

# Use of an Optical Dipole Trap in a Cold-atom Electron Source



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# Abstract

Abstract text.



# Statement of Contributions and Originality

No idea what this should look like. I should probably figure that out.



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# 1

## Introduction

The University of Melbourne’s cold-atom electron source (CAES) project aims to create high-brightness, high-coherence electron bunches for use in coherent electron diffractive imaging. The imaging of nanoscale objects such as biological molecules [1,2] and defects in solid-state devices [3] by ultrafast, single-shot electron diffractive imaging would provide important information about structures and the dynamic processes of important biological molecules such as membrane proteins.

### 1.1 Imaging of Bio-molecules

In order to determine the structure of biological molecules imaging techniques with atomic resolution are required. A number of techniques are capable of determining these structures [4–6] and the most successful to date has been x-ray crystallography [7,8]. Unfortunately the crystallisation process required for x-ray crystallography is difficult and to date only a small proportion of proteins have been successfully crystallised [9].

#### 1.1.1 Membrane Proteins

Membrane proteins are proteins that are associated with or attached to the membranes of cells. They are involved in detecting and conveying external signals into cells. This allows the cells to interact with and respond to their environment [10]. Membrane proteins are important in determining immune responses, interactions with pharmaceuticals, cell adhesion to form tissues and controlling important metabolic processes such as salt balance, energy production and photosynthesis [11].

Determining the structure of these molecules is a key step in understanding their chemical and biological function as well as how they will respond to drugs. The importance of knowing the atomic structure of biomolecules is exemplified by the enormous progress made in various fields of

biology once the double-helical structure of DNA was determined from x-ray images in 1953 [12]. Once a protein's structure and function are known then it becomes possible to design drugs [13] where needed and to more fully understand how the protein behaves in its biological system.

The development of new imaging techniques, such as ultrafast single shot diffraction, and new light sources, such as x-ray free electron lasers (XFELs), have been driven by the goal of overcoming the limitations of x-ray crystallography. Ultrafast single-shot diffraction imaging also has the potential to be able to determine the dynamic structure of biological molecules.

### 1.1.2 Ultrafast, single-shot, coherent diffractive imaging with electrons

X-ray diffraction from crystals was first observed a century ago [14] and resulted in a Nobel prize being awarded to William Bragg and his son. Since then coherent diffractive imaging (CDI) has been performed on a myriad of different samples with coherent beams of x-rays and electrons.

Ultrafast, single-shot imaging requires a very bright source of radiation in order to provide enough scattered information on the detector before the sample takes damage from the illumination [15]. Single-shot imaging with a sufficiently bright source and a short enough interaction time would be able to image protein molecules, and other bio-molecules, without the need for crystallisation [16].

With femtosecond timescale single-shot imaging it is possible to observe such things as molecular vibration and dynamic chemical processes [17]. With the sophisticated imaging techniques currently in development around the world and the continued improvement of radiation sources it will become possible to create 'molecular movies' [1] of these processes. Unfortunately, the brightnesses required for single shot imaging with electrons requires multi-billion-dollar XFEL facilities.

Electron sources however may be able to provide cheaper alternatives. Electron interactions with molecules are significantly stronger than those of x-rays. For similar energies the electron interaction with a sample is  $10^5 - 10^6$  times stronger than that of x-rays [18]. This means that while a huge facility is required to generate x-ray light of sufficient brightness a table-top source of electrons may be able to provide bright enough radiation for CDI.

## 1.2 Melbourne cold-atom electron source

If bright, coherent, femtosecond long bunches of electrons can be produced from the Melbourne CAES then CDI can be performed on a range of structures and eventually molecules.

In order to produce electrons in the CAES Rubidium atoms are cooled and trapped in a retro-reflective magneto-optical trap (MOT) that is loaded from a Zeeman slower [19–21]. The valence

electrons of the trapped atoms are then ionised using a two-stage ionisation process.

The ionisation process is tuned such that the electrons are given the minimum energy required to ionise ensuring that the electrons are ‘cold’ (approximately 10 K [22]).

The cold electrons are accelerated out of the cloud by a uniform electric field generated by charged parallel plates, guided to the neighbouring sample chamber and focused onto the target sample. After passing through the sample the resulting diffraction pattern is incident upon the detector. The diffraction pattern recorded by the detector can be used to determine the structure of the sample using standard CDI techniques.

During the ionisation and acceleration stage the magnetic and optical trapping must be turned off. The optical trapping interferes with the ionisation stage and the magnetic trapping would have extremely strong effects on the electron paths due to the low mass of the electrons. This means that, during these phases, the atom cloud is no longer trapped and begins to undergo thermal expansion and fall due to gravity.

This cycle of trapping, ionisation, acceleration and imaging occurs with a frequency of 10 Hz during normal operation.

### 1.3 Stability of the cold-atom electron source

In its current state the CAES suffers from a number of technical issues that are preventing the observation of diffraction through samples. One of these issues is the instability of the position of the electron signal on the detector which is due to the instability in the atom cloud. Variations in the magnetic environment as well as the long turn-off time of the magnetic trapping could also be interfering with the electron paths.

During the standard 10 Hz cycle the atom cloud formed by the MOT has approximately 93 ms to fill which does not provide enough time for the trap to saturate. The distribution of the atoms within the cloud therefore varies from cycle to cycle. The atom distribution also varies during a single cycle as atoms ‘slosh’ within the trap. These issues are exacerbated when the trapping is turned off and the cloud begins to fall and expand.

