there is a gain medium, usually in the form of an atomic or molecular sample. The gain medium is pumped by some source of energy. The pumping sustains a population inversion in the gain medium, thereby coherently amplifying the lasing mode via stimulated emission. If the losses in the cavity are low, the lasing mode may build up to extremely

high amplitudes. One of the cavity mirrors is partially transmitting, allowing a small amount of the lasing mode to leak out into the laser beam.

To aid understanding of an atom laser on the simplest level, it is beneficial to compare its physical components with those of an optical laser. The physical elements of an atom laser are depicted in Figure 4.2. Just as the lasing mode in an optical laser is a source of monochromatic and coherent photons, the BEC is a source of monochromatic, coherent atoms for an atom laser. Both the lasing mode and BEC contain multiple populated modes. However, one of these modes is macroscopically populated with a large number of bosons. In an optical laser, the lasing mode is held within a cavity, while for an atom laser, the BEC is constrained by a either a harmonic magnetic or optical potential. Various outcoupling mechanisms, which are described later in this chapter, correspond to the output mirror of an optical laser. To date, no pumping mechanism has been experimentally demonstrated in conjunction with an atom laser. Theoretical proposals and experimental advances towards a truly continuous atom laser are presented in the following section.

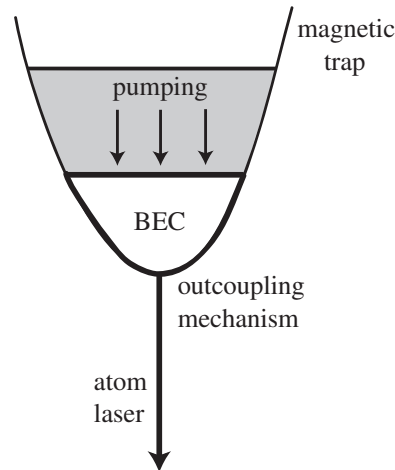


Figure 4.2: The elements of an atom laser.

4.2 The Pumped Atom Laser

The current state of the art atom laser is the equivalent of an optical laser, which has had the pump switched off and is merely draining the cavity reservoir. In order to produce a truly continuous atom laser, a method to continuously replenish the condensate is required, which does not disturb the outcoupling mechanism or the coherence properties of the condensate. One such pumping scheme would be to continuously evaporate from a thermal cloud surrounding a condensate, whilst also continuously replenishing the thermal cloud with cold atoms.

Such a scheme is difficult to implement experimentally for two reasons. Firstly it is not straight forward to replenish the thermal cloud without disturbing the BEC. All processes along the route to BEC thus far are non-continuous. First, atoms are collected in a MOT, cooled via polarisation gradient cooling, then optically pumped into a single magnetic

sublevel, transferred to a magnetic trap and finally, evaporatively cooled to the transition temperature, as detailed in Chapter 2. Not only are all of these processes non-continuous, but they also produce stray resonant photons and magnetic fields. The resonant photons would heat and destroy a BEC [31] and any time dependent stray magnetic fields would make any state-changing outcoupling mechanisms extremely difficult to employ. Several possible solutions to the problem of continuously loading a trap have been proposed and are discussed in Section 4.2.1. The second technical difficulty with pumping by continuously evaporating from a surrounding thermal cloud is due to the traditional methods of evaporation and outcoupling being incompatible. The same rf transition is used for evaporative cooling as is used to outcouple atoms into the atom laser beam. Therefore an outcoupled atom passing through the evaporation shell will have some probability of being spin flipped either back into a trapped state or into an antitrapped state. This situation is depicted in Figure 4.3. The problem may be solved by using a Raman transition for evaporation. In this way, the evaporation shell may be spatially selected, such that the outcoupled atoms do not pass through the evaporation shell. For example, a pair of overlapping vertical Raman beams with a dark spot in the centre would satisfy this requirement. Another problem with this pumping scheme is that thermal atoms would also be outcoupled into the atom laser, adding noise to the beam.

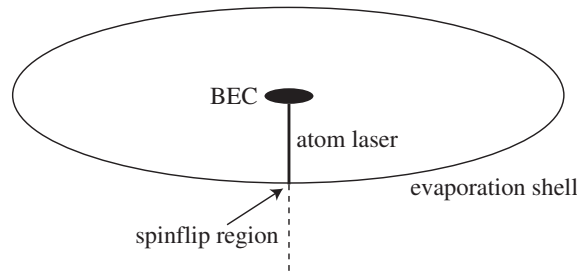


Figure 4.3: Illustration showing how an outcoupled atom may be spin flipped out of the atom laser by the evaporation field.

4.2.1 Continuous Loading of a Trap for BEC

There has been one experimental demonstration of a ‘continuous’ BEC by Ketterle’s group at MIT [32]. The condensate they produced was not truly continuous, but rather was replenished periodically in a non-coherent manner. For this reason, without significantly more work, it is not a useful method of replenishing a BEC for pumped atom laser experiments. A first BEC was created and translated to a separate chamber for storage. A second BEC was then created and merged with the first using moving optical tweezers. This process was repeated several times for demonstration of its ‘continuous’ nature. Before merging, the two condensates had random relative phases. Therefore the phase of the first condensate was altered by the merging process. The size (and therefore density) of the condensate also varied with each merging event. After merging, the resultant BEC consisted of 2.3×10^6 atoms. During the 18 s interval before the next condensate arrived for merging, the BEC decayed to 1.0×10^6 atoms. These phase and intensity fluctuations would be passed on to the atom laser beam, eliminating its first and second order coherence. It has been suggested that the phase fluctuations could be fixed with phase

coherent amplification [33, 34] and the intensity fluctuations with a feedback scheme [35]. However, the technical solutions employed in this experiment for solving the problems of stray resonant light and magnetic fields are not solutions that could be used for a pumped atom laser. In order to avoid stray light, a mechanical shutter inside the vacuum system was used. The shutter was closed during the MOT sequence and opened for merging of the condensates, which is obviously not a continuous solution. In addition, outgassing through this shutter into the UHV environment limited the lifetime of the BEC. To avoid stray magnetic fields, an optical dipole trap was used. However for the state-changing outcoupling mechanisms discussed in this thesis, a magnetic field is needed to separate the Zeeman levels. An alternative to state changing outcoupling mechanisms would be to use a $2n$ photon optical transition in an optical trap. This would outcouple by giving the condensate atoms a momentum kick sufficient to escape the optical potential, but no change in Zeeman energy would be necessary. Therefore a bias field would not be required to separate the Zeeman levels. In this case however, a constant magnetic field is needed to ensure that the stray fields do not cause precession of the atomic spin, yet the stability of this field may be much less than that of a field used to separate the Zeeman levels for outcoupling.

There have been a couple of other experimental demonstrations of the continuous loading of cold atoms into a trap. One such method was the continuous loading of a magnetic trap from an overlapping MOT via a dark metastable state in chromium [36]. However, the temperature of atoms in the magnetic trap was limited by inelastic collisions with MOT atoms and therefore it would not be possible to create BEC in such a trap. Also, the scheme is not directly transferable to alkali atoms, in which BEC has already been demonstrated, due to differences in level schemes.

Another demonstration of continuous loading of a magnetic trap was carried out well before the advent of BEC [37]. Using time varying magnetic fields, an AC trap for high field seeking atoms was created. In the absolute ground state of an atom, the spin alignment is parallel to the magnetic field and therefore the atom is high field seeking, whereas low field seeking atoms, which are customarily trapped, have their spin anti-aligned with the magnetic field. Since the AC trap confines atoms in the absolute minimum energy state, the trapped atoms do not experience 2-body losses like those in traditional low field traps. In this experiment, pulses of atoms from a MOT were repeatedly thrown towards the magnetic trap. Upon reaching the magnetic trap, the atoms were optically pumped into the lowest energy state. Once in the lowest energy state, the atoms were out of resonance with the optical pumping light and remain trapped. This method is not directly suitable for creating continuous atom lasers using state changing outcoupling mechanisms, due to the time varying nature of the magnetic trap. However, a similar scheme, utilising optical pumping to transfer atoms into a magnetic trap, could be used with a conventional magnetic trap for atoms in a low field seeking state.

Another method, currently being developed for continuously loading a magnetic trap for creating pumped atom lasers, utilises an evaporatively cooled atomic beam. As explained in the following section, this evaporatively cooled atomic beam has also been proposed as a continuous atom laser in its own right.

4.2.2 Continuous Evaporation in a Magnetic Guide

Another experimental investigation on the path to creating a pumped atom laser is currently being carried out in Dalibard's group at l'École Normale Supérieure (ENS) in

Paris [38, 39, 40], as well as in Raithel's group at the University of Michigan [41]. Here we shall describe the ENS proposal. The novel method injects a cold atomic beam into a 4.5 m long magnetic guide. A sequence of rf antennas are situated along the magnetic guide to evaporatively cool the atoms. The magnetic guide has a decreasing cross-section to further increase the density of the atom beam as it is cooled. However, as it is not possible to achieve condensation in one dimension, no macroscopic occupation of a single quantum state of the longitudinal motion will occur. Local transverse condensation will occur, but there will be no large scale longitudinal phase coherence. Therefore the output will not be a true 'atom laser', according to the definition given in Section 4.1.1. The current ENS experiment uses pulsed loading from a moving molasses MOT (similar to a 2D-MOT) to load the magnetic guide. The pulsed method is necessary to achieve a high loading rate. However, at a pulse rate of 3.5 Hz, the wavepackets overlap after 60 cm to form a continuous beam with a flux of 7×10^9 atoms/s. The latest paper reports that the two antennas currently in place along the magnetic guide have achieved a large elastic collision rate, significantly increasing the phase-space density of the beam. However, it is estimated that forty such antennas will need to be installed along the magnetic guide to reach degeneracy. The current length of magnetic guide is unlikely to be sufficient for the atoms to undergo condensation.

However, a solution that is being considered for this system is to use the evaporatively cooled atomic beam as a source to continuously replenish a magnetically trapped condensate situated at the end of the 4.5 m magnetic guide. A theoretical proposal of this scheme is presented in [42]. It is shown that an incident beam may be trapped in a potential when collisions with previously trapped particles occur. If an incident particle undergoes an elastic collision with a trapped particle, it may lose energy, causing it to remain trapped in the potential. The excess energy will be redistributed and may be released through evaporation. A steady state may be found, for which the evaporation rate and the rate of arrival of new particles are equal. Furthermore, a resonance exists when the transverse evaporation threshold (for an elongated trap) coincides with the energy of the incident particles. The resonance results in a dramatic increase in the phase-space density of the trapped atoms. This scheme seems to be a good solution to the problem of replenishing the thermal cloud without disturbing the condensate, in order to achieve a continuous source of BEC.

With the use of the ENS system presented above or a similar one, it may be possible to realise a pumped atom laser in the near future. The continuous, evaporatively cooled atomic beam source solves the problem of the non-continuous nature of the processes usually employed to achieve BEC. The great length of the magnetic guide eliminates stray magnetic fields. Resonant photons are also greatly reduced by the length of the tube. It has been suggested that a curved magnetic guide would further reduce the number of resonant photons reaching the condensate.

4.2.3 An Alternative Method

Another method, which is not quite of the truly continuous nature, but which may still create atom lasers useful for applications, is to create an extremely large BEC to use as a source for atom lasers. Using buffer gas cooling [43], Doyle's group at Harvard University proposes to make condensates with more than 10^{10} atoms.

4.3 Non-State Changing Outcoupling

The majority of demonstrated outcoupling mechanisms have involved coupling atoms held in a magnetic potential from a trapped magnetic sublevel to an untrapped sublevel. Such mechanisms are described later in this chapter. However, there have been two examples of non-state changing outcoupling, which we shall describe first.

The first of these was a quantum tunneling effect demonstrated by Anderson and Kasevich [7]. In this experiment, a condensate was loaded into the top of a vertical array of optical traps, formed by a standing wave. Tunneling between traps was induced by acceleration due to gravity. Constructive interference between lattice sites resulted in macroscopic falling pulses of atoms. The size of the pulses was adjusted by altering the depth of the optical wells. In the limit of low density, mean field interactions may be ignored and the frequency of the pulses, $\omega = \frac{mg\lambda}{2\hbar}$, is simply determined by the gravitational potential difference between lattice sites. It was found that for densities $n > 10^{13} \text{ cm}^{-3}$, the mean field interaction was large enough to cause significant dephasing between lattice sites. For large densities, degradation of the interference was observed. The limitations of this novel form of atom laser, namely that it is inherently pulsed and that the density of these pulses is limited, mean that it is not likely to be considered further in the development of a pumped atom laser.

A second unconventional form of atom laser was also produced using optical methods [8]. A single spin state condensate was produced in a strongly focused optical trap by applying a magnetic field gradient stronger than the transverse optical confining force. The field gradient removed all atoms except those in the magnetically insensitive $m_F = 0$ state. It is desirable to create atom lasers in states insensitive to magnetic fields, so that the beam direction and energy is not affected by stray magnetic fields. Due to a small MOT (6×10^7 atoms), the condensate had only 7000 atoms in the $m_F = 0$ state. From such a condensate, an atom laser was produced by smoothly lowering the optical trapping potential. Atoms from the condensate fell out of the trapping region under gravity, producing an atom laser up to 1 mm long (~ 15 ms). The flux of the atom laser was well below that which has been produced using rf outcoupling. However, this is probably due to the small number of atoms in the condensate. The benefits of this scheme are that the outcoupling is not limited by the stability of magnetic fields. The down side to this is that the outcoupling is dependent of the laser intensity fluctuations. However, currently it is technically easier to intensity stabilise a laser than it is to eliminate stray magnetic fields and produce a highly stable magnetic trap. The issue of magnetic fields is important for the realisation of a truly continuous atom laser, as the production of cold atoms to replenish the condensate requires the use of magnetic fields. However, this outcoupling method could not be extended to a pumped atom laser. A thermal cloud is required to replenish the condensate, but the strong magnetic field gradient and shallow optical potential used in this demonstration would not allow for the confinement of a thermal cloud.

