One-dimensional Bose gas on an atom chip

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3 Experimental Setup

3.1 Introduction

In this chapter the experimental setup is described. It begins with a general discussion of our design considerations followed by a description of the five main parts of the setup. The central and most innovative part of the experimental setup is formed by the microtrap that is treated with some detail.

The concept of the “atom chip” combines the advantages of scale reduction and reproducibility with the possibility to trap atoms under very strong confinement. The confining force for atoms is proportional to the gradient of the magnetic field strength. Figure 3.1 illustrates that chip traps can have very high gradients with a simple example: the side guide. This tube-like atom trap is created with a chip in the $xy$-plane at $z = 0$, when the field from a current $I$ through a wire along $x$ is compensated by a homogeneous bias field $B_{\text{bias}}$ along $y$. A trap occurs at a distance $z_0$ from the chip surface. The trap position and the gradient of the magnetic field at that point are given by the Biot-Savart law, and can be written as

\[ z_0 = \frac{\mu_0 I}{2\pi B_{\text{bias}}}, \]

\[ \frac{\partial B}{\partial z} = \frac{\mu_0 I}{2\pi z^2}, \]

where $\mu_0$ is the magnetic permeability of free space. For a current of 2 A and a bias field of 40 G, the trap is 100 $\mu$m away from the surface where the gradient is 4 kG/cm. Moreover this gradient grows quadratically with decreasing wire current at constant bias field. We exploit this feature to trap ultracold atoms at low density in extremely elongated traps to eventually reach the regime where the transverse atomic motion is frozen out due to the strong confinement and the low atomic interaction energy: the gas becomes one-dimensional. This 1D regime requires small atomic interaction energy that can be achieved by reducing the total number of trapped atoms and hence the linear density.

This chapter is organized as follows. After a general discussion on the design criteria in Sec. 3.2, we describe the design and construction of the microtrap in Sec. 3.3. Thermal properties of the microtrap are discussed in Sec. 3.4. In Sec. 3.5 the layout of our ultra-high vacuum system is given, Sec. 3.6 explains the dispenser.
Figure 3.1: Creating a two-dimensional trap with a wire and an external field. Top: wire field, center: external field, bottom: resulting total field. The left-hand column shows magnetic field lines and the right-hand column gives the magnitude of the field at $y = 0$ for a wire current $I = 2$ A and an external field $B_{bias} = 40$ G. In this example, the trap forms at a distance $r_0 = 100$ μm from the wire axis, and the gradient at the trap center is $|B'(r_0)| = 4$ kG/cm, assuming an infinitely thin wire (Fig. adapted from [101]).

atom source. Sec. 3.7 deals with the design and control of the magnetic field coils around the vacuum system. An overview of the laser setup is given in Sec. 3.8. In Sec. 3.9 we give some details on the imaging system including a discussion of the achieved optical resolution and a signal-to-noise analysis. Section 3.10 covers the computer system used to control the experiment. Finally, concluding remarks are given in Sec. 3.11.

3.2 Design considerations

The design of the setup was inspired by two successful experiments on Bose-Einstein condensation in microelectronic traps performed in the year 2001 in the groups of Jacob Reichel in Münich and Claus Zimmermann in Tübingen [44, 45] and by the work of Schmiedmayer and his group at the university of Heidelberg [102]. Especially the Münich experiment was attractively simple albeit that only small condensates were obtained. For our design a relatively small number of atoms in the condensate...
($\sim 10^4$) was enough to reach our first aim, the study of one-dimensional condensates. In this section some of our design choices that have led to the construction of a stable and productive setup are laid out. For the modelling of the magnetic field we used the *Mathematica* software (Wolfram) with the *radia* add-on that was written at the European Synchrotron Radiation Facility in Grenoble.

### Single chamber

On a chip, thanks to the strong confinement, BECs can be produced an order of magnitude faster than with conventional traps, in only one second of evaporative cooling. The background-pressure-limited lifetime of a BEC at a pressure in the $10^{-10}$ mbar range is in the order of 10 s. Efficient loading of a magneto-optical-trap (MOT) requires a partial pressure of at least $10^{-9}$ mbar. Many experimental set-ups meet both requirements by connecting two vacuum chambers through a small aperture and maintaining the required pressure imbalance by differential pumping. In that case atoms are magneto-optically cooled at the high-pressure side and subsequently transferred to the low pressure region through the aperture, as was described for example in Kai Dieckmann’s thesis [103]. The atoms can be transferred in a beam [14, 104–106] or as a cloud using a magnetic transfer scheme [107, 108]. On an atom chip however, ten times faster cooling, allows a ten times higher background pressure. This takes away the need to load a “BEC”-chamber from a separate “vapor”-chamber. Instead enough pressure difference can be attained by inducing a pressure gradient in time. This was done in ref. [109] by loading the MOT from a pulsed atom source and in ref. [110] using light induced atom desorption. We load our MOT by pulsing a rubidium dispenser. A few seconds after the end of the pulse the pressure has dropped sufficiently to reach BEC in the same vacuum compartment.

### Free space versus mirror MOT

We have adopted the mirror-magneto-optical-trap (mirror-MOT) technique that was introduced by Reichel et al. [111]. The working of the mirror-MOT is identical to that of the standard 3D MOT [112] the only difference is that the laser beams in the plane of the MOT coils are reflected off a mirror (see Fig. 3.2). Upon reflection the circularly polarized light changes handedness thus maintaining the proper handedness with respect to the quadrupole magnetic field vectors. Using this method limited optical power ($\approx 50$ mW total) is sufficient to trap and cool enough atoms close to a surface to eventually reach BEC.