This instability in the distribution of the atoms results in instability in the initial distribution of the electrons. This is apparent on the detector as shot-to-shot variations in the position of the electron beam. Mitigating this instability would make the application of imaging techniques easier as well as allowing the various electron optics to be used more reliably.

### 1.4 Optical dipole traps

Optical dipole traps (ODTs) may prove to be the solution to this stability problem. An ODT consists of a focused, Gaussian laser beam that is detuned from the atomic resonances of the

target atomic species. The atoms will feel a force towards the high intensity regions of the laser, ie. the centre of the beam and the focus.

### 1.4.1 History of optical dipole trapping

The use of the optical dipole force as a confining mechanism was first proposed by Askar'yan in 1962 [23] for plasmas and neutral atoms. Ashkin successfully demonstrated the trapping of micron-size latex spheres suspended in water using a focused Gaussian lasers in 1970 [24]. The first optical trapping of atoms was demonstrated by Chu et. al. in 1986 [25] where a ODT was used to trap sodium atoms.

Since then ODTs have been used extensively in atom optics and have proven invaluable in the creation of Bose-Einstein condensates (BECs) and atom lasers.

### 1.4.2 Optical dipole traps in the cold-atom electron source

The main advantage of ODT for the CAES is trapping without magnetic fields or on-resonance lasers. This means that the atom-cloud can remain trapped during the ionisation and acceleration phases of electron generation. This should reduce the current instability in the electron beam path.

ODT also provide the opportunity to experiment with other techniques such as evaporative cooling to compress the atom-cloud and optical lattices [26] to counter disorder induced heating.

ODTs used in the CAES must meet several criteria in order to be useful;

- The trap depth must be at least as deep as the temperature of the atoms in the MOT which is approximately  $70\text{ }\mu\text{K}$  [22]. A trap depth of ten times the average temperature of the MOT atoms should be sufficient to trap the majority of the atoms in the trapping region. The trap depth is affected by the power, the detuning from resonance and the size of the beam.
- The lifetime of the trap must be in excess of the length of the ionisation and acceleration phase which is not longer than 10 ms. The lifetime of the trap is affected by the temperature of the atoms and the scattering rate of the trapping light field which is determined by the intensity of the light at the trap and the size of the detuning from resonance.
- Ideally the size of the trap would encompass the entire MOT however this is impractical due to the laser power available. The minimum size of the trap should be the size of the excitation region which is of order  $500\text{ }\mu\text{m}$  [27].

Two light sources are available for the production of the ODT. The first is a 780 nm external cavity diode laser (ECDL) seeded tapered amplifier (TA) which can be detuned to a wavelength of 785 nm with an applicable power of 500 mW. The second is a 1064 nm, 20 W fiber laser.

This project focusses on the use of the TA source due to its relative safety and the fact that it was ready first.

## 2

# Theory

## 2.1 Energy Levels of Rubidium

The MOT makes use of a closed transition of rubidium in order to create the atomic cloud. The ODT and absorption imaging also interact with this transition. The various energy levels and transitions are shown in figure 2.1.

The  $5^2S_{3/2}F = 3 \rightarrow 5^2P_{3/2}F = 4$  transition in rubidium forms a closed loop. Atoms are excited to the  $F=4$  state and then spontaneously decay back to the  $F=3$  state. The atom is forbidden to decay into any of the  $5^2P_{1/2}$  states since such a transition would not conserve parity. The excited atoms are also forbidden to decay to the  $5^2S_{3/2}F = 2$  state since this would require an angular momentum change of 2 which a single photon cannot supply

There is a small chance that an atom absorbing a photon will be excited to the  $F=3$  state after which the atom can decay to either the  $F=3$  ground state or the  $F=2$  ‘dark’ state. If the atoms enters the ‘dark’ state then it no longer interacts with the cooling beams and thus remains in the ‘dark’ state and is no longer trapped. The repump laser is tuned to the  $5^2S_{3/2}F = 2 \rightarrow 5^2P_{3/2}F = 3$  transition so that atoms can be reintroduced to the cycling transition and remain trapped.

## 2.2 Electron Generation in the Cold-Atom Electron Source

The CAES uses two stage photoionisation as its primary method of electron production. This method provides strong control over the excess energy of the ionised electrons which is essential to the production of cold electrons. Control of the initial electron bunch shape is also possible as described by McCulluch et. al. [22].

Two lasers with different wavelengths can be used for efficient ionisation of atoms while producing cold electrons. An excitation laser takes the atoms from the ground state to an intermediary

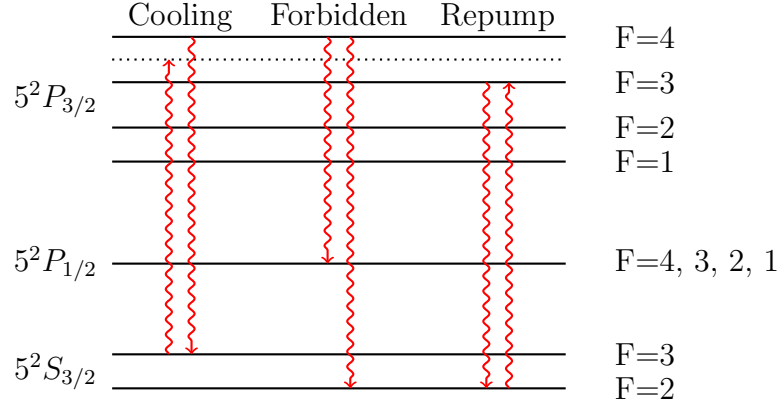


Figure 2.1: The energy levels involved in trapping rubidium in a MOT. The first two transitions show the cycling transition that is used by the main cooling lasers in a MOT. The third and fourth red lines show two forbidden transitions. If the cooling laser excites to the  $F=3$  level then it is possible for the atom to decay to the ‘dark’  $F=2$  state. The repump laser serves to restore these atoms to the cycle. The dotted line indicates the detuning required for Doppler cooling.

excited state and an ionisation laser takes the excited atoms from the intermediary state to the ionisation continuum. The excess energy of the ionised electrons can be controlled by varying the wavelength of the ionisation laser.

