Measurement of dynamical properties of ultracold atom rubidium clouds

O.L. Moreira

IPFN, Instituto Superior Técnico, Avenida Rovisco Pais 1, 1049-001 Lisboa, Portugal

Quantum phenomena are usually observed at very small scales, but clouds of ultracold atoms allow us the possibility to observe such kind of phenomena at macroscopic scales. An efficient way to obtain such a cloud is through the implementation of a magneto-optical trap, which is based on the simultaneous laser cooling and magnetic confinement of a vapor of atoms, held in ultra high vacuum. The first objective of a research group at Instituto Superior Técnico, which provided the support for the thesis discussed here, is to obtain such a cloud, composed of Rb 85 atoms at a temperature of 10^{-4}K. Such goal was very recently achieved and was extremely demanding from an experimental point of view, since it required a careful calibration and synchronization of different devices (laser diodes, amplifiers, magnetic coils, optical devices) As a natural continuation the task of measuring the state of the ultra cold atom cloud contained inside the magneto-optical trap has already started. This thesis introduces and discusses several theoretical and technical aspects leading to the successful implementation of the magneto-optical trap and presents the initial results from the operational setup able to produce ultracold atom clouds, which is the first of its kind and still unique in Portugal.

I. INTRODUCTION

Observing the properties of atoms in a gaseous state is a complicated affair at normal room temperature. The main reason can be explained by the thermal-kinetic model of the energy of atoms:

$$\frac{1}{2}m\bar{v}^2 = \frac{3}{2}k_B T \tag{1}$$

where m is the mass of the atom, $\bar{v}$ is its mean velocity, k_B is the Boltzmann constant, and T is the temperature in kelvin. With rubidium, this implies a velocity around 293 m/s. Such high speed value makes quite difficult to accurately measure its properties through spectroscopy methods, since fast movements of atoms results in broadening and displacement of their spectral lines. [1]

Since we can't reduce the mass of atoms, the only viable solution to this problem is reducing the room temperature. However usual refrigeration techniques aren't enough. Only with temperatures below a millionth of a kelvin do atoms slow down enough for spectroscopy methods to be able to produce accurate results. This led to the appearance of a new field of research in physics, ultracold atoms. To achieve the required kind of controled temperature over a cloud of atoms, the most viable solution is laser cooling combined with a Magneto-Optical Trap. [2]

Research of ultra cold atoms is of extreme importance for other areas in the field of Physics, in particular bosonic superfluidity, quantum magnetism, dynamic properties of quantum many-body systems, Efimov states, and superfluidity Barder-Cooper-Schrieefer (BCS). It is then necessary to develop and understand correctly the processes of producing and conserving, in a stable manner, those same ultra cold atoms. Connected to those issues there are also important technical problems to solve, such as developing advanced optical methods to gather data from the experiment, without any direct physical contact with the ultra cold atom cloud. Finally, it should be noticed that the production of an ultra cold atom cloud has never been sucessfully accomplished in Portugal before.

This paper is divided in five sections. As already noticed the first section introduces and describes the main subject, in the second section we provide a brief overview of Magneto Optical Traps, in the third section the Diagnostic Methods developed and used are discussed, in the fourth section we present some of our initial MOT results and in the fifth section conclusions about the work done are made, giving enphasis not only to the relevant properties of the work in progress but also to its possible applications.

II. MAGNETO OPTICAL TRAPS

The creation of an ultra cold gas is usually made with the use of a Magneto-Optical Trap (MOT) in ultra high vacuum. The MOT trap can collect atoms either from a vapour or from an atom beam. Laser beams, calibrated with frequencies shorter than the atomic resonance frequency, are used to slow down the atoms. In a second step, the atoms on the MOT are transfered to a purely magnetic trap or in alternative to a purely optical trap. Either way, the temperature of the captured atoms is reduced even more by the evaporation cooling. In magnetic traps, a radio frequency can be applied to remove the more energetic atoms with more energy from the trap through transition of spin states. Through elastic collisions at low temperatures the remaining atoms obey to a Maxwell-Boltzmann distribution. Finally, reached low enough temperatures and high enough densities, occurs the transitions that creates a BEC or a degenerated Fermi gas.

