Characterizing and Optimizing Laser Beams for Optical Dipole Trapping and Evaporative Cooling of Ytterbium Atoms

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Recent advances in technology have made it possible to cool atoms down to the Bose Einstein Condensate (BEC) level, specifically through laser trapping and cooling. The lasers used need to have a specific wavelength, though the position of the foci and the power are also key. Profiling a beam can be quite difficult, especially for very small waists. If the beam can be well known, it still remains to find what it should be. In this paper, a method of profiling beams is described, as well as a simple analytical discussion of how the beam's parameters can be optimized.

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BEAM PROFILING

In order to cool the atoms to BEC temperatures, a crossed optical dipole trap (ODT) is used. The atoms are loaded into it from a different kind of trap, a magnetic optical trap (MOT), and the trap depth is lowered to evaporatively cool the atoms. Of course, this only works well if the beams are well know, specifically their waists and the positions of their foci.

CCD cameras can be used to do this, but they can be quite expensive and may be limited by pixel resolution issues. At the very least, they introduce many complexities that are not usually worth the distraction. In this proof of concept, the beam is coupled into a single-mode fiber to output only the TEM_{00} mode, and have a shape that is Gaussian and theoretically very simple. The collimated output of the fiber is then focused by a lens to a waist w_0 at the origin. The intensity profile for propagation along the z-axis is given by [2]:

$$I = \frac{2P}{\pi w(z)^2} e^{-\frac{2x^2}{w_x(z)^2} - \frac{2y^2}{w_y(z)^2}}. \tag{1}$$

The waist is a function of z:

$$w(z) = w_0\sqrt{1 + (z/z_r)^2}, \tag{2}$$

where $z_r = \pi w_0^2/\lambda$ is the Rayleigh length. What is actually measured in a lab is the power, a spatial integration of the intensity. The waists could be different in x and y, and this test is only sensitive to one dimension at a time.

An old method used for calculating waists simply involved putting a razor blade on a translation stage and scanning it along the x-axis, perpendicular to the axis of propagation. This setup shows the "razor" on two translation stages, parallel and perpendicular to the beam.

Using a power meter to capture the unblocked light gives an error function (the integral of e^{-r^2}, referred to as "erf"), which can be calculated numerically very easily. This integral is with respect to x, the direction of motion. This method is easy to understand physically, but cannot resolve very small waists, and it is very difficult to get w_0 without doing many measurements.

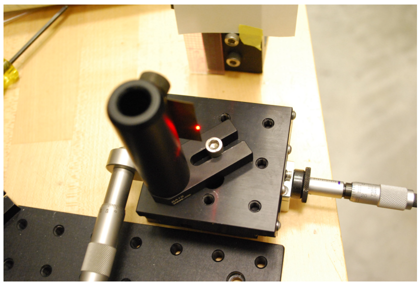

FIG. 1: Picture of the setup used, with blade cutting beam

Another method is to scan along the axis of propagation, in this case z. The power is now a function of z, and can be easily derived, giving:

$$P(z) = \delta + I_0 * (erf(\frac{\sqrt{2}(x_0 + z\sin\theta)}{w_0\sqrt{1 + (\frac{z\cos\theta - z_0}{z_r})^2}}) + 1), \tag{3}$$

with the origin taken to be the focus and x_0 and z_0 the coordinate offsets from that. The 1 comes from the definition of erf, which starts at 0 and not negative infinity. Physically, that infinity is reasonable because the power meter is much larger than the beam. In reality, the translation is not perfectly perpendicular, so that $x_0 = x_0 + z\sin\theta$ and $z_0 = z_0 + z\cos\theta$. There is also a background term, but that is simply an offset. This is the form of one dimensional slices of the two dimensional landscape of x_0 and z_0 shown:

Multiple data runs at different x offsets show the progression from a maximum at the focus to a minimum. Physically, this is because the blade blocks more (less) than half of the light is x_0 is positive (negative), and the beam is getting tighter and therefore less (more) light is getting past it. Figure 3 shows fits with one data set that are slices through Figure 2:

This data was fit using ROOT, and the best fits were those that had a parameter space neither too steep nor