In the CAES the excitation laser is resonant to the D2 transition of the trapped  $^{85}\text{Rb}$  atoms (780.24nm). This resonance results in efficient population transfer to the excited state. The ionisation laser can be set to couple the first excited state to a Rydberg state rather than to the ionisation continuum directly which results in resonant transitions. The resonant transition to a Rydberg state followed by field ionisation induced by the accelerating electric field (see figure 2.3) is more efficient than other ionisation pathways which rely on non-resonant behaviour. Field ionisation results in free electrons with very little energy ( $T \approx 10\text{K}$  [22]) and are thus called ‘cold’.

The cold electrons are then accelerated with an electric field and steered with a number of magnetic devices through the sample and onto the detector.

## 2.3 Optical Dipole Traps

The following derivation of the dipole potential and scattering rate for ODT follows the one presented in Grimm and Weidemüller [28].

An electric field,  $E$ , from laser light of frequency  $\omega$  will induce an atomic dipole moment  $\mathbf{p}$  in

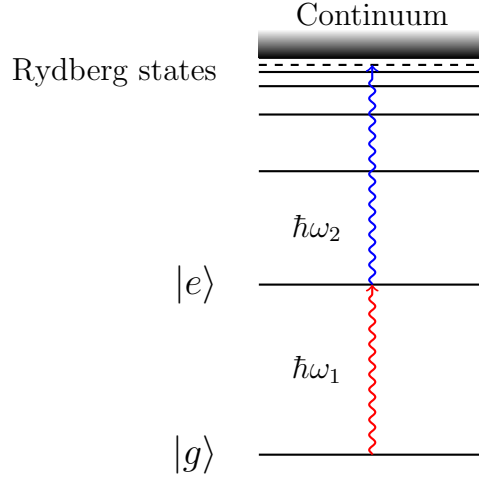


Figure 2.2: Energy level diagram for an atom undergoing two-stage ionisation. Resonant excitation from the ground state,  $|g\rangle$  to the excited state  $|e\rangle$  is achieved with a coupling laser of frequency  $\omega_1$ . A second laser of frequency  $\omega_2$  is used to couple  $|e\rangle$  to a Rydberg state. The atom is then field ionised by the uniform electric field.

an atom placed within the light field. Using standard complex notation we can write,

$$\mathbf{E}(\mathbf{r}, t) = \hat{\mathbf{e}}\tilde{E}(\mathbf{r}) \exp -i\omega t + c.c. \quad (2.1)$$

where  $\hat{\mathbf{e}}$  is the polarisation unit vector. The amplitude of the dipole moment,  $\tilde{p}$ , is related to the electric field amplitude,  $\tilde{E}$ , by

$$\tilde{p} = \alpha\tilde{E}. \quad (2.2)$$

$\alpha$  depends on the driving frequency,  $\omega$  and is called the complex polarisability.

The induced dipole moment,  $\mathbf{p}$  has an interaction potential with the electric field,  $\mathbf{E}$  given by

$$U_{dip} = -\frac{1}{2}\langle\mathbf{p}\mathbf{E}\rangle = -\frac{1}{2\epsilon_0 c}Re(\alpha)I, \quad (2.3)$$

where the time average over the rapidly oscillating terms is indicated by the angle brackets, the field intensity is  $I = 2\epsilon_0 c|\tilde{E}|^2$  and the  $\frac{1}{2}$  takes the the induced nature of the dipole moment in account. The dipole force results from the gradient of the interaction potential

$$\mathbf{F}_{dip}(\mathbf{r}) = -\nabla U_{dip}(\mathbf{r}) = \frac{1}{2\epsilon_0 c}Re(\alpha)\nabla I(\mathbf{r}). \quad (2.4)$$

The dipole force is a conservative force and is proportional to gradient of the intensity of the light

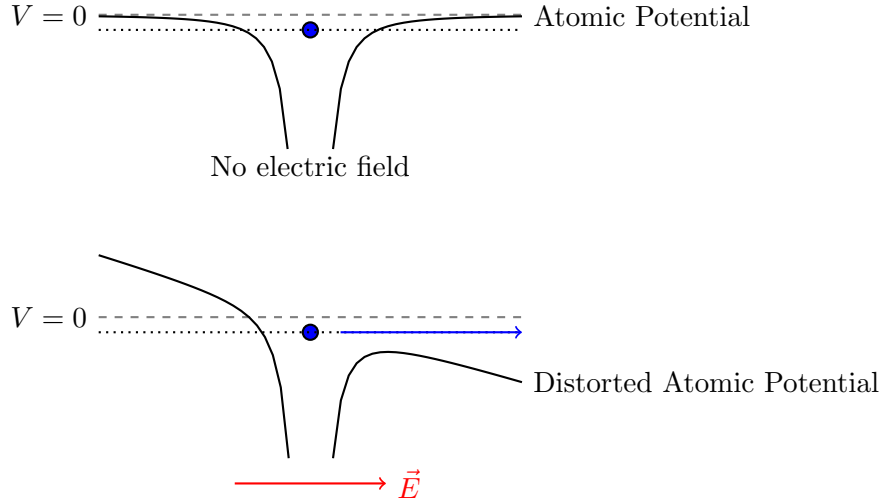


Figure 2.3: The top diagram depicts an atom excited to a Rydberg state without the presence of an electric field. The lower diagram show the same atom in the presence of an electric field. The electric field distorts the atomic potential in such a way as to allow the atom to become ionised. The solid black lines represent the atomic potential, the dashed lines the zero field ionisation threshold, the dotted lines the energy of the valence electrons, the blue circles show the electrons and the red arrow the direction of the electric field.

field.

