Experiments on two-component quantum gases on an atom chip

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Citation for published version (APA):

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Chapter 3
Experimental setup & methods

3.1 The CELSIUS experiment

This chapter describes the scientific apparatus and the methods used to perform experiments with two-component 1D quantum gases of $^{87}\text{Rb}$. There are several approaches to making one-dimensional gases. Crossed optical lattices were used to create arrays of equidistant elongated potentials, leading to a multitude of 1D gases. This was used in some of the ground-breaking experiments in the groups of D. S. Weiss [38], I. Bloch [39] and W. D. Phillips [106]. The crossover from the 3D to the 1D regime has been studied in early work with atom chips [107, 108, 109] and atom chips were proposed to create Tonks-Girardeau gases [110]. Coherence lifetimes of internal states in excess of 1 sec have been shown to be independent of the atom-surface distance, which makes this technique interesting for atomic clock applications [111]. In late 2002 our group started designing an atom chip-based experiment, mainly with the aim of reaching the strongly interacting regime but also to access phase and density fluctuations of individual realizations of a 1D gas. This is in contrast to experiments based on optical lattices, where averaging over many lattice sites is hard to avoid [112]. In 2006, our group succeeded in reaching the Bose-Einstein phase transition and also entered the 1D regime.

A detailed description of the pre-existing setup can be found in [90, 113]. Here, we sketch the basics of the experimental apparatus to have a self-contained description. In the next sections, we focus on the changes and additions made in the course of this PhD work, and in particular on the features required to study the two-component 1D Bose gas. The outline is as follows. First, a summary is given of the basic features of the vacuum system, the laser system, the atom chip and the RF-generation, mentioning also the relevant changes made since the previous PhD thesis [113]. Subsequently, the main additions we made to the CELSIUS (Chip Experiment for Low-dimensional, Strongly Interacting Ultracold Systems) experiment, namely the subsystem for microwave generation (section 3.2), a secondary imaging system for imaging along the 1D-axis (section 3.3) and a super-imposed optical lattice along the 1D-axis (section 3.4) are described and characterized in some detail.

3.1.1 Vacuum system

The vacuum system to generate ultra-high vacuum (UHV) conditions for experiments with ultra-cold gases is built around the science chamber (see figure 3.1). This science chamber is custom-made from stainless steel and has an octagonal cross-section. It holds six anti-reflection (AR) coated CF40 viewports and one uncoated CF100 viewport which provide
optical access for MOT-, pump- and probe-light. Two additional CF16 viewports are used for monitoring the loading of the MOT by means of small infrared sensitive cameras. The atom chip including its electrical feedthroughs and water cooling is inserted into the top port of the science chamber via a 4 + 1-way cross-piece. The bottom port connects the pump section, consisting of a demountable turbo-molecular pump, an ion getter pump and a titanium-sublimation pump. For maintenance purposes, the pump section can be separated from the science chamber with a gate valve. After pump down and a bake out at 180° C an ionization gauge indicates a residual pressure of $\approx 10^{-11}$ mbar.

![Figure 3.1: Main vacuum chamber (“science chamber”) surrounded by magnetic field coils. (a) Schematic (adapted from [90]). (1) Compensation coils, (2) Science chamber, (3) MOT coils, (4) Y-Bias coils, providing a homogeneous field along the Y-direction for tight waveguide potentials. (b) Photo of the vacuum chamber surrounded by coils, optics, electrical connections and water cooling (blue tubes). The atom chip mount is visible on top of the chamber.](image)

The science chamber is surrounded by three sets of coils (indicated in figure 3.1(a)), which provide the magnetic fields for magneto-optical trapping, the compensation of fields in arbitrary direction and the tight confinement needed for the generation of 1D gases. All coils are powered by programmable analog current supplies (Kepco / BOP 20-10M, BOP 20-20M, BOP 36-12M and BOP 20-5M) and switched (except for the four compensation coils at 45° angles) using home-built MOSFET switches to enable rapid switching.

