Rydberg atoms on a chip and in a cell
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In this chapter the main experimental setup will be described as it exists at the end of the project. Some results, in particular those discussed in chapter 6 are based on a modified sub-set of the setup which will be discussed in that chapter. The results presented in chapter 7 are based on an older version of the atom chip, but most of the experimental environment does not diverge significantly from what is described here. Any relevant differences will be mentioned in the respective chapters.
3.1 LASER SYSTEM

In this section the laser system used in the experiments will be described. This includes the two lasers used for cooling, the laser system used for imaging the atoms and the laser used for Rydberg excitation. As most of the techniques used are very well established only a brief outline of those techniques will be given. For further details references to the relevant literature are provided.

All lasers used in the experiment are commercial Extended Cavity Diode Lasers (ECDLs) in the Littrow configuration [72]. They are stabilised to atomic reference spectra obtained from Rb vapour cells. Using saturated absorption spectroscopy [73] one can obtain sub-Doppler features for the necessary high-precision frequency references. From the absorptive spectroscopy signal one can generate a dispersive signal for top-of-fringe locking using frequency modulation (fm) spectroscopy [74]. A good summary of the methods employed can be found in [73, 75–77]

3.1.1 MOT LASER

![Figure 3.1](image)

Figure 3.1: $^{87}$Rb level scheme showing the hyperfine splitting of the $5^2S_{1/2}$ ground state and the $5^2P_{3/2}$ excited state. All laser beams used for cooling and detection are indicated in the figure with the transitions they address. The Rydberg laser system and level scheme are treated separately below.

Two lasers are necessary for magneto-optical trapping and cooling in $^{87}$Rb: one on the actual cooling transition $F = 2$ to $F' = 3$, the other for repumping atoms that have spontaneously decayed to the wrong hyperfine ground state $F = 1$, as indicated in Figure 3.1. The schematic
of the setup for the cooling laser is depicted in Figure 3.2. It is based on a Toptica TA-100 Master Oscillator/Power Amplifier (MOPA) unit operating at 780 nm. A saturated absorption spectroscopy setup as shown in the figure is used to stabilise the laser to the $F = 2$ to $F' = (1, 3)$ crossover, 212 MHz below the $F = 2$ to $F' = 3$ transition. A double-pass Acousto-Optic Modulator (AOM) is then used to shift the laser up by 200 MHz for a total detuning of $-13$ MHz. During polarisation-gradient cooling the AOM frequency is shifted such that the beam is red detuned by up to 55 MHz from resonance.

A single-mode polarisation-maintaining fibre is used to bring the light to the experiment and produce a well-defined Gaussian beam profile. The maximum power obtainable in the cooling beams after the optical fibre is $\approx 80$ mW.

Finally it is also possible to generate an optical pumping beam from the same source during the experimental cycle. For this purpose the Electro-Optic Modulator (EOM) is used to rotate the polarisation of the beam by $\pi / 2$ such that it is diverted into a dedicated beam path at a polarising beam splitter cube. Using a separate AOM it is then shifted to be resonant with the $F = 2$ to $F' = 2$ transition. Passing the beam through an independent optical fibre it can be used to spin-polarise the atoms if an appropriate quantisation field is applied. This is an important step before loading the initial magnetic trap, as otherwise a large fraction of the atoms will not be in a magnetically trappable state.

### 3.1.2 REPUMP LASER

A further laser is used during the Magneto-Optical Trap (MOT) stage to bring atoms which have decayed to the $F = 1$ ground state back into the cooling cycle. This repumping laser system is based on a Toptica DL-100 diode laser at 780 nm. It is frequency stabilised to the $F = 1$ to $F' = 2$ transition in a saturated absorption spectroscopy essentially identical to that depicted in Figure 3.2. It is passed through an EOM used only as a fast on-off switch and a shutter before being guided to the experiment through another single-mode polarisation-maintaining fibre. After the fibre we reach a maximum power of approximately 15 mW in the repumping beam.