The oscillator absorbs power from the light field which is re-emitted as dipole radiation. This is given by,

$$P_{abs} = \langle \dot{\mathbf{p}} \mathbf{E} \rangle = 2\omega \text{Im}(\tilde{p} \tilde{E}^*) = \frac{\omega}{\epsilon_0 c} \text{Im}(\alpha) I \quad (2.5)$$

The complex part of the polarisability gives the out of phase component of the dipole oscillation which results in absorption. Absorption can be interpreted in terms of photon scattering in cycles of absorption and emission of photons of energy  $\hbar\omega$ . This corresponds to a scattering rate of

$$\Gamma(\mathbf{r}) = \frac{P_{abs}}{\hbar\omega} = \frac{1}{\hbar\epsilon_0 c} \text{Im}(\alpha) I(\mathbf{r}). \quad (2.6)$$

### 2.3.1 Atomic Polarisability

The atomic polarisability,  $\alpha$  can be calculated by using Lorentz's model for a classical oscillator [citation please](#). In this picture an electron with mass  $m_e$  and charge  $e$  is considered to be bounds to the core elastically with an oscillation frequency  $\omega_0$  which corresponds to the optical transition



frequency.

The polarisability can be calculated if the equation of motion,  $\ddot{x} + \gamma\dot{x} + \omega_0^2 x = -eE(t)/m_e$ , is integrated for the driven oscillation of the electron to give

$$\alpha = \frac{e^2}{m_e} \frac{1}{\omega_0^2 - \omega^2 - i\omega\Gamma_\omega} \quad (2.7)$$

where the damping rate due to radiative energy loss is

$$\Gamma_\omega = \frac{e^2\omega^2}{6\pi\epsilon_0 m_e c^3}. \quad (2.8)$$

By substituting  $e^2/m_e = 6\pi\epsilon_0 c^3 \Gamma_\omega / \omega^2$  and the on-resonance damping rate  $\Gamma \equiv \Gamma_{\omega_0} = (\omega_0/\omega)^2 \Gamma_\omega$  we get

$$\alpha = 6\pi\epsilon_0 c^3 \frac{\Gamma/\omega_0^2}{\omega_0^2 - \omega^2 - i(\omega^3/\omega_0^2)\Gamma} \quad (2.9)$$

While this is classically derived it serves as a good approximation for far-detuned dipole traps due to the relatively low scattering rates and hence low saturation [28].

### 2.3.2 Optical Dipole Force and Scattering Rate

Using equation 2.9 in 2.3 and 2.6 in the case of large detuning and negligible saturation we can derive

$$U_{dip}(\mathbf{r}) = -\frac{3\pi c^2}{2\omega_0^3} \left( \frac{\Gamma}{\omega_0 - \omega} + \frac{\Gamma}{\omega_0 + \omega} \right) I(\mathbf{r}), \quad (2.10)$$

and

$$\Gamma_{sc} = \frac{3\pi c^2}{2\hbar\omega_0^3} \left( \frac{\omega}{\omega_0} \right)^3 \left( \frac{\Gamma}{\omega_0 - \omega} + \frac{\Gamma}{\omega_0 + \omega} \right)^2 I(\mathbf{r}). \quad (2.11)$$

Most experiments are performed with  $\omega$  relatively close to the resonance,  $\omega_0$ . In this case the detuning  $\Delta \equiv \omega - \omega_0 \ll \omega_0$ . Here we can make the rotating wave approximation and set  $\omega/\omega_0 \approx 1$ . The equations above simplify to

$$U_{dip}(\mathbf{r}) = \frac{3\pi c^2}{2\omega_0^3} \frac{\Gamma}{\Delta} I(\mathbf{r}), \quad (2.12)$$

and

$$\Gamma_{sc}(\mathbf{r}) = \frac{3\pi c^2}{2\hbar\omega_0^3} \left( \frac{\Gamma}{\Delta} \right)^2 I(\mathbf{r}). \quad (2.13)$$

These equations provide the basis for understanding the operation of dipole traps. The sign of the detuning is clearly important. For below resonance or ‘red’ detuning ( $\Delta < 0$ ) the dipole potential is negative and atoms are drawn into the high intensity portions of the light field. Above resonance or ‘blue’ detuning ( $\Delta > 0$ ) results in repulsion from the high intensity regions of the light and a positive potential.

The potential scales with  $I/\Delta$  and the scattering scales with  $I/\Delta^2$  which means that for a certain potential depth high intensity and detuning will result in the least scattering.

