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Master Thesis

A modular control system for cold atom experiments

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Abstract

Faculty Name
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Master in physics

A modular control system for cold atom experiments

by Aske Rolighed Thorsen

In this thesis I present a new modular experiment control system for cold atom experiments. The program is called ALICE and has been used to run the QMM experiment. The program has been found to be able to reliably reproduce the same cold atom cloud as the existing control system. The program will be fully implemented in the experiment in the near future.

Acknowledgements

I would like to thank the QMM group for providing a wonderful environment to complete my master project in. A special thank to Mark Bason and Mario Napolitano for proof reading my thesis. I would also like to thank Jacob Sherson for always providing inspiring discussions. Lastly, I have to thank the love of my life Paola, for bearing with me and supporting me in this last hectic period.

Contents

Abbreviations

FPGA	**F**ield **P**rogrammeble **G**ate **A**rray
VHDL	**V H D L**
UI	**U**ser **I**nterface
MOT	**M**agneto **O**ptical **T**rap

Chapter 1

Introduction

Bose Einstein Condensate (BEC) was first proposed in 1925, and experimentally realised in 1995 [1]. A BEC can be created by cooling a cloud of Bosonic atoms to their ground state. Here the atoms undergo a phase transition to the BEC.

The research field have been developed far in the last 20 years. Going from using magneto optical traps to manipulating pure optical trap, there the atoms are confined to high intensity regions. Using a light beam to create a standing wave it has been possible to create a periodic trap (optical lattice). High resolution objective have been used to image a single site in such an optical lattice [2]. An ordered set of atoms in a periodic trap can be used as a basis for a quantum computer.

In the Quantum Measurement and Manipulation (QMM) group at Aarhus University lead by Associate Prof. Jacob Sherson. In the QMM group we are building an Rb^{87} BEC experiment to study dynamics in an optical lattice. Such as probing the super-fluid to Mott, creating super lattices in order to work toward making a quantum computer. Work on non destructive probing of atoms using Faraday rotation have been carried out in [3]. A cold atom cloud is cooled and the BEC transition is crossed. The crossing of the transition is probed multiple times.

To accomplish all this a flexible control system is required. Since all the challenges of realising this goal are not yet known, it is important to have a flexible system that can be extended easily to meet up new requirements.

In this thesis I will present a program named ALICE that I developed for the QMM group. The motivation for building the program is to lower the barrier for creating new types of experiments by giving an environment where different tasks in the experiment are embedded in blocks that can be reused and changed. This will allow us to quickly go down a new rabbit hole and explore the physics from many different angles, therefore new ideas will be easier to be tried out.

Creating an experimental control system from scratch is a huge task, that requires a thorough knowledge about programming and the use of digital and analog hardware.

The main result of this thesis is that I have reproduced a sequence from the old control system. This sequence allows to produce a cold atom cloud of 20 µK. In the sequence it is required to control: the 2D and 3D MOT, the timing of the cooling and optical pumping, the transport of the atoms to a second chamber, where an evaporative cooling will take place by applying a microwave sweep. By controlling both light pulses and camera triggers, that had to be timed with μs precision, I was then able to image the cold cloud after the evaporation.

I spent the majority of the time developing and debugging the program. So in the end there was only one week of time to do measurements, during which I tested the new features of ALICE in order to highlight some of the future possible experiments.

There are 4 main chapters in this thesis. In chapter 2 I will explain the steps used in the experiment. The focus will be laid on the steps used to produce a cold atom cloud. Chapter 3 describes in detail the new experimental program and future implementation. Chapter 4 describes the experiment used to test the new modularity of the program. In chapter 5 I will outline the preliminary work done for making active stabilization of the magnetic field in the laboratory. Due to lack of time this project has not been implemented in the experiment yet.

Chapter 2

Experimental setup

2.1 Introduction to experimental setup

In this chapter I will go over the steps for preparing the atoms for loading them into a crossed optical trap, where the final step toward a BEC is made.

I will focus mainly on the technical side of the preponderation in order to explain the steps I make in the experiment.

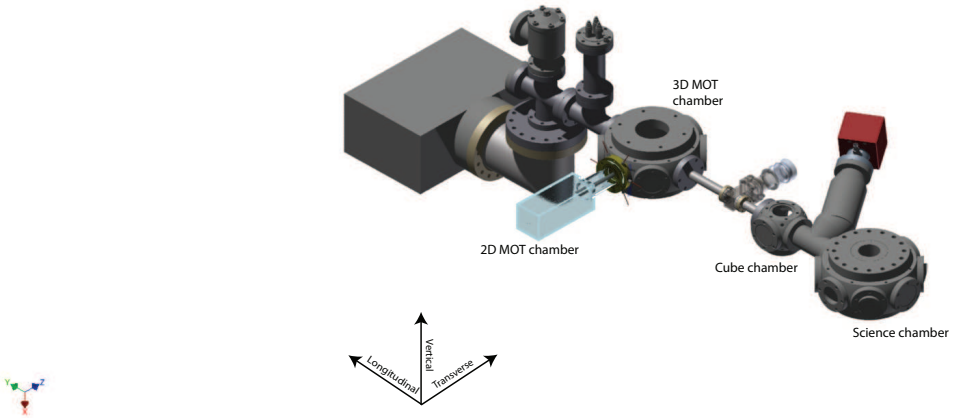


FIGURE 2.1: Experimental set-up

The experimental set-up is shown on figure 2.1.

There are tree main chambers of interest, 2D MOT chamber where the atoms are trapped in cigar shaped, and pushed into the 3D MOT chamber. Here the atoms are cooled and prepared for transport to the Cube chamber. The transport is done in a magnetic trap made by a set of coils mounted on a transport stage. The stage can move between the 3D MOT chamber and the cube chamber. In the cube chamber the atoms are hold in a second magnetic trap produced by two coils mounted onto the cube chamber. In the cube chamber the atoms are cooled further with evaporative cooling, and loaded into a optical trap. In future experiment the atoms is transported to the Science chamber where we will work with the optical lattice and make the high resolution imaging.

The reason for moving the atoms is twofold, one it offers better optical access and two the vacuum can be better due differential pumping between the 3D MOT chamber and the Cube chamber. This gives better lifetimes.

I will in the next section explain the physics behind the different steps in more detail.

2.1.1 Doppler cooling

When an atom absorb a photon, that atom will receive a momentum of $\hbar\vec{k}$ in the propagation direction of the beam. By spontaneous decay the atom will get a momentum transfer of $\hbar\vec{k}$ but in a random direction. In average the momentum transfer from the emitted photon will sum to zero. The atoms experience a force in the direction of the laser beam $F = \Gamma_{scat}\hbar\vec{k}$ where $\Gamma_{scat.}$ is the rate of scattered photons. This rate depend on the detuning from the transition.

In the case where the atoms sees two counter propagating beams, the net force on the atoms will be given by the difference in the scattering rates for the two beams. By red detuning the two beams the scattering rate is changed. For an atom moving toward laser beam the detuning will be Doppler shifted $\delta = \delta_0 - \vec{k} \cdot \vec{v}$.

This give rise to a velocity dependent scattering rate for the two laser beam, and the net effect will be that the atoms are cooled. This effect can not cool the atoms al the way to 0 K.

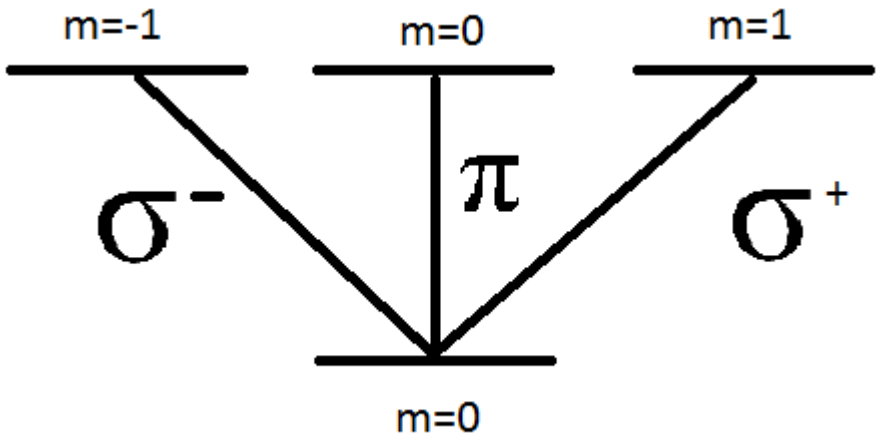


FIGURE 2.2: magnetic selection rules. The allowed transition is dependent on the polarization of the laser light.

Since the momentum transfer happens in discrete quantity of $\hbar\vec{k}$, this will give rise to random work that causes heating. The temperature where the cooling and heating balance out give rise to the Doppler cooling limit 2.1.

The natural linewidth of the D_2 transition in Rb^{87} [4] is approximate $\Gamma = 6\,\text{MHz}$. This yields a Doppler limit of $150\,\mu\text{K}$.

$$k_b T_{min} = \frac{\hbar\Gamma}{2} \tag{2.1}$$

The concept of 1D laser cooling is easily extended to 2D and 3D.

The Doppler cooling do not provide us with a special confinement. In order to trap the atoms we have to apply a magnetic gradient. Combined with the laser light gives us a MOT (magneto Optical Trap).

2.1.2 MOT

In the MOT a magnetic gradient is applied, this induces a spacial dependent Zeeman shift in the hyperfine structure given in equation 2.2 where g_f is the Landé g-factor and μ_B is the Bohr magneton.

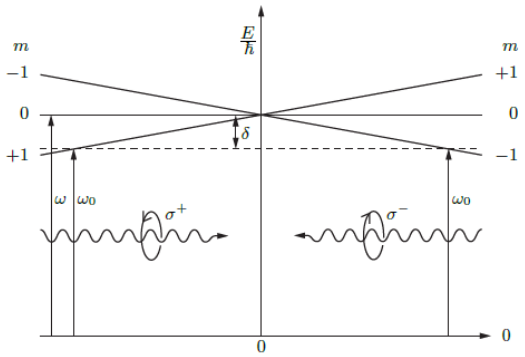


FIGURE 2.3: Scheme for spacial confinement in a MOT. Modified from [5]. The atomic hyperfine level becomes shifted to resonant when moving toward higher magnetic field. The scatting rate from the beam with σ^- increases.

The selection rules in the dipole approx. of the light-atom interaction relate polarization with the change in the magnetic quantum number between ground and excited states . 2.2 for transition between the hyperfine states. On figure 2.3 it is shown how the $\Delta m = 1$ $\Delta m = -1$ respective get shift down to resonant.

When the polarisation of the cooling beam is chosen to the right polarization, the spatial dependent Zeeman shift will induce a trapping force, since the scattering rate for the two beam will be spatial dependent. [1].

$$\Delta E = g_F m_F \mu_B B \tag{2.2}$$

In our set-up we apply a quadrupole field produced by two coils in anti Helmholz configuration.

2.1.3 Loading the MOT

In our experiment we use a 2D MOT to trap the atoms in a cigar shaped cloud. A beam is applied along the trapping axis pushing the trapped atoms into the 3D MOT chamber. This allow for fast loading of the 3D MOT, around 3 s. The parameters we

[1] Since our quadrupole field is radial symmetric and mirror symmetric around the x-y plain. The polarization applied need to be identical along the symmetry axes. Often in the literature the counter propagating beam is shown as $\sigma^+\sigma^-$ respectively. Seen along one of the beam axis this is also correct, but can confuse when setting things up in the laboratory

control during the MOT loading is detuning and shutter for the 2D, 3D, push light, and the current in transport coils.

2.1.4 Sub doppler cooling

It is possible to cool atoms in an optical molasse to temperature lower then the Doppler limit see equation 2.1. This is called sub Doppler cooling, or Sisypfus cooling. Consider first the situation in 1D where two counter propagating beam interfere, since we are using circular polarized light the two counter propagating beams will interfere, so the polarisation will be space dependent with a period of $\frac{\lambda}{2}$. The different Zeenman sub levels will see a different energy shift due to the AC stark shift.