### 3.1.3 PROBE LASER

To detect the atoms we require a further laser stabilised to the $F = 2$ to $F' = 3$ transition. This laser system is also based on a Toptica DL-100 diode laser at 780 nm and stabilised to a saturated absorption signal derived from a setup such as the one shown in Figure 3.2. This laser is stabilised to the $F = 2$ to $F' = 3$ transition directly. This way it can be used in the frequency stabilisation of the Rydberg excitation laser as will be discussed below. However, this requires the use of two double-pass AOMs to allow for frequency tuning of the laser necessary for measuring absorption spectra in our setup. Furthermore, magnetic fields present in the setup can make it necessary to tune the probe laser in order to resonantly address a certain transition. This arrangement can be seen in Figure 3.3. To achieve the necessary tunability the first AOM is fixed at $-80$ MHz for a total double-pass detuning of the beam of $-160$ MHz. The second AOM is connected to a Voltage-Controlled Oscillator (VCO) frequency source (Mini-Circuits ZOS-100+), thus shifting the beam by $+50...+100$ MHz per pass and giving a total frequency tuning range of $-60...+40$ MHz around resonance in double pass. The VCO signal is
Figure 3.2: Schematic of the MOT laser setup. In the lower part of the picture the saturated absorption spectroscopy setup is shown. This is present in a similar form also in the other laser setups. The greater fraction of the beam is passed through an AOM for frequency control. An EOM is used to switch between two different beam paths, for cooling and optical pumping respectively. Both paths are passed through single-mode polarisation-maintaining optical fibres to the experiment.

passed through a fast switch (Mini-Circuits ZYSWA-2-50DR) and amplifier (Mini-Circuits ZHL-2) before reaching the AOM, allowing well-defined pulse switching with a rise-time of approximately 30 ns. The AOM configuration is shown in Figure 3.3.

3.1.4 RYDBERG LASER

For Rydberg excitation in a three-level $5s - 5p - n\ell$ scheme we use a commercial frequency-doubled Toptica TA-SHG system at 479…488 nm in combination with the probe laser already described above. The Rydberg excitation laser contains a MOPA unit operating at 958…976 nm and a resonant cavity frequency-doubling stage employing a temperature-stabilised non-linear crystal achieving a maximum output power of approximately 300 mW in the blue. The wavelength range of this laser allows us to address any Rydberg state with effective principal quantum number $n^* \geq 17$. States of very high $n$ can in principal be addressed up to the ionisation limit, but for $n > 100$ this becomes impractical due to the greatly reduced coupling strengths. Furthermore the $d$-state fine-structure splitting starts to approach the spectral resolution of our laser system at very high $n$. Only transitions to states where $\ell = 0$ or $\ell = 2$ are dipole-allowed in
Figure 3.3: Schematic of the probe and Rydberg laser setup. In the upper part of the figure one can see the spectroscopy setup to generate EIT signals in a vapour cell, which are used for frequency-stabilisation of the coupling laser. In the lower half the two double-pass AOMs necessary for frequency tuning of the probe are depicted.

the absence of an external electric field. In the presence of an electric field also other states, such as \( \ell = 1 \) states or manifold states can be addressed. These effects will be discussed further in chapter 6.

To frequency-stabilise this laser we use fm-spectroscopy on an EIT signal obtained in a vapour cell, similar to the setup discussed in [78]. To obtain an EIT signal the probe and coupling beam are counter-propagated through a rubidium vapour cell. The probe beam, which is stabilised to an independent saturated absorption spectroscopy setup, is observed on a fast photo-diode after passing through the vapour cell. If one now scans the frequency of the coupling beam across a Rydberg resonance one can observe an induced transparency peak in the probe transmission. A schematic view of this is shown in Figure 3.3.

To generate a dispersive error signal we modulate the probe laser current at 20 MHz using a dual-channel Toptica Pound-Drever-Hall (PDH) module. The first channel of the PDH module is used for demodulation of the saturated absorption spectroscopy used to frequency-stabilise the probe laser. The second channel is used in the EIT setup to generate an error signal for stabilising the coupling laser. The modulation of the coupling laser used for stabilizing the
Figure 3.4: Design drawing of the central part of the vacuum system. On the left the chip mounting structure (see Figure 4.9 for a detailed view of this part) and the copper tube (in white) connecting it to the 6-way chamber. On the back of the chamber the 20-pin feed-through; electrical connections can be seen in parts of the figure as multi-colored wires. The four remaining ports of the 6-way cross are connected to a four-pin feed-through, vacuum gauge, rough pump and main pumping system respectively (clockwise, starting at the top).

doubling cavity is strongly suppressed in the doubling stage, and can therefore not be used directly for frequency stabilization.