We also connected the Rubidium dispenser to such a switch to allow digital switch off as an additional safety measure. Two of these dispensers are mounted inside the vacuum chamber slightly below the atom chip. One of them emits away from the atom chip, the other one towards it. We started operating with the dispenser emitting towards the chip in April 2008, after the previously used dispenser showed signs of depletion.

### 3.1.2 Laser system

Two commercial semiconductor diode lasers in an external cavity setup (Toptica DL100) provide light with a wavelength of 780 nm. One of these lasers serves as the master laser
for cooling, pumping and imaging atoms (for a detailed description see [90]). The other laser is used for re-pumping atoms that have fallen into a dark state out of the cooling cycle (see [113]). Both lasers are frequency-locked to atomic transitions in $^{87}$Rb with a frequency modulation technique [114]. Acousto-optical modulators (AOMs) are used to shift the frequency of the light for different applications. Mechanical shutters and electro-optical modulators (EOMs) switch laser light on and off before it is coupled into polarization-maintaining single mode optical fibers guiding it to the optical components surrounding the science chamber.

The original optical setup was extended by a second imaging system (see section 3.3), enabling simultaneous imaging along the $x$- and $y$-axes. Furthermore, we added an optical lattice along the $x$-axis, which is described in Sec.3.4. Due to limited optical access, only one of these two additions to the experiment can be used at a time. The optical lattice caused a need for more laser power. Therefore the injection locked high-power laser described in [90] was replaced by a tapered amplifier. The amplifier is mounted in a custom-made housing [115] and yields an output power of 290 mW at current of 0.9 A and 25 mW seeding power.

### 3.1.3 Atom chip

At the heart of our experiment is the atom chip. The atom chip is a micro-fabricated gold wire pattern (see figure 3.2) on a silicon substrate. In combination with two layers of three macroscopic wires each under the atom chip itself and the external field coils, the on-chip wires serve to generate the extremely steep and elongated potentials necessary for experiments with 1D gases. The characteristics and functions of the individual chip wires numbered 1-8 are listed in table 3.1. The chip is mounted upside-down on a water-cooled copper block at the center of science chamber. Apart from dissipating the heat caused by ohmic heating of the wires, the mount provides electrical vacuum feedthroughs which serve to connect the chip wires to their current sources.

For the experiments presented in this thesis, the following chip wires were used: Wire 5 for trapping, wires 3 and 6 for radio-frequency dressing and wire 4 for RF-induced evaporative cooling. Before the measurements presented in chapter 5, an electrical short between wire 7 and 8 occurred due to an accident involving too much current because of a mistaken connection. This is evident by a resistance measurement between all chip wires, displayed in table 3.2.

### 3.1.4 Radio-frequency generation

The various radio-frequency (RF) fields for evaporative cooling, coherent transfer between different Zeeman states and dressing atoms in our experiment originate form four direct digital synthesis (DDS) evaluation boards (Analog Devices / AD9854). The boards are housed in a custom-made rack, which provides them with power, interfacing to the control computer and a reference frequency. The RF generation is treated in great detail in [113]. The 10 MHz reference frequency is derived from a frequency standard (see 3.2) and routed
Figure 3.2: Atom chip wire pattern. The characteristics of the individual wires are given in table 3.1. The length of the black scale bar is 500 µm. The wires are defined by 5 µm wide trenches in the 1.8 µm thick gold layer.

<table>
<thead>
<tr>
<th>wire</th>
<th>w (µm)</th>
<th>R (Ω)</th>
<th>function</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>10</td>
<td>3.15</td>
<td>double box structure</td>
</tr>
<tr>
<td>2</td>
<td>5</td>
<td>3.70</td>
<td>wiggle test wire</td>
</tr>
<tr>
<td>3</td>
<td>50</td>
<td>1.47</td>
<td>Z wire, radio-frequency field</td>
</tr>
<tr>
<td>4</td>
<td>10</td>
<td>3.89</td>
<td>1.00 mm box</td>
</tr>
<tr>
<td>5</td>
<td>125</td>
<td>0.72</td>
<td>Z wire, initial trapping</td>
</tr>
<tr>
<td>6</td>
<td>10</td>
<td>2.42</td>
<td>0.20 mm box, RF evaporation</td>
</tr>
<tr>
<td>7</td>
<td>30</td>
<td>2.06</td>
<td>Z wire, radio-frequency field</td>
</tr>
<tr>
<td>8</td>
<td>20</td>
<td>2.30</td>
<td>0.90 mm box</td>
</tr>
</tbody>
</table>