4.4 The Resonant Width of the Condensate

The ground state of alkali atoms is split into two hyperfine states, as shown in Figure 2.1. In a magnetic trap, ^{87}Rb condensates can be made in either the $F = 1, m_F = -1$ state or the $F = 2, m_F = 2$ state. Various one and two, and even four photon transitions exist for transferring atoms from the magnetically trapped condensate state to an untrapped (usually $m_F = 0$) atom laser state. These include rf transitions between the Zeeman

states of a single hyperfine level, microwave transitions between the two hyperfine levels and Raman coupling between Zeeman states via a higher, optically spaced level. All of these outcoupling mechanisms are dependent on the energy spacings of the Zeeman states, which depend on the magnetic field.

Without gravity, the resonance condition for any state changing outcoupling mechanism would be satisfied on an ellipsoid of constant magnetic field. However, gravity introduces a sag, which displaces the condensate from the magnetic field minimum. The displacement is easily found by equating the downwards force of gravity, $F_g = mg$, with the upwards force due to the magnetic field minimum, $F_{mag} = \frac{dV}{dz} = m\omega_\rho^2 z$, to give $z_{sag} = g/\omega_\rho^2$, where z_{sag} is the displacement from the centre of the magnetic field minimum and ω_ρ is the angular radial trapping frequency. For our trap, $z_{sag} = 3.5 \mu\text{m}$. Outcoupling will therefore occur at the intersection of the displaced condensate with the surface of an ellipsoid of constant magnetic field as shown in Figure 4.4.

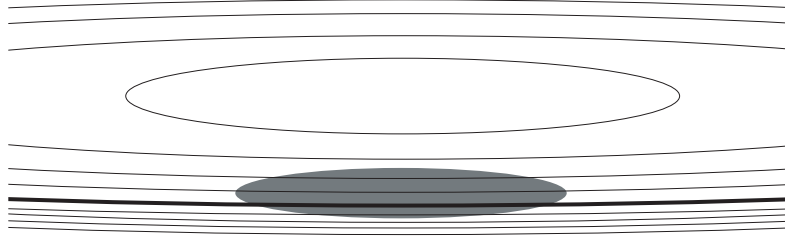


Figure 4.4: The sag of the condensate due to gravity, viewed perpendicular to the weak trapping axis. The grey ellipse represents the condensate and the contour lines show magnetic field magnitude, which increases away from the central minimum. The outcoupling frequency is depicted by the thick, black line.

In order to calculate the spatial range, over which outcoupling may be expected, the resonant width of the condensate must be determined. In the Thomas Fermi approximation, which assumes that the kinetic energy may be ignored as it is a lot less than the interaction energy [44], the size of the condensate in the vertical direction is

$$2R_{TF} = 2\sqrt{\frac{2\mu}{m\omega_\rho^2}}. \quad (4.4)$$

For typical condensates described in this thesis, $2R_{TF} = 5.2 \mu\text{m}$. The displacement of the upper and lower edges of the condensate from the magnetic field minimum are therefore given by $z_l = g/\omega_\rho^2 + R_{TF}$ and $z_u = g/\omega_\rho^2 - R_{TF}$. To second order, the magnetic field is given by $B = B_o + B_z'' z^2/2$, where $B_z'' = \frac{m\omega_\rho^2}{g_F m_F \mu_B}$. The resonant width for the $m_F = 2$ state is therefore given by

$$\Delta\nu_{BEC} = \frac{g_F \mu_B}{h} (B_l - B_u) = \frac{m\omega_\rho^2}{2hm_F} (z_l^2 - z_u^2) = \frac{g}{h\omega_\rho} \sqrt{2m\mu} \quad (4.5)$$

for which μ may be found using Equation 2.5. For typical condensates made in our lab, $\Delta\nu_{BEC} = 5.5 \text{ kHz}$.

4.5 Radio Frequency Outcoupling

This section gives some background theory for rf outcoupling as well as reviewing the relevant literature.

The transition used for rf outcoupling is that between adjacent Zeeman levels. For $F = 1$ condensates, only one photon is needed to couple atoms to the untrapped $m_F = 0$ state, whereas for $F = 2$ condensates it is a two photon process. This is also the transition that is used for evaporative cooling.

For pulsed rf outcoupling of pulse duration, τ , the frequency of the pulse is broadened such that the frequency width of the pulse is given by

$$\Delta\nu_{rf} = \frac{2}{\tau} \quad (4.6)$$

as shown in [23]. For sufficiently short pulses, outcoupling will therefore occur over a large spatial region and the energy spread of the atom laser will be large. For pulsed outcoupling with $\Delta\nu_{rf} > \Delta\nu_{BEC}$, the outcoupling process is not spatially selective and is therefore largely insensitive to magnetic field fluctuations. Continuous outcoupling (defined below) produces a more collimated atom laser, but is more technically difficult as the magnetic field fluctuations must be less than the frequency width of the outcoupling. For a Rabi frequency (also defined below) of 1 kHz, the magnetic field fluctuations must be roughly less than 1 mG.

The dynamics of pulsed and continuous atom lasers are determined by the Rabi frequency. For rf outcoupling, the angular bare Rabi frequency (hereafter referred to as simply the ‘Rabi frequency’) is given by

$$\Omega = \frac{g_F \mu_B B_{rf}}{2\hbar} \quad (4.7)$$

where B_{rf} is the applied magnetic field amplitude. For long duration outcoupling, the frequency width $\Delta\nu_{rf}$ is approximately equal to the Rabi frequency, due to power broadening. Pulsed outcoupling is defined here as the regime for which the energy width of the outcoupling region is determined by the duration of the pulse. In a complementary manner, continuous outcoupling is defined as the regime for which the energy width is determined by power broadening. For typical condensates in our laboratory, outcoupling is pulsed for $\tau < 350 \mu\text{s}$ and continuous for $\tau > 350 \mu\text{s}$.

A pulsed rf outcoupler was first demonstrated by Ketterle’s group at MIT in 1997 [9]. Up to five short ($5 \mu\text{s}$) pulses of rf were applied. Since only short pulses were used, broadband outcoupling occurred over a wide range of frequencies and hence in a large spatial region. From sodium condensates in the $F = 1, m_F = -1$ state, coupling was demonstrated into both the untrapped $m_F = 0$ state and the antitrapped $m_F = 1$ state. Rabi cycling between the three levels was demonstrated by plotting out the populations in each of the three states against increasing Rabi frequency.

Following on from this, Esslinger’s group at the Max-Planck-Institut für Quantenoptik demonstrated the first continuous rf outcoupling in 1999 [10]. Using weak rf amplitudes of $B_{rf} = (0.2 - 2.6) \text{ mG}$, atom lasers of up to 100 ms were produced. As mentioned above, continuous outcoupling requires small magnetic field fluctuations for repeatable outcoupling. By positioning the magnetic trap within a μ -metal box and using a stable current supply ($\Delta I/I < 10^{-4}$), Esslinger’s group reduced the fluctuations of the trapping field to below the 0.1 mG level. The estimate of the atom laser flux was $5 \times 10^6 \text{ atoms/s}$.

With a definition of ‘brightness’ as the integrated flux of atoms per source size divided by the velocity spreads in each dimension, it was shown that a continuous rf atom laser can be at least six orders of magnitude brighter than any previous atom source. The decay of the condensate with increasing Rabi frequency was plotted, but the distribution of atoms in the untrapped and antitrapped states was not shown. The resonant width of the BEC was also measured and was found to roughly agree with the expression, based on the Thomas-Fermi approximation, given in Equation 4.5.

The first evidence of the first order coherence of an rf outcoupled atom laser was given by Ketterle’s group [45]. By outcoupling from two separate, but phase related condensates, they were able to observe interference between the two overlapping atom lasers. Later, Esslinger’s group showed the first order coherence of an atom laser by outcoupling from a single BEC with two different rf frequencies [29]. This created an atom laser with two separate frequency components, outcoupled from two spatially separated regions in the condensate, resulting in an interference pattern between the two matter waves. The long range, high contrast interference pattern clearly demonstrates the first order spatial coherence of the atom laser beam.

The first order temporal coherence of an atom laser beam was also demonstrated by Esslinger et al., in 2001 [46]. An rf outcoupled atom laser was reflected from a linear magnetic potential, thereby creating a standing matter wave structure. The interference of the reflected front end of the atom beam with the back end was observed to study phase fluctuations in the time domain. Due to the small spatial structure of the interference ($\sim 1/5$ the size of the wavelength of the ^{87}Rb resonance), it could not be measured optically, so a one dimensional magnetic resonance imaging technique was employed. Three series of data were taken with different outcoupling durations (up to 1.5 ms) and it was found that the interference contrast increased for increasing outcoupling duration. This led to the conclusion that the measured linewidth was Fourier limited by the outcoupling duration, as well as by the detection resolution. The measured linewidth for the atom laser was (700^{+400}_{-250}) Hz, which gives an upper limit on the temporal phase fluctuations of the atom laser. In conclusion, they found that outcoupling preserves the first order temporal coherence of the atom laser.

Atom laser divergence was investigated by Aspect’s group at the Laboratoire Charles-Fabry de l’Institut d’Optique in 2001 [47]. The possible sources of divergence in an atom laser that are likely to be significant are diffraction, magnetic lensing and the mean-field interaction between the condensate and atom laser. In order to study the effect of the mean-field interaction, the angular divergence was measured as a function of the thickness of the condensate, which had to be crossed by the outcoupled atoms. This was done by varying the outcoupling frequency, which selects the vertical point of extraction. Their experimental results and supporting theory showed that the mean-field interaction was the dominant source of divergence. As the outcoupled atoms fall through the condensate, the mean-field energy of the condensate is converted into kinetic energy. In cylindrical magnetic traps, which are most common in BEC experiments, the density of atoms in the radial directions is much greater than that in the axial direction. Due to this asymmetry, the divergence of the atom laser is much greater in the direction of the tight axis than in the direction of the weak axis. Images are traditionally taken in a plane parallel to the weak axis, thus measuring the smallest divergence. Aspect’s group found that the minimum divergence of their atom laser was 6 mrad. This is a similar result to Esslinger’s group, whose atom laser divergence was measured to be 3 mrad.

In 2002, Esslinger’s group demonstrated a continuous detection method for atom

lasers [48]. The method involved coherent coupling of the atoms via a Raman transition from the atom laser state in the lower hyperfine manifold to the upper hyperfine manifold, followed by the usual absorption imaging process. A temporal resolution of $260 \mu\text{s}$ was achieved and the detection was nondestructive for the condensate and atom laser outside the detection region. This real time detection could prove to be useful for accurate measurements of atom laser flux, as well as for feedback schemes.

4.6 Raman Outcoupling

A second state changing outcoupling mechanism utilises a Raman transition to produce an atom laser with an initial momentum kick in any chosen direction. The scheme is based on the absorption and stimulated emission of photons from two laser beams. The simplest case is a two photon transition in the $F=1$ manifold, as shown in Figure 4.5. An atom in the trapped $m_F = 1$ state absorbs a photon from one beam with frequency ω_1 and emits into the other beam with a frequency ω_2 . A small frequency difference $\delta = \omega_2 - \omega_1$ between the two lasers and a correct choice of polarisations (one beam with σ^- and the other with π polarisation) results in the atom being coupled to the $m_F = 1$ state.

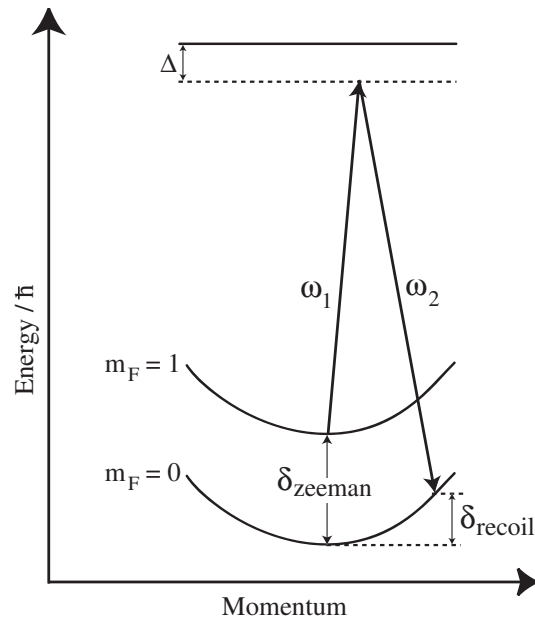


Figure 4.5: Schematic showing the restrictions of energy and momentum conservation on a two photon Raman transition in the $F=1$ manifold. The parabolas correspond to the kinetic energy of the atoms, equal to $\frac{P^2}{2M}$.