A atom moving will have the energy levels shifted according to the magnetic quantum number. The level driven by the present polarisation will be shifted up in energy. The atom can then be excited to a higher level. When the atom fall back into the ground state it can be any of the magnetic quantum states, and the atoms will therefore lose energy corresponding energy difference between the Zeeman levels. This process will go on until the atoms energy is less then the AC Stark shift.

2.1.5 Optical pumping

Since the magnetic trap can only hold atoms with (positive spin) it is beneficial to prepare the sample in this spin state. In order to have a well defined spin there need to be a magnetic axis. This is applied by a set of Helmholtz coils. The spin state is lifted of the degeneracy by the magnetic field. Driving the transition with resonant σ^+ only the $\Delta m = +1$ is allowed. The spontaneous decay allow the transition to move to the right The selection rule for the m quantum number is connected to the polarisation of the optical beam driving the transition. $\sigma^-\sigma^+$ linear polarization.

2.1.6 Transport in magnetic trap

Atoms pumped into the $F = 2$ $m = 2$ with $g_f = \frac{1}{2}$. Equation 2.2 gives that this state is a low field seeker. The state is trapped in the magnetic quadrupole field with magnetic minimum in the center between the two coils. The current is ramped up to 90 A wish

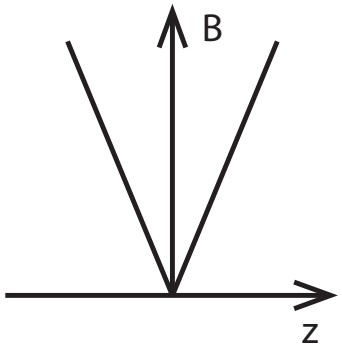


FIGURE 2.4: The spatial dependence of the magnetic field close to the minimum.

yields a gradient of $150\,\mathrm{G\,cm^{-1}}$ in the z direction. The magnetic coil is moved by a transport stage to a second chamber. This gives the advantage of more optical access to preform experiments with the atoms. In this stage the atoms are cooled further by forced evaporative cooling.

2.1.7 Evaporative cooling

In order to cool the cloud of atoms beyond the limit of the sub Doppler cooling we use a technique called evaporative cooling. The general idea is to remove the hottest atoms in the magnetic trap, and thereby lower the remaining average energy.

It happens that the magnetic trap provides the possibility for such a selection. The atoms with the most energy will experience a higher magnetic field, and hence a higher Zeeman splitting. Since the $F = 2m = 2$ state is trapped and the $F = 1m = 1$ is anti trapped, driving this transition will induce a loss of the atom with this energy. The splitting is dependent of the temperature. So by applying a microwave (the transition is about 6.8 GHz) one at remove the hottest atoms in the Bolzmann distribution. By scanning the frequency, the hottest atoms will be moved and the remaining atoms will be cooled [2].

As the atom cloud gets cooler, the average time spend in the center of the trap increase, since $B = 0$ at this point, spin flip to a non trapped state can occur freely. This effect is called Majorana loss. This effect becomes more dominant as the atomic cloud gets cooler. And therefore is is not possible to cool all the way to a BEC in the magnetic trap. We load the atoms into optical trap, and evaporate to the BEC in this configuration.

[2]This process take around $20s$ and losses 2 order of magnitude in atom number.

[3].

2.1.8 Dipole trap

Due to the AC stark shift the atoms see an energy shift that in intensity dependent. For red detuned light the atoms will be attracted to hight intensity regions. The potential is given 2.3.

$$U_{dip} = \frac{3\pi c^3}{2\hbar\omega_0^3}\left(\frac{\Gamma}{\Delta}\right) I(r) \tag{2.3}$$

One great advantage with the dipole trap is that all spin state is trapped.

2.2 Detection methods

The detection methods is equal impotent to the preparation of the atoms. In the QMM experiment we use three different detection methods, fluorescence light from the atoms, is used to measure the number of atoms in the MOT. The absorption picture, this gives The density distribution of the cloud. This can be used to extract the temperature and atom number. The Faraday method descried in [6].

2.2.1 Florescence from MOT chamber

The atoms radiate florescence light in all direction when trapped in the MOT. This light can be used to estimate the number of atoms in the trap. A part of the scatted light can be collected on a photo-diode and measured on a scope. The signal on the photo-diode is connected the the atom number via the rate of scattered photons that is given by equation 2.4. $S_0 = \frac{I}{I_s}$ is the saturation intensity, at where the absorption rate balance out the spontaneous emission rate. In this case half of the population will be in the exited state. The δ is the detuning, for our experiment the detuning is $20MHz$.

[3] A possible way off remove the Majorana loss, is to build a Ioffe-Pritchard trap, where the magnetic minimum is given a offset

$$\Gamma_s = \frac{\Gamma}{2}\frac{S_0}{1 + S_0 + \left(\frac{2\delta}{\Gamma}\right)^2} \tag{2.4}$$

The conversion from voltage to atom number can be calculated with 2.5. Where Ω is the solid angle of the light hitting the detector, η is the conversion from voltage to power.

$$\frac{Atomnumber}{Voltage} = (\Omega\eta\Gamma_s cat\nu h)^{-1} \tag{2.5}$$

Using formula 2.5 I have estimated the number of atoms detected with the fluorescence signal. The conversion factor becomes $1.7 \times 10^9 \ \frac{Atoms}{V}$.

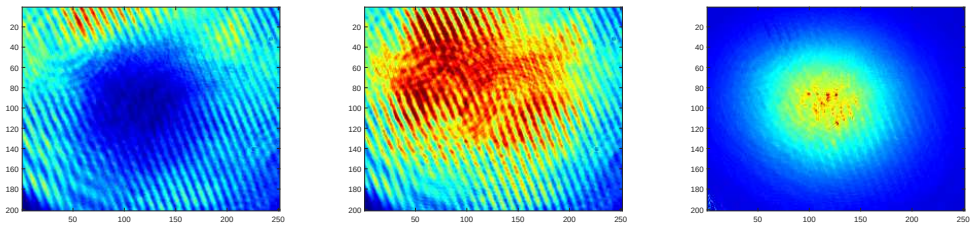
2.2.2 Absorption image

One of the methods used to detect the atoms are absorption imaging. The cold cloud is illuminated with resonant light. The scattering probability will be proportional with the atom density integrated along the imaging axis. The image on the CCD will carry a shadow from the atoms. From Beer s law [7]. We get that the intensity fall exponentially with the optical density (OD) along the image axis. this detection method will destroy the atom cloud completely, since the resonant light will heat the cloud. Therefore the absorption image is the last thing done with the atoms in a sequence.

$$I = I_0 e^{-OD} \tag{2.6}$$

By taking taking a picture with the atom and one without the optical density can be retrieved by 2.7.

$$OD = ln\left(\frac{I_{ref}}{Ishadow}\right) \tag{2.7}$$



(A) Absorption picture, atom are seen as shadow. (B) Background picture, no atoms present (C) Converted absorption picture

FIGURE 2.5: Absorption picture of a hot atom cloud.

2.2.3 Non destructive probing

The absorption image technique completely destroy the cloud of atoms.

A non destructive detection technique is used in the group called Faraday measurement to make multiple probing of the cold atom cloud. A far blue detuned light with linear polarization is shined onto the atoms. If all the atoms are prepared in the same spin state, the light will rotate its polarization axis. The atoms do not get heated since the scattering rate is small. By sending the light through a Polarizing Beam splitter (PBS) the shift in polarization axis can be detected [6].

Linear polarized light can be seen as a superposition of σ^- and σ^+. The Faraday effect can then be explained as an asymmetry between the transitions allowed to be driven by σ^- and σ^+, these rates can be found in [4].

Chapter 3

QMM experimental control "ALICE"

3.1 Introduction

In our experiments and many other cold atoms experiments, more then 30 variables need to be controlled with microsecond precision over a timespan of minutes. The sequences have to be very deterministic, so the system needs to have a accurate clock. Computer control is crucial to fulfilling this task. Many different experimental control system (ECS) have been developed by various groups over the time [8, 9],.

The building of an experimental control system is be a big task, for this reason some experiments often use shared software, one example can be found in ref [8]. In the QMM group experiment existing software from a group from Leibniz Universität Hannover (will be referred to as the "Hannover control") has been used control the experiment as it has been developed. It is planned that ALICE will be used as a replacement for this programme. The reason for developing a new experiment control system was that we wanted a more flexible and abstract way to build the sequences.

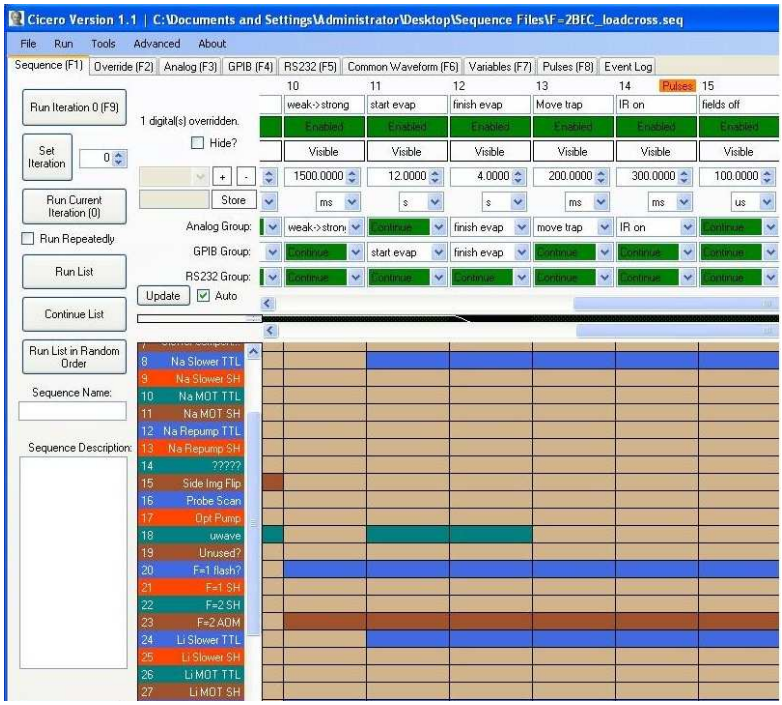
The overview of ALICE will be given in section 3.2, some of the more technical details and design thoughts will be given in section 3.4 and 3.5. In section 3.1.1, I will give an overview of the already existing control systems that are available to the cold atoms community. This section will also work as reference point for the discussion of ALICE.

3.1.1 Comparison to existing experimental controls

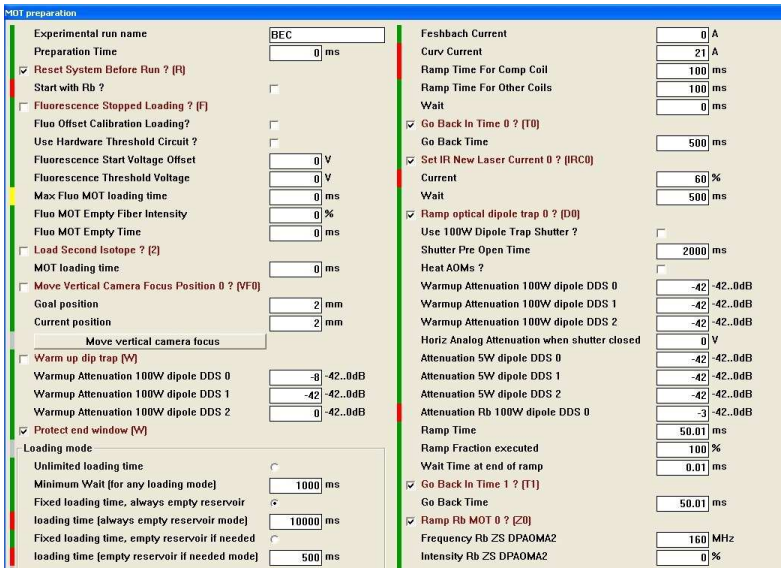
In the process of developing the new ECS I have looked at the other existing projects out there. The two most influential control systems have been the Cicero word generator developed at MIT, and the Hannover control. The later has been the chief source of inspiration for reprogramming the FPGA, that allowed me to swap control system without changing a single BNC cable from the analog and digital output.