Table 3.1: Characteristics of the wires on the atom chip. Widths $w$ and resistances $R$ of the wires are listed along with their functions for experiments (see [113]).

<table>
<thead>
<tr>
<th></th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
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</tr>
<tr>
<td>3</td>
<td>31.0</td>
<td>19.2</td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>4</td>
<td>35.0</td>
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<tr>
<td>5</td>
<td>34.6</td>
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<td>42.0</td>
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<td>7</td>
<td>46.3</td>
<td>37.6</td>
<td>33.1</td>
<td>16.3</td>
<td>11.6</td>
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<td>16.3</td>
<td>11.6</td>
<td>7.2</td>
<td>0.004</td>
</tr>
</tbody>
</table>

Table 3.2: Cross-resistance between the chip wires in kΩ measured after completion of the experiments presented in this thesis. The low resistance between wires 7 and 8 indicates an electrical short.
3.2 Microwave generation

We use a two-photon transition to create coherent mixtures of internal states of $^{87}\text{Rb}$. The hyperfine splitting of the electronic ground state in $^{87}\text{Rb}$ corresponds to a frequency of $\omega_{hf} = E_{hf}/\hbar = 2\pi \cdot 6.834682 \text{ GHz}$ (see figure 2.1). Furthermore, driving the transition from $|F = 1, m_f = -1\rangle$ to $|F = 2, m_f = 1\rangle$ requires $\Delta m_f = 2$, therefore a two-photon transition is needed. In practice, this can be conveniently achieved by combining a microwave (MW) signal of $\omega_{hf} \approx 2\pi \cdot 6.834682 \text{ GHz}$ with a RF signal of a few MHz [84]. To provide the MW signal with a sufficient amplitude at the position of the trapped atoms and computer-controlled tunability of the frequency, we enhanced the experiment by a microwave subsystem which is shown schematically in figure 3.3 and described below.

![Figure 3.3: Schematic of the microwave subsystem. Blue arrows indicate control signals and reference frequencies, the red arrow indicates the part of the MW signal reflected by the antenna and green arrows denote the actual MW signal with frequency $f_{out}$.

3.2 Microwave generation

to all four evaluation boards. We found that this common reference is sufficient to keep the output of the evaluation boards in phase lock. The output of DDS board 1 is directly connected to chip wire 4 (see figure 3.2) for evaporative cooling. The outputs of boards 2 and 3 are amplified by 28.5 dB before they are connected to chip wires 3 and 6, respectively.
A rubidium standard (Symmetricom/Model 8040), based on an atomic clock, provides our lab and the neighboring permanent-magnetic atom-chip experiment \[116\] with a highly stable (Allan deviation averaged over 1 sec less than \(3 \cdot 10^{-11}\)) 10 MHz signal. This is used as a reference for both the RF generation by means of direct digital synthesis (DDS) (see section 3.1.4) and a continuous-wave MW synthesizer. The MW synthesizer output frequency \(f_{out}\) can be tuned by an external RF signal with frequency \(f_{top} \approx 20\) MHz derived from the DDS generator. To achieve this, the RF signal is fed into one of the four phase locked loops (PLL) controlling the synthesizer output frequency \[117\]. The output frequency then is related to the input frequency by

\[
f_{out} = 6830 \text{ MHz} + (2 \cdot (30 \text{ MHz} - f_{top}) - 10 \text{ MHz}).
\]

The synthesizer’s output signal with a power of \(-7.5\) dBm then enters a pin modulator which is used to rapidly switch on and off the MW signal. The modulator is switched by a TTL pulse originating from the experiment control computer. In this way, the frequency (via \(f_{top}\)) and the on/off status of the MW pulse are set by the computer, while the amplitude is fixed.