As previously mentioned Gaussian beams are used for red-detuned ODTs. A Gaussian beam’s intensity  $I(r, z)$  at a given radius  $r$  from the beam centre and distance from the focus  $z$  can be defined as [29]

$$I(r, z) = I_0 \left( \frac{w_0}{w(z)} \right)^2 e^{-2r^2/w(z)^2} \quad (2.14)$$

where  $I_0$  is the intensity at the centre of the focal point,  $w_0$  is the beam waist at the focus and the beam waist  $w(z)$  is

$$W(z) = \sqrt{1 + \left( \frac{z}{z_0} \right)^2}. \quad (2.15)$$

Here  $z_0$  is the Rayleigh length and is given by

$$z_0 = \frac{\pi w_0^2}{\lambda}. \quad (2.16)$$

Gaussian beam diagram? i- only if time permits

These equations can be used to simulate an ODT. Using the light sources similar to those described in chapter 3 we can create generate the potential depicted in figure 2.3.2. The potential has been converted to an effective temperature,  $T_{eff}$  using

$$T_{eff}(r, z) = \frac{2}{3k_B} U(r, z) \quad (2.17)$$

where  $U$  is the potential and  $k_B$  is Boltzmann’s constant.

Still need to talk about how these equations make a trap as well as some theoretical numbers

### 2.3.3 lifetime

hmmm what to do here....

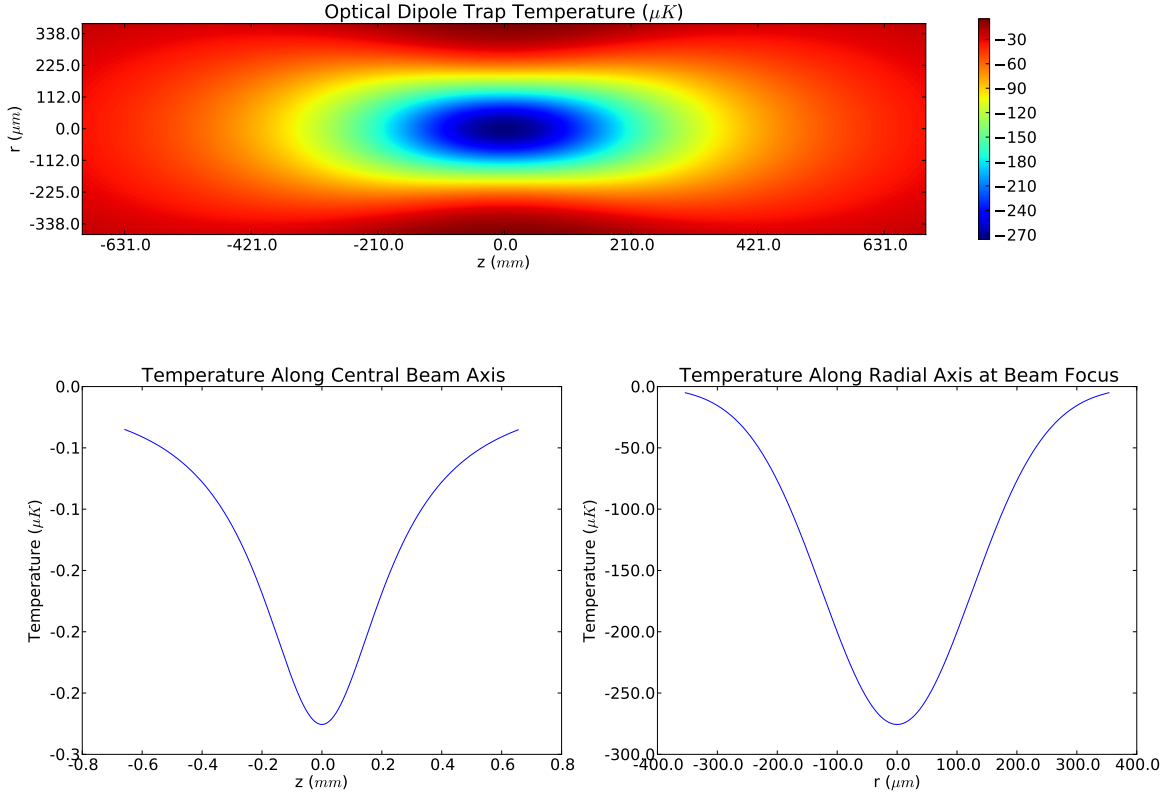


Figure 2.4: The effective temperature of a single beam optical dipole trap is depicted here. The total power of the simulated beam is 500mW with a detuning of 2nm red of the  $^{85}\text{Rb}$  D2 resonance and a beam waist of  $250\mu m$ . The top graph shows a cross section through the centre of the beam (note that the scale and units on each axis are different). The graph on the bottom left shows the effective temperature along the  $r=0$  axis and the graph on the right shows the temperature along the  $z=0$  axis.

### 2.3.4 Configuration

The simplest form of optical dipole trap consists of a single focussed Gaussian beam that can trap atoms at the focus. These simple traps have been used since the 1980s [25] and are frequently used to form BECs and atom lasers [30–32].

Single beam traps have strong confinement in the direction perpendicular to the beam and relatively weak confinement along the beam. A trap with strong confinement in all directions can be created by crossing two beams. Crossed beam traps are used frequently to produce BECs [33–37].

diagram!

remember to mention polarisation stuff for the crossed beam trap

## 2.4 Imaging

In order to determine the spatial distribution of the atoms at a given time techniques for imaging are required. Numerous techniques for imaging are available the simplest of which are fluorescence and absorption imaging.

### 2.4.1 Fluorescence Imaging

Near resonant light passing through atom clouds (such as the optical molasses lasers in a MOT or a specific probe beam) will be absorbed and re-emitted in a random direction. These scatter photons can be easily detected and images of the scattered photons can be easily produced. This method is easy to do and has the advantage that imaging can be done on any axis. The signal is rather weak however since the scattered photons are equally distributed in all directions so only a small portion will reach the detector. Due to the strong interaction of the laser light with the atoms this is a destructive imaging method.

diagram i should probably define destructive and non-destructive imaging methods

Fluorescence imaging is very easy to accomplish with the Melbourne CAES when used to view the MOT due to the fluorescence from the cooling lasers. However it is not practical for use with atoms trapped in an ODT since with the significantly reduced atom count the signal from fluorescence imaging will not be detectable.