The Cicero word generator is written in `C#`, and comes with a GUI (Graphical User Interface) that provide an intuitive way to modulate the physical output, in contrast to other text based control programs, (cite Fast line based experiment timing system for Labview). The Cicero system is split in two parts, a server which manages the hardware communication, and a client which offers a Graphical environment to edit the sequence of events that are required to make the experiment. The hardware for generating the output is managed by analog and digital output cards from National Instrument. The output of these cards are updated by an external clock. To remove redundant buffer, the external clock is generated by an FPGA that is able to vary the time between updates. In times where no output is changed, such as loading the MOT, the clock i paused. This free up space on the board, but still leave some redundancy between the channels, all channels are updated for one event on one channel. This mean that if a complicated analog ramp, or digital pulse train is made on one output channel, an equal amount of memory is used in all other channels. If memory consuming events is made on different channels in a sequence, the memory can be a limiting factor. This issue is dealt with by the new hardware in ALICE, this is descried in section **??**.

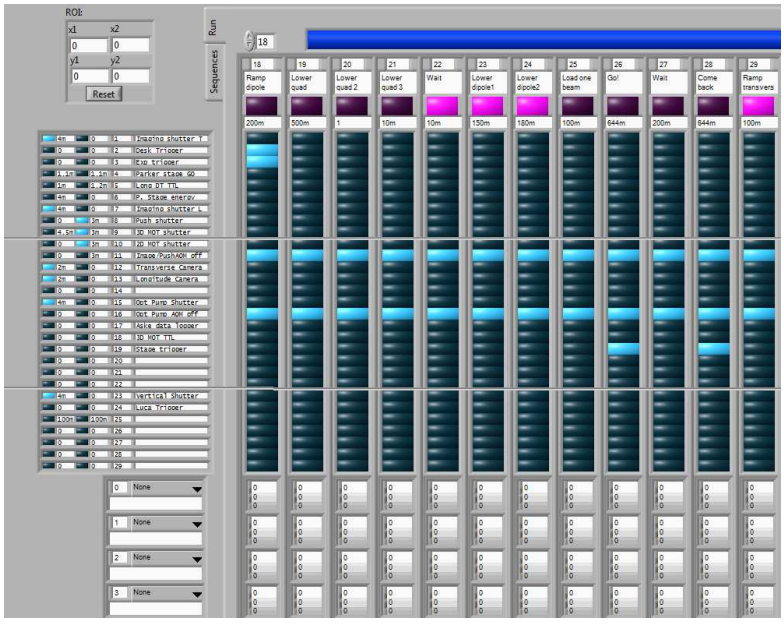
The Hannover control system gives the user a more direct way to programme the sequence, the output is defined in a timeslot as seen on fig. 3.1c. In this control system all variable have to be redefined in all timeslots. To change the sequence can therefore be a vary big work, since unrelated events that are in nature independent of each other, such as the task to take a absorption picture of the cloud, and moving the magnetic trap. One often wants the flexibility to shift such two events time wise to each other, and define other events in parallel.



(A) Front panel of the Cicero Word Generator client.



(B) Front panel of the Strontium experiment [9].



(C) Front panel of the Hannover control.

3.1.2 Other experiments

The "Lattice" experiment, one of the two other cold atoms groups at Aarhus university is an example of a complete experimental control system build from the ground. It is described in [10].

This experiment works stable but is difficult to set up new experiments. The program is written in Borland Delphi, a programming languages not widely used, at lest in our department. This mean that it is challenging to change the program at its core. And therefore is was not desirable to adopt this experimental control system into our experiment.

3.1.3 Requirements

In conclusion I have not found a suitable experimental control system that gives us the flexibility we wants. From the systems considered I have found object oriented programming is a way to build a scalable and flexible program. To use the memory on our output card efficiently one have to empty the buffer with non equidistant timing. In order to increase user friendliness The sequence can be defined in meta data and later compiled to output sequence, creating an abstraction layer between the user and the hardware.

3.1.4 Choosing programming languages

When starting a big programming project, such as building software for a complete experimental control, the choice of programming languages will be among the most important considerations. I chose Labview, because of its gentle learning curve and the easy interfacing with hardware. The idea is that other members in the group will be able to implement new hardware on their own. So the task of writing drivers for new equipment can be delegated to more then one person in the group. Labview supports object oriented programming, which I have used extensively in this project. One very important feature of Labview is the possibility to use Labview code to programme a FPGA. This allowed me to customize our hardware, and optimize the memory use. Since this is one of the key elements in the experimental control system, having a shallow

learning curve is imperative. It made it possible to focus on what the hardware needed to do, and not so much about how to do it. Labview 2012 and newer also comes shipped with the Actor framework, which combines object oriented programming which queued message handling. This is used to set up communication between different parts of the control system. This is another example,in which Labview has a good way to solve challenging tasks. Labview is an easy way into programming quite complex control and data acquisition systems.

3.2 Outline of experiment control

The purpose of an experiment control system is to make the operation of the equipment more easy. I will here present the idea of a fully automated lab see figure 3.2. At the current state not all the elements are implemented.

The main part of the software will be the Client and Server which manages the production and execution of the sequence. At the moment we have a stand alone camera program, it will be possible in the future, to couple it together with the client. The main advantage is that the camera parameters, such as exposure time can be scanned or that the sequence can shift camera module, to image the atoms from different axes. The data is then to be analysed by our fit program. Parameter depended variable such as trap frequencies or time off flight is often used in the data analysis, And have to be extracted from the sequence parameters. By connecting all the blocks the relevant parameters can be propagated with the data, and the data analysis can be fully automated. This is very important to achieve closed loop optimisation. It will also be of great advantage when long experiments where multiple parameters are scanned, to have a running data analyses with a way to plot the extracted data in multiple ways. During long scans, it can be hard to know if the settings is correct, or if there is a failure, like a laser going out of lock. This has to be fixed before the scan can continue. An on-the-fly data analysis will also enable one to flag the point in the sequence at which the error accrued, and restart from the point.

Another part of the experiment control system is the logging of external parameters, such as laser powers, temperatures and magnetic fields. This will over time enable us to correlate the different parameters to the performance of the experiment.As an example

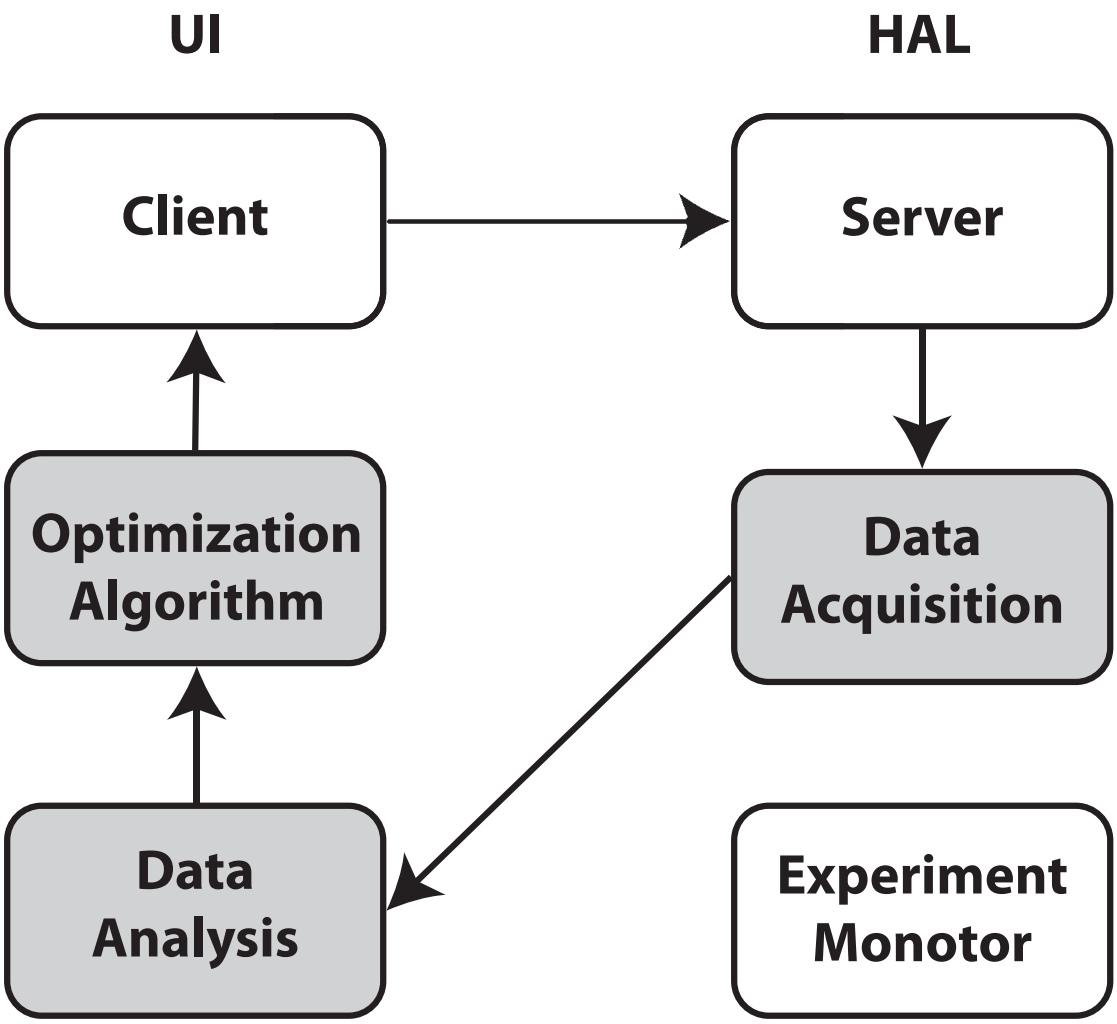


FIGURE 3.2: The different parts of the program. The Lab client generates the sequence and sends it to the hardware server. Data acquisition collect data from each experiment. The experiment monitor log environment variable such as temperature and magnetic fields. The Data Analysis enables closed loop feedback, and parameter optimization.

experiments with spin dynamic require often good control of the magnetic field. By logging this parameter drift in the bias magnetic field can be detected and corrected.

3.3 The functionality of ALICE

In this section I will describe the overall functionality and thoughts behind the Server Client modules of ALICE.

3.3.1 Server

The server is the part of the program running the experiment. Its job is to prepare the hardware and start the sequence. The server is connector to a FPGA that control the analog and digital output. A software timed loop is embedded in the output, to manage software control such as GPIB commands. The output channels have independent timing and can interpolate to save memory. The idea is that the channels are seen as independent resources. and can therefore be used independently. To make a high resolution ramp on one output channel do not cost memory for the rest of the system. The FPGE can be connected up to 4*16 analog channels with between 100 to 400 point for each channels. The distribution of memory can easy be redistribute between the channels and require only a recompiling of the FPGA. This can be done without changing the connection in the experiment, and offer a great deal of flexibility.

Up to 64 digital channels can be controlled by the FPGA. All channels have durations that go up to 3.5 minutes which is enough for most experiments, a typical experiment duration is between $30 - 60$ seconds.

3.3.2 Client

The client works as the editor of the experimental sequence. Outputs such as an analog ramp or digital pulse are defined in Waves. The Waves are an abstract class, and as such, the experiment can be expanded by adding new types of waves by writing new child class. This make it possible to incorporate software timed command, and reprogramming of hardware during the sequence. The Client offers structure order events such as waves relative to each other, as an example the loading the atoms into the magnetic trap comes after the optical pumping. These operations are often complex and require a lot of different channels. The client offers a way to group waves together into blocks. The blocks works as high level building blocks for the sequence, gives a simpler way to construct the sequence. The variables can be connected to output variable fields. This way the variable is available from outside the block, and can be changed in a scan, or used in an optimization algorithm.

Elements in the sequence can be looped, this allows for an easy way to repeat a experiment, this will be demonstrated in section 4.2. Variables can be changed between loop iteration. This make it easy to scan variables within a sequence.