The transition must be highly detuned to eliminate any population in the upper state and to thereby suppress spontaneous emission. For large detunings, it is not possible to make two photon $\Delta m_F = 2$ transitions (i.e. directly from $m_F = 2 \rightarrow m_F = 0$ in the $F=2$ manifold). This fact is not widely known and is explained in Section 6.3. However, it is possible to make $\Delta m_F = 2$ transitions with four photons, as shown in Figure 4.6.

A Raman outcoupled atom gains a momentum kick upon absorption and emission of each photon. Considering just one two photon Raman transition, simple momentum

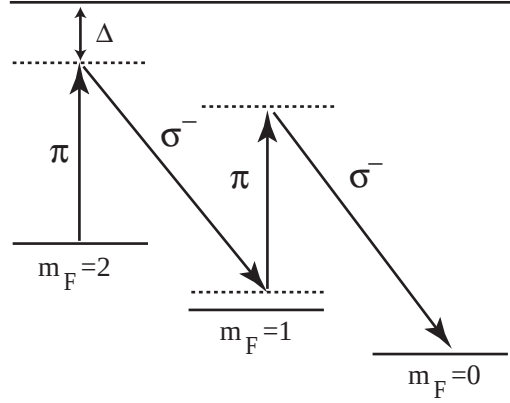


Figure 4.6: The four photon Raman outcoupling scheme in the $F=2$ manifold.

conservation requires that, for two laser beams with wavevectors k (assuming $\delta \ll \omega$) and separated by an angle θ , the atom gains momentum

$$P = 2\hbar k \sin\left(\frac{\theta}{2}\right). \quad (4.8)$$

Obviously the momentum will be maximum for counter-propagating laser beams. Energy conservation requires that the difference in Zeeman energy between the two states is equal to the recoil energy of the atom plus the energy difference between the two laser beams:

$$g_F(\Delta m_F)\mu_B B = \frac{P^2}{2M} + \hbar\delta. \quad (4.9)$$

Combining the energy and momentum conservation equations for $\Delta m = 1$ results in the following resonance condition,

$$\frac{\mu_B B}{2} = \frac{2\hbar^2 k^2 \sin^2(\frac{\theta}{2})}{M} + \hbar\delta. \quad (4.10)$$

For the four photon transition, the outcoupled atoms end up with twice the momentum, $P = 4\hbar k \sin(\frac{\theta}{2})$. This results in the following resonance condition for the frequency difference between the two laser beams,

$$\frac{\mu_B B}{2} = \frac{4\hbar^2 k^2 \sin^2(\frac{\theta}{2})}{M} + \hbar\delta. \quad (4.11)$$

The two photon resonance condition is no longer satisfied, so we would expect less coupling to occur to the intermediary $m_F = 1$ state, and similarly to the antitrapped states. However, depending on the width of the condensate and the width of the Raman transition, coupling to the intermediary state may still occur.

One of the main benefits of Raman outcoupling compared with rf outcoupling is the well defined, tunable momentum. The Raman scheme allows the production of an atom laser in any direction with any value of initial momentum between $(0 - 4)\hbar k$. The Raman outcoupling scheme dramatically reduces the transverse momentum width of the atom laser compared with rf outcoupling. As explained previously, Aspect's group found that the main source of divergence in atom lasers is the expansion due to the mean field

repulsion of the condensate. This causes an isotropic momentum spread in the extracted atoms. The momentum kick imparted to the Raman outcoupled atoms allows them to leave the condensate region faster than the rf outcoupled atoms, which merely fall under gravity. As a result of the reduced interaction time with the condensate, the momentum spread is smaller than in the rf case. Therefore Raman outcoupling produces a more collimated atom laser.

As a lead up to Raman outcoupling, the techniques of Bragg diffraction were developed [49, 50]. Bragg diffraction can be viewed as a Raman transition between two different momentum states. Unlike Raman outcoupling, the Bragg process does not change the internal magnetic state of the atom. Bragg diffraction was used to investigate various properties of condensates, including measurements of mean-field energy, intrinsic momentum uncertainty and coherence length.

The first and only demonstration of Raman outcoupling was by Phillips' group at NIST in 1999 [11]. They used a time orbiting potential (TOP) trap, which meant that the resonance condition was only satisfied for small time intervals when the magnetic field was the correct value for outcoupling to occur. Therefore they were limited to pulses of maximum 14 μ s duration and could not demonstrate a continuous Raman atom laser. Using two nearly counter-propagating Raman lasers, both two photon ($\Delta m_F = 1$) and four photon ($\Delta m_F = 2$) outcoupling was demonstrated in the $F = 1$ manifold of sodium. The Raman lasers were detuned 1.85 GHz from the upper level to suppress spontaneous emission and the laser intensities were varied up to 300 mW/cm². Due to the pulsed nature of the experiment, stability of the magnetic field, laser intensities, detuning and the frequency difference between the lasers was not an issue.

In 2001, Esslinger's group studied the optical manipulation of a ⁸⁷Rb atom laser, using the same techniques as utilised in Raman outcoupling [51]. By changing the magnetic state of the atom laser beam, they were able to demonstrate reflection, splitting, focusing and storage in a resonator. The apparatus consisted of two horizontal, co-propagating laser beams placed below the condensate. An rf outcoupled atom laser in the $F = 1, m_F = 0$ state passing through the two Raman beams was spin flipped into the $F = 2, m_F = 1$ state, which accelerated upwards due to the magnetic field gradient. No momentum transfer took place, due to the co-propagating nature of the lasers. By changing the intensity of the lasers, they were able to reflect varying fractions of the atom laser beam. In order to satisfy the resonance condition for the 2 ms during which the Raman lasers were switched on, various components of the system were actively stabilised. Since the two Raman beams were extracted from two separate lasers, a phase-locked loop was employed to stabilise the frequency difference between the two lasers to < 10 Hz. The Raman beams were detuned by (70 ± 15) GHz from the $5P_{1/2}$ transition to suppress spontaneous emission. A stable current supply was used for the magnetic trap with a relative stability of $\frac{\Delta I}{I} < 10^{-4}$. It was found that the Raman laser power needed to be stabilised to avoid significant differences in the light shifts for different states. The lasers had a relative intensity stability of 3 parts in 1000. The position noise of the Raman beams also resulted in an additional relative intensity fluctuation of 3 parts in 1000.

Flux Limitations of Continuous Rf Atom Lasers

5.1 Introduction

The first of the two main investigations carried out during my honours year was into the limits on the peak homogeneous flux of continuous rf outcoupled atom lasers. We found that the peak homogeneous flux possible in an $m_F = 0$ atom laser beam is significantly below that which would be expected by a very simple model equating the peak flux to the number of atoms in condensate divided by the outcoupling duration. It is also significantly below that predicted by such complex models as [52], which do not encapsulate all of the physics.

Previous experiments in our laboratory indicated that a continuous atom laser, produced by state changing outcoupling, would have a stringent limit on the peak homogeneous flux [53]. Pulsed rf experiments, carried out on the second generation BEC machine, showed that beyond a critical flux, classical fluctuations increase with increasing flux. The fluctuations arise from the interaction of atoms in other Zeeman states with the atoms in the untrapped $m_F = 0$ state. Most notably, these interactions cause blurring between pulses and the disappearance of pulses. The reason for this is that once atoms have been outcoupled to the untrapped state, successive pulses may couple the atoms either further into antitrapped states, or back into trapped states. The pulsed rf data was directly compared with a one dimensional Gross-Pitaevskii model with no adjustable parameters and close qualitative agreement was found.

Other evidence to suggest that the flux in continuous atom lasers would be inherently limited is the theoretical prediction of a ‘bound state’ [54, 55]. It was predicted that for certain conditions of coupling out of a cavity mode, such as a BEC, a significant fraction of the initial population would remain trapped in a bound mode, overlapping the cavity mode, rather than populating the atom laser output. The binding energy of the bound state was predicted to increase with increasing coupling strength. The fraction of the initial population coupled to the bound state was found to be dependent on the cavity mode energy and to be maximal at a value of $2/3$ for a cavity mode energy of zero. Previous atom laser experiments have not continuously operated with sufficiently strong outcoupling fields, which are needed to observe the bound state.

In addition to the classification of atom lasers into pulsed and continuous types, given in Section 4.5, it is also useful to divide them into (at least) two types depending on the strength of the outcoupling field. Definitions of the weak and strong coupling regimes are necessary in order to predict whether the atom laser will be dominated by classical fluctuations or bound state behaviour. Several definitions have been given previously in

the literature, which give some idea of the division between the weak and strong coupling regimes. These definitions are all based on a comparison of the coupling strength with various parameters. All the definitions assume that the outcoupling width is significantly less than the frequency width of the condensate, i.e. continuous outcoupling. The most stringent condition for weak coupling requires $\Omega \ll \omega_\rho$ [56, 57]. For our system, this corresponds to $\Omega \ll 1.6$ kHz. A more relaxed condition, derived in [58], requires $\Omega \ll 1.6\sqrt{\frac{g}{R_{TF}}}$ for weak outcoupling, where R_{TF} is the Thomas Fermi width of the condensate, given by Equation 4.4. For our system this condition corresponds to $\Omega \ll 3.1$ kHz. Note that the theories developed in the three papers mentioned thus far, all assume the populations in the antitrapped states to be small enough to ignore. Only the trapped and untrapped states are included in the calculations presented in these papers.

The only continuous atom lasers demonstrated to date were those by Esslinger's and Aspect's groups [10, 47]. Both of these atom lasers operated with Rabi frequencies up to 2.2 kHz, which, using the criteria for weak coupling given above, is in, or just on the edge of, the weak coupling regime. Before the work presented in this thesis, no continuous atom laser had been operated in the strong coupling regime and therefore the bound state had not been observed.

In the experiments completed during my honours year, we found that there is a flux limitation in the weak regime, due to the interaction between multiple Zeeman states. We found that as the Rabi frequency was increased, atoms were increasingly coupled into the antitrapped states, rather than into the $m_F = 0$ atom laser state, thus limiting the possible peak flux. In the strong coupling regime we observed the predicted bound state and cessation of outcoupling into the atom laser. These results are published in [59].

5.2 Experimental Setup

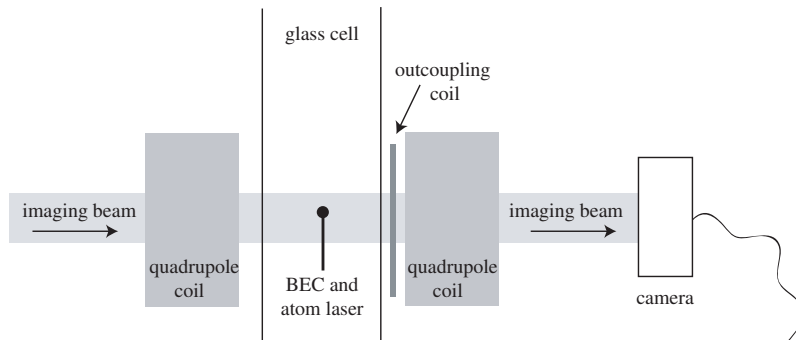


Figure 5.1: The experimental arrangement for rf outcoupling. Not to scale. The view is along the weak axis of the trap and gravity is downwards.

The experimental apparatus is depicted in Figure 5.1. Condensates were made as described in Chapter 3. Following evaporative cooling, the condensate was left to settle for 100 ms. A Stanford Research Systems 30 MHz synthesized function generator (model number DS345) set in gated burst mode produced a pulse up to 200 ms long. The rf pulse was radiated perpendicular to the weak axis of the magnetic trap through a single wire loop of radius 22 mm. The loop was positioned 18 mm from the BEC. The calibration of the outcoupling field is described in Section 5.2.1. Following outcoupling, the condensate

and atom laser were allowed time, usually a few ms, to separate before trap switch off. The entire system was then left to expand for another few ms prior to the imaging pulse. Before each set of runs, the upper edge (i.e. lowest possible outcoupling frequency) of the condensate was found by sweeping the rf frequency. The frequency width of the resonance was typically ~ 5 kHz, in agreement with Equation 4.5. Unless otherwise stated, for the results presented in this chapter, the outcoupling frequency was set 2 kHz from the upper edge of the condensate.

5.2.1 Calibration of the Outcoupling Magnetic Field

Precise calibration of the outcoupling magnetic field is necessary to determine the Rabi frequency and thereby to draw conclusions about outcoupling in the weak and strong regimes. Previous groups [9, 10] calibrated their outcoupling loops by directly measuring the magnetic field from an identical coil away from the experimental apparatus. Due to the presence of vacuum systems and magnetic coils it is not possible to measure the field from the actual coil in situ. This method is imprecise, as the presence of other coils significantly alter the field produced by the outcoupling coil. Therefore previous groups were only able to measure to a precision of 20%. For our experiment, we thought it necessary to calibrate our coil more precisely. We did this by fitting Rabi cycling curves, obtained from pulsed outcoupling, with numerical simulations, as shown in Figure 5.2. This calibration method enabled us to determine the magnetic field to within less than 5% error.