3.2 VACUUM SYSTEM

We use a fairly simple and compact vacuum system for our experiments. At the heart of the system is an all-quartz square-cuboid cuvette angled at 45° to the normal containing the atom chip proper. All operations, including preparation of the initial MOT are done here. The cuvette is connected to a spherical square 6-way CF-63 vacuum chamber made of 304 stainless steel. The port opposite the cuvette holds a 20-pin feed-through supporting at most 10 A per pin used for connecting chip wires and dispensers. We use enriched $^{87}$Rb Dispensers (Alvatec s-type) as the source of rubidium. A 4-pin feed-through used for connecting the lens (see chapter 4) and a thermocouple occupies a further port. A Varian UHV-24p ion gauge is mounted in the spherical square chamber through a fourth port to monitor pressure in the system. The final two ports are connected to valves. One of these valves is only used during the initial bake-out to connect a turbo-pump to the system. The second valve connects to the pumping section of the vacuum system, containing a Varian 916-0061 titanium sublimator and a Vacion Plus 75 Starcell ion-pump. The titanium sublimator is pulsed on at irregular intervals, while the ion-pump is the main system pump and is running continuously. By closing the gate-valve the pumping section can be disconnected from the main vacuum chamber, to keep the pumps under vacuum e.g. while changing the chip. After bake-out at 140 °C for one week we achieve a base-pressure of $1 \times 10^{-11}$ mbar.
3.2.1 MAGNETIC FIELD COILS

The glass cuvette is surrounded by three pairs of water-cooled magnetic field coils. Two of the pairs are connected to a single Kepco BOP 36-12M bi-polar current supply each, and configured to produce homogeneous fields between each coil in the pair. Of the final pair each coil is individually connected to identical current sources, also Kepco BOP 36-12M. This pair can hence be used with either parallel or antiparallel currents running in the coils. The latter is used in the initial MOT stage, while homogeneous fields are necessary for the bias field in later stages of the experimental cycle. A more detailed description of the coils is given in [79].

3.2.2 THE ATOM CHIP

The latest generation atom chip design is discussed in great detail in a later chapter. At this point only information about the instrumentation surrounding the chip is provided. For further details on the chip the reader is referred to chapter 4.

![Diagram](image)

**Figure 3.5:** Wires defined in the silver foil layer of the chip. There are two independent h-wires which can be used in either u- or z-configuration, two small u-wires inside each h-wire, and two pinch-wires along the sides of the h-wire.

Our chip design features two layers, a permanent magnetic FePt layer, as well as a 250 μm thick silver foil layer on which wires are defined using spark erosion. A total of 6 wires are defined as shown in Figure 3.5. Each h-wire is connected to two feed-through-pins in parallel for each connection of the z, allowing a maximum current of 20 A to flow for the z-wire configuration. All other wires are limited to 10 A by the feed-through. In a normal sequence we use one h for both u- and z-wire. The u-wire part is connected to a Kepco BOP 20-10M and the z-wire part to a Kepco BOP 20-20M current source with a common ground for both sources on the upper bar of the h. The pinch-wires are connected to a single Delta Electronics ES 015-10 current source. The second h-wire as well as the inner u-wires are not in use during normal operations.
### 3.3 RADIO-FREQUENCY EVAPORATION

To cool the atoms below the temperatures achievable using optical cooling techniques we use forced radio-frequency evaporation in a magnetic trap [46]. To generate the necessary frequencies we use an Analog Devices AD9959 Direct Digital Synthesis (DDS) evaluation board capable of generating frequencies up to 40 MHz. The DDS is programmed using the Viewpoint DIO64 digital Input/Output (I/O) card (see below) at 2 MHz programming clock frequency and (after an initial, serial setup-phase) with 4 bits in parallel. This allows a frequency to be programmed in 20 μs. Linear frequency ramps can be programmed directly in the device, requiring 56 μs for programming. Non-linear ramps are not directly supported by the device and have to be programmed step-wise. The maximum update rate is then given by the 20 μs required for programming each step.