The client will be a building block responsible for generating the sequence. The sequence can be seen as a model for an experiment, that can be modulated through the free variables.

3.4 Server module

The server module is built around a queue that can hold a batch of sequences, and load and run the one at a time. This set up will allow for many more advanced features in the future, such as random scrambling of a scan run, repetition of the last scan, or repeats the run if it gets flagged as failed. It will also be possible to change the order of the queue and put in scheduled calibration and benchmark runs. This will be valuable when long experiments are performed, in order for keep track that the state of the experiment stays within certain limits. For each run The server are compiling the sequence and load it to the FPGA. The software timed commands is also prepared and started in a parallel with the FPGA.

3.4.1 Hardware

The hardware used in the QMM experiment is listed below, and cost around 7000 €in total.

- PCI-7813R
- SCB - 68 R-series
- NI 9264 (16 analog channel module 25kS/s/ch
- NI 9263 (4 analog channel module 100kS/s/ch

The key equipment in the control system is the PCI-7813R from National Instruments. This board contains a FPGA (Field Programmable Gate Array) and 196 KB on board

memory. Compared with the boards used by the Cicero control system this board lack memory. This will be made up for by the ability to calculate output at runtime. The PCI-7813R is mounted in the back of the experiment computer, and connected with a chassis with room for 4 Digital to Analog Converter (DAC) modules, at the moment we have connected two NI 9264 with 16 analog channels and one NI 9263 with 4 channels. The digital channels are connected by the SCB - 68 R-series which acts as a breakout box.

The analog output is grouped into bundles of 4/16 on the FPGA, corresponding the DAC modules. Functions (called vi in Labview) for managing these bundles are developed to change output modules, if requirements to the experiment are changed, as an example we could be needing faster analog output, or more channels. This can be changed at a later time. The vi runs in cycles of 4/16 and updates the output in a sequence. With a loop rate of 20 MHz this gives a time resolution of $\frac{16}{20\,\mathrm{MHz}} = 800\,\mathrm{ns}$, 200 ns for the 4 channel box. This is much faster then the output bandwidth of the analog DAC modules.

The digital is all updated in the one loop. This correspond to time resolution of 50 ns.

3.4.2 Analog output

For this FPGA the memory is limited, so in order to make better use the FPGA the analog channels are lineary interpolated between two values in a given time interval. For each channel a three arrays are available, time, value and slope. When a channel is updated the value will be set to output and on the next iterations the slope will be added, thereby changing the value. The slope is calculated such that the output will reach the end point of the ramp in the given time interval. Since all channels have individual timing, it is possible to use resource independently. This will later be shown to give us some advantages. Whit the 32 bit used for the clock, the maximum time for a sequence is $\frac{2^{32}}{20MHz} \approx 3.5min$ which will for most purposes be enough.

3.4.3 Digital output

The digital channels are made differently. To save memory all the digital channels are embedded in a 64 bit value with one timing array, this is preferable compered to having 64 channels with each have a 32 bit timing array, since the timing would take up most

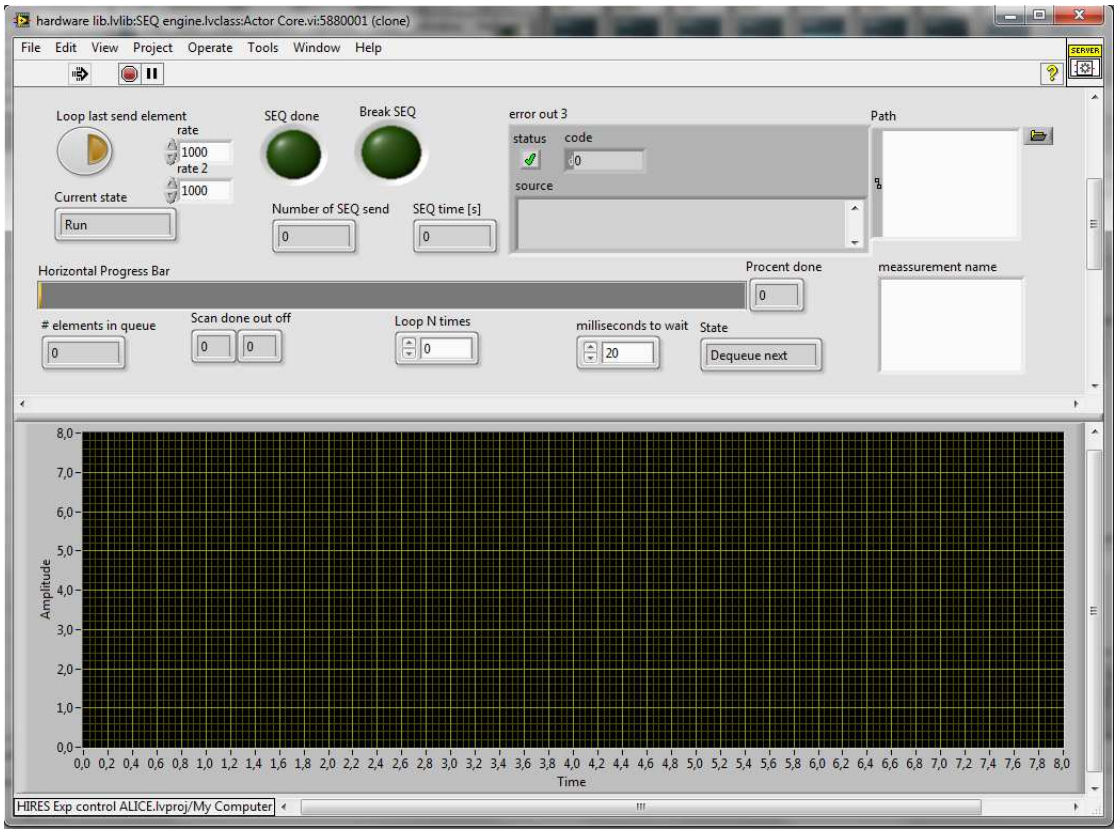


FIGURE 3.3: Picture of the server UI

of the memory. This means that all digital channels are updated at the same time. The number of digital memory is set to 4096. If this later turns out to not be enough, one can simply redistribute the memory, to make more space for the digital channels.

3.4.4 VISA

In Labview one can make priority loop, which will execute before a loop with lower priority. This ensures that other processes do not interfere with the timing of the VISA command. The expected timing precision is around $10ms$. The VISA protocol can be used to control expernal hardware, such as power-supplies via GPIB commands.

3.4.5 Calibration module

Each channel can be calibrated and given a unique name. The idea is that a channel is calibrated and named when connected. For the digital channels it are possible to pre delay the rising and falling edges separately. This allows us to take care of delays in

ensuring when shutter are closed, one can specify in the program at with time shutter should be closed or camera triggers send, and the calibration ensures that the trigger is pre-delayed by the right amount of time to make this happen. The analog channels can be set to a defaults value, which is important for our Acousto Optical Modulator (AOM) as they should always be on for the majority of the time. As a future implementation one can also imagine for applying multiple look-up tables for different ways to specify a variable. For example the AOM driving frequency could be specified in absolute detuning from the resonance in various different units, or the power of the optical traps could be calibrated to trap frequency. This will allow the user to look at the system from a totally different way. Maybe more intuitively for other users, and new discussion can be made. The easy translation between different unit could. Other calibration settings can also be stored here, such as camera calibration.

3.5 Client module

The client is built up of two different types of objects: Waves and blocks which will be described in more detail in section 3.5.1 and 3.5.2. The user interface lets one build a structure of events, by specify when the elements starts relative to another event. Events can both be started parallel to other events or in sequential order. The UI is shown in figure 3.4. There are two windows in the UI the sequence window and the Public block window. The Public block window works as a deposit for already constructed blocks. These elements can be dragged and dropped to the sequence window. In the sequence window the elements can be placed in the order that the sequence will be executed in. Waves can also be added to via the new wave button. This will open up a new window where the wave can be configured.

3.5.1 Waves

The basic elements of the sequence are the waves. A wave are in this context is an object representing an event in the sequence. The wave contains a time interval, data for the event and a channel to connect to the event. The channel is used as an abstract concept and can be a physical channel, such as analog or digital output channels, but it can also be a software channel for controlling software timed command such as GPIB.

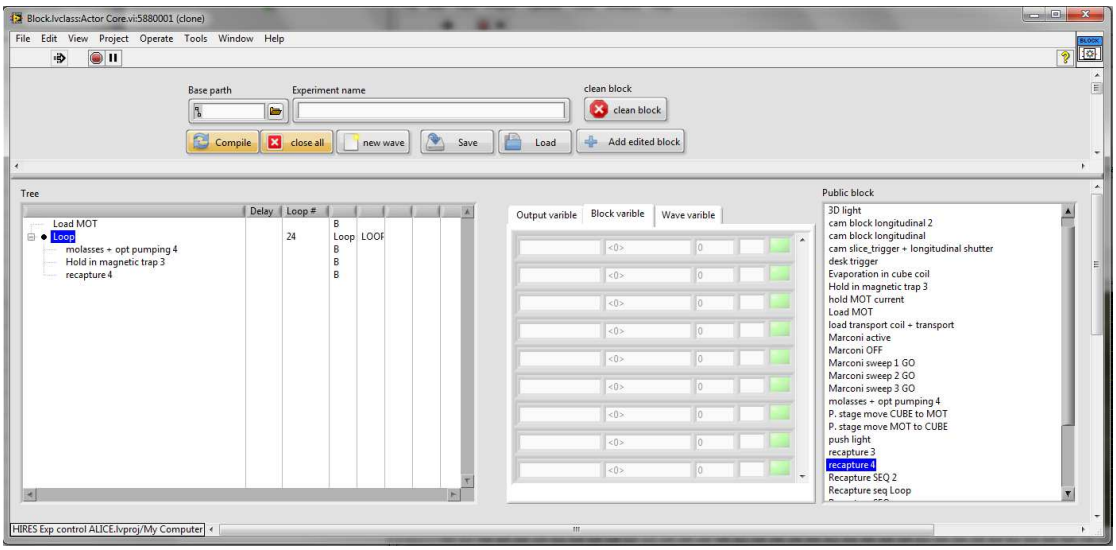


FIGURE 3.4: Client UI, a looped recapture seq can be seen in the picture

The starting time of a wave is defined relative to another event, And more waves can be started relative to the same event. This mean that it is natural to use a tree structure

- Analog wave
- Digital wave
- VISA command wave

3.5.2 Blocks

The block class is created as a way to group waves together in a tree structure. As a special feature, it is possible to use both block and wave objects as part of the sequence. This means that that part of the sequence can be used, and decorated with waves and other blocks. In Labview it is not possible to use a class for its own data. This restriction is circumvented by using inheritance. A parent class is created, and used in the child private data. When the block class is used, a type definition is used to specify which child class is used. This enables us to enter the blocks on equal levels as the waves. This also affects the way the sequence is compiled. The compilation calculates the absolute starting time for each wave, recursive function calls is used to compile blocks within the sequences.

The client module is a second version. An early prototype was build to test server module, and hardware. The blocks of sequences could be constructed, and set together

in an array. this limitation of not being able to set blocks in parallel was the main reason for programming version 2. The idea is that two blocks of sequence can be completely independent of each other. Such as evaporating atoms in the trap, and run a picture of the cloud. Therefore there is reason to be able to place for example a camera module in parallel to the main sequence.

To capture the feature of stating parallel sequences a tree structure is chosen. It is a known element from computer science, and graph theory. A tree offers a unique way of ordering a set of elements that gets the start time from its parent. In the first module a homebuilt version was used, but it was found that using Labviews native tree structure, this was made possible due to easy access to Look Up Tables (LUT). Only a tag is saved in the tree structure to reference to the object in the LUT. The client module is responsible for modulate the sequence, and work as the user interface.

The most important part of the control system is the sequence manager. It is here that the modules are edited and tested. The user interface is shown in figure 3.4.

My software takes advantage of the fact that the analog channels is independent of each other. Waves, can easy be translated relative to each other, opposite the old hires program.