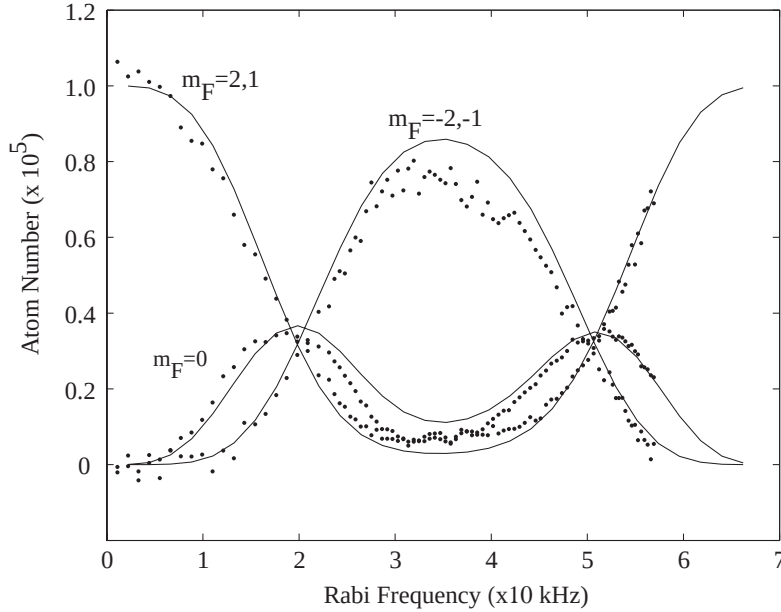


Figure 5.2: Rabi cycling between the Zeeman sublevels, used to calibrate the outcoupling coil. The population in various Zeeman sublevels are plotted against Rabi frequency. The dots represent the experimental data, while the solid lines are the theoretical calculation carried out by Nick Robins.

For $50 \mu\text{s}$ single pulsed outcoupling, the Rabi frequency was increased from 0 Hz to the maximum we could achieve with an available power amplifier. The atoms in different

magnetic states were separated due to gravity and the magnetic field gradient, allowing the populations to be extracted from absorption images. Figure 5.2 shows clear Rabi cycling from the trapped states, into the untrapped and antitrapped states and back again. The variation in spacing of the data points is due to a nonlinearity in the power amplifier, which was calibrated using induction in a second coil. The theoretical calculation was done by Nick Robins, using a 3D Gross-Pitaevskii model of the five state system, as described in [53]. The simulation had no free parameters and was fitted to the experimental data by adjusting the Rabi frequency axis.

It was found that magnetic field is a factor of 5 less than that which would be expected from a simple calculation of the field radiated from a single loop of wire. The discrepancy presumably arises from the close proximity of one of the quadrupole coils to the outcoupling coil (see Figure 5.1).

5.3 Results

5.3.1 Weak Coupling Regime

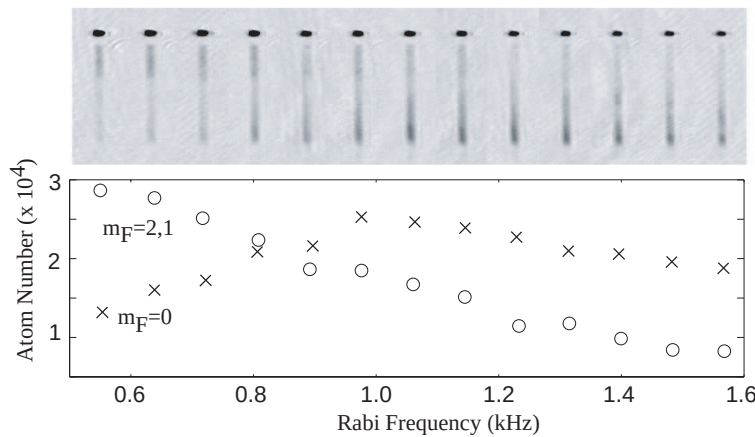


Figure 5.3: The lower figure is a plot of atom number as a function of Rabi frequency for a 10 ms atom laser. The circles denote the population in the trapped states, while the crosses denote population in the atom laser state. The upper figure shows the raw absorption images, from which this data has been extracted, averaged over six identical experiments. The field of view for each image is 1.5 mm by 0.5 mm. The trapped atoms are at the top, while the atom laser has fallen due to gravity. The antitrapped states are not in the field of view.

Figure 5.3 shows our experimental data in the weak coupling regime. The experimental sequence was 10 ms outcoupling, followed by 3 ms delay for the atom laser and condensate to separate before the trap switch off and a further 2 ms expansion period before the image sequence. The graph shows the number of trapped atoms (circles) remaining after outcoupling, which includes both $m_F = 1$ and $m_F = 2$ states, plotted against the Rabi frequency. The decline is clearly monotonic, in agreement with the results of Esslinger's group [10]. However, comparison with the atom number in the $m_F = 0$ state (crosses) indicates that decline in the trapped atom population does not lead to a simple increase in the atom laser population. It may be concluded that atoms are also being coupled into

the antitrapped $m_F = -1$ and $m_F = -2$ states. It is clear from the graph that the peak atom laser flux occurs at ~ 1 kHz. From the upper image in Figure 5.3, it can be seen that this value also corresponds to the most homogeneous laser beam. Beyond a Rabi frequency of 1 kHz, the atom laser beam develops steadily worsening density fluctuations with a prominent peak in the leading edge of the beam. We found the same behaviour for all continuous atom lasers, which were completely observable with our imaging system. Due to our limited field of view, only for outcoupling times of up to 25 ms were we able to observe the entire atom laser beam. For shorter outcoupling times, such as the 3 ms data presented in Section 5.3.3, we were also able to observe the antitrapped states, which begin to be populated above Rabi frequencies of 800 Hz.

It would appear that one solution to the problem of flux limitation, which is caused by the interaction between multiple Zeeman states, would be to reduce the system to only two levels. Aspect's group [47] demonstrated such a system by utilising the nonlinear Zeeman shift in the $F=1$ manifold. At a bias field of 54 G, the second order contribution of the Zeeman shift is non-negligible and only one transition is on resonance. Another solution would be to use Raman outcoupling. The momentum kick from the Raman lasers removes the atoms more quickly from the outcoupling region. The combination of the momentum kick and the fact that the resonance condition is dependent on the individual Zeeman states should result in a larger homogeneous flux limit than that observed in rf outcoupling.

However, the demonstration of the bound state, described in Section 5.3.2, implies that all continuous rf outcouplers, including the two state system, are inherently flux limited. It is also likely that the bound state will be present for the Raman outcoupler. This is discussed further in Section 6.2.3.

5.3.2 Strong Coupling Regime and the Bound State

Figure 5.4 shows our data of the first observation of a bound state in an atom laser. The experiment measured the remaining number of atoms in the trapped states ($m_F = 1$ and $m_F = 2$) following a period of outcoupling as a function of Rabi frequency in both the weak and strong regimes. Data for both 100 ms (circles) and 200 ms (dots) outcoupling durations are shown. Note that for these long outcoupling times, the atom laser flux is below our detection sensitivity. The results show that the trapped atoms are progressively depleted at increasing, but weak, Rabi frequencies until no atoms remain in the trap. The point at which the condensate is fully depleted varies with the length of outcoupling. Comparison of the two data sets shows that for longer outcoupling times, the condensate is depleted more quickly. At ~ 4 kHz, trapped atoms start to reappear. This point is essentially independent of the outcoupling duration, as seen by comparing the 100 ms and 200 ms plots. The number of atoms increases with Rabi frequency until at ~ 9 kHz the number stabilises to around 70% of the initial condensate number. The other 30% of atoms are expelled at the start of the outcoupling period, as indicated by Figures 5.3 and 5.5. Similar behaviour was observed for outcoupling durations as short as 50 ms. For shorter outcoupling times than this, the initial decay of the condensate is more gradual and the condensate is not fully depleted before the onset of the bound state (see Figure 5.3).

The data was collected in such a way that ensured no systematic shifts in the trap bias field occurred. Every ten data points, five runs were made at coarsely separated Rabi frequencies and compared with a reference set, which was taken at the beginning of the data collection. 10 ms outcoupling was also performed periodically to locate the bottom

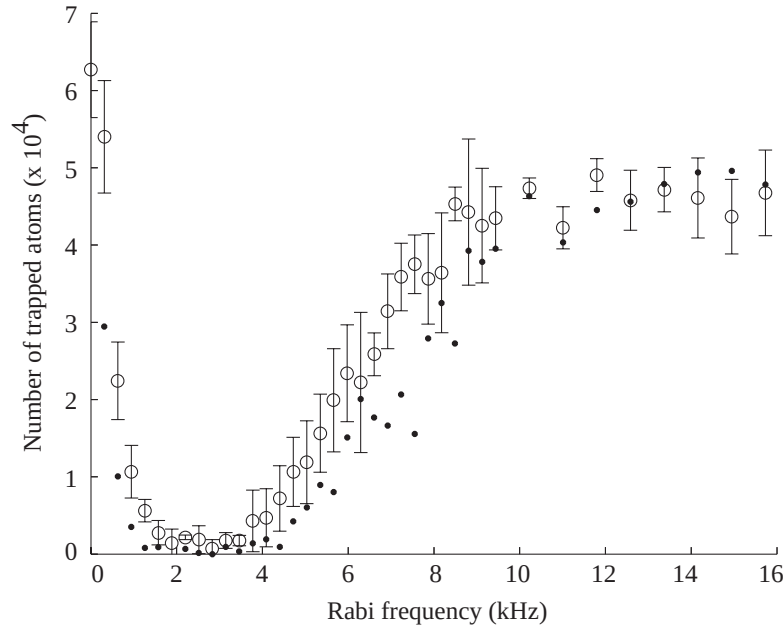


Figure 5.4: The population remaining in the trapped states as a function of Rabi frequency for a 100 ms atom laser (circles) and for comparison a 200 ms atom laser (dots). Each data point corresponds to a separate run of the machine.

of the trap. Four data sets were taken for the 100 ms atom laser to produce the error bars shown in Figure 5.4.

The effect of the bound state clearly identifies the weak and strong outcoupling regimes and the intermediate crossover region. Weak outcoupling is the region in which the atom laser flux is homogeneous and increases with increasing Rabi frequency, as expected by a naive model. For all of our data, we observe weak outcoupling for Rabi frequencies less than 1 kHz. Strong outcoupling is the regime in which the bound state exists. We observe strong outcoupling at Rabi frequencies greater than 4 kHz, independent of the outcoupling duration. In the strong coupling regime, the atom laser no longer operates.

The bound state may be understood by considering the system in the ‘dressed state’ basis. In this basis, the dressed eigenstates are linear combinations of the bare Zeeman states, trapped in effective potentials created by the avoided crossings. In the strong coupling limit, for the $F = 2$ atom laser, diagonalisation yields a prediction of between 31.25% up to a maximum of 62.5% of the atoms remaining trapped, assuming a non-adiabatic projection onto the dressed states. Our experimental observation of 70% is inconsistent with these values, suggesting some degree of adiabatic transfer.

5.3.3 3 ms Outcoupling

The experimental data presented in Figure 5.5 summarises the results described above. The plot on the left of the figure shows absorption images of the condensate and atom laser beam in a series of 35 experiments with a 3 ms continuous atom laser. Gravity is downwards and each vertical strip in the figure represents a separate run of the machine. For each run, following 3 ms of outcoupling, the system was left to evolve for a further 4 ms before the trap was switched off and 2 ms later an image was acquired. The Rabi

frequency was increased for successive runs. The figures on the right show an extended view of selected runs. Due to the short outcoupling, the antitrapped states are in the imaging field of view. At low outcoupling strengths, the atom laser beam flux increases gradually and homogeneously until ~ 1 kHz. At around this value, increasingly severe density fluctuations begin to occur in the atom laser, due to a loss of atoms into the antitrapped states, as shown in Figures 5.5(a) and (b). A further increase in the Rabi frequency incrementally shuts down the output into all states (see Figure 5.5c) starting around 4 kHz. In the limit of strong outcoupling, 30% of the atoms are emitted from the trap shortly after the beginning of the outcoupling period. The other approximately 70% of the atoms remain localised in the trap in the bound state.

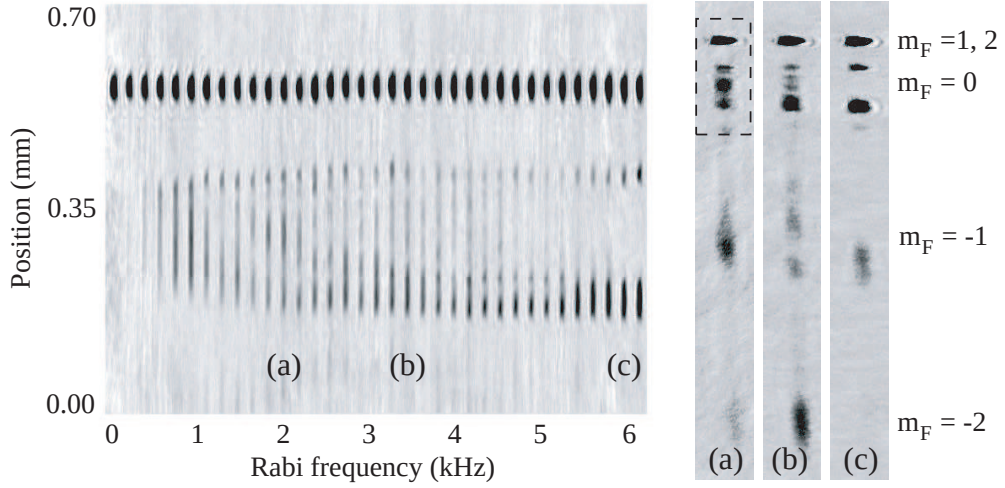


Figure 5.5: On the left, an optical depth plot of 35 independent experiments shows the spatial structure of a 3 ms atom laser as a function of Rabi frequency. The final image in this data set was taken at a Rabi frequency of 16 kHz. The figures on the right show an extended view of the data labeled (a), (b) and (c) in the main figure, in order to capture the antitrapped Zeeman states. The dashed rectangle corresponds to the image shown on the left.