### Stainless steel versus glass cell

In cold atom experiments worldwide virtually each lab has its own vacuum system and magnetic field coil design. The use of a small glass cell, to perform the main physics experiments in, is popular. It allows a dense packing of magnetic field coils

\[\text{download free at www.esrf.eu/Accelerators/Groups/InsertionDevices/Software/Radia}\]
close to the center of the experiment while sufficient optical access is maintained. In our case the multitude of electrical feedthroughs and the water feedthrough for cooling of the chip, required for our microtrap, makes the use of a single glass cell less straightforward. In the original München setup [44] the pumping speed was limited because the chip mount and current leads formed a bottle neck. Besides good access for pumping another advantage of a stainless-steel chamber is the easy use of double-sided AR coating on the windows (difficult for glass cells) that improves the imaging quality. Thirdly the application of wires in vacuo to produce strong magnetic-field gradients relaxes the requirements on the proximity of magnetic-field coils considerably. In our case the final reason to choose a stainless steel chamber was the availability of a finished nicely crafted vacuum chamber with an octagonal cross-section (180 mm diameter) that was produced in the Huygens Laboratory, Leiden, The Netherlands [113]. This chamber gives ample optical access and provides for the easy connection of many electrical feedthroughs.

A very elegant alternative approach was followed by the group of Jacob Reichel in a new generation of experimental setups where they have replaced the top cover of their cell with an already connected microchip [114] combining easy connection, good optical access and the possibility of cooling the chip without compromising the pumping speed.

Efficient and reproducible chips enable wider applicability

The development of efficient and reproducible “atom chips” could facilitate the quick setup of new cold-atom experiments world wide at a reduced cost. In this way more researchers could do experiments on ultracold atoms: physical systems that are governed completely by quantum mechanics. Such a development would bring the world of quantum mechanics closer to our daily experience. \(^{2}\)

Advantages of scale reduction

Another advantage of the use of small current-carrying wires to trap atoms is the dynamical flexibility. It is easy to rapidly switch off 2 A of current in a chip wire because of the low resistance and low inductance. This is in sharp contrast to the high voltages needed to push down the hundreds of amperes of current in the large coils used in conventional BEC machines. The chip wires can be switched rapidly in about 30 \(\mu\)s limited by the current source bandwidth, contrarily the magnetic bias fields that are generated by the outside coils have a relatively long switching time of 1.2 ms limited by the current source voltage. The chip setup allows also to economize on the lasers because small BEC’s are efficiently produced from modest initial atom numbers. There is no need for a high power tapered-amplifier diode or a titanium-sapphire laser. In our setup for example we use only three simple diode lasers. By keeping the laser setup small we reduce costs but we also reduce the man hours of maintenance. The complete setup involves only one optical table with

\(^{2}\)An example of such an initiative is the on-line atom chip experiment in Germany (www.physnet.uni-hamburg.de/ilp/sengstock/en/ELearning.php).
room for both the lasers and the vacuum system with the atom chip, with a total footprint of only 4 m$^2$.

**Formulation of design criteria**

In the design process, that involved three successive test traps before reaching the final microtrap, we have identified the following essential elements:

- The magnetic trap should have a large enough capture volume,
- The trap should provide an adequate mode match with the optically cooled atom cloud.
- To start evaporative cooling the atomic collision rate should be raised. This is achieved by increasing the magnetic field gradient. During this compression the trap should always be deep enough so that the heated atoms are not squeezed out of the trap.

From these key requirements we can derive typical values for the currents to be used in the wire layers. The required currents in turn impose constraints on the thermal properties of the microtrap.

### 3.3 Microtrap for cold atoms

The core of the experimental setup is formed by the microtrap for cold atoms shown in Fig. 3.2(a). This trap consists of three layers of current-carrying wires. The surface layer is formed by a silicon substrate coated with a patterned gold layer. On this "atom chip" a Z-shaped wire is defined that is usually operated at a current of 2.25 A. Behind the substrate are two layers containing three parallel copper wires each, in the $x$ and $y$-direction, respectively. These "miniwires" have a diameter of 300 $\mu$m and typically run at 10 A. The design and development of the microtrap assembly formed by the chip, the miniwires and their mount was the crucial and most innovative step in the buildup of our experimental setup.

**Microtrap elements – mirror-MOT**

For the effective implementation of a mirror-MOT the mirror should reflect the cooling laser beams under a 45° angle without birefringence. Metallic coatings are well suited for this purpose. Our metal of choice is gold because it has a high reflectivity of $\approx 98\%$ at 780 nm, it does not oxidize like silver or aluminium and it has a similarly high electrical conductivity necessary for the on-chip wires. The surface dimensions of the chip (16 $\times$ 25 mm) are adjusted to the diameter of the MOT beams.
We start the trapping and cooling process with a mirror-MOT stage where the quadrupole magnetic field is generated by the MOT coils (see 3.7). In a second step we replace this quadrupole field by a magnetic field that is generated by the miniwires, the wire-MOT stage. The proper magnetic field is essentially generated with a current $I$ on the surface of the mirror that follows a H-shape (green line in Fig. 3.2) and a homogeneous bias field $B_y$ along $y$. The central section of the H in the $x$-direction together with $B_y$ form a side guide along $x$. We estimate the trap position and gradient using Eq. (3.1); with a current of 10 A along $x$ [equally divided over three parallel red wires in Fig. 3.2(a)] and $B_y = 5$ G we find the trap minimum at $z_0 = 4$ mm where the gradient is $12.5$ G/cm. The wire sections of the H that run in the $y$-direction provide a confining gradient along $x$. The currents in the “legs” of the H run in opposite directions. Therefore the magnetic field is zero in the trap center and the field lines point outwards in the $xz$-plane for positive $z$. In a volume of radius $z_0$ the magnetic field resembles the ideal quadrupole configuration for a MOT reasonably well. For $z_0 = 4$ mm this volume is comparable to the volume where the cool light beams intersect.
Microtrap elements – magnetic trap

