Chapter 7

CO₂ Laser

7.1 Introduction

The CO₂ laser that was used in this work was a Coherent DEOS GEM Select 100. The principle of operation of a CO₂ laser is not discussed in detail here as it is covered in many textbooks, e.g. reference [154]. Briefly, there is a mixture of CO₂, N₂ and He gases contained between electrodes in the gain region of the cavity. An RF field is applied between the electrodes which creates a discharge. The first vibrational mode of the N₂ molecules (which has a very large excitation cross-section) is excited. This state is metastable and close in energy to the first asymmetric stretch mode of the CO₂ molecules. The CO₂ molecules are excited due to collisions with the N₂ (collisions are augmented by the presence of the He). The first asymmetric stretch mode of the CO₂ molecules decay to the first symmetric stretch mode, resulting in laser output at a wavelength of 10.6 μm. The laser produces a single mode, horizontally polarised beam with a power of 100 W.

7.2 Using the CO₂ Laser

Adding the CO₂ laser into the existing experimental setup required great care and preparation. As well as the necessity of ZnSe optics discussed in section 4.4.2, it is necessary to water cool the laser itself, its power supply, the AOMs (which receive 40 W of RF power) and the laser power meter.
The laboratory door was interlocked such that the laser would shut down immediately should the door open. The interlock was also connected to flow meters in the water cooling circuit to prevent overheating should the water pressure drop. When not in alignment mode, the beam path was completely enclosed. Points in the beam path of very high intensity (such as the foci of telescopes) were enclosed in pipes. The CO\textsubscript{2} laser is pumped by an 2kW RF D1000L power supply. The RF supply is in turn powered by a 35V, 60A Agilent 6573A DC power supply.

### 7.2.1 Installation

The CO\textsubscript{2} laser was secured to a platform which was mounted above some of the second MOT optics adjacent to the vacuum chamber, see figure 7.1. The use of this platform was necessary to raise the laser beam path up to the required height and also due to the lack of space on the optical table on which to place the laser directly. The output beam of the laser was measured (using knife-edge measurements, see section 7.2.2) to have a $1/e^2$ radius of $1.8\pm0.2$ mm and a divergence of 4.2 mrad. This was in agreement with the technical specifications provided for the laser \cite{155}.

### 7.2.2 Beam Profiling

Knife-edge measurements \cite{156} are a way of measuring the size of a laser beam by measuring the power drop at a detector as a function of the position of a sharp opaque blade moving across the path of a laser beam. When performing measurements on high power CO\textsubscript{2} laser beams the blade used must be sufficiently robust to withstand the laser radiation. Also, any reflections from the blade must be blocked. A schematic of the knife-edge measurement setup employed for the CO\textsubscript{2} laser is shown in figure 7.2.

Another way of measuring the profile of a CO\textsubscript{2} laser beam is to use a specialist beam sampler. During a demonstration of a Spiracon BPS beam sampler the transverse mode of our laser was measured in the near field, directly after the laser output. A false colour image of the beam profile can be seen in figure 7.3.

We found that this commercial profiler was cumbersome to use and fringes
Figure 7.1: Schematic of the intended CO\textsubscript{2} laser beam path. The position of the CO\textsubscript{2} laser and its optics in relation to the vacuum chamber. The orange elements represent ZeSe optics.
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Figure 7.2: Experimental setup for profiling the \textit{CO}_2 laser beam. The lens is necessary for measuring large diameter beams.

were present on the beam profile images which were not on the beam itself.

Figure 7.3: False colour image of the \textit{CO}_2 laser beam profile. The stripes in the profile are due to the measuring instrument.

7.2.3 Initial Alignment

To convey the \textit{CO}_2 laser beam to the experiment, the output beam was reflected through 90\textdegree before being telescoped down in size using a 7:4 telescope, thus allowing \(>98\%\) transmittance of the beam through the input aperture of
the AOM. The zero order beam from the AOM was reflected $90^\circ$ downwards into a heatsink beam block located on the optical table surface. The optimised first order diffracted beam was reflected back towards the chamber, see figure 7.1. At this point the alignment of the CO$_2$ laser became more critical and also more difficult to achieve because of space restrictions. The following section outlines the methods employed to align the first order CO$_2$ beam from the AOM.

7.3 Methods of Alignment

Aligning the CO$_2$ laser was difficult and great care had to be taken. Because the radiation is of high intensity and in the far infrared, typical methods of beam detection were not accessible. The pointing stability from the AOM is critically dependent upon its temperature [108]. The diffracted beam takes about 5 minutes to reach thermal equilibrium, during which time the beam was deflected through $\sim$5 mrad. For our experimental arrangement this results in a displacement of the beam spot at the chamber of 1 cm. For this reason the alignment of the beam was (in the most part) conducted at a full power of $\sim$65 W.