3.5.3 Diagnostics

ALICE offers an abstract way of generating the experiment sequence, but it is often useful to be able to analyse the output in greater detail. To aid this requirement a set of diagnostic tools are built. They are shown in appendix B. The output is plotted in a graph, where it is possible to zoom and select output channels to be displayed. this can help giving an overview off which channels are used during the sequence. The channel consumption shows the memory use of the individual channels.

3.6 Further development of ALICE

3.6.1 Priority events

At the moment an event on a channel cannot be overwritten by another event, it will just create a time error. A situation where it will be an advantage to overwrite a channel is where we take the absorption image. In order to release the atom cloud, the trap holding the cloud need to be turned off, before to allow for time of flight (TOF). If the camera block has permission to overwrite the channels that hold the atoms in trap then we will be able to have block preparing the system in the right state in order to work. One could easy take a movie for example the evaporation ramp, at arbitrary points.

3.6.2 Scratch interface

The user interface is planned to be upgraded. The idea is to use the graphical idea from Scratch programming languages, 3.5. The user interface consist of an UI where blocks and waves can be locked together in a tree structure. The blocks should have some sort of scaling to represent the duration of the different blocks. In contrast to scratch the ALICE program will have blocks added in the horizontal direction, to represent the time flow of the sequence. This will give a nice tool for the higher level events, such as the camera module.

3.6.3 Advanced sequence scheduler for server module

The server is build as a queue that is emptied one sequence at the time. By building a more advanced queue handling, it is the goal to be able to rerun a sequence on a failed run flag, if no atoms are detected, and schedule automatic rerun. Repeating sequences for better statistics or randomising a group of sequences that scans over a variable to avoid catching systematically drift in the system. When the experiment is not run, a dummy sequence can be looped to keep the system warm. When a long experiment over many days is preformed, regular benchmark sequences can be incorporated to test the stability of the system.

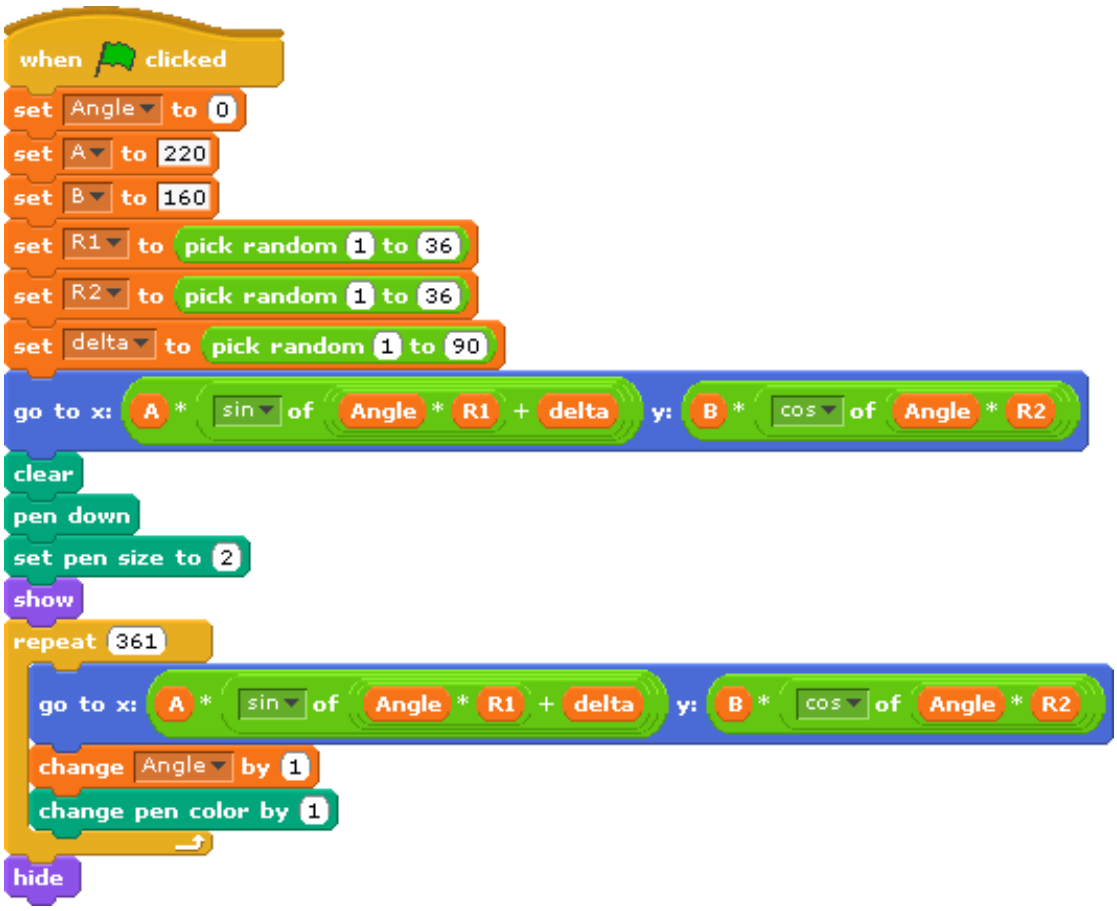


FIGURE 3.5: Example of a scratch program.

3.7 Conclusion

ALICE offer a new way of modulating the timed events in a modern cold atom experiment. The overall important features bundling of events and reuse of these bundles. This enables the us to design blocks that can be used by non lab users.

Chapter 4

First experiments with ALICE

4.1 Intro

The following experiment is meant to prove of the principles of some of the new features in ALICE. I will present simple examples of the experiment that are easy to do with ALICE than with the Hannover control. I will also describe future experiments where using these new features will be an advantage.

In section 4.2 I will present an experiment where the atoms are loaded into the magnetic trap and afterwards loaded back into the MOT again. This process will be repeated up to 24 times in a single sequence, and the parameters that influence the loading into the magnetic trap will be investigated. The recapture sequence is an example of how to do multiple experiments in a sequence. In section 4.3 I will present an experiment, where a cloud of atoms is transported to the cube chamber and hold in a second magnetic trap. This procedure frees up the transport coil to move back, and the MOT is loaded a second time, while an evaporation sequence is being made on the first cloud of atoms. This illustrate the possibility of doing multiple tasks in parallel in a singe sequence.

In section 5.2 I will present the first try to do closed loop optimization of parameters future optimisation to be incorporated will be discussed.

4.2 Multiple recapture

-

During the recapture experiment we load the MOT with 8×10^8 atoms. The atoms are cooled further down with Sisypfus cooling and pumped into the $F = 2$ $m = 2$ state, so they are in a low field seeking state and can be trapped in the magnetic trap. The atoms are loaded into the magnetic trap and hold for about 1 s, and then they are released into the MOT again. By measuring the fluorescent light, the fraction of atoms trapped can be measured. This serve as a good way to optimize the loading into the magnetic trap.

4.2.1 Sequence elements

The sequence is built up by the blocks listed an explained below. The last four blocks are looped in order to do multiple recapture experiments.

- Load MOT: controls the light for the the loading time it is the only free variable.
- Molasses: the MOT is turned off and the atoms are hold in the optical trap for 9 ms and the cooling light is detuned 36 MHz in order to apply Sisypfus cooling.
- Optical pumping: Control a bias DC magnetic field, to create a quantization axis for the spin of the atoms. The optical pump light is applied for SI1.5ms.
- Load magnetic trap: The Bias field for the optical pumping is hold on for 10 ms while the current in the coil is ramped up to 90 A, giving a gradient of 150 G/cm in the z axis.
- MOT: The MOT is turned on. The fluorescent signal can be observed again.

The effect of the optical pump time is investigated in this experiment.

4.2.2 Results

After I run a first test, I was able to find out that the maximal amount of repetitions is limited to 24. The limitation is the memory of the channel that was controlling the

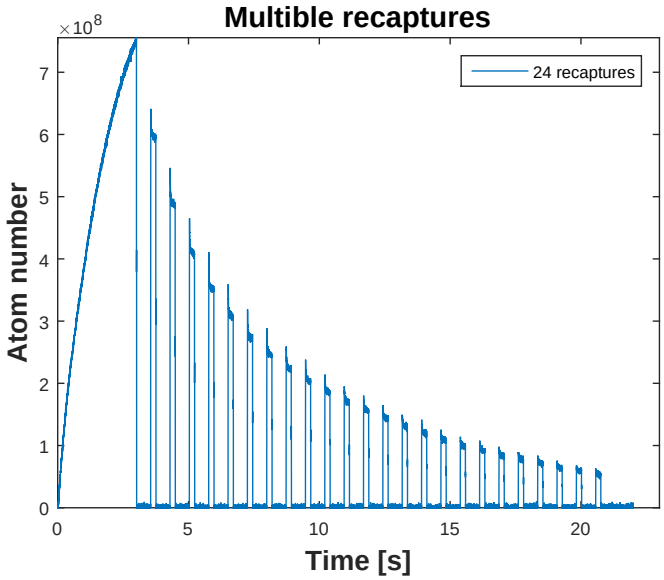


FIGURE 4.1: Recapture experiment repeated 24 times. Hold 500 ms in magnetic trap. The fluorescence signal is converted to atom number.

detuning of the cooling light for the MOT. The recapturing fraction is calculated as the ratio of atoms before and after the atoms are held in the magnetic trap.

The effect of the optical pump time on the recapture fraction is investigated. The recapture fraction is calculated as the ratio of two adjacent recapture signals. Figure 4.2 shows the recapture fraction as a function of the atoms that can be trapped. The recapture is more efficient when the number of the atoms falls, causing the recapture fraction to reach up to 90%. The reason could be that when we load the MOT to its maximum, there the are some looser trapped atoms. When we load the atoms into the magnetic trap the first time, we loose a bigger fraction of the atoms than when the atom number is smaller. The effect, I have just described, will be added to the effect of the optical pump-time.

The optical pump time was scanned from 0.05 ms to 8 ms. The pump time was kept constant within the sequence. The errorbars comes from averaging over 5 repetitions of each sequence. The different graphs correspond to different atom number. As seen on figure 4.3, there is a strong dependence on the optical pump time when it is lower than 1.5 ms, where it flattens out for higher optical pump time.

I scanned the optical pump time in a single sequence to show how I am able to use the loop feature in ALICE to do experiments with different parameters values in a single sequence. In figure 4.4 the recapture fraction is plotted as a function of optical

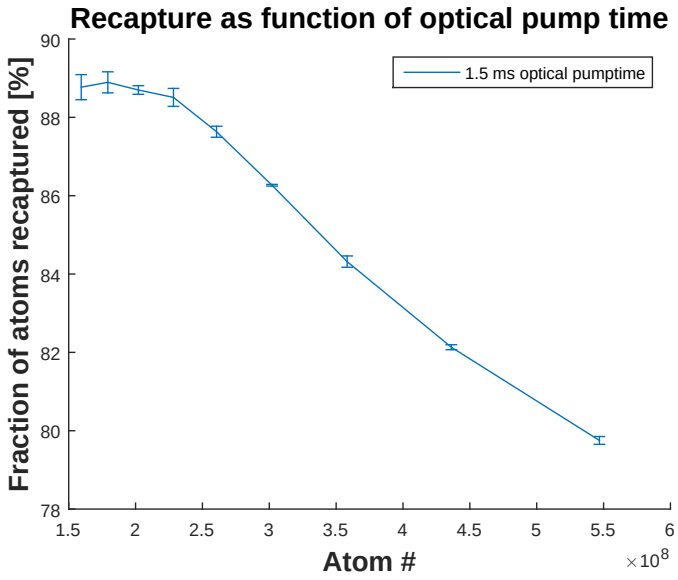


FIGURE 4.2: The recapture fraction as a function of atoms. The optical pump time is 1.5 ms.