The MOT in our experiment consists of both an optical trap based on laser cooling and a magnetic trap based on magnetic confinement operating simultaneously, both to be described in the following sections, yet, evaporation cooling has not been planned since the temperatures we are expecting to reach relying just on the optical and magnetic methods should be low enough to start obtaining new results. The MOT will thus allow us to measure parameters of the atom cloud equation of state. A basic MOT schematic can be observed in figure 1.

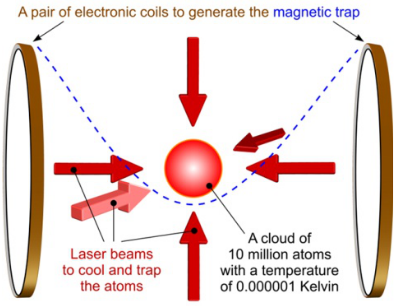

FIG. 1: Basic MOT schematic.[10]

A. Laser Cooling

Laser cooling was proposed simultaneously in 1975 by two groups. One of those groups was composed by David J.Wineland and Hans Georg Dehmelt, and the other by Theodor W.Hansch and Arthur Leonard Schawlow. The process was demonstrated in practice in 1978 y Winelard, Drullinger and Walls, and later replicated y Neuhaser, Hoenstatt, and Dehmelt.

Most photons that approach an atom will not interact with that atom in any way since it is basically transparent to most light frequencies. But for a certain spectrum, very limited, it is almost sure that the photon will be absorbed. Doppler cooling uses light whose frequency is calibrated slightly lower of the eletronic transition of the atom whose temperature we intend to lower. Due to the Doppler effect this will result in the atom absorbing more photons on the trap, if they are moving in the direction of the light source. Thereafter, if we apply light from two opposite directions, the atoms will absorb more photons from the beam aimed at the direction opposed to the movement. In each absorption event, the atom loses momentum equal to the photon's momentum. If the atom, now in the excited state, spontaneously emits a photon, it will be pushed by the same amount of momentum, but in a random direction. The result of this absorption and emission process is that the atom loses speed. Repeating this process multiple times, the speed of the atom will lower in a gradual way, and thereafter so it will its kinetic energy. Since the temperature of an atom is directly proportional to its kinetic energy, lowering it will result in the cooling of the atom.[7]

Ideally, this method only needs two beams with opposite directions. But since the excited atom emits photons in random directions, there's a significant probability that it will drift outside the laser beams, ruining the process. This can be compensated by using multiple beam pairs from opposite directions that cross each other in a single point, and that this way "push" the atoms to that area and guarantee a stable system. In this experiment there will be used three pairs of beams, each pair making a ninety degree angle with the other two.

Laser cooling has several limitations. First, there's a minimum atom temperature that we can reach, depending on the kinetic energy gained each time a photon is released. Second, the atom concentration must be minimal, since otherwise there will occur collisions between them. [8] Therefore laser cooling must be realized with a gas dispersed in vacuum. Finally, only a few atoms have electronic transitions that can be harnessed by commercial lasers from normal laboratories. For most atoms, we would need high power lasers to perform laser cooling on them. Such lasers are very expensive, and are usually more unstable as well, meaning that it is much harder to perform experiments with them. For the ^{87}Rb that we will use, the experiment requires a beam wavelength of 780 nm; such wavelength that can be produced by economic and reliable lasers commercially available.

B. Magnetic Confinement

The magnetic confinement part of our trap comes from a magnetic quadrupole, a pair of copper coils through which we will pass electric current. This results in a Zeeman shift, which increases with the radial distance from the center of the trap.[3] [4] The magnetic coils must be symmetric with oppositely directed currents, positioned in a way that the same axis passes through both their centers. This kind of setup is called anti-Helmholtz coils, as seen in figure 2. For the atoms to stop, we want the magnetic field B in the middle point between both coils to be 0, which means the distance between both coils must be $h = 2R$, where R is the radius of the coil.