Due to the re-programming of the DDS boards at the beginning of each experimental cycle, \(f_{top}\) cannot be set at all times. Since the synthesizer needs a time of \(\approx 5\) ms to lock onto a frequency, a low amplitude fixed 20 MHz signal originating from a frequency generator (not shown in figure 3.3) is mixed with the higher amplitude \(f_{top}\) signal. In this way, the synthesizer is kept from unlocking.

The resulting MW pulse is amplified by a solid state MW amplifier. Finally, the output of the amplifier is connected via a circulator to a tube-shaped antenna, popularly known as cantenna (see below). The circulator’s reverse port is terminated with a 50 \(\Omega\) dummy load. This deflects back reflections off the cantenna due to impedance mismatches and prevents damage to the amplifier by the reflected signal. The cantenna is placed directly outside the CF100 window of the vacuum chamber (see figure 3.4(b)), aiming at the region below the atom chip. On the opposite side of the science chamber, a pickup pin antenna of length \(\lambda_{out}/4 \approx 11\) mm is installed to monitor the timing and the amplitude of the MW pulses. The orientation of the pin antenna is perpendicular to the plane of the atom chip.

**Cantenna design**

Since no appropriate directional antenna for 6.8 GHz was readily available, we decided to adapt a design widely used for WiFi-communication (\(\approx 2.4\) GHz). It is based on a metallic tube with an open and a closed end. Therefore this design is often referred to as cantenna. The signal carrying cable is connected to a metal pin antenna inside a conducting cylinder (see figure 3.4(a)).

According to \[118\], four parameters are crucial for good operation of the cantenna. First, and most important is the diameter of tube. The mode with the lowest cut-off frequency is the so-called \(H_{11}\) mode, in which the electric field lines are mainly perpendicular to the tube cross section with a concentration in the center. The cut-off frequency for this mode
is \( f_c = c/(1.71 \cdot d) \), where \( c \) is the speed of light and \( d \) is the inner diameter of the tube. We chose a brass tube with \( d = 32 \text{ mm} \) such that only the \( H_{11} \) mode is excited. The cut-off frequency for the next mode is at 7.15 GHz for our choice of the diameter. Second, the length of the pin should be \( \lambda_0/4 = 11 \text{ mm} \), where \( \lambda_0 \) is the wavelength of the radiation to be transmitted in free space. Third, the distance of the pin from the back plane should be chosen such that the back-reflected wave interferes constructively with the direct wave. This is the case when the distance is equal to \( \lambda_G/4 = 18.4 \text{ mm} \) with \( \lambda_G = c/\sqrt{f_{\text{out}}^2 - f_c^2} \) the wavelength of the mode excited inside the tube. Finally, the overall length of the tube should be such that reflections from the transition from the tube to free space are suppressed. According to [118] the optimal length to achieve this is \( 5/8 \lambda_G + n \lambda_G/2 \) with \( n = 0, 1, 2, \ldots \). Out of space considerations, we chose for \( n = 1 \) and therefore the total tube length is 64.3 mm. For tunability of the distance between pin and back plane, the back plane was made of a massive copper cylinder, which tightly fits into the tube, but can still be moved in and out.

### 3.3 Dual imaging

In addition to the experiments performed with two-component Bose gases, described in chapters 5 and 4, we used radio-frequency dressed potentials to create double-well potentials. These result in two elongated clouds separated by a couple of microns. By changing the relative amplitude or phase of the two RF signals making up the double-well potential, the angle between the two ensembles in the \( y-z \)-plane can be tuned to arbitrary values between 0 and \( 2\pi \). Only in the case where the clouds are separated along the \( z \)-axis (vertically) can they be imaged separately and can their in-trap distance be determined. We release the atoms from the double-well potential to investigate the coherence between the split clouds. After some time of flight, they overlap due to expansion and we record the interference patterns.