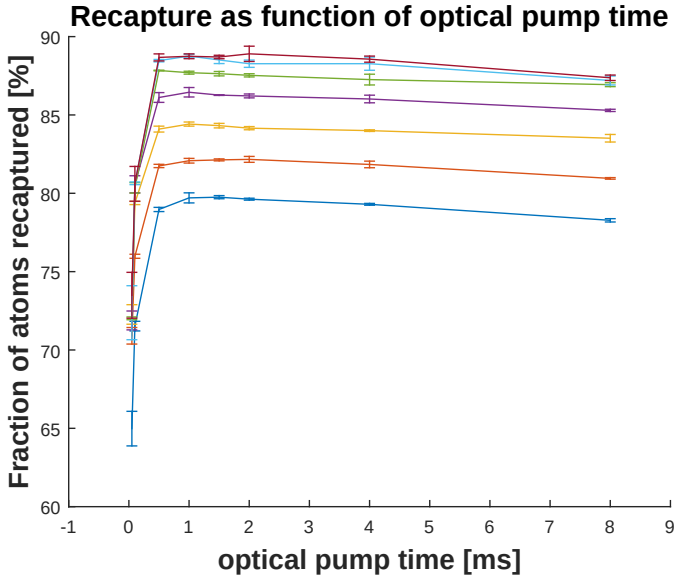


FIGURE 4.3: The recapture fraction as function of optical pump time. The different plot represent the recapture fraction at different atom numbers.

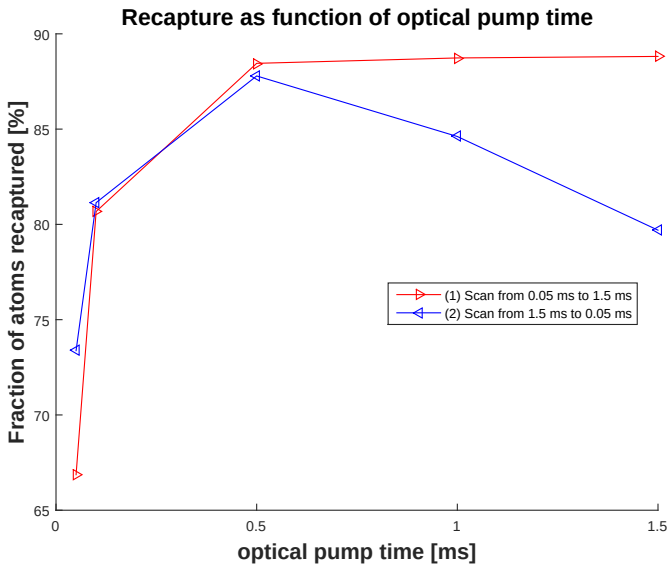


FIGURE 4.4: Optical pump time scanned in a single sequence.

pump-time. The variable is scanned from 50 µs to 1.5 ms and reversed in the second, to see if the two scans will be the same. As can be seen in the figure, the scan that stated at 1.5 ms had a lower recapture fraction, which correspond to the effect of a lower recapture fraction when the number of atoms is high, as seen in figure 4.2. Effects such as the atom number dependence of the recapture fraction make it difficult to do a single sequence measurement consisting of multiple experiments. This will have to be considered for future experiments. But it shows that ALICE is capable of making complicated sequences with great ease.

4.3 Parallel loading of MOT

In this section I will discuss some of the advantages of building sequences with parallel blocks.

A lot of operations in the sequence are actually independent from each other, as for instance taking an absorptions picture somewhere in the sequence or the loading and transport of atoms. This feature can be exploited to do flexible probing.

In the [3] we made multiple probing of the BEC transition. This was done by triggering externally the camera module. And so the probing was done with equal time interval

between the triggers. In ALICE it will be possible to group the probing around the transition point very easily, allowing a better time resolution of the transition.

Another possibility will be to pipe lining the experiment in order to create a continuous source of atoms in the science chamber[11], and thereby shorten the duration of a single experiment or build up the number of atoms available in the BEC. The first step toward this is taken in order to test the ability to place blocks in parallel in ALICE.

In this experiment I will use the feature that the atoms are transported in one magnetic trap and stored in the secondary magnetic trap placed on the cube chamber. Thereby the transport trap is free to move back to the MOT chamber without effecting the atoms, and start a second loading. To fit this procedure into a timeslot based experimental control would be a daunting task, and thereafter to change some timing related would be even more challenging. But since ALICE can make parallel threads, independent blocks can be translated relatively in time.

The sequence uses some of the blocks of the previous section, and I will only describe the new blocks. The MOT is loaded, cooled and transferred into the magnetic trap. The magnetic trap is then transported to the cube chamber. Here the cloud is transferred to a second magnetic trap. At this point the transport trap is free to move back to the MOT chamber, while the evaporation sequence starts in parallel.

4.3.1 Sequence elements

- Transport1: trigger the transport stage to move the atoms to the cube chamber, while keeping the current at 90 A.
- Transfer to cube coil: ramp the current in the transport coil down to zero, while ramping the cube coil up to 150 A.
- Transport2. trigger the transport stage to move back to the MOT chamber.
- Evaporation: Hold cube coil at 150 A while the micro wave sweep is started.
- Absorbtion picture: trigger camera and light for shadow picture and background.

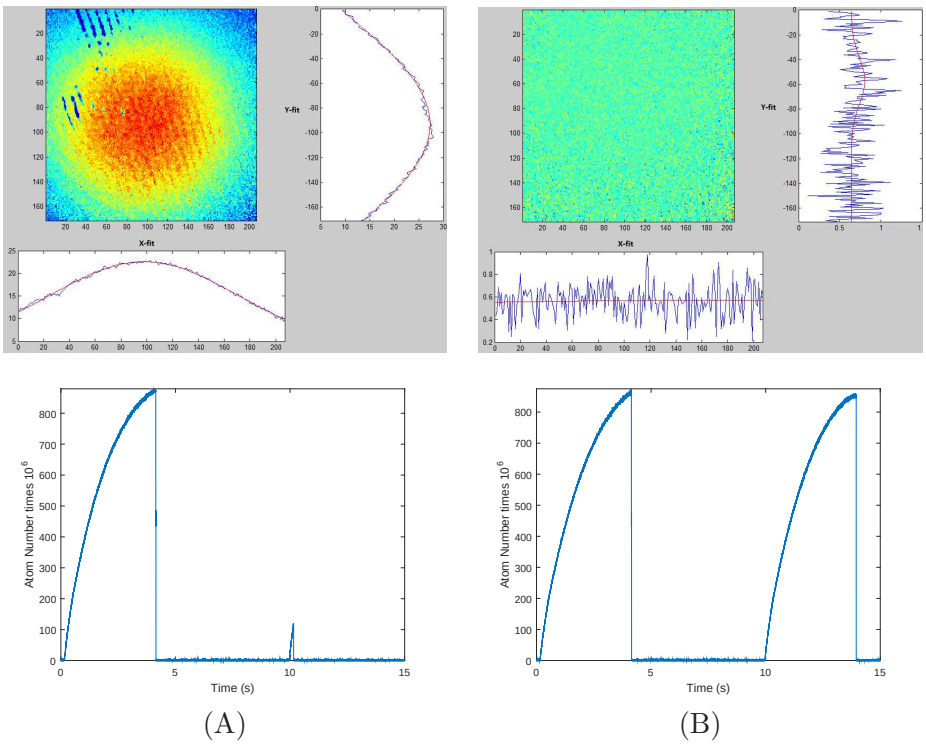
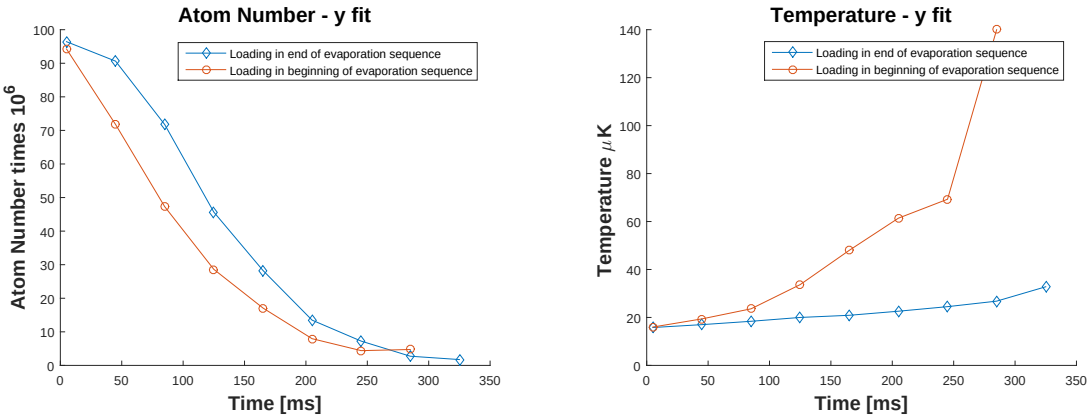


FIGURE 4.5: Show the Fluorescence signal and the absorption picture. A) MOT loaded second time for 165 ms B) MOT loaded second time for 4 s

4.3.2 Results

I measured the fluorescence of the MOT light during the sequence. In figure 4.5 shows the absorption picture along with the fluorescence signal. The second loading is 165 ms and 4 s long. The 4 s loading completly destroys the atom cloud in the cube chamber. Instead by loading MOT for only 165 ms, 1×10^8 atoms could be loaded in the MOT while still having atoms left in the cube chamber.

The atom loss and heating are measured as a function of loading time. The loading was started at two points in the evaporation sequence, at the end and at the beginning. Figure 4.6 shows that the atoms number is reduced by half by a loading time of just 100 ms. This is only enough to load a tenth of the atoms that are normally loaded into the MOT. The problem is the stray light from the MOT. Since there is a direct line of sight between the two chambers, the heating rate of the atoms in the cube chamber is too high.



(A) (B)

FIGURE 4.6: A) The atom number after evaporation and 15 ms of time of flight.

4.3.3 Discussion

As in [11] the problem is the stray light from the MOT chamber. One way of solving this problem would be to build a shutter into the vacuum chamber. A shutter was build into another experiment at Aarhus University, but was not used more then ones since the vibration broke the glass chamber of the 2D MOT.

Another possibility is to use an optical trap to hold the atoms in. Since the cooling light from the MOT is heating up the cloud, we could transfer all atoms from the $F = 2$ $m = 2$ state to $F = 1$ $m = 1$ state by a microwave pulse, this is possible in the optical trap since all spin state is trapped. This will make the detuning 1×10^3 larger. Using 4.1 we can see that this will lower the scattering rate with a factor 1×10^6 and thereby will shield the atoms from the cooling light.

$$\Gamma_s = \frac{\Gamma}{2} \frac{S_0}{1 + S_0 + \left(\frac{2\delta}{\Gamma}\right)^2} \tag{4.1}$$

The MOT light also contains some re-pumper light that will be able to scatter atoms in the $F = 1$ $m = 1$. But the power is one tenth of the cooling light. So the shattering will be smaller.

Chapter 5

Additional experiments

5.1 Introduction

In this chapter I will present experiment that is not incorporated with ALICE, but will be implemented at a later point. I will also present some of my thoughts concerning the magnetic field stability in the laboratory. Do to time limitations, I did not incorporate these schemes in the experiment.

5.2 Optimization

Here I present the result of the optimisation of the beam alignment for the cross dipole trap. In this simple set-up the sequence was not altered, instead the overlap of the optical trap is altered by a secondary program developed by Jens Schultz Laustsen, bachelor student in the QMM group. All data presented here is taken in collaboration with Jens. The optimization is done by using a simplex algorithm. The idea was to use ALICE, but due to time constrains, the old program was used to make a loosely connected closed loop optimization.