The formula that gives the magnetic field in this situation is [2]

$$B(x) = \frac{\mu_0 n I R^2}{2((\frac{h}{2} - x) + R^2)^{\frac{3}{2}}} - \frac{\mu_0 n I R^2}{2((\frac{h}{2} + x) + R^2)^{\frac{3}{2}}} \quad (2)$$

Where B is the magnetic field in Tesla, μ_0 is the permeability of empty space constant, n is the number of coils per unit length, R is the radius of the coils, I is the current flowing through the coils,h is the distance etween the coils, and x is the distance from one of the coils to the point where we want to calculate the magnetic field. It follows from Equation (2) that $B = 0$ when $x = (1/2)h$

If an atom moves away from the center of the trap and emitts a photon, the magnetic resonance from the laser beam frequency will most probably push it back to the center of the trap. Basically, the addition of the magnetic quadrupole increases the precision of the experiment, helping to ensure that the gas is concentrated in the cross point between the laser beams and thus creating better conditions for the experiment to succeed.

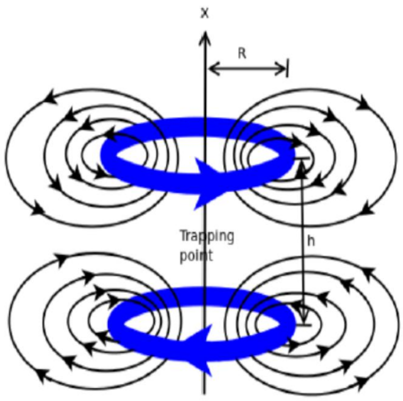

FIG. 2: Magnetic Field produced by Anti-Helmholtz coils

C. Experiment Control

A typical cycle from our experiment will consist in different phases, that are executed in a sequential manner. In each of this phases it is necessary to generate multiple tension signals, that control the great number of electronic devices needed for the creation of ultra cold quantum gases. Some of these signals need to last some seconds, others need to last just some hundreds of microseconds. And those signals need to be synchronized with each other with a precision in the order of hundreds of microseconds. Using a signal generator for each device would imply a significant waste of valuable time reprogramming all generators every time an experimental parameter was to be changed. It is much more pratical to use a PC with boards capable of producing analog and digital signs, where we can control the signals through programs with graphical interactions. However, for such setup, the generation of signals can be disturbed by the own PC internal components. Thereafter, in this experiment we will use a central computer to control and synchronize the different electronic devices, but the signals themselves will be generated from separate systems with proper shielding.

The program that will make make possible the synchronized generation of signals will be Labview, a commercial program from National Instruments specialized in the control of electronic devices from graphical interfaces.

III. DIAGNOSTIC METHODS

There are multiple parameters that must be used to characterize neutral atoms confined in a MOT. These parameters are, for example, the number of atoms, their temperatures, and their density inside the trap.

A technique to measure the temperature of confined atoms is the release and capture method. It consists on first turning off the trap, which releases the atoms, and after a time, t_{off}, we turn on the MOT again, which will capture again some of the atoms. This will produce a fluorescence signal. Considering that the atoms in the trap are in a Maxwell-Boltzmann distribution, and knowing the time of recapture, t_{off}, we can deduce the atom cloud temperature.

The time of flight (TOF) is another possility that could be used to measure the temperature of the atoms. This method consists in having a resonance beam working as a probe, under the trap, at a distance corresponding to several diameters of the cloud radius. When the atoms are released from the trap, and go through the probing beam, we will detect a fluorescence signal based on time. Assuming that the atom velocities obey a Maxwell-Boltzmann distribution, the atomic temperature can be deduced from the form of the florescent signal. Besides that, those fluorescent signals can be used to count the number of atoms confined in the trap, or to obtain information about what is the percentage of atoms in an excited state. In this experiment, this method will be used to count the number of ^{87}Rb atoms caught in our MOT.