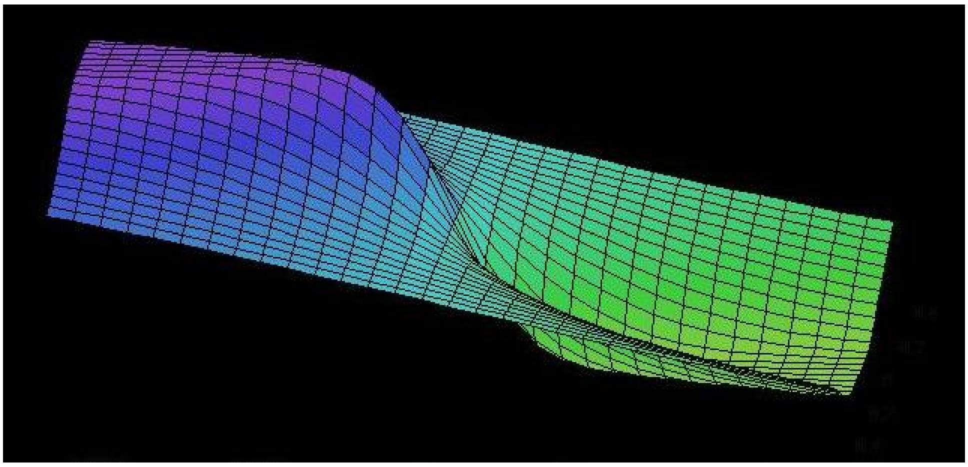

FIG. 2: A 3D plot of power, with z into the page

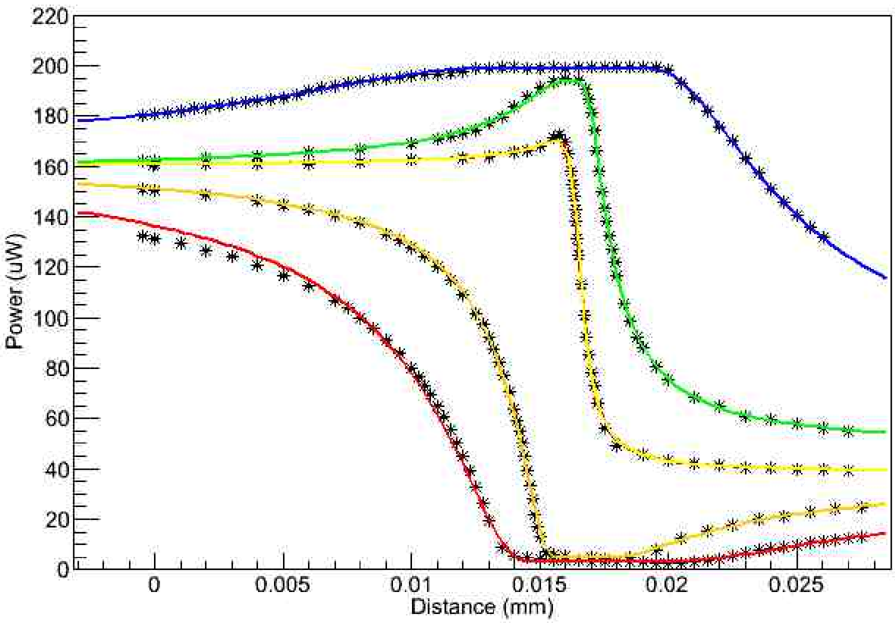

FIG. 3: Slices in x, power vs. z

too flat in w_0, that is, neither too large or too small an x offset. The data set shown is actually the worst fit, because the blade is too far from the beam.

The example setup used a 250 mm focal length lens to focus a beam that had an approximate diameter of 2 cm. This gives a theoretical minimum waist of $5\mu m$, and the combined waist measurements give $10.6 \pm .4$. The previous measurements were indirect, and assigned a somewhat arbitrary error of 10%. This method can hopefully be used to give needed information about the beams, with smaller errors than previous values. Even better data can be collected if a more professional setup were used, and if small effects due to diffraction were taken into account. Another possible improvement, though probably in this case unjustifiable, would be to take data with robotic help and greatly improve precision and reliability.

PARAMETER OPTIMIZATION

In these experiments, evaporation efficiency and atom number at condensation are the key measures of a trap configuration. What can be tweaked in the setup of the ODT are the beam powers and waists, and the angle between the two beams. The setup that I investigated was for the Ytterbium atom interferometry experiment, and