5.3.4 Computational Simulations

Computational simulations were performed to model the system by Nick Robins. Although it is not my work, it is included here for completeness. The Gross Pitaevskii model of the $F = 2$ atom laser system was solved numerically in one dimension with no free parameters, as described previously in [53].

Figure 5.6(a) shows the populations in the trapped, untrapped and antitrapped Zeeman states for 15 ms of outcoupling at a Rabi frequency of 800 Hz. As the simulation is computationally intensive, only 15 ms of outcoupling was modelled. However, this short duration shows qualitatively the same behaviour as we observed experimentally for long outcoupling durations. The total number of atoms decreases with time, due to the finite spatial grid and absorbing boundaries used in the simulation. The trapped states tend towards zero, while the atom laser state reaches a peak early in the outcoupling. This initial burst of atoms qualitatively agrees with the experimental data in the weak coupling regime,

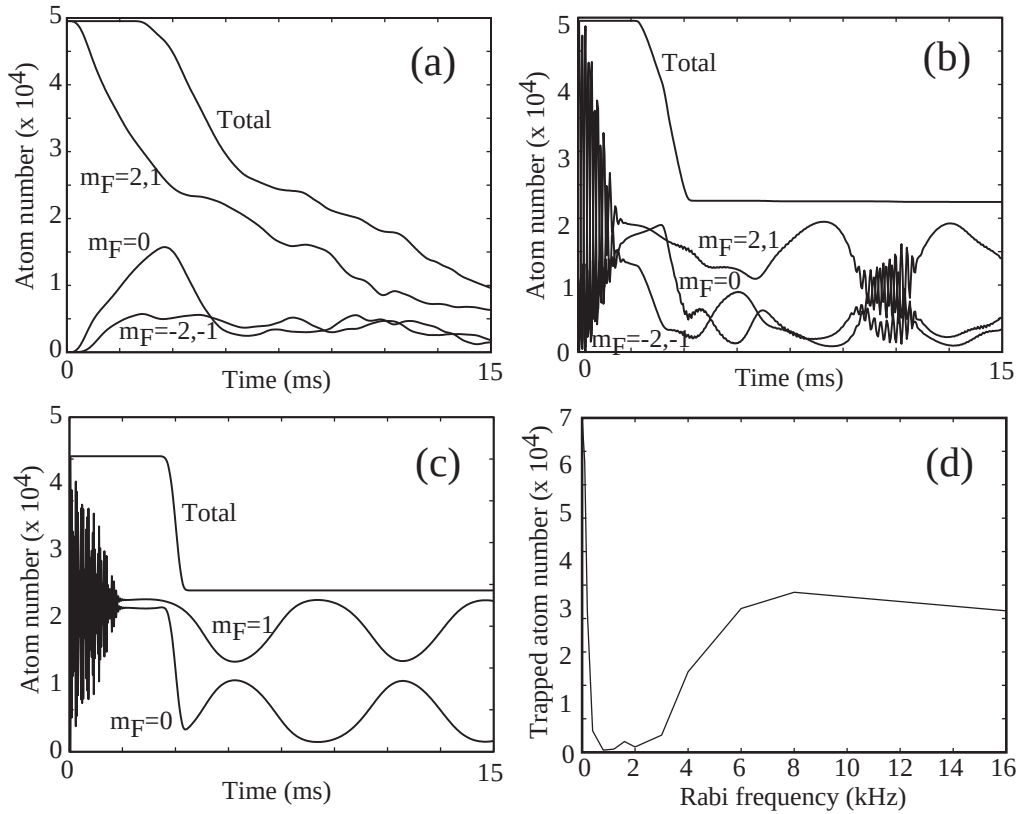


Figure 5.6: Theoretical results obtained by solution of the 1D-GP equation by Nick Robins. The top figures (a) and (b) show the Zeeman populations in the five state system as a function of time for 15 ms of outcoupling. The Rabi frequency in (a) is 800 Hz and in (b) is 16 kHz. In (c) the behaviour of a ‘pure two state system’ is shown with 15 ms of outcoupling at a Rabi frequency of 16 kHz. (d) shows the total atomic population remaining in the magnetic trap after 100 ms of output coupling as a function of Rabi frequency.

shown in Figures 5.3 and 5.5. Figure 5.6(b) shows the results of a simulation identical to Figure 5.6(a), but with a Rabi frequency of 16 kHz. Clearly, the behaviour is very different in the strong coupling regime. Following initial high frequency oscillations between the different Zeeman states, slightly more than half of the atoms are ejected from the trapping region. The remaining atoms, which are populated across all five Zeeman states, are trapped and undergo a lossless population exchange between the different states. This phenomenon is understood by identifying the trapped atoms as being in a superposition of the dressed state eigenvectors. Figure 5.6(c) shows the same results for a two state system, such as that demonstrated in [47]. This indicates that the bound state is inherent to rf outcoupling, regardless of the number of states. Therefore a two level system could not be used to increase atom laser flux, as suggested previously. Figure 5.6(d) reproduces the experimental data shown in Figure 5.4. The number of atoms remaining in the trap after 100 ms of outcoupling is shown as a function of Rabi frequency. The population of the bound state represents less than half of the initial condensate number, which is quantitatively inconsistent with our experimental observation of 70% of the atoms in the bound state. However, the behaviour qualitatively matches that of the experiment,

supporting our experimental observation of the bound state. It is expected that a full 3D model would accurately capture the dynamics of our experiment, but it is beyond the scope of the present work.

5.4 Conclusion

In conclusion, we have demonstrated that the rf outcoupler is inherently flux limited. For low Rabi frequencies, up to a value of ~ 1 kHz in our system, the atom laser flux increases homogeneously as desired with increasing coupling strength. However, for Rabi frequencies larger than 1 kHz, increasingly severe density fluctuations occur along the atom laser beam, due to coupling between all five of the Zeeman states. As the Rabi frequency is increased further into the strong coupling regime, the atom laser switches off all together and the atoms remain trapped in a bound state. For our experimental parameters, the onset of the bound state corresponds to a Rabi frequency of ~ 4 kHz. For continuous outcoupling in the strong coupling regime, we found that $\sim 30\%$ of the atoms are emitted shortly after the coupling begins, while the other 70% remain trapped in the bound state. These results agree qualitatively with a computational simulation of a one dimensional Gross Pitaevskii model of the system.

A Continuous Raman Atom Laser

The second of the two main investigations carried out during my honours year was into Raman outcoupled atom lasers. Having discovered that there is a peak homogeneous flux limit achievable by rf outcoupling, the obvious next step was to study the peak flux achievable with Raman outcoupling. Simple considerations of the momentum kick given by Raman outcoupling indicate that the flux limitations of both the multistate behaviour at low coupling strengths and the bound state behaviour at higher coupling strengths will occur at higher fluxes than for the rf atom laser. The only previous work done on Raman outcoupling, as described in Section 4.6, was carried out in pulsed mode, due to the use of a time varying magnetic trap. In order to study the homogeneous flux of Raman outcoupled atom lasers, we produced the first continuous atom laser based on Raman outcoupling. This chapter describes the production and presents the results of the first continuous Raman outcoupled atom laser. We have not yet carried out studies into the flux limits of such an atom laser, due to the breakage of our vacuum system. However, this work will be completed in the near future on the fourth generation ANU-BEC machine, which is currently under construction.

6.1 Experimental Setup

The theory concerning the experimental apparatus for Raman outcoupling is described in Section 4.6. The optics setup used to produce the two optical beams for Raman outcoupling is shown in Figure 6.1. The two beams were sourced from a single 70 mW diode laser on a laser table separate to the BEC table. The laser beam was split into two beams, which were both double passed through separate AOMs. Having the AOMs in double passed configuration allowed the frequency of the laser to be shifted without deviation of the laser beams throughout the remainder of the optics. The frequency difference between the two AOMs was set to ~ 165 kHz, according to Equation 4.11 and depending on the value of the magnetic field bias. The AOMs were driven by two phase locked Agilent 80 MHz function generators (model number 33250A), operated in external amplitude control mode. By measuring the beat note on a spectrum analyser, we inferred that the frequency difference was stable to at least 10 Hz, which is the resolution of the spectrum analyser. It is likely that the frequency difference was stable to $6 \mu\text{Hz}$, which is the precision of the function generators.

The two beams were separately coupled via single mode, polarisation preserving optical fibres to the BEC table. On the BEC table, the two beams passed through collimating lenses and the upwards propagating beam passed through a quarter wave plate, which was adjusted to produce circularly polarised light. The downwards propagating beam was linearly polarised. Upon reaching the condensate, the maximum intensity in each beam

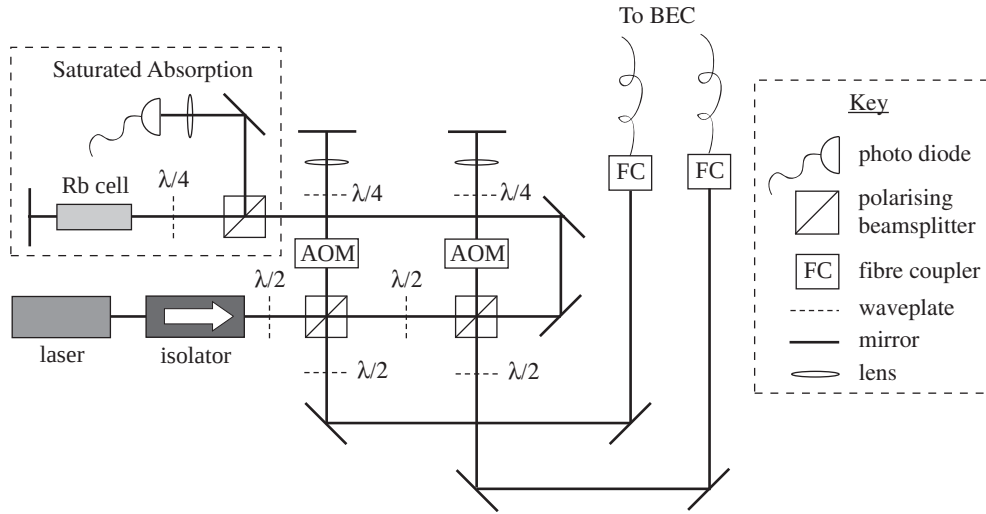


Figure 6.1: The optical setup used to prepare the laser beams for Raman outcoupling.

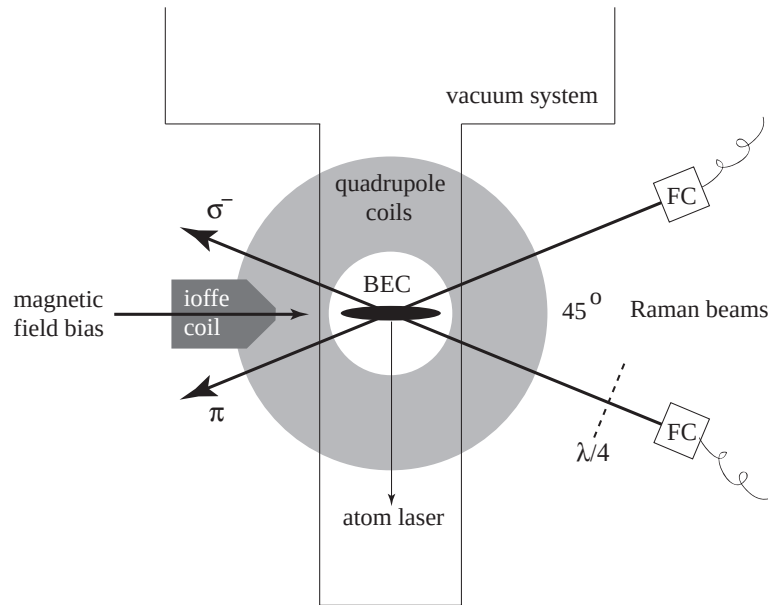


Figure 6.2: Schematic showing the alignment of the Raman beams with respect to the condensate.

was 250 mW/cm^2 . The beams were aligned parallel to the weak axis of the magnetic trap with a separation of 45° , as shown in Figure 6.2. A separation of 45° was the largest that was possible in our system, due to the spatial restrictions of our vacuum system. In the ideal case, the two Raman beams would be counter-propagating, in order to achieve a maximum momentum kick of $4\hbar k$ downwards, equivalent to a velocity of 2.35 cm/s . In our system the atoms were outcoupled with a momentum of $4\hbar k \sin(45^\circ/2)$, equivalent to an initial velocity of 0.90 cm/s . With the Raman beams at an angle to the magnetic field bias, it is necessary to consider the polarisation projection upon the axis of the field, rather than that along the beam axis. In our setup, the magnetic field bias is along the

axis of the ioffe coil. For a laser beam of linearly polarised light, propagating at an angle θ to the field axis and with a polarisation orthogonal to the field axis (ie. into the page in Figure 6.2), the projected polarisation is independent of the angle θ . However, for light linearly polarised in the opposite direction (ie. in the plane of the page), the useful light will remain linearly polarised with respect to the field axis, but the amplitude will be reduced by a factor of $\cos \theta$. Therefore circularly polarised light, which is a combination of the two orthogonal linear polarisations, will be projected as an elliptical polarisation, with an eccentricity of $\sin \theta$. To obtain circularly polarised light along the field axis, it is necessary to input elliptically polarised light along the beam path. Furthermore, for vertical Raman beams, which impart the greatest momentum to the outcoupled atoms, it is not possible to create circular polarisation with respect to a horizontal field bias. A solution to this problem would be to create a magnetic trap with a bias in the vertical direction. However, for elongated traps, such as the one that we use, evaporation to BEC is not possible in a vertical orientation, due to the increased gravitational sag. It is possible however, to evaporate in a tightly confining, isotropic trap with a vertical bias. Such a trap would create atom lasers with greater longitudinal divergence, due to the increased condensate density in these directions. Therefore to produce an atom laser with low divergence, the magnetic trap must be loosened after condensate production.