Another method is the absorption image. In this method a resonance beam, working as a probe, goes through an atom sample that absorbs part of the light and emits it again in an isotropic way. This will create a shadow in the probe beam, that can be magnified with lenses, and directed to a CCD (charge-coupled-device) camera. Knowing the lens magnification, we can calculate the number of particles from the obtained image [2][3]

$$N = \frac{4\pi I_c}{\sigma\rho\varepsilon_p\gamma_p(0,96)^k} \tag{3}$$

where I_c is the photodiode current due to the trapped atoms, σ is the solid angle from the camera lens, ρ is the current generated by the photodiodes in ampere/watt, ε_p is a photon's energy in joule, k is the number of uncoated glass surfaces between the trapped atoms and the detector, and γ_p is the photon scattering rate in photons/(atom.second). To obtain this last parameter we need another expression [3]:

$$\gamma_p = \frac{\Gamma}{2}\frac{\frac{I}{I_s}}{1+\frac{I}{I_s}+4\frac{\Delta}{\Gamma}^2} \tag{4}$$

where I is the intensity of the six trapping beams used in the MOT, I_s is the saturation intensity, normally

I_s=4,1 mW/cm^2 is the saturation intensity for randomly polarized light in Rb, Δ is the detuning from the resonance, Γ is the natural linewidth of the transition, approximately 6MHz for Rb.

We can even combine this method with the TOF method, to deduce the temperature through the absorption image. We will rely on the absorption image method to measure the temperature and number of ^{87}Rb caught in our MOT.

To measure the fluorescence, three CCD cameras will be installed, fixed on bars for an easier alignment, plus the respective lenses necessary for the magnification. Each camera covers a different angle of the experiment; it is important to take in account that the cameras placement should be carefully selected in order to avoid interfering with the laser beams required to keep the MOT functioning. The cameras will be calibrated to allow the conversion of the measured electric voltage, U_{PD}, for the detected optical power.

The diagnostics and control of the experiment is centered around a "control computer", from where the researcher can control the experiment's parameters and process the data received. It has been equipped with a Solid State Drive to allow faster storage and manipulation of images, since that will be a key part of the data gathering and processing.

A. Computer Boards

The control computer was planned and custom built with specific boards for both controling the experiment and gathering the obtained data. For this, we installed the following specialized boards: NI PCI-6220 with 15 Analog Inputs; NI PCI-6723 with 32 analog outputs; NI PCI-5154 to work as an integrated digital oscilloscope with 3 channels; NI PCI-8252 with three IEEE 1394a ports to both the CCD cameras, control their parameters, and transfer their recorded data to the computer at high speed.

B. Connectors

Most electronic devices produce magnetic fields that can interfere with other nearby electronic devices. Usually this interference is minimal and can be safely ignored, but for this experiment we need very high temporal precision, and thus it becomes a priority to minimize the interference from external devices on the control computer. For starters, the central computer is placed a few meters away from the experiment itself. Then, the data is transfered through three shielded cables that link to one of three shielded connector blocks, plus an individual firewire cable for each of the CCD cameras.

The connector blocks chosen for this are NI SCB-98, chosen for both their compatibility with the analog in/out boards installed on the computer. However since it uses screw terminals for connections with devices other than the control computer, we designed and welded support boards with coaxial connectors to make it easier and faster to add or remove connections as needed.

C. Shutters

The diagnostics process demands the ability to swiftly stop or restart the laser beam. Simply turning the laser device itself on or off is too slow, so the ideal solution is to use shutters to allow us to quickly interrupt the path of the laser beam, and then quickly restore it.

Such path shutting simply requires moving a tiny opaque surface a few milimiters to the side upon receiving an electric signal; however, commercially available shutters were found to be quite expensive. That's why we chose to build our own shutters, based on a an inexpensive design from Todd P.Meyrath based on two boards, one for the shutter itself and another for receiving the trigger signal that ensures minimal delay. [9]. Some improvements were made to the PCB layouts in order to make them fit better with the other components of the experiment. Leftover copper wire was also used with with a flattened tip instead of aluminium foil flag as the part to interrupt the laser beam itself, since we deemed the aluminium foil not stable enough on the long run. The first functional prototype can be seen in figure 3 and 4.

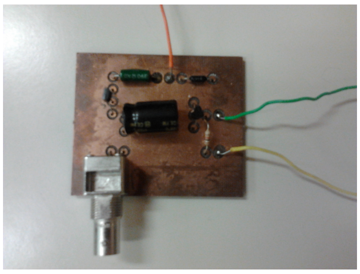

FIG. 3: Shutter support board

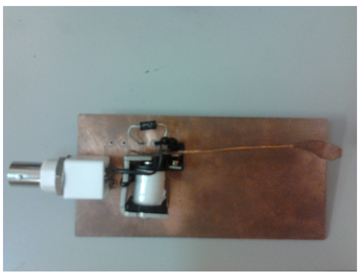

FIG. 4: Shutter board

D. Camera

The CCD cameras used are BASLER a601f kind. They can operate mostly on an automated way but in ordder to get their best performance their characteristics were studied in detail.