In a typical experimental setup, elongated ultra-cold gases are probed with light perpen-
dicular to their long axis (according to our definition the $x$-axis). In this manner, the physics governing the atomic density and motion along the $x$-axis can be studied. To study the atom clouds along the $x$- and the $y$-axis and to fully characterize RF potentials, we added a second imaging system, which is used to take absorption images along the $x$-axis.

**Figure 3.5:** Schematic of the dual imaging setup. The laser beams used for the first and the second imaging setup are indicated by dashed green and full blue lines, respectively. The laser beam for magneto-optical trapping are colored red.

**Figure 3.6:** Absorption images of interfering atoms. The images were taken simultaneously with the first (indicated by the blue bar) and second (red bar) imaging system. The right figure shows the integrated optical density in arbitrary units for imaging along the $y$-axis and the $x$-axis in blue and in red, respectively.

Figure 3.5 schematically depicts the changes made to the optical setup to enable dual imaging. To gain optical access to the $x$-axis, which is otherwise occupied by two counter-propagating MOT laser beams, we inserted two polarizing beam cube splitters (PBS) to overlap the imaging laser with the MOT beams. Due to the geometry of the chamber and the fact that the first imaging lens of the second imaging system has to be placed behind
the beam splitter, the distance atoms-lens, which mainly determines the characteristics of the imaging system, is 20 cm, as compared to 10 cm for the first imaging system. This difference translates to a measured effective pixel size in the object plane of $p_x = 4.07 \mu m/pixel$, whereas it is $p_y = 2.15 \mu m/pixel$ for the first imaging system. We chose an achromat with $f_1 = 200 mm$ focal length as first lens, followed by a second lens with $f_2 = 350 mm$ focal. This results in a theoretical magnification of 1.75, compared to a magnification of $\approx 3$ for the imaging along the $y$-axis. The CCD camera used for the second imaging system, is a newer version (Roper Scientific / Coolsnap EZ) of the camera in the first imaging system (Roper Scientific / Coolsnap ES). A TTL signal originating from the experiment control computer triggers the camera and a LabView program, which is processing incoming images. This program runs on an independent computer, which is identical to the experiment control computer.

An example of simultaneously taken images is given in figure 3.6. For this, the atoms have been prepared in an elongated trap and coherently split in the vertical/$y$-direction by means of radio-frequency dressed potentials. After being released from the double-well potential, the two coherent ensembles expand and overlap. Absorption images, taken after 14 ms time-of-flight, clearly feature horizontal interference patterns.

While the probe light is linearly polarized in the first imaging setup, due to the $\lambda/4$-phase plates needed for the MOT beams it is circularly polarized in the second imaging system. This causes detection efficiency differences. These differences can not be explained by the differing cross-sections alone. Also optical pumping plays a role and is different depending on polarization and the axes. To characterize the system, we probed all combinations of imaging directions and quantization field directions for sequential and simultaneous imaging. The resulting calibration factors are shown in table 3.3. The higher numbers in the case of simultaneous imaging correspond to reduced absorption due to cross-talk.

<table>
<thead>
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<th>simultaneous imaging</th>
</tr>
</thead>
<tbody>
<tr>
<td>quantization axis</td>
<td>y  x</td>
</tr>
<tr>
<td>y</td>
<td>1.00 2.77</td>
</tr>
<tr>
<td>x</td>
<td>2.42 1.26</td>
</tr>
<tr>
<td>x</td>
<td>1.39 2.88</td>
</tr>
<tr>
<td>y</td>
<td>2.94 1.64</td>
</tr>
</tbody>
</table>

**Table 3.3:** Observed calibration factors from absorption to relative atom numbers. The factors were measured for either sequential or simultaneous horizontal (along the $y$-axis) and longitudinal (along the $x$-axis) imaging with a quantization field aligned along the $x$- or $y$-axis. The table is scaled to the case of the upper left corner.