After the optical cooling stages we magnetically trap the atoms in a Ioffe-Pritchard (IP) magnetic field configuration (see Sec. 2.2). For the IP field we invert the current in one of the miniwires along \( y \) [blue wires in Fig. 3.2(a)] thus turning the quadrupole field into an IP-field configuration. In the subsequent stage we transfer the atoms to the on-chip Z-wire [white wire in Fig. 3.2(a)] that provides a strongly confining potential. In this stage the miniwires are only used to give small corrections to the fields and gradients and eventually to generate the focusing pulse used for experiments described in Chapters 5 and 6.

3.3.1 Layout and construction

In the description of the wire pattern layout we refer to the frame of reference in Fig. 3.2, where the center of the chip surface is at the origin. A detailed drawing including the dimensions of the boron nitride ceramic disc is shown in Fig. 3.3(b). The 300-\( \mu \)m-diameter Kapton-coated copper miniwires run along \( x \) and \( y \) in two layers centered at \( z = -0.5 \) mm and \( z = -0.8 \) mm respectively. The spacing between the wires within one layer is 0.65 mm and 3 mm, for the wires along \( x \) and \( y \) respectively. These wire layers exactly fit in grooves in the boron-nitride ceramic disc that is machined with a CNC computer-controlled mill. An exploded view of the chip mount parts is shown in Fig. 3.3(a). We machine our ceramic disc from boron-nitride because it is as easily machinable as Macor but has a thermal conductivity that is 20 times higher.

All parts are bonded with Epo-tek H77 epoxy except for the silicon substrate that was glued to the boron-nitride ceramic with Epo-tek 377. The miniwires are electrically connected using standard vacuum-compatible sub-D-type gold plated connector pins. We strip the Kapton from the end of the miniwire and press it, along with a piece of bare copper, into the male pin. The resistance of the miniwires (including the connection to the male pins) is 10 m\( \Omega \). With a current of 10 A typically 1 W per wire is dissipated over the whole length of the wire resulting in negligible heating. At a current of 20 A the wire sections that are suspended in free space between the connector pins and the ceramic disc start to heat up moderately. All copper elements used in the microtrap assembly are made of oxygen-free high-conductance (OFHC) copper. The copper heat sink is connected with four bolts (M3) to the end cap of a stainless-steel (type 316L) rod with an outer (inner) diameter of 16 mm (8 mm). This rod is welded to a CF40 flange for insertion into the vacuum system. A polyvinyl chloride (PVC) tube of 6 mm diameter runs coaxially inside the stainless-steel rod. Cooling water enters the system through the inner (PVC) tube. Water flows out of the tube towards the stainless-steel to copper interface, where it removes heat from the microtrap assembly, before flowing back on the outside of the PVC tube. We typically run 0.1 l/min of tap water through the system.

The gold-coated silicon substrate or “atom chip” was produced using the facilities of the Amsterdam nanoCenter (located at AMOLF, the FOM Institute for Atomic
Figure 3.3: (a) Exploded view of chip mount. (1) silicon chip with gold layer; (2) miniwires; (3) connector pins (male); (4) Boron-Nitride ceramic element; (5) female connector pin; (6) copper heat sink; (7) water-cooled stainless steel rod. (b) Dimensions of boron-nitride ceramic disc. The exact position of the miniwires and their numbering is indicated. All sizes are in mm.

<table>
<thead>
<tr>
<th>part</th>
<th>description</th>
<th>supplier</th>
</tr>
</thead>
<tbody>
<tr>
<td>electrical feedthrough</td>
<td>Sub-D 15 pin</td>
<td>Allectra</td>
</tr>
<tr>
<td>D-sub connector pins (fe)male</td>
<td>gold plated</td>
<td>Allectra</td>
</tr>
<tr>
<td>Kapton insulated wires</td>
<td>1mm diameter</td>
<td>Allectra</td>
</tr>
<tr>
<td>Kapton insulated wires</td>
<td>0.3mm diameter</td>
<td>Allectra</td>
</tr>
<tr>
<td>boron-nitride ceramic</td>
<td>high purity grade</td>
<td>Saint Gobain</td>
</tr>
<tr>
<td>UHV compatible epoxy</td>
<td>low outgassing</td>
<td>Epo-tek H77/377</td>
</tr>
</tbody>
</table>

Table 3.1: Parts used in the microtrap assembly and their supplier.