The CCD camera possesses both a IEEE-1394 and RJ-45 sockets. Only the IEEE-1394 socket needs to be plugged in for basic operation, since that socket alone can provide the power, receive instructions from the computer and then send back the captured images from the camera to the computer. However, to improve the camera's perfomance one needs to use the RJ-45 socket as well. This socket can be used to send an external trigger signal to make the camera start recording a photo with a delay of just 22 microseconds. It can also be used to detect when the camera ended taking a photo, meaning we can send the External Trigger again. Sending the photo trigger through the IEEE-1394 cable requires a much larger and unstable time delay, and won't allow us to detect when we can start taking a photo again. Since at certain stages of the experiment we need to take photos in very quick sucession, it's quite important to minimize every delay involved.

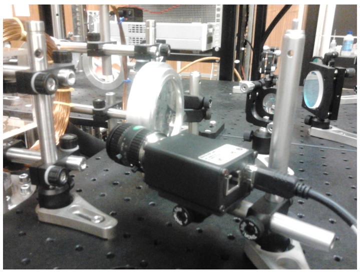

FIG. 5: One of the three Basler a601f cameras used in the experiment, already mounted in position.

Another important detail of this CCD camera is that we can control some of its working parameters, which are pre-set according to the manufacturer own specifications. First we have the *Brightness*, that controls how "sensible" the camera is to the ambient light. A higher Brightness will allow the camera to detect lower intensities, but will make it "blinded" if there's too much light. A Brightness too low will allow it to capture images under strong ambient light, but also render it unable to detect anything if the ambient light is weak. Next we have *Gain*, that is an electronic amplification of the video signal. This means that for a strong Gain the signal is boosted electronically, adding more voltage to the pixels on the camer, amplifying their intensity, and therefore brighten the image. Thus a positive Gain parameter will allow us to see details that couldn't be noticed by adjusting Brightness alone. However setting the Gain too high will result in an heavily granulated image and we'll start losing details. Finally we have Exposure time, which is how much time the camera spends capturing light to produce an image before sending it back to the computer. A high *Exposure* time will theoretically always result in a better image, but not for us. Since the events we want to capture in pictures change multiple times under the span of a few miliseconds, we want to set up our exposure time short enough to capture each event by itself, or the resulting picture would be a blurred image of the whole process, much like trying to take a normal photo of a moving object.

IV. DIAGNOSTICS SOFTWARE

In order to gather and process the data resulting from the experiment, several programs were created, using Labview$^{\mathrm{TM}}$and Matlab$^{\mathrm{TM}}$. The programs were created using the stock examples included with Labview and Matlab as asic templates (not always fully documented), and were designed to provide simple and pratical interfaces for the specific needs of different experimental activities. The diagnostics software is described in the following sections.

A. V1AnalogVoltageCOLORtrigger

This diagnostics software was used was used in the initial phase of the experiment, when the objective was simply to make sure the MOT was working as intended and to maximize the number of ultra cold atoms captured.

For those ojectives the program combines the control of 8 output channels, two real-time camera feeds and a brightness measurer. Each channel allow an user to increase or decrease the respective output intensity with a precision of one hundreth of a volt with the mouse or in alternative to simply input in new values with the keyboard, altough that method of input is slower for small voltage changes. In addition, two virtual switches were added, each one allowing to change simultaneously the output of two specific channels according to a pair of values defined by the user, otherwise the value of each channel needs to be changed, one at a time. As for the camera feeds, one shows the original grey scale images the camera is capturing and the other shows an image with artificial coloring, where the shades of grey are converted to a rainbow spectrum, with the brighter areas turning to red, and the darker areas turning to blue. The camera is working on continuous mode, averaging 12,5 photos per second. Altough the camera is capable of faster photo rates, the process is slowed down due to the color processing of the snapped pictures. Finally, the program also calculates the average of light intensity each pixel has, in order to measure in real-time the density of the ultra cold atoms gas cloud in the MOT. The more atoms that are captured, the bigger the fluorescence they'll produce, and the more brightness the pixels will capture.