The DDS output is connected to a Mini-Circuits ZFL-500HLN pre-amplifier which in turn feeds an Analog Devices AD835 voltage multiplier to adjust the rf amplitude level. A switch (Mini-Circuits ZYSWA-2-50DR) allows us to quickly switch the radio-frequency field on and off before the final stage Amplifier. This can either be a 25 W Amplifier Research 25A250A or a Mini-Circuits ZHL-32A with a maximum output power of approximately 800 mW. The resulting field drives a small two-winding coil of 2 mm thick stranded, isolated copper wire with a radius of 1.6 cm. If this coil is driven at 10 W it produces a field of approximately 50 mG at a distance of 2.5 cm for frequencies below 50 MHz, sufficient for efficient rf evaporation. The coil is positioned on the y-axis as close as possible to the chip and at the height of the chip surface.

### 3.4 IMAGING

All data collection on the atoms is done using resonant absorption imaging [48, 80, 81]. We use absorption imaging in two different geometries:

**Parallel Imaging** in which the probe beam is propagating parallel to the chip plane. While it is not possible to resolve individual micro-traps with this method, it does allow us to observe effects which depend on the distance to the chip surface, such as described in chapter 7. In a variation of this, commonly referred to as grazing-incidence imaging, the probe beam is propagating under a shallow angle to the surface. If it is then reflected off the surface one obtains two images of the atoms, particularly well suited to accurately determine the distance of the atoms from the surface.

**Perpendicular Imaging** in which the probe beam is propagating perpendicular to the chip surface. In this way the beam also passes through the atoms twice, but the two images come to lie atop each other. In this configuration we can observe each individual trap site in the array of micro-traps created by the magnetic layer on the chip. This method is used in the experiments described in chapter 8. The theoretical limits of this method in our setup are also discussed in chapter 5.

For an excellent review of imaging techniques used in atom-chip experiments, also see [80].
The imaging beam is observed using an Andor iKon-M 934 back-illuminated deep-depletion CCD camera. This camera provides 1024 × 1024 pixels of 13 × 13 μm² in size and can be cooled to −80 °C to reduce dark counts. The quantum efficiency is above 90%, and each pixel is digitised with 16 bit accuracy. Readout time is about 300 ms for a full frame in the fastest acquisition mode. A Fast Kinetics mode is available for a drastic improvement of readout speed if only part of the sensor is illuminated while the other part is used as temporary storage for the acquired data.

3.5 COMPUTER CONTROL

The experiment is controlled by an Amplicon Ventrix 4020 PC providing 7 PCI as well as 4 PCI Express x1 and one PCI Express x16 slots. On this computer we run labalyzer, a software package for controlling the experiment written in python¹.

The software controls two National Instruments 6713 PCI cards each providing 8 12-bit analog output channels with ±10 V maximum output range. It also controls a Viewpoint DIO64 digital I/O card providing 64 digital lines in four banks. One bank of 16 lines is used directly in the experiment. A second bank is used to programme the DDS as described in section 3.3. The timing of the entire experimental cycle is hardware-controlled by the DIO64 card. In addition to directly triggering various devices it also triggers all updates on the National Instruments cards. The camera used for absorption imaging (see 3.4) is connected to the computer using USB. A National Instruments 6014 PCI card is available in the computer for analog input, but is not routinely used in the experiment, with the exception of the measurements discussed in chapter 6. Our software is also able to control Virtual Instrument Software Architecture (VISA) devices such as oscilloscopes, function generators or voltage sources as necessary.

Each experimental cycle is defined in a tab-separated text file, called a timeframe. A brief excerpt of such a timeframe is shown in Table 3.1.

