Literature Review

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1 Introduction

The University of Melbourne's cold-atom electron source aims to be able to create high-brightness, high-coherence electron bunches for use in coherent electron diffractive imaging. 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 structure and dynamic processes of nanoscale objects.

Membrane proteins, for example, are very important for some reason *(ASK VIVIEN get some references)*. Determining the structure of these molecules is a key step in understanding their chemical and biological function. 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 [4]. Once a protein's structure and function are known then it becomes possible to design drugs [5] where needed and to more fully understand how the protein behaves in its biological system.

In order to determine the structure of these biological molecules atomic, sub-nanometre imaging resolution is required. A number of techniques are available for determining these structures [6–8] however the most successful to date has been x-ray crystallography [9, 10]. Unfortunately the process of crystallising these membrane proteins is difficult and to date relatively few have been crystallised [11].

New imaging techniques and light sources such as x-ray free electron lasers and ultrafast single-shot diffraction have been driven by the goal of overcoming the limitations of x-ray crystallography. Ultrafast single-shot diffraction imaging also has the potential to determine dynamic structure of biological molecules. The Melbourne cold-atom electron source is aims to produce bright, coherent bunches of electrons for use in diffractive imaging.

1.1 Ultrafast, single-shot, coherent diffractive imaging with electrons

X-ray diffraction from crystals was first observed a century ago [12] 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.

Electrons have a shorter wavelength than x-rays thus allowing a higher limit on the attainable resolution for CDI. [REFERENCE would be nice]

1.1.1 Single-shot diffractive imaging

Single-shot diffractive imaging with an x-ray source of sufficient brightness should be able to produce a diffraction pattern from scattered x-rays from a single molecule before the molecule is destroyed by the Coulomb explosion which follows photoionisation within the molecule [13, 14]. Single-shot imaging aims to avoid the need for crystallisation with x-ray imaging since with a sufficiently bright source should allow imaging of any molecule.

With femtosecond timescale single-shot imaging it becomes possible to observe such things as molecular vibration and dynamic chemical processes [15] with the sophisticated imaging techniques currently in development it will become possible to create "molecular movies" [1] of these processes.

1.2 Melbourne cold-atom electron source

The University of Melbourne's cold-atom electron source project aims to produce an electron source for coherent diffractive imaging. If bright, coherent, femtosecond long bunches of electrons can be produced then CDI can be performed on a range of structures.

The cold-atom electron source operates by first illuminating laser-cooled rubidium atoms with a resonant 780 nm excitation laser followed by a 5 ns 480 nm ionisation laser pulse. The electrons are then accelerated in a uniform electric field and guided and focused onto the target.

[CHANGE THE FIGURE SO IT DOESN'T HAVE THE DIPOLE TRAP]

When extracting the ionised electrons from the atom cloud it is necessary to turn off the magnetic trapping fields [AND THE ZEEMAN SLOWER?] in order to prevent magnetic distortions of the electron bunches' paths. This means that just before electron extraction the cloud is no longer trapped and is beginning to expand. The use of trapping mechanisms that do not interfere with the electron bunches, such as an ODT, will help prevent this expansion and thus stabilise the initial position of the electron bunches which tend to drift at present due to dispersal of current, and hence magnetic field, in the magnetic coils and their power supplies.

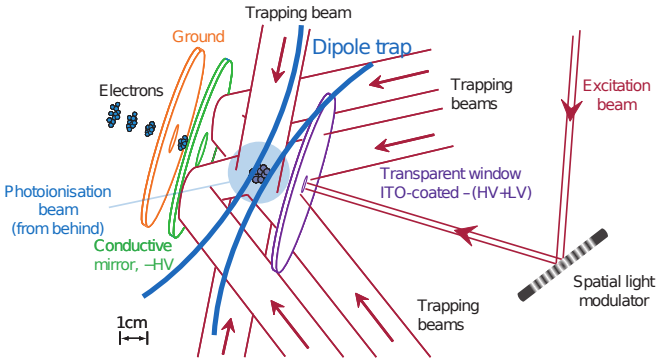

Figure 1: Quasi mirror MOT with optical dipole trap (ODT)

Using an ODT in this system will also allow an increase in the brightness and coherence of the source due to higher atom cloud densities during the ionisation process.

1.2.1 Brightness

Brightness is important in single-shot CDI due to the need to maximise the scattered signal and thus ensure sufficient sampling of the specimen within the exposure time.