The CCD camera is being operated in Internal Trigger mode during this program, meaning only the IEEE-1394 socket is needed for control and data retrieval. Options have been added to directly control its Brightness and Gain parameters in real time to adjust for different luminosity conditions.

B. FotoSincronizada

Once we have a stable MOT, in order to perform the diagnostics of the atoms trapped inside, either by Release and Capture, Time of Flight or Absorption Imaging, we need high precision synchronization between each of the experiment's devices and the CCD camera. Not only that, since the diagnostics methods demands the activation of specific parts of the experiment in sucession with just hundreds of miliseconds of waiting time between each "step", we needed a way to automate the process, while still allowing the human user to change specific parameters in an easy way.

FotoSincronizada was developed for this purpose as a more advanced version of V1AnalogVoltageCOLORtrigger. Whereas with V1AnalogVoltageCOLORtrigger the user controls multiple output channels to control the experiment device through manual input on the computer, FotoSincronizada takes the parameters it needs from two .txt files, representing a series of "steps". One .txt file for the time intervals between each "step", and the other for the new voltage values to be assigned to each channel at the start of the respective step. This way different .txt files can be prepared beforehand for different tasks, and quickly replaced in the program when needed. Once a full set of steps is completed, the program loops and restarts from the first step; this way, statistically significant data can be acquired from the diagnostics that took place multiple times. Operating additional control devices can be achieved easily with FotoSincronizada by increasing in it the number of output channels. The number of output channels that can be operated has always been increased to allow to control more devices.

The camera itself must be set on External Trigger mode for greater temporal precision, meaning the RJ-45 socket needs to be plugged in as well as the IE-1394 socket.

C. ImageProcessing

The diagnostics process does not end with just gathering data from the experiment. Once we have captured the images we want, we need to apply a series of alghorithm to them to produce our final results. Said alghorithms are related to different techniques of image processing, and need to be applied on many images; therefore the task of processing such images has been automatized on a computer.

To such end it was developed in Matlab the the ImageProcessing software. With ImageProcessing the user selects a set of images, and ImageProcessing then procceeds with the request and outputs temperature and density graphs of the observed ultra cold atom clouds, plus a fake colored image built by combining the data from the initial images.

V. MOT RESULTS

Shown in Figure 6 are recent shots obtained with the three cameras of the operational MOT, showing the fluorescence produced by the rubidium vapor inside the glass cell (bright spot near the middle of the images in all cases).

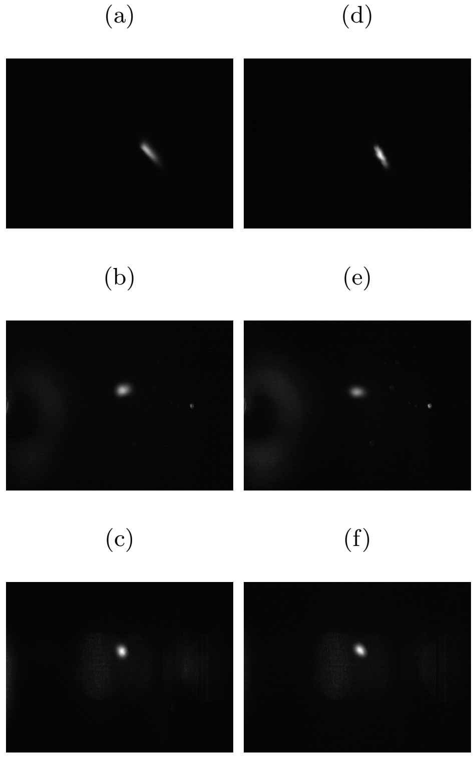

FIG. 6: Preliminary fluorescence results: photos (a), (b) and (c) correspond to simultaneous shots taken with the 3 cameras of the operational MOT; photos (d), (e) and (f) are similar shots, taken one minute later.