and Molecular Physics). The production will be described in detail in the forthcoming thesis by J.J.P. van Es [115]. Here we describe the production process only briefly. Furthermore the treatment of the wire layout is restricted to the 125-μm-broad Z-wire that was used for all experiments described in this thesis. A few of the
eight other wires present on the chip were employed during the work described here. Especially one neighboring wire was used as an antenna to perform radio-frequency evaporative cooling. A 300-μm-thick high-purity silicon substrate is covered with two layers of different types of photo-resist resulting in a total layer thickness of \( \sim 2 \mu m \). The resist is exposed to UV-light through an optically patterned mask (produced at MESA+, University of Twente, The Netherlands). Developing the double resist layer results in a resist pattern that has an undercut. A very smooth 1.8-μm thick gold layer is deposited onto the substrate using vapor deposition. A lift-off procedure, that is facilitated by the undercut in the resist, finally shows the wires that are defined by \( \geq 5-\mu m \) wide gaps in the gold layer. We use a Z-shaped wire because it is the most simple way to generate a IP field configuration with a single wire and a bias field \([116]\). In addition, such a Z trap can be easily compressed by increasing the bias field \( B_y \). If we compress in this way, the trap is automatically deep enough and the heated atoms are not squeezed out. In our first chip design we incorporated only very elongated traps made of narrow wires, as a result the radial compression was too high and the axial trap depth too low to achieve high enough atom number and density to reach BEC. The Z-wire height is fixed at 1.8 μm by the chip production process. In choosing the width \( w \) and length \( d \) of the central section of the Z-wire we have to make a compromise between on the one hand high attainable trap frequencies (small \( w \)) and a large trapping volume (large \( d \) and large \( I \)) while ensuring on the other hand to keep the ohmic heating within bounds (small \( d \), small \( I \), large \( w \)). Our resulting Z-wire is shown in Fig. 3.4; it has a 3-mm-long 125-μm-wide central section with leads that fan out, thus limiting the total resistance to 0.7 Ω. This low resistance allows us to run a relatively high current of 2.25 A through the wire without overheating the chip thus ensuring a large enough trap volume. At this current and with a 40-G bias field the trap minimum sits at \( z_0 = 90 \mu m \) where the gradient of the magnetic field is 3.7 kG/cm. An excellent starting point for evaporative cooling.

### Assembly

In the assembly process special care is taken to create optimal epoxy adhesion layers. The two epoxy components were carefully weighted on a precision balance and mixed. We heat the mix to \( \approx 40^\circ \)C to decrease the viscosity. This mixture is degassed in a desiccator for one minute. Keeping the epoxy for longer in vacuo harms the mixture because essential chemical components get extracted. The epoxy was cured in air at 150°C for 1 hour. During the warm up trajectory the epoxy becomes very fluid and tends to creep onto the mirror surface. To prevent this from happening the chip edges were designed to extend 1 mm over the supporting boron-nitride layer. In Fig. 3.5 we show some pictures taken during the construction process of the microtrap.\(^4\) The assembly process is performed in several curing stages. In

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\(^3\)An order of magnitude higher current density was reached with a total current of 1 A in a 5-μm-wide chipwire: \( 10^{14} \text{A/m}^2 \).

\(^4\)Large part of the chip mount production was performed by the fine-mechanical engineer W. van Aartsen at the University of Amsterdam.
the first curing stage the ceramic disc is glued onto the copper heat sink and the connector pins for the chip wires are glued in place. In the subsequent curing stage the miniwires and their connector pins are glued into the groves in the ceramic disc. After removing the excess epoxy with a mill and careful cleaning we place a drop of Epo-tek 377 in the middle of the ceramic disc and glue the microchip on it in the last curing stage. We press the chip in its exact position with a special mold and a weight that has only 3 needle-like contact points with the chip to do minimal damage to the very soft gold layer. The alignment error of the on-chip Z-wire with respect to the miniwires achieved in this way was smaller than 50 μm. The eight on-chip wires are connected to the contact pins with 20 μm-diameter aluminium wires with a wire bonding technique.\textsuperscript{5} Each contact pad was bonded with 10 wires except for the Z-wire where we have used 14 wire bonds. The microtrap wires are then connected to a set of sub-D-type vacuum feedthroughs. The maximum bake-out temperature for the chip mount in the vacuum system is limited to 180 °C by the Kapton around the copper wires and the used epoxy. After bake out, the chip mount was compatible with ultra high vacuum conditions as expected; the experiment is operated at a pressure of $10^{-10}$ mbar.

\textsuperscript{5}Wire bonding was performed by J. Rövekamp at the National institute for subatomic physics (NIKHEF) in Amsterdam.
3.4 Thermal properties of the microtrap

For the design of the microtrap assembly an analysis of the thermal properties was performed. We measure a steady-state total thermal resistance of 10 K/W when we send a current through the on-chip Z-wire and cool with a water flow of 0.1 l/min. Measurements of the steady-state thermal resistance of the mount and of the heating as a function of time were reproduced by a Finite Element Method (FEM) simulation and were compared to an analytic study of the heat flow through the chip mount [117]. In Sec. 3.4.1 we use the heat equation to get an analytic handle on the FEM simulation results that are presented and discussed in Sec. 3.4.2.
3.4.1 Thermal conduction – analytic approach

Heat flow in a homogeneous medium, characterized by its specific heat $c$, density $\rho$ and thermal conductivity $\sigma$, is described by the heat equation

$$\frac{\partial T}{\partial t} = \frac{c}{\rho \sigma} \nabla^2 T. \quad (3.3)$$

We look for solutions to this partial differential equation for a model system that represents the microtrap assembly. Figure 3.6 illustrates the dimensions used in describing the finite system of length $l$. The area $S$ is equal to that of a heat source, in our case a gold layer of width $w$ and length $d$ of which the thickness $h$ determines the resistance. In a system that is symmetric around an axis ($z$) the heat equation can be solved using Fourier series [118]. From the Fourier series we can obtain estimations of the thermal behavior in two limiting cases where the heat flow is approximately symmetric around $z$: (i) close to the wire in the regime $(l - z) \ll d$; (ii) for large distances $(l - z) \gg d$. We write the solution to the heat equation in one dimension. At position $z = l$, a constant power $P$ is dissipated, while at $z = 0$ the temperature is kept constant

$$\delta T(z, t) = \frac{P}{\sigma S} z + \sum_{n=1}^{\infty} A_n \sin k_n z e^{-\gamma_n t}, \quad (3.4)$$

$$\gamma_n = \frac{\sigma}{\rho c} k_n^2, \quad k_n = \frac{(2n - 1)\pi}{2l}. \quad (3.5)$$