7.3.1 Thermal Paper and Imaging Plates

The coarse alignment of the laser beam was performed using thermal paper. The paper turns black (or sets on fire) in the presence of strong thermal radiation. By placing a piece of thermal paper in the path of the beam we could locate the beam position. To align the laser through the vacuum chamber, the full power first order beam was blocked using a fire brick. Then a piece of thermal paper was adhered to a cap containing a small central hole and then the cap placed over the viewport. The beam path would then be unblocked briefly allowing a mark to be burned onto the paper. Figure 7.4 shows a progression of paper pieces used to align the laser beam. Moving left to right then top to bottom we can see how the burn pattern becomes closer to the desired beam path (indicated by the small hole in the thermal paper) as successive iterations are made to the optical alignment.
Figure 7.4: Progression of used thermal paper pieces. The burn pattern gets closer to the center (blue dot) with each iteration of the beam alignment.
Another useful tool for detecting the coarse position of the beam was a Macken Instruments phosphorescent plate [157]. When illuminated with UV radiation, the plate glows yellow. In positions where the CO$_2$ laser beam is incident on the plate the phosphorescent glow is suppressed and a dark patch observed. An photographic example of this can be seen in figure 7.5.

Figure 7.5: Using a thermal imaging plate to locate the CO$_2$ laser beam. The laser spot appears as a black mark on a fluorescent yellow background.

Once coarse alignment of the CO$_2$ laser beam through the chamber was achieved, more sensitive methods of alignment were adopted.

### 7.3.2 Resonant Tracer Beam

A resonant tracer beam was used for fine alignment. This beam was provided by a Toptica DLX laser at a wavelength of 780 nm. The beam was overlapped with the CO$_2$ laser beam using a ZeSe combining slide after the AOM. The slide reflects only about 30\% of the 780 nm light and so a beam with power of around 250 mW was used. Once the beams were overlapped over a distance of several meters, adjustments to the beam path were made using the 780nm light alone. The schematic of the setup for this tracer beam can be seen in figure 7.6. The 780 nm beam was centered through the ZeSe viewports on the science chamber and we found that the MOT could be blown away by sweeping the beam’s frequency through resonance.
Figure 7.6: Schematic of the tracer beam setup. A 780 nm beam is overlapped with the CO₂ laser beam so that adjustments to the beam path can be made with the CO₂ laser turned off.
For our experimental configuration (requiring a CO$_2$ beam focus at the centre of the science chamber), the shortest available focal length lens that we could use outside the vacuum chamber was $f = 15$ cm. We then took account of the other available lens focal lengths and decided on using a 1:4 expanding telescope to enlarge the beam diameter to 10 mm. This results in $\ll 1\%$ loss of beam power on a 2” diameter lens and a $< 1\%$ Fresnel ripple from hard-edged truncation of the beam from the lens holder [158]. From Gaussian beam optics, for a collimated beam of $1/e^2$ radius $R$, and wavelength $\lambda$, focused by a lens of focal length $f$, the beam waist $w_0$ is given by [105],

$$w_0 \approx \frac{f \lambda}{\pi R}. \quad (7.1)$$

From this expression we calculated that by using a input beam radius of 10 mm we achieve a beam waist of 50 $\mu$m hence this is the value we adopted for the numerical modeling of chapter 3.

For a number of reasons we found difficulty in aligning the tracer beam once the expanding telescope was inserted. Firstly, the 780 nm beam was attenuated by the ZnSe optics resulting in a weak and difficult to see beam. Also, reflections from the front and back face of the combining slide were present resulting in a smeared beam spot. The tracer beam was aligned as well as possible and then focused into the centre of the science chamber. Fine adjustment of the focusing lens was achieved using a micrometer-adjusted 3-axis translation stage. We observed the focus of the beam by blowing away only the centre of the MOT. Placing the expanding telescope between two steering mirrors is a far from optimum arrangement but was necessary in this case as there was not space to place it elsewhere.