Before each set of runs, the value and stability of the Zeeman splittings was checked using 10 ms rf outcoupling. Using Equation 4.11, we were able to estimate the frequency difference necessary for Raman outcoupling to be 4.4 kHz below the measured Zeeman splitting. The diode laser used for the Raman outcoupling was not locked. The detuning of the laser from the $5P_{3/2}, F = 3$ transition was measured on an optical spectrum analyser and was found to have a long term stability of ± 3 MHz. For continuous outcoupling, the Raman laser had a relative intensity stability of around 1 part in 1000. It was therefore not necessary to actively stabilise the laser intensity. For pulsed outcoupling, the intensity had a relative stability of only 3 parts in 100, due to the variable response of the AOM in the initial switch on period. The problems caused by this instability are detailed in Section 6.2.2.

6.2 Results

Figure 6.3 illustrates a typical continuous atom laser produced using Raman outcoupling in our laboratory. For continuous outcoupling the typical experimental sequence was 8.5 ms outcoupling, followed immediately by the trap switch off and a 2 ms expansion period.

6.2.1 Dependence on Detuning and Polarisation

We found that we needed very large detunings to eliminate heating of the condensate. Close to the one photon resonance, the atoms spontaneously emit from the upper state and very few two photon transitions take place. Figure 6.4 shows a comparison between two atoms lasers produced with different detunings. Figure 6.4(a) is the same atom laser as shown in Figure 6.3, produced with a detuning of 300 GHz to the red of the $5P_{3/2}, F = 3$ transition. Figure 6.4(b) shows an atom laser produced with a detuning of 6 GHz to the blue. There is clearly more heating of the condensate and atom laser when the Raman laser is less detuned. This is consistent with previous Raman coupling experiments. Esslinger's group used a detuning of 70 GHz to the red to suppress spontaneous emission. Phillips' group were able to use a detuning of only 1.85 GHz to the red, because they were using

pulsed outcoupling, for which heating is not such a problem. Interestingly, we found that detuning to the red caused considerably less heating than detuning the same amount to the blue.

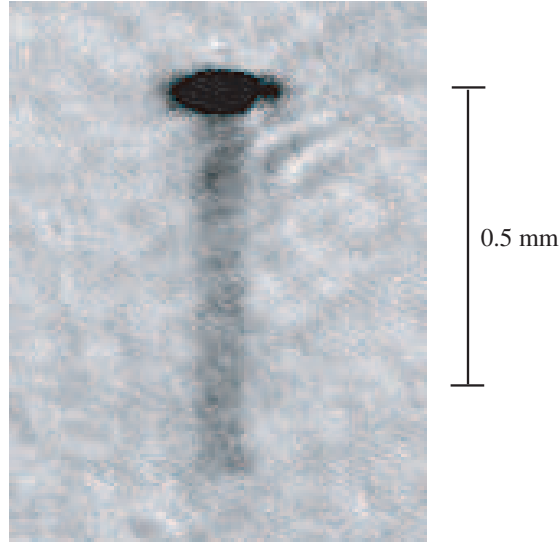


Figure 6.3: An atom laser produced with 8.5 ms of Raman outcoupling. The Raman laser was detuned 300 GHz to the red of the $5P_{3/2}$ transition.

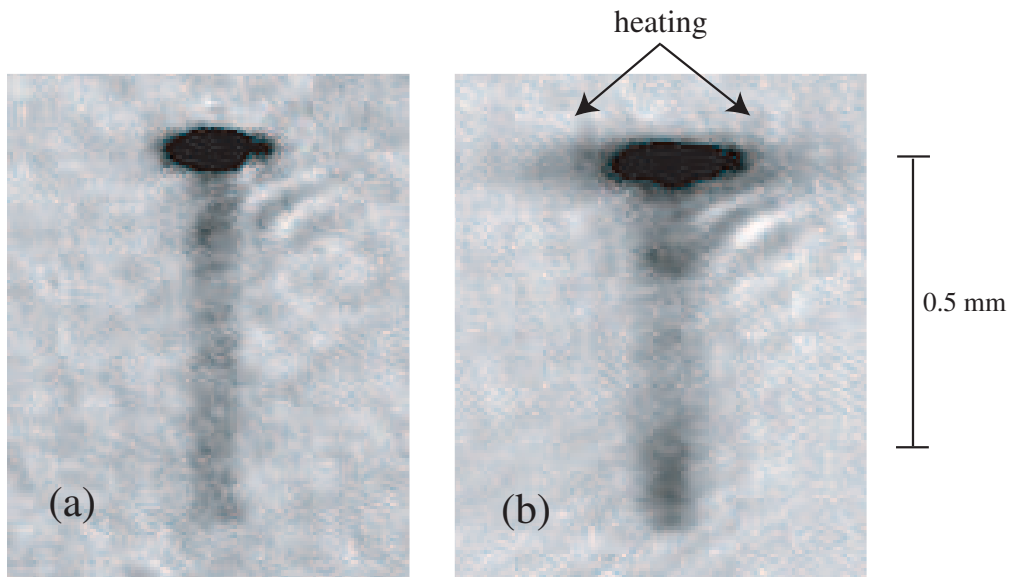


Figure 6.4: Both of the atom lasers shown above were produced with 8.5 ms outcoupling. The one photon detuning was varied from $\Delta = 300$ GHz to the red in (a) to $\Delta = 6$ GHz to the blue in (b).

The dependence on polarisation was such that we could turn off the atom laser output by adjusting the quarter wave plate on the upwards propagating Raman beam. By adjusting the polarisation so that the upwards propagating beam was linearly polarised, we were able to limit the allowed transitions to only $\Delta m_F = 0$ transitions. Therefore for such an arrangement of polarisations, no Raman transitions took place. We found that maximum outcoupling occurred for equal beam intensities of $(10 - 30) \text{ mW/cm}^2$, depending on the detunings of the one and two photon transitions.

6.2.2 Pulsed Outcoupling

Despite the success of continuous Raman outcoupling, we were unable to reliably demonstrate pulsed Raman outcoupling. Figure 6.5 shows a set of pulsed runs, with no implemented change of experimental parameters between runs. The experimental sequence was $100 \text{ } \mu\text{s}$ of outcoupling, followed by an 8.4 ms wait before the trap was switched off and a further 2 ms expansion period prior to the image pulse. A $100 \text{ } \mu\text{s}$ pulse was used, as this was the shortest convenient period within the bandwidth of the analog input of the Agilent function generators. The trap was switched off immediately after the coupling pulse and the image was taken after a 2 ms expansion. Obviously some parameter is unstable and each successive run is taking a different, apparently random point in the Rabi cycle.

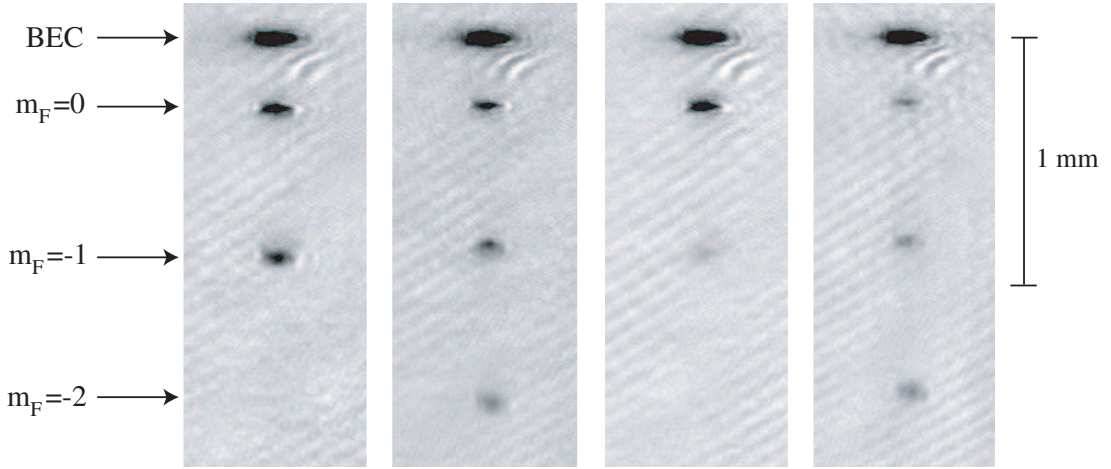


Figure 6.5: These four images were taken in consecutive runs with no changes made between runs. $100 \text{ } \mu\text{s}$ of coupling was applied at a detuning of 6 GHz .

One possible cause may be intensity noise. As mentioned above, on the time scale of the pulsed outcoupling, the AOMs used for switching turned on slowly. The AOMs did not reach maximum power before the pulse was finished and the peak power during the pulse varied by as much as 3% between runs. Therefore the two photon Rabi frequency, given by

$$\Omega_{ac} = \frac{\Omega_{ab}\Omega_{bc}}{4\Delta} \quad (6.1)$$

where Ω_{ab} and Ω_{bc} are the one photon Rabi frequencies from a to b and b to c respectively, also varied by at least 3%. The detuning noise is negligible, as for the detuning of $\Delta = 6 \text{ GHz}$ used in the pulsed experiments, the relative stability is less than 5×10^{-4} . As a result of the failed pulsed experiments, we were unable to accurately calibrate the Rabi

frequencies for the Raman outcoupler by comparing experimental Rabi cycling data with theory, as done for rf outcoupling in Section 5.2.1. The intensities could not easily be directly measured, due to the lack of space between the vacuum system and the final optics used in delivering the light to the condensate. To install a photodiode just before the light entered the vacuum system, would have required major reshuffling of the MOT optics and Raman fibre couplers, as well as a reduced angle between the Raman beams.

A solution to the problem for future pulsed Raman experiments would be to include a third AOM directly after the isolator. With the AOM in single pass configuration, as shown in Figure 6.6, the first order beam would be driven through the current setup. The AOM would run off the factory driver, powered by a TTL triggerable Agilent 20 MHz function generator. In this setup the AOM switches on the order of 10 ns and the power is very stable.

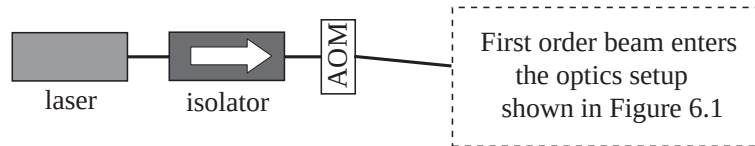


Figure 6.6: The placement of a third AOM for fast shuttering of the Raman beams in future experiments.

6.2.3 Indications of Flux Limitations and the Bound State

Although the vacuum system broke before we had a chance to measure the flux limitations of the Raman outcoupled atom laser, there are a few indications in our preliminary data that the behaviour will be qualitatively similar to the rf outcoupling case.

The first evidence is that we saw coupling to the antitrapped states, as shown in Figure 6.7. This is not unexpected, as the difference in the resonance condition between successive Zeeman states is 2.2 kHz, which is roughly the same as the width of the Raman transition. Power broadening of the outcoupling frequencies would cause coupling to occur between all five Zeeman states. Therefore, at least for the parameters used in our lab, the Raman system is a multistate one and is likely to follow the same switch off dynamics as the rf system, due to the interplay between multiple Zeeman states.

The second piece of evidence in our data, which points towards flux limitations of Raman atom lasers is shown in Figure 6.8. The structure in the atom laser looks somewhat similar to that seen in Figures 5.3 and 5.5, indicating complex dynamics between multiple Zeeman states.