### 2.4.2 Absorption Imaging

Absorption imaging is another destructive imaging method that makes use of an on-resonance probe laser. In absorption imaging a collimated probe laser is directed through the atoms and onto the detector. As in fluorescence imaging the photons will be absorbed and reemitted in

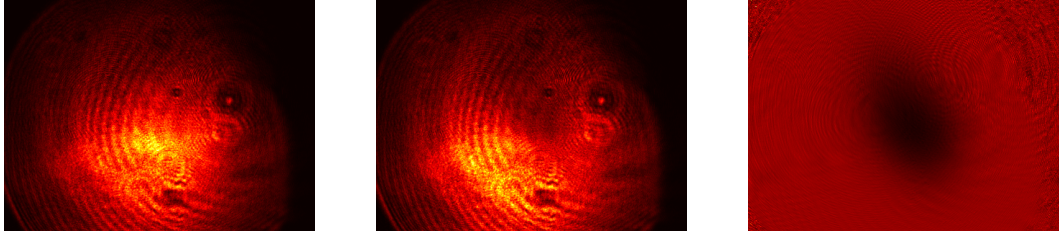


Figure 2.5: The above images are an example of absorption imaging. The image on the left is that of the on-resonance probe beam taken while the magnetic trapping of the magneto-optic trap was turned off and no atoms were trapped. The centre image shows the probe beam after it had passed through the atom-cloud of the normal magneto-optic trap and the corresponding shadow is clearly visible. The transmission function of the atoms (see equation 2.18) is shown in the right image.

random directions. After the light has passed through the atoms a ‘shadow’ due to the photons absorbed by the atoms will be left in the probe beam.

diagram

The signal from absorption imaging is much stronger than that for fluorescence however it is not possible to get quantitative information for dense clouds of atoms due to the exponential drop in transmission [38]. This is not a problem for the atoms trapped in the CAES since no compression is currently being used on the MOT or ODT.

The strong interaction between the laser and the atoms means that with a ‘fragile’ trap this imaging technique will give many of the atoms enough energy to escape the trap.

### 2.4.3 Absorption Imaging Analysis

If  $I_0$  is an image of the probe beam taken while there are no atoms present and  $I$  is an image of the probe beam with the atoms present then the transmission function for the atoms,  $T$ , can be calculated with

$$I = TI_0. \quad (2.18)$$

Each point in  $T$  corresponds to the integrated column density of the atoms in the cloud at that point and this information can be used to determine a number of different metrics such as the temperature of the atoms and the total number of atoms.

### 2.4.4 MOT Temperature

An atomic distribution in an ideal MOT atom cloud should be a Gaussian distribution whose two dimensional density can be modelled by

$$\rho(x, y) = \rho_0 \exp\left(\frac{x^2}{\sigma_x^2} + \frac{y^2}{\sigma_y^2}\right) \quad (2.19)$$

where  $\rho_0$  is the central density and  $\sigma_x$  and  $\sigma_y$  are the 1/e radii of the distribution.

If the trapping lasers and magnetic fields are turned off the atom-cloud should begin to expand thermally. The r.m.s thermal velocity,  $v_0$ , is related to the temperature of the cloud,  $T$ , via [39]

$$v_0 = \sqrt{\frac{2k_B T}{m_{Rb}}} \quad (2.20)$$

where  $k_B$  is Boltzmann's constant and  $m_{Rb}$  is the mass of rubidium. The 1/e radius of the atom cloud,  $r$ , at time  $t$  after it has been released is given by

$$r(t) = \sqrt{r_0^2 + (v_0 t)^2}. \quad (2.21)$$

Here  $r_0$  is the initial 1/e radius of the cloud.

The temperature can be calculated by taking a number of absorption images for various values of  $t$  and then fitting each of the atomic distributions to equation 2.19. The various cloud radii can then be fitted to equation 2.21 and a temperature can then be calculated with equation 2.20.

### 2.4.5 Atom Count

It is useful to know the number of atoms in a given absorption image. To do this we need to know the magnification of the optical system in front of the detector as well as the power of the probe laser.

As the probe laser traverses through the atoms cloud its intensity obeys Beer's law [citation](#),

$$I(x, y) = I_0(x, y)e^{-D(x, y)} \quad (2.22)$$

where  $I_0(x, y)$  is the intensity of the beam before the cloud,  $I(x, y)$  is the intensity after the cloud and  $D(x, y)$  is the optical depth along the probe beam's axis. The coordinates  $(x, y)$  denote a given position in the plane perpendicular to the probe beam. The optical density is given by [citation](#)

$$D(x, y) = \sigma \int_{-\infty}^{\infty} n(x, y, z) dz. \quad (2.23)$$

Here  $\sigma$  is the absorption cross-section and  $n(x, y, z)$  is the atomic density distribution. The details of  $n(x, y, z)$  are unimportant for many applications where only the total number of atoms,  $N$ , is required.

Using equations 2.22 and 2.23 we can get

$$D(x, y) = -\log_e\left(\frac{I}{I_0}\right) = \sigma \int_{-\infty}^{\infty} n(x, y, z) dz. \quad (2.24)$$

By integrating across the image we obtain

$$\int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \frac{1}{\sigma} D(x, y) dx dy = N. \quad (2.25)$$

Practically  $I$ ,  $I_0$  and  $D(x, y)$  will be two dimensional arrays of pixels, so the integrals can be rewritten as sums giving

$$N = A \sum_{(x,y)} \frac{1}{\sigma} D(x, y) \quad (2.26)$$

where  $A$  is the scaled area of the detector.