Here $A_n$ are the Fourier coefficients and $k_n$ the wavevectors. The first term in Eq. (3.4) gives the stationary solution for $t \to \infty$, while the temporal evolution is expressed through the relation between the relaxation constant $\gamma_n$ and the wavevector $k_n$. From the relation Eq. (3.5) we see that the relaxation time $\gamma_n^{-1}$ increases with the square of the wavelength $2\pi/k_n$ of the contributing Fourier component. Equation (3.4) gives access to comprehensive estimates for the stationary and dynamical thermal properties of our chip mount. These estimates can be used to gain insight in the more realistic FEM analysis.

(i): At small distances, close to the gold-silicon interface $|(l - z) \ll w \ll d|$, we have the simple case of one-dimensional flow and the stationary term in Eq. (3.4) yields for the thermal resistance $R_t = \Delta z / \sigma S$ in a layer of thickness $\Delta z$. Let us assume that this homogeneous heat flow approximation holds for depths up to $w/2$. The thermal resistance of such a silicon layer is then 1 K/W with $w = 125 \, \mu\text{m}$. An estimate for the time constant for the heating of this layer can be found from Eq. (3.5). The Fourier component with the longest relaxation time $\gamma^{-1}(k)$ corresponds to $k = \pi/w$ and by inserting the values for silicon (Table 3.2) we find a relaxation time of $\sim 20 \, \mu\text{s}$. Thus, this thin silicon layer heats op on a timescale much faster than the timescale of the experiment and the steady-state value forms an inevitable lower bound on the thermal resistance if we use silicon as a substrate.
Figure 3.6: Schematic drawing (not to scale) of the chip mount indicating the layer structure and the dimensions used for the thermal analysis. Some properties of the layers are listed in Table 3.2. The dimensions can be found in Table 3.3.

<table>
<thead>
<tr>
<th>Fig. 3.6</th>
<th>material</th>
<th>heat conductivity $\sigma$ [W/Km]</th>
<th>specific heat $c$ [J/kgK]</th>
<th>density $\rho$ [kg/m$^3$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1) gold</td>
<td>300</td>
<td>132</td>
<td>19.3 · 10$^4$</td>
<td></td>
</tr>
<tr>
<td>(2) silicon</td>
<td>148</td>
<td>710</td>
<td>2330</td>
<td></td>
</tr>
<tr>
<td>(3) Epo-tek 377</td>
<td>0.2</td>
<td>1.0 · 10$^3$</td>
<td>1175</td>
<td></td>
</tr>
<tr>
<td>(4) Boron Nitride</td>
<td>27</td>
<td>1468</td>
<td>1900</td>
<td></td>
</tr>
<tr>
<td>(5) Epo-tek H77</td>
<td>0.66</td>
<td>1.0 · 10$^3$</td>
<td>2.5 · 10$^3$</td>
<td></td>
</tr>
<tr>
<td>(6) copper</td>
<td>400</td>
<td>385</td>
<td>8920</td>
<td></td>
</tr>
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</table>

Table 3.2: some physical properties of the materials used for the fabrication of the microtrap.

(ii): In the limit of distances large compared to the radial dimensions $[(l - z) \gg d]$ we look at the heating of the total mount, also an approximately one-dimensional problem. An estimate for the heating time constant is found again from Eq. (3.5). The largest part of the mount is formed by the copper heat-sink of length 40 mm. We insert the values for copper (Table 3.2) and find a relaxation time of 6 seconds.

For intermediate distances $w \lesssim (l - z) \ll d$ the heat flow problem has to be treated in two dimensions. At this distance range (and within the silicon) the system can be approximated by a line-like heat source of infinite length on a silicon half-space substrate. The temperature increase at the gold silicon interface as a function of time is then given by the incomplete gamma function [119]

$$\delta T(t) = \frac{hw\rho_c}{2\pi\sigma} \Gamma\left(0, \frac{c_p w^2}{4\pi^2\sigma t}\right),$$

(3.6)
where $j$ is the current density, $\rho_e$ is the electrical resistivity, and $h$ is the wire thickness. This function is plotted in Fig. 3.7(b).