In the brief period before experiments were ceased, we carried out an experiment to search for evidence of the bound state. As in the rf case (see Section 5.3.2), we took a series of runs with increasing Rabi frequency, monitoring the number of atoms remaining in the condensate after 52.5 ms of Raman outcoupling. Following a slow decrease in the observed number of atoms in the condensate, we found that the number of atoms was below detection at an intensity of $\sim 15 \text{ mW/cm}^2$. As we increased the intensity to its maximum value of 250 mW/cm^2 , we did not observe a return of the trapped atoms, which would imply the existence of the bound state. At the maximum intensity, we checked that the atoms were not being blown away by one photon absorption, due to the intense coupling field. Upon detuning the two photon frequency difference, we observed a return

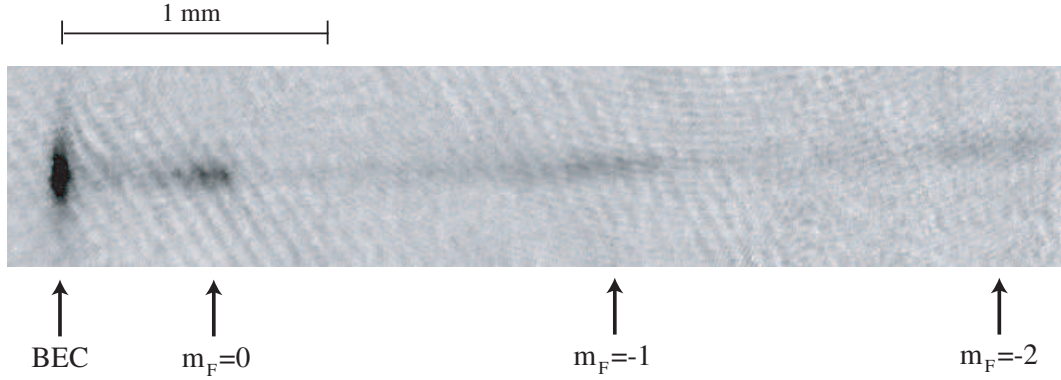


Figure 6.7: A multistate atom laser produced with 8.5 ms outcoupling duration. The detuning of the fields from the upper state was $\Delta = 6$ GHz. Note that the acceleration due to gravity points to the right.

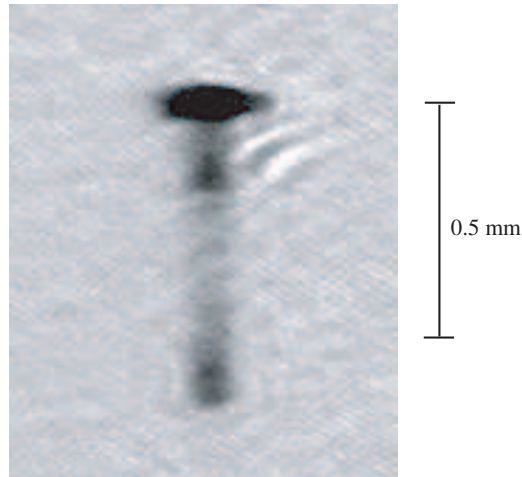


Figure 6.8: An atom laser produced with 8.5 ms of Raman outcoupling.

of the condensate atoms, thereby proving that we had actually observed a two photon effect. Therefore the experiment was inconclusive and future experiments will need to employ higher laser intensities, as well as accurate calibration of Rabi frequencies.

In conclusion, we believe that the Raman outcoupled atom laser will have a similar flux limit to the rf atom laser. However, due to the momentum kick and the small difference between the resonance condition for different Zeeman states, it is likely that the atom laser will switch off at a higher Rabi frequency. It would be beneficial to use Raman beams with a larger angular separation, as well as a transition with a smaller wavelength, in order to increase the momentum kick and the difference between the resonance conditions for adjacent Zeeman levels.

6.3 Derivation of the Supression of Two Photon $\Delta m_F = 2$ Transitions

In the pulsed Raman outcoupling paper by Hagley et al. [11], it is stated that ‘in the case where the detuning of the lasers from the excited state is large compared with the excited-state hyperfine structure splitting, it is not possible to drive $\Delta m_F = 2$ transitions directly with two photons because the ground state looks like a spin 1/2 system for which there are only two states.’ However it is not explained further why this is the case and this fact is not widely known. The calculation of transition amplitudes outlined below proves that for large detunings, it is not possible to drive two photon $\Delta m_F = 2$ transitions. However, we have no clear, single picture as to why this is the case.

The amplitude of a one photon transition from state a to state b is given by

$$\begin{aligned} \mu_{ab} &= e(-1)^{1+L'+S+J+J'+I-m'_F} \langle \alpha' L' || r || \alpha L \rangle \\ &\times \sqrt{(2J+1)(2J'+1)(2F+1)(2F'+1)} \\ &\times \begin{Bmatrix} L' & J' & S \\ J & L & 1 \end{Bmatrix} \begin{Bmatrix} J' & F' & I \\ F & J & 1 \end{Bmatrix} \begin{pmatrix} F & 1 & F' \\ m_F & q & -m'_F \end{pmatrix} \end{aligned} \quad (6.2)$$

where e is the charge of an electron, the undashed and dashed values correspond to states a and b respectively, $\langle \alpha' L' || r || \alpha L \rangle$ represents the radial part of the dipole moment and the arrays with curly braces and parentheses are $6j$ and $3j$ symbols respectively [60].

The amplitude of a two photon transition from state a to c via b is simply

$$\mu_{ac} = \frac{\mu_{ab}\mu_{bc}}{4\Delta} \quad (6.3)$$

where Δ is the common detuning of both fields from the upper state b .

For Raman transitions in alkali atoms, there are often multiple allowed transitions from a to c via other states near b with different values of F . Close to resonance, where Δ is a lot less than the spacing of the upper F manifolds, these other transitions have relatively small amplitudes and may be ignored. However, for a far detuned two photon transition, such that the detuning is a lot greater than the spacing of the upper F manifolds, the transition can no longer be considered to occur via a single upper state. Instead, the amplitude of the two photon transition from a to b must be found by summing all possible transitions via different upper states. For example, in the $F = 2$ manifold of the ground state of ^{87}Rb , there are five allowed two photon transitions from the BEC state which result in a change of $\Delta m_F = 1$. These five transitions are depicted in Figure 6.9. Choice of polarisation selects whether the $\Delta m_F = 1$ change occurs on the absorption or stimulated emission path. For circularly polarised light on the absorption path, there are three allowed transitions, shown as solid lines in the figure. Starting from the $5S_{1/2}, F = 2, m_F = 2$ BEC state, two photon transitions can be made via one of the $5P_{3/2}, F' = \{1, 2 \text{ or } 3\}, m'_F = 1$ upper states to the $S_{1/2}, F = 2, m_F = 1$ state. Assuming that the detuning is large enough to be constant over all these transitions, summing the amplitudes of all allowed transitions as follows

$$\frac{\mu_{2 \rightarrow 1'} \mu_{1' \rightarrow 2} + \mu_{2 \rightarrow 2'} \mu_{2' \rightarrow 2} + \mu_{2 \rightarrow 3'} \mu_{3' \rightarrow 2}}{4\Delta} \quad (6.4)$$

where the subscripts denote the F manifolds, results in a two photon transition amplitude of $\frac{+4.2 \times 10^{-38} \text{ C}^2 \text{ a.u.}^2}{4\Delta}$. Similarly, for linearly polarised light on the absorption path, shown with dotted lines in Figure 6.9, the two allowed transitions via the upper states $5P_{3/2}, F' =$

$\{2 \text{ or } 3\}, m'_F = 2$ sum to a transition amplitude of $\frac{-4.2 \times 10^{-38} \text{ } C^2 a.u.^2}{4\Delta}$.

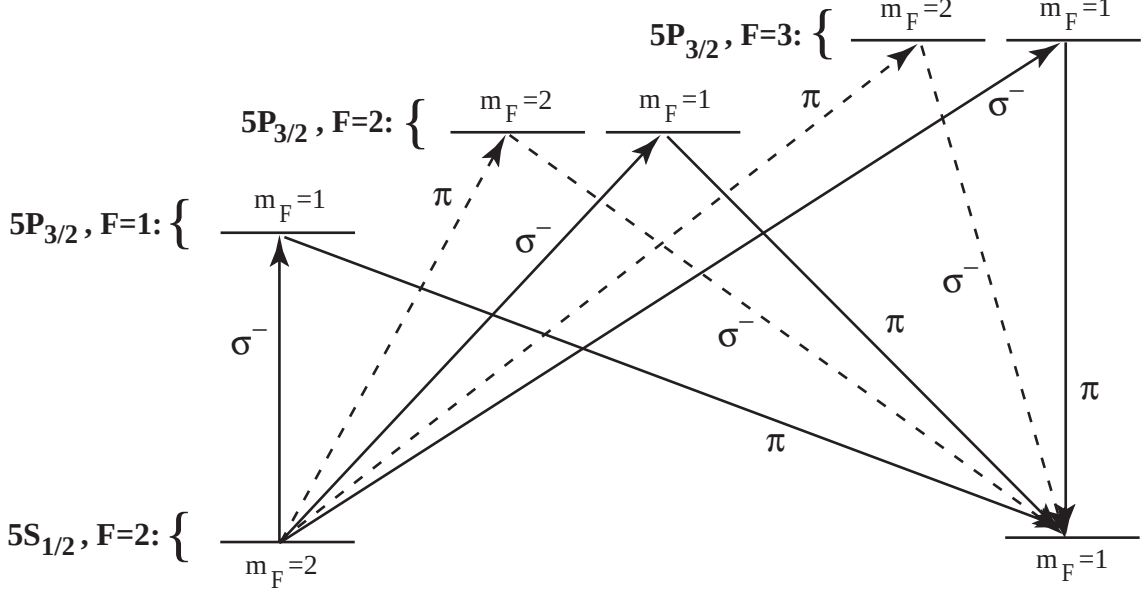


Figure 6.9: The allowed two photon transitions from the $F = 2, m_F = 2$ ground state to the $F = 2, m_F = 1$ ground state. The solid lines represent transitions with circularly polarised light on the absorption path, while the dotted lines represent transitions with linearly polarised light on the absorption path.

Notice that if we ignore polarisation and sum over all allowed two photon transitions, the resultant transition amplitude is zero. This effect is due to quantum interference between the different paths. A non-zero transition amplitude occurs only when the allowed transitions are restricted by polarisation.

For the case of two photon $\Delta m_F = 2$ transitions from the $5S_{1/2}, F = 2, m_F = 2$ condensate state directly to the $S_{1/2}, F = 2, m_F = 0$ atom laser state, there are three possible transitions via one of the $5P_{3/2}, F' = \{1, 2 \text{ or } 3\}, m'_F = 1$ upper states. Again assuming large detuning and summing the amplitudes of all allowed transitions results in a net zero amplitude. Since all transitions require the same polarisations, it is not possible to restrict the set of transitions as in the $\Delta m_F = 1$ case above. Therefore the probability of a $\Delta m_F = 2$ transition is zero for large detunings.

6.4 Conclusion

In conclusion, we have made the first experimental demonstration of a continuous Raman outcoupled atom laser. Due to large laser intensity noise when operating in the pulsed regime, we were unable to accurately calibrate the Rabi frequencies. However, the qualitative results we have obtained are still useful. We found that a large one photon detuning ($\gg 6$ GHz) was needed to reduce the heating below detection levels. At such large detunings, we have shown that it is not possible to drive two photon $\Delta m_F = 2$ transitions directly from the condensate state to the atom laser state. As expected, we found that the polarisation dependence was such that we were able to switch off the atom laser output by altering the polarisation of one of the Raman beams. Although we were unable to

quantitatively investigate the flux limitations, there are a number of indications in our data that the Raman outcoupler is flux limited in a similar manner to the rf outcoupler. The first indication is that we observed coupling to the antitrapped states, even though these transitions were detuned from resonance. Secondly, we observed structure in the atom laser beam, similar to that seen in the rf case, which is caused by the coupling between multiple Zeeman states. Therefore it is likely that the Raman outcoupler will show qualitatively the same flux limiting behaviour as the rf outcoupler.

Conclusions and Future Directions

In this thesis, we have presented the experimental results of investigations into the beam fluctuations and flux limitations of continuous atom lasers.

For a radio frequency outcoupler operated in the continuous regime, it was shown that above a critical value of the Rabi frequency, the atom laser begins to have increasingly large classical intensity fluctuations due to coupling between multiple Zeeman levels. For our experimental parameters, this critical Rabi frequency was ~ 1 kHz, which is well below previous theoretical definitions of the weak coupling regime. At a Rabi frequency of around 4 kHz, the onset of the bound state was observed. For Rabi frequencies larger than this (ie. in the strong coupling regime), the continuous atom laser output completely switched off. We measured that around 30% of the atoms were emitted from the condensate region during a brief period at the beginning of the outcoupling, while the other 70% remained trapped. This was understood by considering the system in the dressed state basis. Comparison of our experimental results with computational simulations completed by Nick Robins showed good qualitative agreement.

Following the work on rf outcoupling, we investigated Raman outcoupling, with an aim to complete similar studies of the atom laser flux limitations to those completed for rf outcoupling. In this thesis we have presented the results of the first continuous Raman outcoupled atom laser. Due to limitations of our current BEC machine, we were unable to complete studies of the beam fluctuations and flux limitations of Raman outcoupled atom lasers. However the initial results, which we have presented here, indicate that the Raman outcoupler is likely to show the same qualitative behaviour as the rf outcoupler.