The absorption cross-section is given by [40],

$$\sigma = \frac{\sigma_0}{1 + 4(\Delta/\Gamma)^2 + (I/I_s)} \quad (2.27)$$

where  $\Delta$  is the frequency detuning of the pump light ( $\Delta = 0$  for on-resonant light) and  $\sigma_0$  is the on-resonance, low-intensity cross-section

$$\sigma_0 = \frac{\hbar\omega\Gamma}{2I_s}. \quad (2.28)$$

If on-resonant light with an intensity much less than the saturation intensity is used  $\sigma \approx \sigma_0$  and

$$N = -\frac{A}{\sigma_0} \sum_{(x,y)} \log_e \left( \frac{I(x, y)}{I_0(x, y)} \right). \quad (2.29)$$

If the low-intensity condition is not satisfied then the following must be used

$$N = -A \sum_{(x,y)} \frac{1 + (I(x, y)/I_s)}{\sigma_0} \log_e \left( \frac{I(x, y)}{I_0(x, y)} \right). \quad (2.30)$$

The pixel scale factor can be calculated by placing an object with known dimensions (such as

a ruler) at the object plane and then determining the number of pixels taken up by the object. Simply multiplying the pixel scale factor squared by the area of the probe beam on the detector to get  $A$ .

### 2.4.6 Other Imaging Methods

There are a number of other imaging techniques that can be used to image cold-atom clouds some of which are destructive and some are non-destructive. The non-destructive methods are particularly useful for imaging delicate systems such as BECs. An example of a minimally destructive technique is diffraction contrast imaging [41]. There are other techniques such as diffractive dark-ground imaging [42] and phase contrast imaging [43]. Each of these techniques has its own useful properties but few are as simple to setup and perform as absorption and fluorescence imaging.

## 2.5 Trap Stability

not sure what to do here - might drop this section

## 2.6 Stability of the Electron Signal

The stability of the electron signal incident on the detector can be analysed fairly simple. For a given iteration,  $i$ , of the experiment the electron signal will have an average spatial centre given by

$$\mathbf{x}_i = \frac{1}{\sum c(p)} \sum c(p) \mathbf{x}(p) \quad (2.31)$$

where both sums are over all the pixels,  $p$ , of the detector,  $c(p)$  are the counts for a given pixel and  $\mathbf{x}(p)$  are the locations of each pixel.

The average of a set of measurements,  $\bar{\mathbf{x}}$ , and the associated variance,  $\mu$ , for a set of size  $n$  are given by

$$\bar{\mathbf{x}} = \frac{1}{n} \sum_{i=0}^n \mathbf{x}_i \quad (2.32)$$

$$\mu^2 = \frac{1}{n} \sum_{i=0}^n (\mathbf{x}_i - \bar{\mathbf{x}})^2 \quad (2.33)$$

These simple calculations can be used to analyse the spatial variation of the electron signal and the variance can be used as a metric for determining whether the stability of the source is being improved by changes.



any other cunning stats tricks for this?



# 3

## Experiment

The CAES at the University of Melbourne has been assembled over a number of years. The experimental cycle can be divided into several parts which will be briefly described in this chapter. More details of the various experimental apparatus can be found in the group's recent papers [21, 22, 44] and theses [27, 39, 45].

### 3.1 Magneto-Optic Trap

The first stage of the experiment is trapping rubidium atoms in a MOT. An oven is used to create Rubidium vapour with a temperature around 350K which is collimated and directed down the axis of the Zeeman slower. The Zeeman slower slows the atoms down such that when they reach the main chamber they can be trapped by the combined magnetic and optical traps.

#### 3.1.1 Rubidium Oven

Rubidium atoms in a reservoir are heated in an oven to approximately 80 °C. The resulting vapour effuses through a heated drift tube and is then incident on a 'cold-cup' aperture resulting in a collimated beam. At this point the atoms have a velocity in the region of 300m/s. This is shown in figure 3.1

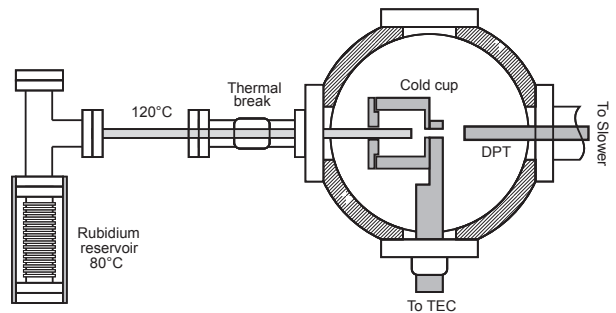


Figure 3.1: taken from Andy's thesis. This figure shows the rubidium atom source.

### 3.1.2 Zeeman Slower

The Zeeman slower cools the atoms from having a velocity of order 300m/s to 35m/s. This is achieved with doppler cooling using red-detuned light. As the atoms slow down the resonance condition changes so a magnetic coil with a tapered pitch is used to maintain the interaction. Another solution which is not implemented in this system is to use a frequency ‘chirp’ in the cooling light.

An Eagleyard tapered amplifier seeded with light from two ECDLs is used for the doppler cooling. The first ECDL produces the cooling light and the second is used to repump any atoms that fall into a dark state.

The ECDL is locked on to the appropriate frequency using a saturated absorption configuration [46].