### 3.4.2 Thermal conduction – Finite Element Method

For a more detailed three-dimensional study of the thermal properties of our chip mount design a finite element method (FEM) simulation was performed using the MSC-Marc software package [117]. The chip mount was modelled with 2500 elements where the smallest elements near the heat source have a size of 2 $\mu$m. The chipwire was simulated by imposing an uniform heat load at the wire surface area of $125 \times 3000$ $\mu$m$^2$. The modelled layers from top to bottom and their respective thickness are listed in table 3.3. A three-dimensional image of a quarter section of the modelled mount with the equilibrium temperature distribution for 1 W heat load is shown in Fig. 3.7(a). The epoxy layers with their low thermal conductance form a distinct barrier for the heat flow to the next layer. The heating process after the heat load is turned on is also calculated dynamically. The temperature rise at three positions on the symmetry axis is shown in Fig. 3.7(b). The equilibrium values for the thermal resistance of the modelled layers at the symmetry axis are listed in table 3.3. Two values for the thickness of the Epo-tek 377 layer were simulated because this thickness is not exactly known experimentally. The measured value for the total thermal resistance is $9.9 \pm 0.1$ K/W. The dynamic FEM results [Fig. 3.7(b)] show that in the first 6 ms (inset) the temperature at the silicon-gold interface is already at half its final value, and that the realistic heating exceeds that of the analytic expression for a semi-infinite silicon slab of Eq. (3.6) already within the first millisecond (as expected from the Fourier analysis). On the long timescale of 6 s we see that only the copper is still getting warmer (in agreement with the Fourier analysis) but that the total equilibrium value is approached already to within 3%. This dynamical behavior was found to be in qualitative agreement with measurements performed on a neighboring chipwire with a smaller width of 10 $\mu$m for times between $10^{-4}$ s and 10 s. What is the relevant process for our experimental situation? One experimental cycle takes a constant 10 s or 20 s and is repeated typically more than 20 times. This cycling together with the constant flow of cooling water through the chip mount will guarantee a constant long-term temperature stability of the microtrap. The current pulses through the chipwire take $\sim$1 s or longer by which time the steady-state situation is almost reached. We conclude that for our purposes the value of the steady-state thermal resistance is the relevant quantity that has to be minimized in our design. The epoxy layer that bonds the silicon substrate to the boron-nitride ceramic layer forms the largest contribution to the total equilibrium thermal resistance (see table 3.3). Therefore this epoxy layer was the focus of our attempts to improve the total thermal conductance of the mount. Our favorite epoxy that we use in other parts of the mount (Epo-tek H77) is filled with ceramic grains to increase the thermal conductivity. These grains with a diameter of $\approx 20$ $\mu$m make it impossible to create thin layers. We therefore employed the same type of epoxy with proven low outgassing rate but without the filler (Epo-tek 377) to bond the silicon layer to the boron-nitride ceramic. We have tested Epo-tek 377 by
3.4 Thermal properties of the microtrap

Figure 3.7: (a) Finite element method simulation of thermal properties of the chip mount. Shown here is a quarter section of the mount with the equilibrium temperature distribution for a heat load of 1 W generated at the gold wire location. The modelled layers from top to bottom are silicon, Epotek 377 (20 μm), boron-nitride, Epotek H77 and copper. The epoxy layers with their low thermal conductance clearly form a barrier for the heat flow to the next layer. (b) Dynamic thermal results of the finite-element-method simulation. Shown here is the temperature increase in the first 6 s after a heat load of 1 W at the gold wire location is turned on for three positions on the symmetry axis: silicon-gold interface (black straight line), boron-nitride-Epotek 377 interface (red dashed line) and copper-Epotek H77 interface (green dotted line). The inset shows a zoom of the first 6 ms. Here the curve for the incomplete gamma function, Eq. (3.6), that models an infinite silicon layer is shown for comparison (blue dash-dotted line). This comparison shows that already in the first millisecond the heat flow has encountered the first epoxy layer and the heating is faster than for the case of the semi-infinite silicon slab.

bonding microscope slides and studying the layer homogeneity and thickness under an optical microscope. Spreading the epoxy (prepared as described in Sec. 3.3.1) over one of the surfaces followed by curing of the bond under pressure resulted in the inclusion of air bubbles in the epoxy layer. An almost perfectly homogeneous filling was obtained when a drop of epoxy was deposited in the middle of one of the parts before putting the parts together under pressure. The “smearing” method resulted in a layer thickness of 25 μm. The “drop” method resulted in thin layers of 12 ± 3 μm and was used for the fabrication. The layer thickness achieved in the final chip mount fabrication could not be measured. We assume that the Epo-tek 377 layer is thicker than the test results because the (mechanically milled) boron-nitride surface is less smooth than that of the microscope test slides. We had to apply more epoxy per bonded area than was used for the tests. We estimate the layer thickness between 20 μm and 80 μm. These thicknesses were used in the FEM simulation results. Within the simulated range the FEM thermal resistance agrees quantitatively with the measured value. The accuracy of the measurement and simulation of the thermal conductance do not allow to establish the thickness of the first epoxy layer with good accuracy. The important contribution to the total thermal resistance
Experimental Setup

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<td>0.4</td>
<td>$40 \times 10^3$</td>
<td>0.4</td>
<td>0.4</td>
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<tr>
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<td>8.5</td>
<td>$41 \times 10^4$</td>
<td>10.7</td>
<td>9.9 ± 0.1</td>
</tr>
</tbody>
</table>

Table 3.3: Thermal resistance of constituting chip mount layers from FEM simulation compared to the experimentally measured value. Simulations were performed for 20 μm and 80 μm thick Epo-tek 377 layers. The experimentally measured value is shown in the last column.

however suggests that we can still improve the performance, for example by finding an epoxy that is a better thermal conductor or finding a way to make thinner layers.

3.5 Vacuum system

Our vacuum setup is shown in Fig. 3.8 [113]. It is built up around a science chamber with an octagonal cross section (1). The octagon contains both the microtrap (8) and dispenser atom sources (9). Ultra high vacuum (UHV) conditions are maintained using the combination of an ion getter pump (IGP) (6) and a titanium sublimation pump (TSP) (5). Both are located in the pump section that can be separated from the science chamber with a gate valve (3). The pressure can be monitored with a Bayard-Alpert type ionization gauge (7). The microtrap is connected with a custom-made 4+1-way cross (10) that is pumped with an additional small ion-getter pump (11). The science chamber and the pump section can be separately evacuated using a turbo molecular pump through valves (2) and (4) respectively. A 100-W halogen light bulb is positioned in the science chamber to aid the bake out. All parts are made of the commonly used stainless steel type (304) except for the science chamber, the 4+1-way cross and the chip mount where we have used the less magnetic stainless steel type (316L).