The optimisation parameter comes from the fitting program written in Matlab, that can run continually, and export the the fit parameters to a text file. Then the optimization program polls the latest fit parameter, and make a decision of moving the mirror. This type of closed loop is very weak connected, since the optimization program have no way of stopping the sequence, so that the optimum is found or the signal is lost. Therefore

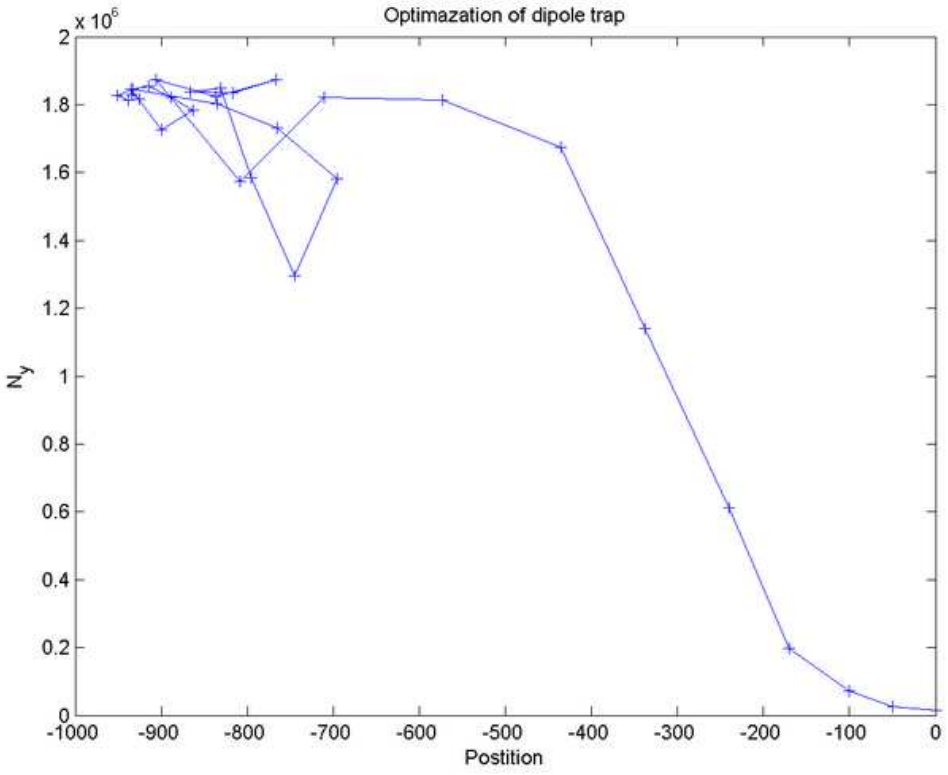


FIGURE 5.1: Atom number vs position of the mirror

this procedure can not run completely autonomously. That said, this procedure still offers an efficient way to scan the dipole beam position.

Figure 5.2 shows the atom number loaded into the crossed dipole trap as a function of the position of the mirror. The mirror gives the beam a movement of $0.5\frac{\mu}{step}$. The mirror is moved away from the crossing point, and the algorithm is set to find the optimum. As it can be seen from the movement correlated with the loaded atom number, one can see the hysteresis of the mirror motor. This hysteresis imposes some demands on the algorithm used, since it cannot relay on knowing the absolute position. On the first try we got from 1.2×10^6 to 1.8×10^6, which has increased by 50%. This shows that there is a lot of potential in incorporating optimization algorithms, therefore this should be a standard module in ALICE.

In the optimization described above, only one parameter was optimized. In the future this will be extended to a higher dimension. In principle all the variables in the sequence can be made available for an optimization algorithm. The choice of algorithm depends on the task. An evolutionary optimization algorithm have been used to optimize up to

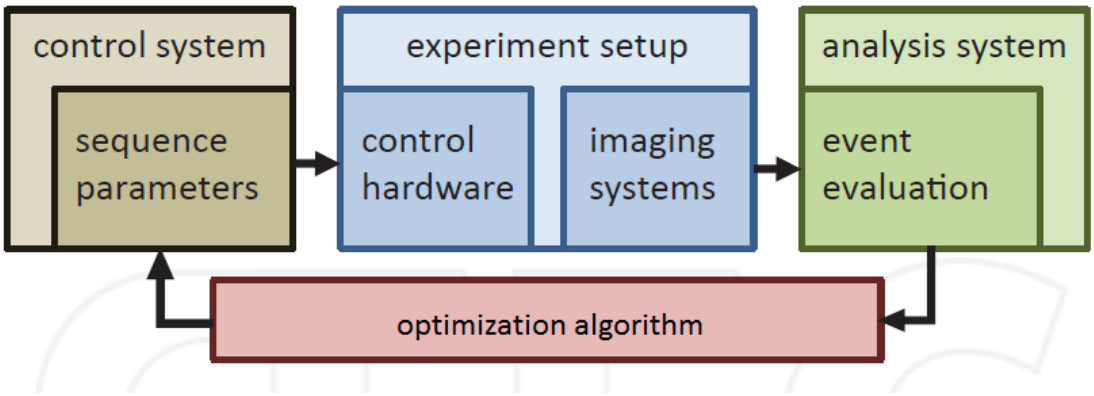


FIGURE 5.2: Closed loop scheme. Modified from [14]

21 correlated variables [12]. The idea behind this algorithm is that a set of parameter spaces (generation) is used to generate a set of sequences. After all the sequences are evaluated, the best parameter spaces are saved and used to generate permutations, which are used in the next generation of sequences.

In a future experiment we will need to load a BEC into an optical lattice, which has also been optimized using a Chopped RAndom Basis (CRAP) algorithm [13]. The CRAP algorithm can be used to optimize time dependent parameters in a many-body quantum system.

A lot of different task need to be optimized in our experiment, in order to prepare the atoms to a state where they can be used to do quantum computing. It is therefore most likely that we will use several different optimization strategies. It will be of great value to us to have a general framework that will allow us to easily incorporate new optimization algorithms in a closed loop. Figure 5.2 shows the general idea behind a closed loop optimization.

5.3 Magnetic field stabilization

5.3.1 Spin state

The spin state in the ground level of $Rb87$ works as a good two level system. Because the transition $F = 2$ $F = 1$ is forbidden in the dipole approximation, the spin state have a long lifetime. This makes this transition suitable for a qbit in a quantum computer.

The long lifetime comes at a price. The resonant driving frequency is dependent on the magnetic field. For the $F = 2$ $F = 1$ line in $Rb87$ the magnetic field dependence is $3 \cdot 0.7MHz/G$.

By applying a microwave pulse to the atoms at a frequency around 6.8 GHz, we can drive the transition in an oscillating Rabi cycle. The population of the two spin state is controlled by the duration of the microwave pulse. A pulse that makes a complete transfer is called π pulse, by choosing half this duration the atoms can be put in a superposition of the two states, which is called a $\frac{\pi}{2}$ pulse.

The control of the atoms depends on the magnetic field, since it induces an unknown phase evolution. If the magnetic field varies during an experiment, or from experiment to experiment, one will observe a limited time during which the atoms can reliably be controlled due to an unknown phase evolution in the system. This is called the coherence time.

In order to improve the coherence time in our future experiments, I will here outline some of the possible solutions.

5.3.2 Magnetic noise

The magnetic field has been measured in the laboratory with two types of sensors. A fast sensor (Mag-03 from Bartington) with a bandwidth of 3 kHz and a slow sensor (RM3100 from PNI) with a bandwidth of up to 550 Hz.

A typical sample of the magnetic noise is measured with the Bartington sensor (see figure 5.3). The signal is measured in AC mode on an oscilloscope, since we are only interested in the fluctuations. Frequencies higher then 3 kHz are filtered away. The magnetic field noise is periodic and contain mainly 50 Hz and 150 Hz. The noise is approximately 3 mG. This means that, in the worst case, our phase evolution will be off by 6.3 kHz. This gives an estimate off around 200 µs coherence time. In order to be able to use our spin state as a qbit, a coherence time of the order of 100 ms is desirable.

The slow drift in the magnetic field can be measured with the PNI sensor (see figure 5.4). The average magnetic field in the laboratory is around 0.5 G. The magnetic field from the magnetic trap is seen as the repeated spikes in the signal.

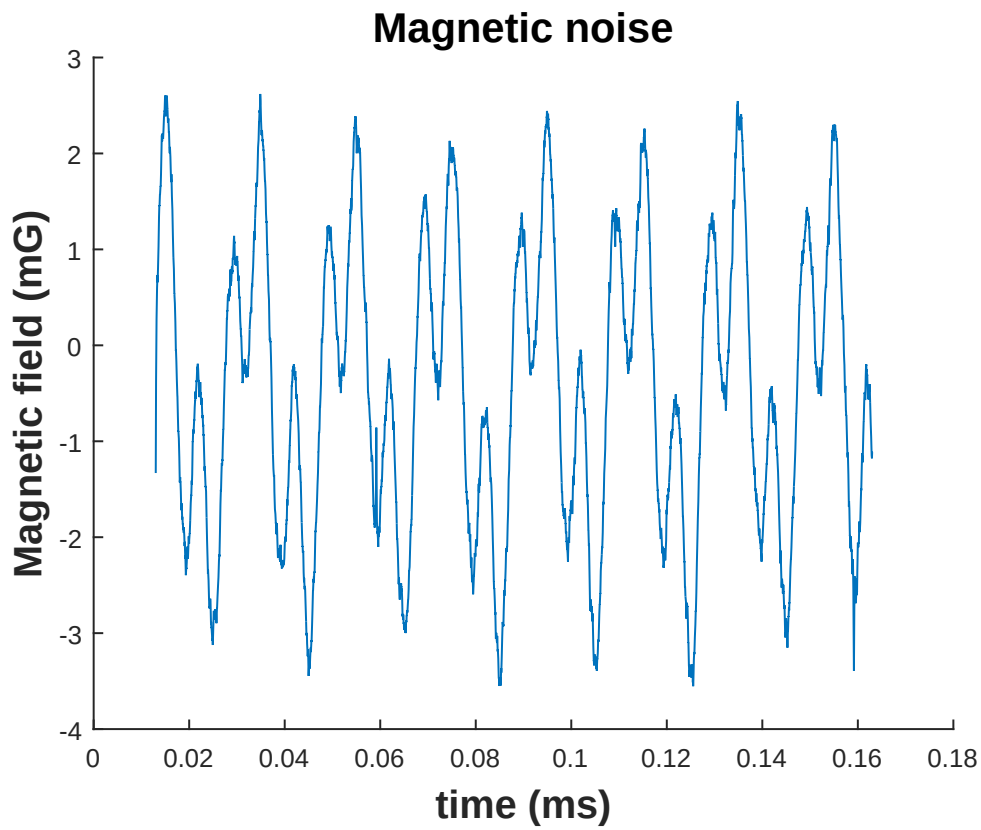


FIGURE 5.3: Magnetic noise in the laboratory.

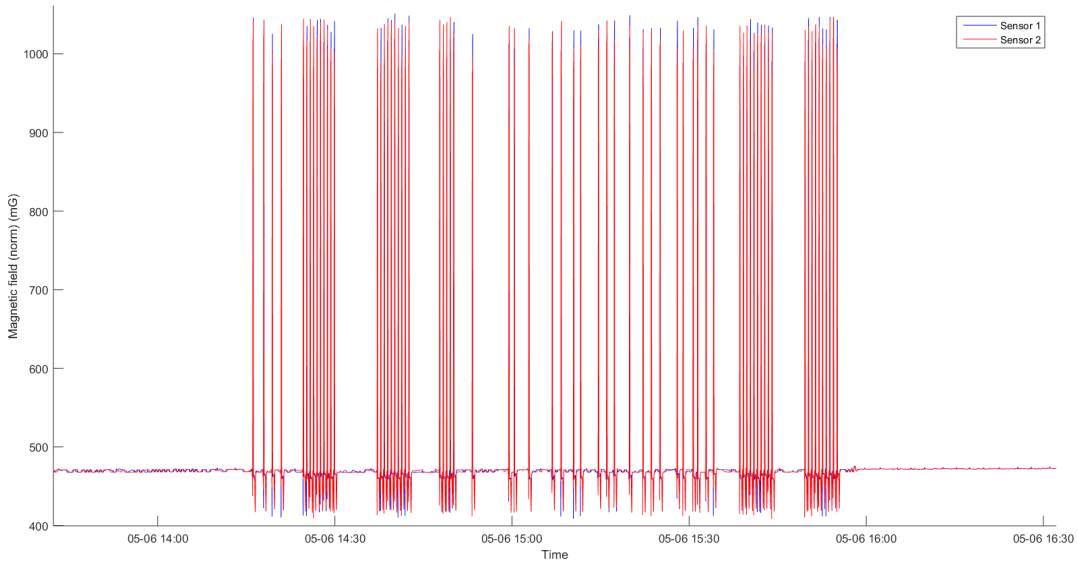


FIGURE 5.4: Long term variation of the magnitude of magnetic field.