### 7.4 Search for the Dipole Trap Signal

Once the tracer beam was focused on to the MOT we assumed that the focus of the CO$_2$ beam would be in close proximity. Hence we began to search for signatures of a dipole trap using various methods. The input CO$_2$ beam was focused into the science chamber and the emerging output beam focused onto the power meter and used as a diagnostic.
7.4.1 Time of Flight Technique

Initially we began the search for the dipole trap signal by using a standard time of flight technique similar to that described in section 6.5.2. In this case however, we allowed over 35 ms of ballistic expansion so that the vast majority of atoms from the MOT had fallen away under gravity and out of the field of vision of the camera. The CO\textsubscript{2} laser was left on for the duration of the experimental cycle and then turned off only when the fluorescence imaging pulse was applied. We expected to see fluorescence from atoms trapped in the CO\textsubscript{2} beam after the rest of the MOT has dissipated but no signal was observed. Next, an experimental cycle was initiated so that a time of flight image was taken every 1.5 s and displayed on a monitor. The focusing input lens for the CO\textsubscript{2} beam was then translated through an \( x, y, z \) grid covering a cubic centimeter in steps of 0.5 mm. No signal was observed for the > 1000 lens positions adopted and so we moved on to try alternative methods.

7.4.2 Anti-Trap Signal

During previous work [49–51] we observed the dipole trap signal by making use of the difference in polarisability of the \( 5S \) and \( 5P \) states. The technique was implemented as follows, The MOT was made as large and diffuse as possible by reducing the B-field gradient to around 1 G/cm and reducing the magnitude of the detuning to less than 5 MHz (as close to resonance as possible without experiencing excessive flickering of the MOT). The CO\textsubscript{2} laser was then turned on. In the region of the CO\textsubscript{2} beam focus, the atoms experience a much greater light-shift in the excited state than the ground state and the atoms will experience blue detuned MOT light and be heated from the trap. This is illustrated in figure 7.7. For our beam parameters we expect a differential light-shift of over 30 MHz at the focus of the CO\textsubscript{2} beam. The focus of the dipole trap then shows as a dark stripe in a light background which can be seen to move as the input lens is adjusted. In this work we used this technique for several days without seeing any evidence of the dipole trap.

A variation on this technique was also implemented where a cycle was im-
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Figure 7.7: Principle of anti-trap technique. a) The atomic energy levels in free space, the laser cooling beam is red detuned. b) The CO$_2$ laser light creates a light-shift in the ground and excited states. c) The atomic transition energy in the CO$_2$ beam, the laser cooling light is blue detuned at the centre of the beam.
implemented to step the detuning of the laser from above resonance (so that no atoms were trapped in the MOT) to four linewidths below resonance in the hope that atoms would preferentially load into the region of the MOT overlapped with the CO\textsubscript{2} beam. We would expect then to see a light stripe on a dark background. No evidence for this was observed.

### 7.5 Possible Reasons for Null Result

In the search for the dipole trap signal we believe that there are two possibilities for the null results achieved thus far: firstly, we have achieved a dipole trap and our detection techniques are not sensitive enough to observe it. Second, we have not been able to overlap the CO\textsubscript{2} laser beam focus with the MOT.

We will begin with the first possibility; the detection techniques are not sensitive enough. For the time of flight technique we are confident that even small numbers of atoms $\sim 1000$ can be detected as we have imaged small atom numbers directly from the MOT. However, we are not able to tell if the CO\textsubscript{2} laser turns off as desired (shuttered by the AOM) during the imaging pulse because we do not have a fast enough detector for use with 10.6 $\mu$m radiation. If the CO\textsubscript{2} laser remains on, this would lead to a much reduced imaging contrast as the imaging light frequency experienced by the atoms would not be on resonance if they were still in the trap. For the anti-trap technique it is feasible to suggest that the signal, if present, could be missed easily as the search is conducted in real time and by eye.

The second possibility; no overlap between the CO\textsubscript{2} beam focus and the MOT. Around the science chamber, there is little space in which to make measurements on the CO\textsubscript{2} beam. Since the refractive index of the ZeSe is dependent on wavelength, refraction will cause deflection of the CO\textsubscript{2} beam relative to the tracer beam if the lenses are not centered perfectly. This could lead to the CO\textsubscript{2} beam path being offset from its assumed position. If this is the case, the beam position could fall outside the volume we have searched. Also, downstream from the expanding telescope the Rayleigh range of the CO\textsubscript{2} laser beam is so large that we could not measure changes in the beam size.
above the uncertainty in the knife-edge measurements over the measurement length available (\(\sim 10\) cm). As a result of this we have no measure of the divergence of the CO\(_2\) beam when it reaches the input lens and we cannot calculate (and correct for) the expected shift in position of the focal plane from \(ABCD\) matrices [104] or using the method of Self [159]. This could also make the focus of the CO\(_2\) laser beam fall outside of our search volume.

We believe that the second possibility is probably the most likely and that if we expand the volume of our search parameters, then we will eventually see the dipole trap signature. Work to achieve this is ongoing. The next chapter discusses other planned and ongoing work to improve the current experimental setup and also outlines plans for future experiments using the apparatus described in this thesis.