Seven glass windows give optical access to our vacuum chamber. Five CF40 windows, with a double sided AR coating, are centered at $x = 0$ in the $yz$-plane. A sixth CF40 window is centered at the $x$-axis and is placed at the backside of the vacuum vessel. The CF100 window that seals off the front side of the octagon is uncoated. The conductance from the science chamber to the 5-way cross at the center of the pump section is about 30 l/s justifying the choice of an ion getter pump with a pumping speed of 40 l/s (Physical Electronics 2082040, controller: Perkin and Elmer Digitel 500). The addition of a Titanium sublimation pump (Varian 916-0061, controller: Varian 929-0023) increases the pumping speed for reactive elements but does not pump noble gases. The pressure is monitored with a Bayard-Alpert type ionization gauge (Varian UHV-24p, controller: Varian). We can close the gate
Figure 3.8: Vacuum Setup: (1) science chamber, (2) and (4) venting valves, (3) gate valve, (5) Ti sublimation pump, (6) ion getter pump 40 l/s, (7) ion gauge, (8) microtrap, (9) dispenser atom source, (10) 4+1-way cross, (11) ion getter pump 2 l/s. The scale of the figure is indicated using the size of a central flange.
valve (VAT 10836-CE01) to preserve vacuum in the pump section while opening the science chamber to replace the chip mount or the atom dispensers. Both sections can be evacuated with a turbo pump through all-metal valves (Varian). We pump the 4+1-way cross with the chip mount and its electrical feedthroughs with an extra 2 l/s ion getter pump (Varian 919-0520, controller: Varian minivac) to be sure that this remote piece does not act as a virtual leak.

We reach a vacuum pressure in the $10^{-11}$ mbar using the following procedure.\(^6\) We clean all vacuum parts in an ultrasonic, bath first with acetone and then with ethanol. Secondly we use materials with low outgassing rates in the the microtrap design (see Sec. 3.3). After assembly we perform a vacuum bake out at a temperature of 180 °C limited by the Kapton insulation of the minitrap wires and the two types of UHV compatible Epoxy (Epotek H77 and 377) used in the minitrap. The octagonal chamber was opened several times to exchange the minitrap and the dispensers while maintaining UHV in the pump part by closing the gate valve. We typically bake during seven days while pumping with a 63 l/s turbo-molecular pump (Pfeiffer). We then combine the turbo with IGP pumps. Subsequently we valve off the turbo pump and let the system cool down. We then start the TSP and let it fire during one minute at 47 A each 32 hours. This procedure leads to a pressure below the sensitivity limit of the ion gauge, this indicates a pressure of $\approx 10^{-11}$ mbar.

### 3.6 Dispenser pulsed atom source

We use a non-evaporable getter as a source for rubidium atoms. These so-called dispensers are commercially available (SAES Getters) and are widely used in cold-atom experiments [109]. The dispensers used in our experiment are centimeter-sized stainless-steel containers filled with rubidium chromate and a reducing agent. Rubidium atoms are released when the reduction reaction is initiated upon heating the container above a threshold temperature (600 °C for cesium [120]). We heat the dispenser resistively by applying a current pulse of 11-20 A during 2-4 s.\(^7\) Heating and cooling down can be achieved in this way within 5 s thus altering the gas pressure on the same timescale. The dispensers used in our experiment have an active length of 12 mm and contain $\sim 4.5$ mg of Rb. We found only one study in the literature detailing on the flux from alkali dispensers [120]. Succi and coworkers quote a cesium flux at 5 A dispenser current of 10 mg/min. If this flux can be compared to the Rb case (not specified anywhere) the dispenser would be empty after 450 minutes of continuous operation. Our dispensers were used extensively for about one year and were not empty at the time of replacement. We have mounted our dispensers close to the atom chip on a thick copper high-power vacuum feedthrough (MPF AO756-1-CF, 4-pin power feedthrough copper conductors 23A; 1250V). The assembly is shown in Fig. 3.9. The 6.4-mm-diameter copper rods allow the essential rapid cool

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\(^6\)N.B. all pressure readings are at the position of the ionisation gauge unless explicitly stated otherwise.

\(^7\)The exact pulse shape and duration depend on details of the experiment like the exact cycle time.
3.6 Dispenser pulsed atom source

Figure 3.9: Two dispenser atom sources on CF-40 UHV feedthroughs shown with their orientation with respect to the microtrap. The size of the chip is $25 \times 16$ mm$^2$. Note that the orientation of the dispensers was changed prior to the experiments of Ch. 4-6 (see text for details).