Our group plans to conduct further research into the Raman outcoupler on the next generation BEC machine, in order to quantify the exact form of the flux limitations. A quantitative comparison may then be made between the rf and Raman outcouplers. In order to find the upper limit on the highest homogeneous flux possible for Raman outcoupling, it will be necessary to impart (as close as possible to) the maximum momentum kick of $4\hbar k$. To do this, the Raman beams must be counter-propagating in the vertical direction, which is not possible with the apparatus described in this thesis. As discussed in Chapter 6, for vertically propagating beams, the magnetic field bias must also be vertical, so that the polarisation projections onto the magnetic field axis are such that it is possible to drive two photon transitions. This is possible in an isotropic magnetic trap. If the bound state is to be found, significantly larger laser intensities than those used in our experiment will be required. In addition, the laser intensities need to be stable in the pulsed regime, so that the Rabi frequency may be accurately calibrated by comparison with a theoretical model of the Rabi cycling between Zeeman states. In our experimental setup, this may be done by using the arrangement shown in Figure 6.6.

The results presented in this thesis have significant implications for the future devel-

opment of atom lasers for use in both research and industry. The most critical feature of atom lasers, which will dictate how wide a range of applications they may find, will be the peak homogeneous flux. However, our results have shown that for the commonly used state changing outcoupling mechanisms, the flux can not be arbitrarily increased by increasing the Rabi frequency. The peak homogeneous flux is severely limited due to the dynamics between the multiple Zeeman levels of the ground state. Therefore if a pumped atom laser with high output flux is to be produced, an alternative outcoupling mechanism must be found.

Bibliography

- [1] T.H. Maiman, “Stimulated optical radiation in ruby”, *Nature* **187**, 493 (1960)
- [2] W.G. Unruh, “Experimental black-hole evaporation?”, *Phys. Rev. Lett.* **46**, 1351 (1981)
- [3] Alan Lenef, Troy D. Hammond, Edward T. Smith, Michael S. Chapman, Richard A. Rubenstein and David E. Pritchard, “Rotation sensing with an atom interferometer”, *Phys. Rev. Lett.* **78**, 760 (1997)
- [4] R.B. Doak, R.E. Grisenti, S. Rehbein, G. Schmahl, J.P. Toennies and Ch. Woll, “Towards realization of an atomic de Broglie microscope: helium atom focusing using fresnel zone plates”, *Phys. Rev. Lett.* **83**, 4229 (1999)
- [5] A. Einstein, “Quantentheorie des einatomigen idealen gases: zweite abhandlung”, *Sitzungber Preuss. Akad. Wiss.* **1**, 3 (1925)
- [6] M.H. Anderson, J.R. Ensher, M.R. Matthews, C.E. Wieman and E.A. Cornell, “Observation of Bose-Einstein condensation in a dilute atomic vapor”, *Science* **269**, 198 (1995)
- [7] B.P. Anderson and M.A. Kasevich, “Macroscopic quantum interference from atomic tunnel arrays”, *Science* **282**, 1686 (1998)
- [8] G. Cennini, G. Ritt, C. Geckeler and M. Weitz, “All-optical realization of an atom laser”, *Phys. Rev. Lett.* **91**, 240408 (2003)
- [9] M.-O. Mewes, M.R. Andrews, D.M. Kurn, D.S. Durfee, C.G. Townsend and W. Ketterle, “Output coupler for Bose-Einstein condensed atoms”, *Phys. Rev. Lett.* **78**, 582 (1997)
- [10] I. Bloch, T.W. Hänsch and T. Esslinger, “Atom laser with a cw output coupler”, *Phys. Rev. Lett.* **82**, 3008 (1999)
- [11] E.W. Hagley, L. Deng, M. Kozuma, J. Wen, K. Helmerson, S.L. Rolston and W.D. Phillips, “A well-collimated quasi-continuous atom laser”, *Science* **283**, 1706 (1999)
- [12] A.L. Fetter and J.D. Walecka, *Quantum Theory of Many-Particle Systems*, McGraw-Hill, New York (1971)
- [13] C.J. Pethick and H. Smith, *Bose-Einstein Condensation in Dilute Gases*, Cambridge University Press, Cambridge (2002)
- [14] W.D. Phillips, “Nobel Lecture: Laser cooling and trapping of neutral atoms”, *Rev. Mod. Phys.* **70**, 721 (1998)
- [15] E.L. Raab, M. Prentiss, A. Cable, S. Chu and D.E. Pritchard, “Trapping of neutral sodium atoms with radiation pressure”, *Phys. Rev. Lett.* **59**, 2631 (1987)

-
- [16] J. Dalibard and C. Cohen-Tannoudji, “Laser cooling below the Doppler limit by polarization gradients: simple theoretical models”, *J. Opt. Soc. Am. B* **6**, 2023 (1989)
 - [17] E. Majorana, “Atomi orientati in campo magnetico variabile”, *Nuovo Cimento* **9**, 43 (1932)
 - [18] W. Petrich, M.H. Anderson, J.R. Ensher and E.A. Cornell, “Stable, tightly confining magnetic trap for evaporative cooling of neutral atoms”, *Phys. Rev. Lett.* **74**, 3352 (1995)
 - [19] D.E. Pritchard, “Cooling neutral atoms in a magnetic trap for precision spectroscopy”, *Phys. Rev. Lett.* **51**, 1336 (1983)
 - [20] T. Esslinger, I. Bloch and T.W. Hansch, “Bose-Einstein condensation in a quadrupole-Ioffe-configuration trap”, *Phys. Rev. A* **58**, R2664 (1998)
 - [21] W. Ketterle and N.J. van Druten, “Evaporative cooling of trapped atoms”, *Advances in Atomic, Molecular and Optical Physics* **37**, 181 (1996)
 - [22] W. Ketterle, D.S. Durfee and D.M. Stampur-Kurn, “Making, probing and understanding Bose-Einstein condensates”, from M. Inguscio, S. Stringari and C.E. Wieman, *Bose-Einstein Condensation in Atomic Gases, Proceedings of the International School of Physics Enrico Fermi, Course CXL*, IOS Press Ohmsa (1999)
 - [23] B.E.A. Saleh and M.C. Teich, *Fundamentals of Photonics*, John Wiley & Sons (1991)
 - [24] J.E. Lye, PhD thesis, ANU (2003)
 - [25] N.P. Robins, PhD thesis, ANU (2004)
 - [26] H.M. Wiseman, “Defining the (atom) laser”, *Phys. Rev. A* **56**, 2068 (1997)
 - [27] J.J. Hope and C.M. Savage, “Band gaps for atoms in light-based waveguides”, *Phys. Rev. A* **53**, 3449 (1996)
 - [28] Roy J. Glauber, “The quantum theory of optical coherence”, *Phys. Rev.* **130**, 2529 (1963)
 - [29] I. Bloch, T.W. Hänsch and T. Esslinger, “Measurement of the spatial coherence of a trapped Bose gas at the phase transition”, *Nature* **403**, 166 (2000)
 - [30] D. Hellweg, L. Cacciapuoti, M. Kottke, T. Schulte, K. Sengstock, W. Ertmer, and J.J. Arlt, “Measurement of the spatial correlation function of phase fluctuating Bose-Einstein condensates”, *Phys. Rev. Lett.* **91**, 010406 (2003)
 - [31] J.E. Lye, J.J. Hope and J.D. Close, “Nondestructive dynamic detectors for Bose-Einstein condensates”, *Phys. Rev. A* **67**, 043609 (2003)
 - [32] A.P. Chikkatur, Y. Shin, A.E. Leanhardt, D. Kielpinski, E. Tsikata, T.L. Gustavson, D.E. Pritchard and W. Ketterle, “A continuous source of Bose-Einstein condensed atoms”, *Science* **296**, 2193 (2002)
 - [33] Mikio Kozuma, Yoichi Suzuki, Yoshio Torii, Toshiaki Sugiura, Takahiro Kuga, E. W. Hagley and L. Deng, “Phase-coherent amplification of matter waves”, *Science* **286** 2309 (1999)

-
- [34] S. Inouye, T. Pfau, S. Gupta, A.P. Chikkatur, A. Görlitz, D. E. Pritchard and W. Ketterle, “Phase-coherent amplification of atomic matter waves”, *Nature* **402**, 641 (1999)
 - [35] S.A. Haine, A.J. Ferris, J.D. Close and J.J. Hope, “Control of an atom laser using feedback”, *Phys. Rev. A* **69**, 013605 (2004)
 - [36] Piet O Schmidt, Sven Hensler, Jörg Werner, Thomas Binhammer, Axel Görlitz and Tilman Pfau, “Continuous loading of cold atoms into a Ioffe-Pritchard magnetic trap”, *J. Opt. B* **5**, S170 (2003)
 - [37] E.A. Cornell, C. Monroe and C.E. Wieman, “Multiply loaded, ac magnetic trap for neutral atoms”, *Phys. Rev. Lett.* **67**, 2439 (1991)
 - [38] E. Mandonnet, A. Minguzzi, R. Dum, I. Carusotto, Y. Castin and J. Dalibard, “Evaporative cooling of an atomic beam”, *Eur. Phys. J. D* **10**, 9 (2000)
 - [39] P. Cren, C.F. Roos, A. Aclan, J. Dalibard and D. Guéry-Odelin, “Loading of a cold atomic beam into a magnetic guide”, *Eur. Phys. J. D* **20**, 107 (2002)
 - [40] T. Lahaye, J.M. Vogels, K. J. Günter, Z.Wang, J. Dalibard and D. Guéry-Odelin, “Realization of a magnetically guided atomic beam in the collisional regime”, *Phys. Rev. Lett.* **93**, 093003 (2004)
 - [41] B.K. Teo and G. Raithel, “Atom reflection in a tapered magnetic guide”, *Phys. Rev. A* **66**, 051401R (2002)
 - [42] C.F. Roos, P. Cren, D. Guéry-Odelin and J. Dalibard, “Continuous loading of a non-dissipative atom trap”, *Europhys. Lett.* **61**, 187 (2003)
 - [43] R. deCarvalho, J.M. Doyle, B. Friedrich, T. Guillet, J. Kim, D. Patterson and J.D. Weinstein, “Buffer-gas loaded magnetic traps for atoms and molecules: a primer”, *Eur. Phys. J. D* **7**, 289 (1999)
 - [44] Franco Dalfovo, Stefano Giorgini, Lev P. Pitaevskii and Sandro Stringari, “Theory of Bose-Einstein condensation in trapped gases”, *Rev. Mod. Phys.* **71**, 463 (1999)
 - [45] M.R. Andrews, C.G. Townsend, H.-J. Miesner, D.S. Durfee, D.M. Kurn and W. Ketterle, “Observation of interference between two Bose condensates”, *Science* **275**, 637 (1997)
 - [46] M. Köhl, T.W. Hänsch and T. Esslinger, “Measuring the temporal coherence of an atom laser beam”, *Phys. Rev. Lett.* **87**, 160404 (2001)
 - [47] Y. Le Coq, J.H. Thywissen, S.A. Rangwala, F. Gerbier, S. Richard, G. Delannoy, P. Bouyer and A. Aspect, “Atom laser divergence”, *Phys. Rev. Lett.* **87**, 170403 (2001)
 - [48] Michael Köhl, Theodor W. Hänsch and Tilman Esslinger, “Continuous detection of an atom laser beam”, *Phys. Rev. A* **65**, 021606 (2002)
 - [49] M. Kozuma, L. Deng, E.W. Hagley, J. Wen, R. Lutwak, K. Helmerson, S.L. Rolston and W.D. Phillips, “Coherent splitting of Bose-Einstein condensed atoms with optically induced Bragg diffraction”, *Phys. Rev. Lett.* **82**, 871 (1999)

- [50] J. Stenger, S. Inouye, A.P. Chikkatur, D.M. Stamper-Kurn, D.E. Pritchard and W. Ketterle, “Bragg spectroscopy of a Bose-Einstein condensate”, *Phys. Rev. Lett.* **82**, 4569 (1999)
- [51] I. Bloch, M. Köhl, M. Greiner, T.W. Hänsch and T. Esslinger, “Optics with an atom laser beam”, *Phys. Rev. Lett.* **87**, 030401 (2001)
- [52] Robert Graham and Dan F. Walls, “Theory of strong outcoupling from Bose-Einstein condensates”, *Phys. Rev. A* **60**, 1429 (1999)
- [53] N.P. Robins, C.M. Savage, J.J. Hope, J.E. Lye, C.S. Fletcher, S.A. Haine and J.D. Close, “Fluctuations and flux: the limits of multistate atom lasers”, *Phys. Rev. A* **69**, 051602 (2004)
- [54] J.J. Hope, G.M. Moy, M.J. Collett and C.M. Savage, “Steady-state quantum statistics of a non-Markovian atom laser”, *Phys. Rev. A* **61**, 023603 (2000)
- [55] John Jeffers, Peter Horak, Stephen M. Barnett and Paul M. Radmore, “Bound mode of an atom laser”, *Phys. Rev. A* **62**, 043602 (2000)
- [56] H. Steck, M. Naraschewski and H. Wallis, “Output of a pulsed atom laser”, *Phys. Rev. Lett.* **80**, 1 (1998)
- [57] J. Schneider and A. Schenzle, “Output from an atom laser: theory vs. experiment”, *Appl. Phys. B* **69**, 353 (1999)
- [58] F. Gerbier, P. Bouyer and A. Aspect, “Quasicontinuous atom laser in the presence of gravity”, *Phys. Rev. Lett.* **86**, 4729 (2001)
- [59] N.P. Robins, A.K. Morrison, J.J. Hope and J.D. Close, “Shut down of an atom laser”, cond-mat/0501747
- [60] Harold J. Metcalf and Peter van der Straten, *Laser Cooling and Trapping*, Springer (1999)