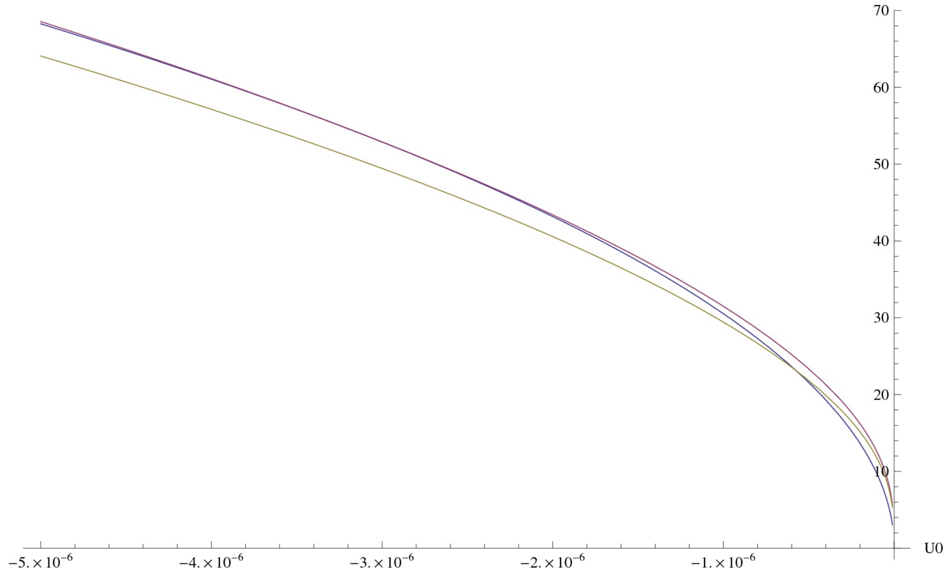

FIG. 4: Frequency vs Trap Depth (unscaled units)

perpendicular beams are the most efficient for Ytterbium. The degrees of freedom left are simply a departure from symmetry, which for the most part should not matter. However, Ytterbium is a heavy enough element that for low trap depths, gravity breaks the symmetry. Therefore, for low powers at least, there should be some interesting effects.

The goal of evaporative cooling is to increase the phase space density and achieve BECs as efficiently as possible - over short time scales and not losing too many atoms. For that, you need large atom numbers and high trap frequencies. These quantities work against each other somewhat: atom number is increased by having a larger initial volume to be loaded from the MOT, and trap frequencies are increased by having a tighter and therefore smaller trap. There are some schemes for changing the position of the foci after loading and getting the best of both, but these are technically very challenging and not the purpose of this investigation.

The approach taken here is to maximize the average trapping frequency, $\bar{\omega} = (\omega_x \omega_y \omega_z)^{1/3}$, with the constraint that the initial volume remain constant. The decided-upon geometry of the beams is one vertical and one horizontal, with all of the waists the same except the one in the axis of gravity. Only the radial waists contribute much, and the one in the axis of gravity is the only one for which asymmetry should make sense. For this setup, and neglecting the axial contributions, each frequency is proportional to:

$$\omega_x = \alpha \sqrt{P(\frac{1}{w^4} + \frac{a}{w^4 e_1})} \tag{4}$$

$$\omega_z = \alpha \sqrt{P \frac{1}{w^4}}, \tag{5}$$

$$\omega_y = \alpha P^{\nu} + \beta \tag{6}$$

where P is the power and e_1 is the ratio between the waist in the gravity axis and the waists of the other axes, all of which are the same. The intensity is given by equation 1 of the previous section, and the trap potential is proportional to that, and the frequencies are derived from a harmonic approximation. The frequency in the y axis is much more complicated and was fit numerically. In this axis a linear term is added on to that, making it more complex both to find the dependence on P and the curvature at the minimum of the trap. Both of these things are small deviations and only matter towards the end of the evaporation ramp when the traps are quite weak, and this is precisely the region in need of study.

Another group [1] has a setup that does not decrease trap depth, but rather increases a magnetic field gradient. This is analogous to increasing the strength of gravity or to the weak trap region where gravity is relatively stronger, and is beneficial because it reduces the dependence of frequency on trap depth. However, this method cannot be used for bosonic Yb atoms because they have no magnetic moment in the ground state. Frequencies are of the form:

$$\bar{\omega} = f(a, e_1, w, P) * P^{\nu}. \tag{7}$$

It is important to decrease ν in order to have the largest trap frequencies at the lowest trap depths. Some calculated frequencies are shown in Figure 4.

The blue line shows the normal square root dependence on trap depth, and the purple shows the effect of gravity on that, keeping the frequencies slightly higher. The gold line is an example tweaking of the power ratio, which does not seem to be improving the frequency at all. It was hoped that some change, possibly keeping the trap depth in the vertical direction weak, could cause the frequency dependence on trap depth to decrease and therefore be larger towards the end of the trap. It is still possible that other combinations could realize this, so more should be done to understand the function space.

CONCLUSIONS

It is hoped that parameters producing a line similar to the gold line, starting lower but with a lower dependence that ends up higher, could be found. More will be done to map this parameter space. Even if nothing interesting comes of that, it has been found that the trap depth in the y axis falls sharply at low powers, where the linear term dominates the Gaussian potential. In this region, the horizontal beam power should be kept constant, but the other powers can be treated normally.

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