The first column of the timeframe is reserved for comments, to help the user orient himself in the file. The second column can either contain the keyword External for such things as camera settings or variable definitions. In the case of variable definitions the third column must contain the keyword parameter followed by a value for the variable in the fourth column and the name of the variable in the last column. Any variable names that are legal in python are legal in the timeframe. Recursive variables are possible with a maximum depth of 128 recursions, independent of the order in the timeframe. In the case of name collisions the last definition of the variable is used throughout the timeframe, but a warning is generated notifying the user of this fact. Camera settings such as region of interest or binning are possible with further keywords in the third column.

Regular commands in the timeframe contain a relative timestamp (given in ms but evaluated with µs resolution) in column 2 and a device identifier in column 3. Column 4 defines the final value for this device. This value, as any numerical value in the timeframe can be calculated using any python operations, including those of numpy as long as they return a single value, and may use any of the variables defined at any place in the timeframe. The 6th column determines whether this final value should be programmed immediately, indicated by the

¹A detailed description of the different programme modules is given in Appendix A.
## Table 3.1: Excerpt of a timeframe showing some of the commands used in loading the initial magnetic trap. Text in italics is not part of the timeframe.

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<th>keyword</th>
<th>value</th>
<th>name</th>
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<td>x2</td>
<td></td>
</tr>
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<td>External parameter</td>
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<td>y2</td>
<td></td>
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<td>z2</td>
<td></td>
</tr>
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<td>w2</td>
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<th>value</th>
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<th>rf(^b)</th>
<th>rp(^c)</th>
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<td>A</td>
<td>step</td>
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<tr>
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<td>ramp</td>
<td>t3</td>
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<td>z-wire</td>
<td>w3</td>
<td>A</td>
<td>ramp</td>
<td>t3</td>
</tr>
</tbody>
</table>

\(^a\) Typically one of A (Ampere), V (Volts) or TTL (for digital lines)

\(^b\) ramp function, see text for possible values

\(^c\) ramp parameters, usually ramp time
keyword step, or through any of a number of predefined ramps, indicated by keywords such as ramp, ramp_square, ramp_exp or ramp_log. In the case of a ramp the last column holds the ramp-time as well as any other parameters necessary to define the ramp.

At the beginning of each experimental cycle our control software programmes all devices with the necessary commands to execute during this timeframe, and then hands over to the DIO64 card for hardware triggering of the experimental cycle. During the cycle the software recompiles the timeframe as necessary and then polls the camera for images. Once the camera has acquired images the software calculates an optical density image, displays all images, performs automatic Gaussian fits in two dimensions and saves raw images as well as fit results to disk if requested. It is furthermore capable of scanning any timeframe values automatically in up to three dimensions and provides a live view of the history of fit results, both for the overall runs and for individual scans.

3.6 THE EXPERIMENTAL CYCLE

Each experimental cycle starts by pulsing the dispenser with about 6 A current for a given time. At the same time the MOT beams as well as the repumper beam are turned on, the AOM for the MOT beam is tuned to −12 MHz below resonance and the external coils are set to produce the quadrupole field required for the MOT. After a short hold-time in the MOT to reduce background pressure after the dispenser pulse, the u-wire current is ramped on, while at the same time the external coil currents are changed to produce a homogeneous bias-field in the y-direction. Thereby we shift the position of the cloud to approximately 2 mm from the chip, creating a so-called u-wire MOT (uMOT). Subsequently the u-wire current is reduced and the MOT lasers are detuned to −55 MHz for polarisation gradient cooling. After 3 ms we apply a quantisation field along the x-axis and turn on the optical pumping beam by applying a voltage to the MOT EOM as well as appropriate tuning of the optical pumping AOM. Finally we turn off all laser light, ramp on the z-wire current and again change the external coils to produce a bias-field in y-direction, capturing the atoms in an initial magnetic trap. This is the starting point for all further experiments.

In the case of the experiments described in chapter 7 we release the atoms from this initial magnetic trap, and after a short time-of-flight image from the side in the presence of a laser coupling to a Rydberg state. In the case of the experiments described in chapter 8 we gradually ramp down the z-wire current to bring the atoms closer to the surface, until they eventually can be transferred to the micro-traps formed by the magnetic pattern on the chip. In this case we image in a reflective geometry from below, perpendicular to the chip surface. All these procedures are described in more detail in the appropriate chapters. The limits of reflective absorption imaging in this system are explored in chapter 5.