### 3.1.3 Quasi-Mirror Magneto-Optic Trap

MOTs have been used extensively in atom-optics laboratories to trap and cool atoms of many species. The physics of MOTs is well documented and understood [47].

A conventional MOT consists of six beams which are able to damp the velocity of atoms in all directions where the beam overlap. A simpler design using only four beams is the “mirror-MOT”. Mirror-MOTs typically suffer from a reduced trapping volume [48].

In the CAES the accelerating structure required to extract the electron bunches is integrated with the mirror-MOT, “Quasi-Mirror Magneto-Optical Trap” (QMMOT) [49]. Figure 3.1.3 shows a schematic of the QMMOT where one of the plates is transmissive and the other reflective and both can be charged to provide the accelerating electric field.

The laser power for the MOT is supplied by a Toptica TA seeded by the cooling and repump ECDLs which are locked onto the appropriate atomic transitions using saturated absorption setups. A pair of magnetic coils external to the vacuum system in an anti-Helmholtz configuration provide the magnetic fields for the MOT.

## 3.2 Electron Generation

The generation of electrons is a central part of the CAES and each of the two stages has its own light source.

### 3.2.1 Excitation

The excitation of the atoms in the cloud can be done in one of two ways in the CAES. The first method of excitation is a 50  $\mu$ s exposure of light from an ECDL and the second method is to use

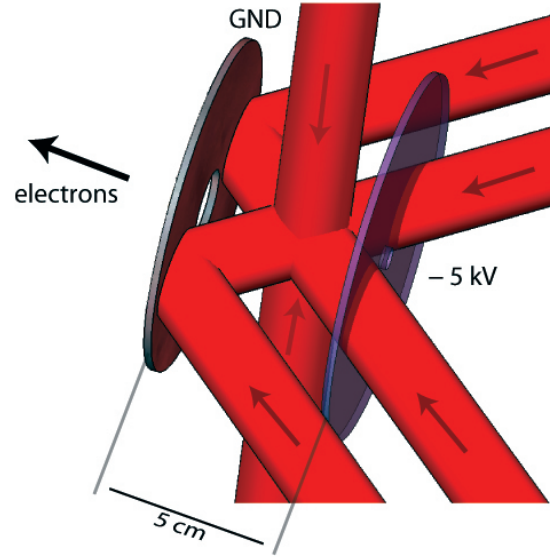


Figure 3.2: *Also taken from Andy's thesis.* Quasi-Mirror Magneto-Optical Trap. Two of the horizontal cooling beams are reflected from the conductive mirror and the other two pass through the conductive window to form the trapping region. To extract electrons a static electric field is applied once the cloud has been ionised.

a pulse from a Newport 3960 fs Tsunami which is able to produce 35 fs long bunches.

### ECDL Excitation

The ECDL is locked onto the  $5^2S_{3/2}F = 3 \rightarrow 5^2P_{3/2}F = 4$  transition of rubidium using saturated absorption and the exposure is controlled with an acousto-optical modulator (AOM). The excitation ECDL beam shares much of its beam path with that of the femtosecond laser and a mirror on a flip mount is used to determine which used for excitation at a given time. .

### Femtosecond Excitation

The Newport 3960 fs Tsunami produces approximately 80 fs long pulses of light with a wavelength centered around 800 nm with a 20 nm linewidth. [27] Femtosecond excitation allows the CAES to produce electron bunches that are picoseconds long.

### 3.2.2 Shaping

The CAES has the ability to create shaped electron bunches. This is done by applying a phase mask to the excitation beam with a spatial light modulator (SLM). The shaped excitation beam causes the distribution of excited atoms in the atom cloud to be proportionally shaped. This results in electron bunches with the same shape as the excitation beam.

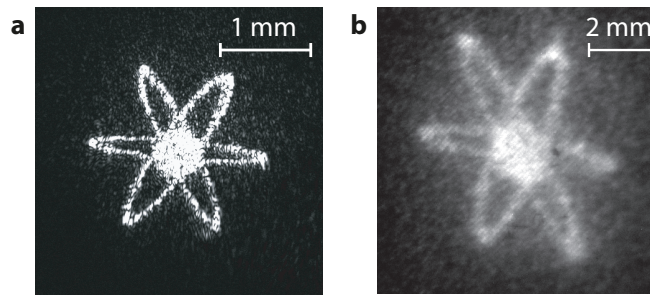


Figure 3.3: *from Andy's thesis*. Shaped electron bunches produced by the Melbourne CAES. Image a) shows the excitation laser intensity profile. b) shows the measured electron density distribution.

### 3.2.3 Ionisation

## 3.3 Sample Chamber

text

### 3.3.1 Beam Steering and Focussing

text

### 3.3.2 magnetic tentacle monster

text

### 3.3.3 Detector

text

## **3.4 Optical Dipole Trap**

### **3.4.1 TA**

text

### **3.4.2 Fiber laser**

text

### **3.4.3 dipole rig**

text

## **3.5 Absorption Imaging**

## **3.6 LabView**

text





# 4

## Results

If I ever get any results go in here.

### 4.1 magnetic control

get some current displacement numbers

### 4.2 absorption images of the mot

#### 4.2.1 metrics

### 4.3 absorption images of ODT

#### 4.3.1 metrics



# Glossary

**AOM** acousto-optical modulator.

**BEC** Bose-Einstein condensate.

**CAES** cold-atom electron source.

**CDI** coherent diffractive imaging.

**ECDL** external cavity diode laser.

**MOT** magneto-optical trap.

**ODT** optical dipole trap.

**SLM** spatial light modulator.

**TA** tapered amplifier.

**XFEL** x-ray free electron laser.



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