For the cold-atom source the transverse brightness at the source is given by [16]

$$B_\perp = \frac{I_p m_e c^2}{4\pi^2 \sigma_x \sigma_y k_B T}, \tag{1}$$

where σ is the root mean squared source size and I_p is the peak electron current.

A pulse of electron's brightness can be increased by a reduction in the length of the bunches, by increasing the density of the bunches or by increasing the number of electrons in the bunch. A short bunch is necessary for ultrafast electron diffraction.

The use of an ODT will allow an increase of the atom-cloud density which will in turn result in an increase of the electron bunch density.

1.2.2 Coherence

Unsurprisingly coherence is an important factor in CDI since this technique relies on the interference of the diffracted waves. The transverse coherence

length of a imaging beam must be approximately twice the width of the object being imaged [17].

For a quasi-homogeneous source [18], the transverse coherence length L_c can be related to the transverse momentum spread, and hence the temperature, through [19]

$$L_c = \hbar/\sqrt{m_e k_B T}. \tag{2}$$

The transverse coherence is determined solely from the temperature of the electrons which is proportional to the temperature of the electron source and the ionisation energy.

The coherence of our electron bunches will be increase with the correct use of an ODT since the trap will serve to reduce the temperature of the atom cloud, and hence the electron bunches.

2 Optical Dipole Trapping

The use of ODTs in the cold-atom electron source will allow greater stability of the atom cloud during ionisation and extraction as well as increasing the density of the atom cloud during these phases with corresponding increases in density.

2.1 History of optical dipole trapping

The use of the optical dipole force as a confining mechanism was first proposed by Askar'yan in 1962 [20] 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 [21]. The first optical trapping of atoms was demonstrated by Chu et. al. in 1986 [22] where a ODT was used to trap sodium atoms.

2.2 Theory of Dipole Trapping

ODTs are sometimes considered to be the simplest form of atom trap since then consit solely of a focused, Gaussian laser beam detuned from the atomic resonances.

2.2.1 Trapping potential

The intensity of a Gaussian laser beam at the beam waist varies with r as

$$I(r) = I_0 e^{-r^2/w_0^2}, \tag{3}$$

where I_0 is the intensity at the centre of the beam at the waist, r is the radial distance from the centre of beam and w_0 is the beam radius at the focus.

The ground state light shift is given by [23]

$$\Delta E_g = \frac{\hbar \Omega^2}{4\delta}, \tag{4}$$

where the Rabi frequency $\Omega^2 = \gamma^2 I / 2 I_s$ and γ is the linewidth, I is the light intensity and I_s is the saturation intensity. Thus the light shift is larger at points of high intensity such as the centre of the beam and the beam focus.

In order to trap the laser is detuned below the resonances such that $\delta = \omega_l - \omega_a < 0$ where ω_l is the laser frequency and ω_a is the atomic resonance frequency. With negative detuning the ground-state light shift is negative everywhere and thus atoms feel a force towards the centre given by the gradient of the light shift, and for $\delta \gg \Omega$ and $\delta \gg \gamma$ the force is given by

$$F \simeq -\frac{\hbar}{4\delta}\nabla(\Omega(r)^2) = -\frac{\hbar\gamma^2}{8\delta I_s}\nabla I(r). \tag{5}$$

At the focus of a Gaussian beam this force is

$$F \simeq \frac{\hbar\gamma^2}{4\delta}\frac{I_0}{I_s}\frac{r}{w_0^2}e^{-r^2/w_0^2}, \tag{6}$$

and thus the transverse trapping potential is given by

$$U = -\int dr F \simeq \frac{\hbar\gamma^2}{8\delta}\frac{I_0}{I_s}e^{-r^2/w_0^2}. \tag{7}$$

It is easy to see with this equation how a negative (red) detuning will result in an inwards, trapping force and a positive (blue) detuning will result in a outwards, repulsive force. Blue detuned lasers can be used for trapping if the beam has a low intensity centre however [24–27].

2.2.2 Scattering rates

More general expressions for the trapping potential can be used to compare the potential to the scattering rate due to photon absorption [28]

$$U_{dip}(\vec{r}) = \frac{3\pi c^2}{2\omega_0^3}\frac{\gamma}{\delta}I(\vec{r}) \tag{8}$$

$$\Gamma_{sc}(\vec{r}) = \frac{3\pi c^2}{2\hbar\omega_0^3}\left(\frac{\gamma}{\delta}\right)^2 I(\vec{r}) \tag{9}$$

The scattering rate should be kept to a minimum in order to prevent the heating atoms in the trap. Fortunately the relationships are such that for large detunings $U_{dip} \gg \Gamma_{sc}$. Such far detuned lasers however do create shallower traps and thus require more powerful lasers to create similar trap depths.