The processing of fluorescence images obtained through the synchronized operation of the different Labview propgrams and experimental devices is performed with *ImageProcessing*, a program which was written entirely in Matlab. The main goal of the program is to combine three images into one in which the ultra cold cloud of atoms is clearly visible. This can be done by combining the images in such a way that the background noise is reduced; with a clear view of the atom cloud one can obtain the light intensities along the X and Y axes. Preliminary results are presented in Figure 7, with

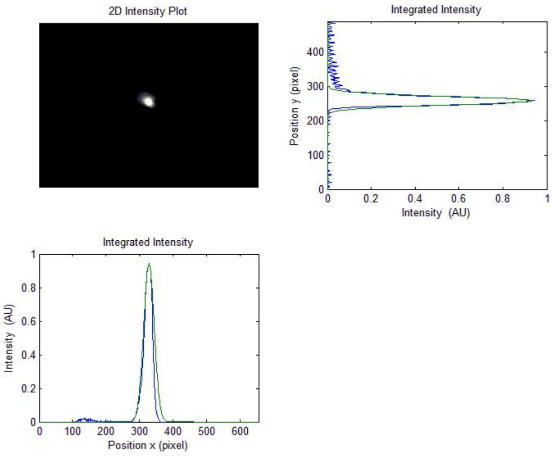

FIG. 7: Light intensity plots produced by *ImageProcessing*.

a compact distribution of the rubidium atoms as evidence of the cloud low temperature. Despite their relevance given the limited amout of time available when the results shown in Figure 6 were obtained and the present moment a detailed discussion of them is beyond the goals of this thesis.

VI. CONCLUSION

- The MOT is currently operational and although the preliminary data analysis has just started it has been already performed a significant amount of research related to the stable operation of the Experimental Setup.

- Many important concepts regarding the topic of ultra cold atoms had been learnt; in parallel, many important skills regarding programming with Labview and Matlab had been acquired; such programming has been found to be deeply interconnected with hardware issues, such as equipment synchronization, and board designing and soldering.

- The task of synchronizing different electronic devices was an important and demanding challenge given the diversity of devices and the variety of specifications and working parameters inherent to the operation of each device. For instance, some devices can not stand high currents or voltages while others are expected to function with high currents and voltages. Thus, finding the “middle ground” for two or more different devices to operate simultaneously was indeed a complex engineering task, whose solution required a detailed analysis of the devices as well as a careful planning and testing of different devices working together. The experience gained so far will be of extreme importance for the future work in the given field of research as well as for the development of research in other fields of experimental Physics.

- The Experimental Setup currently finds itself at an important juncture where it is already able to produce important scientific data; this was achieved, in particular, thanks to the hardware and software solutions described in this thesis. Such solutions will certainly require further optimization in the future and will also provide a solid basis for the development of other technical solutions.

[1] Daniel Adam Steck, *Rubidium 87 D Line Data* **8**, Oregon Center for Optics and Department of Physics (2001).
[2] H.M Elnour, *Development of a Magneto-Optical Trap for Rubidium 87*, Department of Physics, dissertation University of Stelleosch (2013)
[3] F.P. Alexandro Gatto, *Trapping fermionic potassium atoms in a quasi-electrostatic optical dipole potential*, PHD Dissertation, Bonn, (2011).
[4] J. F. Bertelseen , *Ultracold Atomic Gases-Mixtures and Molecules*, Physics and Astronomy University of Aarhus (2007).
[5] JILA, *Joint Institute for Laboratory Astrophysics* http://jila.colorado.edu/about/about-jila.
[6] C. I. Rigby, *Development of a Laser Cooling and Magneto-Optical Trapping Experiment for Rubidium 87 atoms* Department of Physics, Stelleosch University (2013).
[7] Wikipedia, *http://wikipedia.org/wiki/Doppler cooling* (2014).
[8] P. R. K. Dott.Giovanni Luca Gattobigio, Prof. Roerto Calabrese *Manipulation of a Large Magneto-Optical Trap:Application to Four-Wave Mixing* Universita degli Studidi Ferrara, Dottorato di Ricerva in fisica ciclo XIX (2008).
[9] T. P. Meyrath, *Inexpensive Mechanical Shutter and Driver for Optics Experiments* Atom Optics Laboratory Center for Nonlinear Dynamics University of Texas at Austin (2003).
[10] *http://publish.ucc.ie/boolean/2011/00/Russell/42/en*