### 3.4 1D optical lattice

A periodic potential along the elongated direction of atoms confined to one dimension opens new possibilities for their manipulation. A deep lattice will result in a string of small ensembles or even single atoms. Such a system is well-suited to freeze and subsequently study fluctuations of one-dimensional ensembles. If on the opposite, a shallow lattice
is superimposed, this can change the interatomic interactions to the point where the strongly interacting regime is entered [39, 65]. To get access to these promising features, we implemented an optical lattice into the CELSIUS setup. This is the focus of ongoing experiments. Since this work is covered in detail in a master thesis [119], I will only provide a brief description of the changes made to the setup and first results obtained with the optical lattice.

Two counter-propagating laser beams form a standing wave. To avoid scattering light off the atoms, the light frequency is chosen such that it is detuned from the optical transition of the atoms by $\Delta$. Atoms in the standing wave experience a spatially periodic Stark shift. For blue-detuned light ($\Delta > 0$) they are repelled by the maxima of the standing wave, for red-detuned light ($\Delta < 0$) they are attracted.

If the periodic potential is switched on for a time shorter than an oscillation period of an atom in the optical potential, the atoms do not equilibrate, i.e. they do not gather in potential minima or maxima. In this case the standing wave acts as an optical diffraction grating and we observe diffraction of atoms from a “light crystal”. In momentum space, the process can also be regarded as simulated Raman diffraction between two momentum states. An atom absorbs a photon from one laser mode and is stimulated to emit a photon into the counter-propagating mode. In this way the atom changes its momentum in units of $2\hbar k$, where $k$ is the wave number of the light.

For the generation of the laser light for the optical lattice, a home-built external-cavity diode laser (ECDL) is amplified by a tampered amplifier [115]. The light is split equally by a non-polarizing beam cube splitter and coupled into polarization-maintaining single mode fibers, guiding it to the optical setup around the science chamber. Acousto-optical modulators are inserted before the fiber couplers for rapid switching of the light. Doppler-free saturation spectroscopy provides a signal to lock the laser on a spectral feature of $^{87}$Rb.

Figure 3.7 shows the setup around the science chamber adapted for the optical lattice. The x-axis is already occupied by MOT lasers and the optical lattice beams have to be linearly polarized. This is why we replaced the previously used (see figure 3.5) polarizing beam cube splitters (PBS) by non-PBS and moved the quarter wave plates in the MOT beams to positions before the cubes. In this way, half of the power of the MOT lasers and the lattice lasers is lost to the “wrong” port of the NPBS. This is compensated by more laser power which made necessary the insertion of tapered amplifier in the MOT- and the lattice laser system.

To prevent heating of the atoms due to a shaking optical lattice, the right lattice beam in figure 3.7 can be phase-locked to the left beam. Therefore the two beams are overlapped to interfere on a fast photodiode (PD). The photodiode signal is connected to a PID controller and fed back to a piezo crystal with a mirror mounted on it. In this manner, the optical path length and therefore the phase of the right lattice beam is adjusted the left beam and a stable standing wave is formed.

In a first proof-of-principle experiment we flashed the 3 mm wide, unfocussed lattice beams on a small falling Bose-Einstein condensate for 6 $\mu$s after 3 ms time-of-flight (TOF). The resulting absorption image, recorded after a total of 14 ms TOF, is displayed in figure 3.8.
3.4 1D optical lattice

Figure 3.7: Schematic of the optics used to generate an optical lattice. The lasers for the optical lattice are drawn in blue. They counter-propagate in the vacuum chamber, forming the lattice and interfere on the photodiode. The piezo crystal controls the optical path length of the right lattice beam. The laser beams used for imaging and magneto-optical trapping are indicated by green and red lines, respectively.

It clearly shows the first diffraction orders to the left and the right of the central zero momentum cloud.

Figure 3.8: Absorption image of diffracted Bose-Einstein condensate. The three clouds correspond to $p_x = -2\hbar k, 0, 2\hbar k$. 