2.3 Using an optical dipole trap in a cold-atom electron source

An ODT can serve several purposes in the cold-atom electron source including increasing the brightness and coherence of the electron bunches as described earlier.

A number of design choices in the development of this dipole trap are under consideration such as the wavelength of the trap, the configuration of the trapping beam/s and the size of the beam waist.

2.3.1 Available equipment

Two main options are available as far as light sources for the trap,

- a 20mW, 780nm diode laser amplified by a tapered amplifier to 1.8W,
- a 20W, 1064nm fibre laser.

The 780nm diode laser that seeds the tapered amplifier can be tuned away from the 780nm resonance [HOW FAR EXACTLY? what does this do to the TA?] up to [SOME NUMBER] nm. The 1064nm laser is extremely far away from the resonances which will result in reduced scattering rates however lasers with power as high as 20W require more caution in there use as well as suitable high-power optics.

2.3.2 1064nm optical dipole traps

ODTs with a wavelength near 1064nm are frequently used when rubidium Bose-Einstein condensates (BECs) are being formed [29–34]. These BECs are used for many different applications including the creation of atom-lasers [29–31], atomic clocks [35] and obviously further studies into BECs themselves and related trapping mechanisms [32–34].

ODTs with wavelengths at 1064nm are not only used in rubidium BECs. They have to used to form BECs of caesium [36], chromium [37], double-species BECs [38], and even molecular BECs [39].

2.3.3 "Near" 780nm optical dipole traps

Traps made from lasers "near" 780nm are more often used when studying and developing trapping methods [possibly due to reduced costs?]. Such

traps have detunings that vary from 0.5nm [42] to over 60nm [40,41] and are usually referred to as far-off-resonance traps (FORTs). Some of the things that these laser have been used to study are dipole trap loading [43], trapping single atoms [41] and the combination of an ODT with Sisyphus cooling [42].

2.3.4 Configurations

The simplest ODT consists simply of a focussed Gaussian beam [22] and many of the references use this simple configuration.

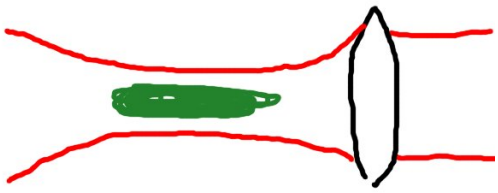

Figure 2: A simple ODT configuration

Crossed dipole trap [cite a selection of references] are a more complicated configuration that can provide a stronger trap as well as control over the shape of the trap and the trapping potentials in various directions. [Examples] Unlike simple dipole traps which create long cigar-shaped traps crossed dipole traps can create spherical traps.

Something about the angles involved. [refind the reference]

Not trapping at the focus. [refind the reference]

2.3.5 Waist size

Not really to do with the litrature.

Fix last lens, vary collimated beam size incident on the final lens using a beam expander.

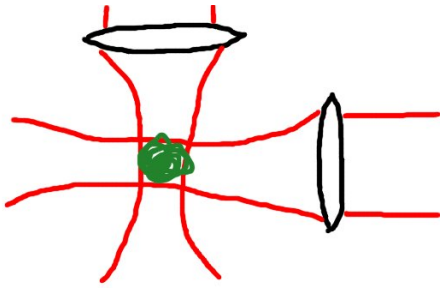

Figure 3: A crossed ODT configuration

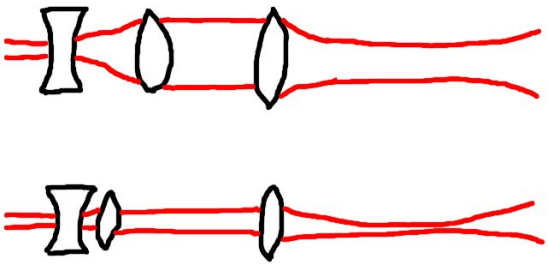

Figure 4: An example setup for controling the beam waist

Glossary

BEC Bose-Einstein condensate.

CDI coherent diffractive imaging.

ODT optical dipole trap.

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