5.3.3 Stabilization of magnetic field

To reduce the magnetic noise level, and thereby increase the coherence time, several tracks have been considered.

The main component of the noise is in phase with the 50 Hz power line. That means by synchronizing the experiment to the power line, we can reduce the shot to shot fluctuations, so that the atoms see the same AC field in every experiment. I started to implement the synchronisation of the power-line on the FPGA, but it is not fully implemented at the moment.

Another way to reduce the magnetic noise is to use an active stabilisation. This can be done by a PID (Proportional-Integral-Derivative) controller. It is quite simple to use, and can be implemented on a FPGA.

It has been shown that the magnetic field can be stabilised to 50 µG in [**?**], and based on that we can estimate that this would yield a coherence time of 10 ms. In this experiment the magnetic field is measured by using the atoms as magnetometer. A full cycle of the 50 Hz is measured by delaying the measurement relative to the power line phase. The magnetic field is then compensated by using an arbitrary waveform generator to generate the anti wave and trigger this to the power line.

This method gives good results, but have some limitations. Firstly the probing of the magnetic field is done over many experiments, so it will take time to calibrate the anti wave. Secondly if our magnetic field environment should change on the time-scale, that it is needed to calibrate and to do the measurement, the anti wave could end up amplifying the noise instead of changeling it.

In the future we will work towards a solution that uses atom as a magnetometer and fast regulation in form of a FPGA to be able to cancel the noise in real-time.

Chapter 6

Conclusion

I have presented a new experiment controls system written in Labview using object oriented programming. The program can be used to build and edit a sequence of timed events. The events are implemented trough an inheritance class pattern, that allows the system to be extended very easily to new types of physical outputs. The events can be bundled together in higher level blocks encapsulating the different tasks in the experiment. This enable the user to build sequences out of high level blocks, which makes it easier to restructure the sequence. In this way the user can have a system that is easier to learn and manage.

I have implemented as the high level blocks that is used to create a cold atom cloud in the experiment. The blocks have been used to test the new features in ALICE. The possibility of looping was used to produce a sequence that repeated a recapture experiment up to 24 times without duplicating blocks. It is also shown that a parameter can be scanned in loop and used to do single shot scan of variables.

The possibility to do different tasks in parallel has been used to trap atoms and transfer them to a second trap, and thereafter the first trap has been loaded with atoms again. This has allowed me to have atoms trapped in two different places simultaneously. Due to stray light between the two traps, it has only been possible to load a limited number of atoms during the second loading. Many steps need to be implemented in order to make these experiments work, but they serve as a prove of principle that the program can generate sequences with parallel tasks.

Moreover a simple optimization algorithm has been used to optimize the loading into an optical trap. This showed the need for a combined system, that allows to create a framework where the many different algorithms can be easily implemented.

Finally I have been investigating the effect on a spin system due to the magnetic field's noise in the laboratory. This will be the first stepping stone towards doing an active magnetic field stabilization. This has to be done to increase the coherence time of Qbit. The main component of noise is coming from the power lines, where the frequencies are 50 Hz and 150 Hz. To stabilize the magnetic noise I have suggested to synchronise the experiment with the power line, and to use a Faraday measurement of the magnetic field to actively stabilize the field while the experiment is running.

Appendix A

D2 transition in Rb^{87}

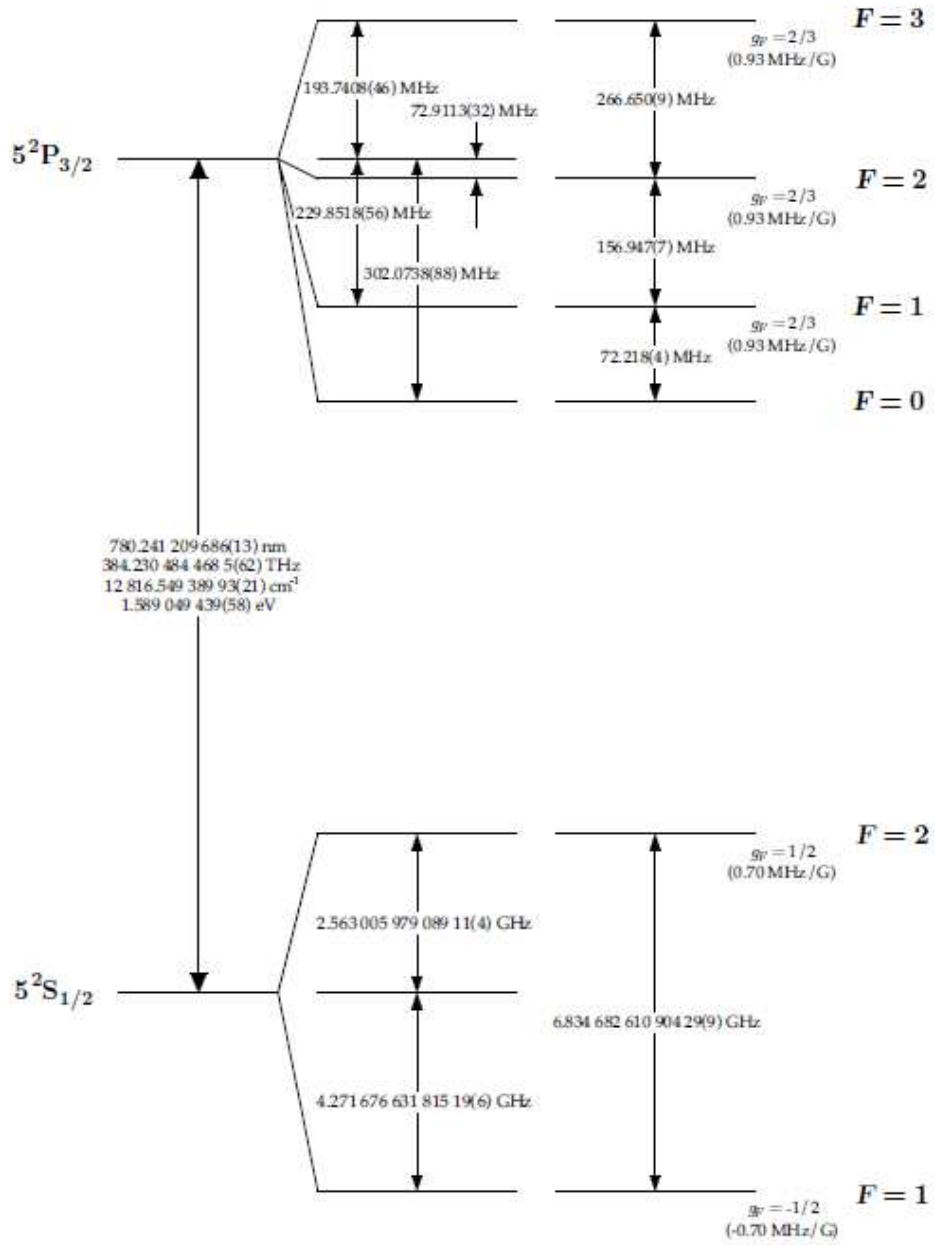


FIGURE A.1: Show the D2 transition in Rb^{87}.

Appendix B

Diasnostic tools for ALICE

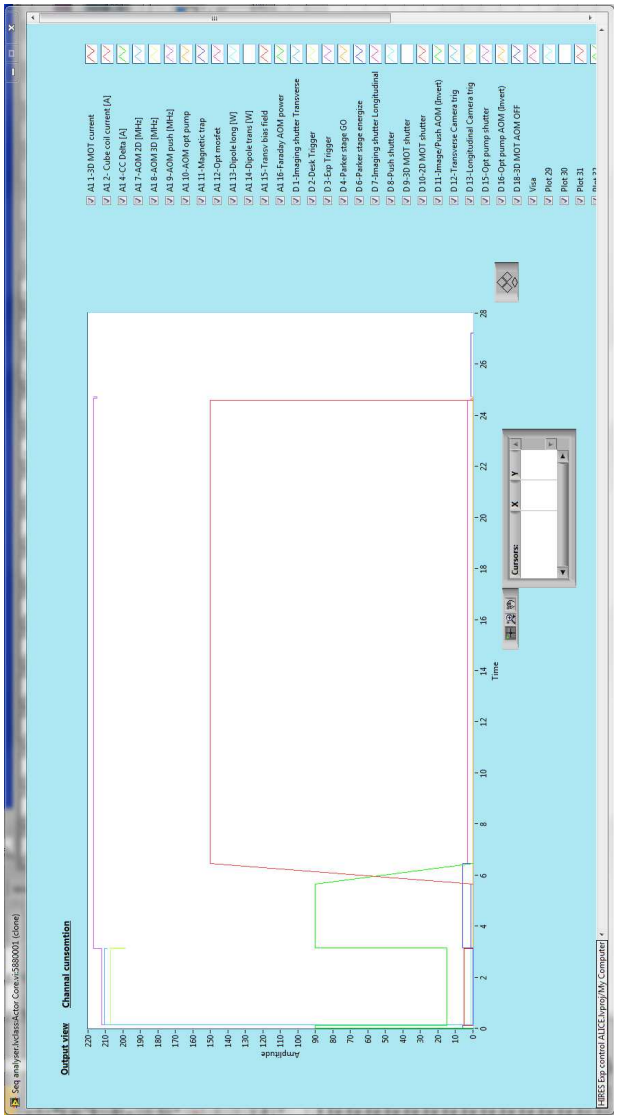


FIGURE B.1: Show the channel value as function of time.

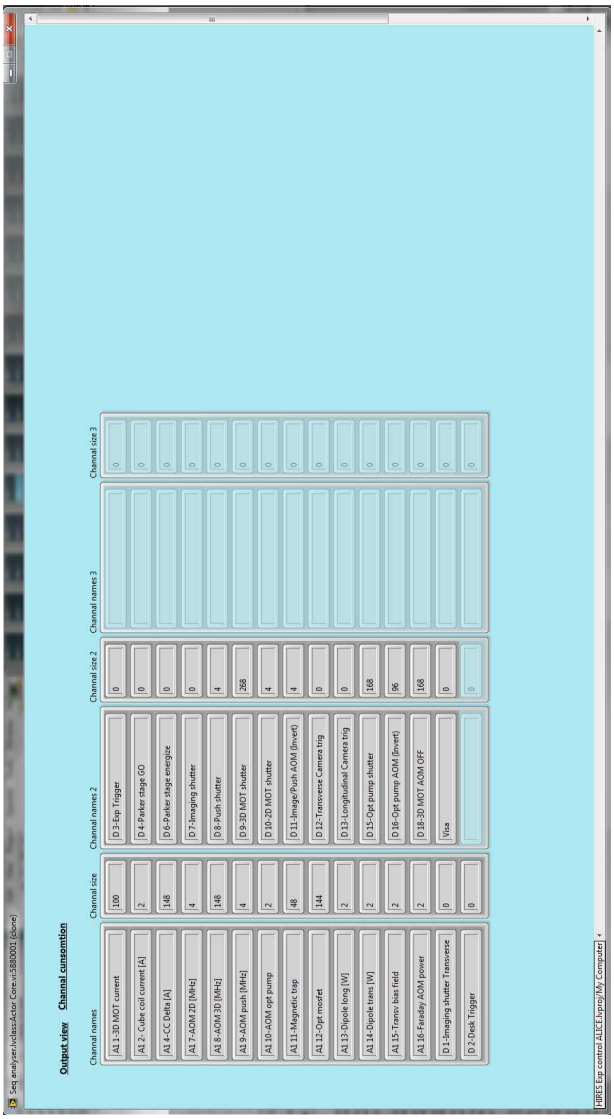


FIGURE B.2: Over view over the channel cunsumtion

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