down of the dispenser after the end of the current pulse. The opening slit of the dispenser is placed close to the chip but the direct line of sight to the center of the MOT is blocked by the rim of the microtrap assembly to prevent a harmful stream of hot atoms from passing through the cold cloud. A bare copper wire runs parallel to the dispenser with counter-propagating current to minimize the generated magnetic field at the position of the MOT. In our setup that was operated in the years 2006/2007 we have pointed the opening slit of the dispensers in the opposite direction facing away from the MOT. By mounting the dispensers in this way we avoid a possible coating of the chip mount with Rb. In initial experiments we had noticed that Rb atoms that had stuck to the microtrap assembly would desorb from the microtrap during the magnetic trapping stage at the moment the assembly heats up. These desorbed Rb atoms had a detrimental effect on the magnetic trapping lifetime. Changing the direction of the rubidium atom beam emerging from the dispenser had no effect on the number of atoms that we could trap in the MOT. The problem of the decreased trap lifetime due to desorbed rubidium was completely solved in the most recent setup where we (i) directed the Rb beam away from the chip; (ii) reduced ohmic heating by reducing the chipwire resistance and improving the thermal conduction of the chip mount and (iii) heated the chip mount to 40°C at moments that the experiment was not running to clean the chip mount from possible Rb contamination. This heating is done by circulating warm water through the cooling water circuit (circulating bath Tamson TC6B).
Light-induced atom desorption

To change the pressure even more rapidly one can use light-induced atom desorption (LIAD) in addition to the dispensers [110, 121]. For LIAD a strong halogen light bulb or a LED that emits in the near UV is switched on during the MOT loading stage to desorb atoms from the vacuum system surface [121]. The efficiency of this method is determined by the ratio of the illuminated surface area to the total vacuum system area. This ratio can be made optimal for glass vacuum cells more easily than for stainless steel chambers. We have performed promising preliminary studies using a light emitting diode array with diodes that emit 700 mW of blue light with a central wavelength of 455 nm (Luxeon V Star royal blue), illuminating the inside of the science chamber through the big CF100 window (Fig. 3.8). Until the time of writing we had not enough reason however to change the current working setup based on pulsed dispensers.

3.7 Magnetic field coils

Figure 3.10 displays the magnetic field coil configuration around the vacuum chamber. These coils are used, together with the microtrap wires, for magneto-optical and magnetic trapping, and manipulation of cold atom samples. All coils are compactly wound with copper wire of rectangular cross-section: $0.8 \times 1.4 \text{ mm}^2$ (Romal). The wire coating is specified for temperatures up to 200 ºC. In this section we briefly describe the characteristics of the miniwires and the magnetic-field coils.
• microtrap wires: A total of six copper miniwires (the layout of these is described in Sec. 3.3.1 and Fig. 3.3) with a resistance of 0.1 Ω inside the vacuum provide both magnetic fields of 1 G/A and gradients 5 G cm$^{-1}$A$^{-1}$ at a distance of 2 mm. The six wires are operated at a current of 10 A using three bipolar power supplies (Kepco BOP 20-10) and one unipolar version (Kepco ATE 6-10) all with a bandwidth of around 16 kHz. These very versatile miniwires serve many purposes and are used for example for the MOT field, to generate an IP type magnetic trap and for the atom-focusing experiments. The on-chip Z-wire with $R = 0.7$ Ω is operated at $I \leq 2.25$ A using a Kepco ATE 15-3 power supply.

• compensation coils: Six coils (1) are added to generate a homogeneous field and a gradient in arbitrary direction, and can be used to compensate the fields from the microtrap wires in any direction. The six compensation coils have 128 windings each. The coils of radius $R = 100$ mm are placed at a distance of $1.8R$ from the center. This is larger than the optimal distance of $R/2$ where the B-field curvature is zero, the so-called Helmholz configuration. The B-field along the axis in the trap center has a magnitude of 1.84 G/A per coil set and a curvature of $B'' = 0.04$ G/cm$^2$. Each coil has a resistance of 1.5 Ω and a self-inductance of 6 mH. The compensation coils are multi purpose. They are used for example to cancel the earth magnetic field, to steer the magnetic field minimum and to add to the bias field in the highly compressed last stage of the BEC production. We run up to 11 A through each coil in a pulsed fashion. Each pair of coils for a specific direction is driven by a single power supply. We use bipolar linear regulated current amplifiers (Kepco BOP 36V, 12A) with a bandwidth of 10 kHz. The switching time for the compensation coils is limited to 2.2 ms by the coil inductance.

• MOT coils: A set of gradient coils (3) is used to generate the quadrupole magnetic field for magneto optical trapping. This coil set was constructed together with the vacuum chamber in the Huygens laboratory in Leiden [113]. For an optimal gradient, coils of diameter $R$ should be placed at a distance $R/2$ from the center. In our case the distance is $2R$, a compromise between coil efficiency and available space. The coils fit exactly around a CF40 flange and have an outer diameter of 130 mm. The 624 turns per coil are wound on a hollow water-cooled w-shaped profile. Each coil has a resistance of 1 Ω and a self-inductance of 24 mH. Each can carry 10 A of current when cooled with water at a flow rate of 5 ml/s. The resulting field gradient on the axis in the center of the trap is about 2.3 G cm$^{-1}$A$^{-1}$. We drive the current with one switched-mode power supply per coil (Delta SM 35-45). The current is shut-off in 0.5 ms using power MOSFETS (Thomson STE53NA50 500V; 53A).

• bias coils: An additional pair of coils (4) strengthens the homogeneous field in the $y$-direction that forms a waveguide together with the miniwires and chipwires. This is used in the last stage of the BEC production where we apply a magnetic field of 40 G in the $y$-direction. These bias coils with 100
square windings (130 mm sides) each, have a resistance of 0.7 Ω, and a self-inductance of 2 mH, and switch in 1.2 ms. The magnetic field in the center is 1.23 G/A. We use a 20 V, 20 A power supply for each coil (Kepco BOP). The bias coils are water cooled and sustain 20 A if pulsed with a 50% duty cycle.

3.8 Lasers

We use only three simple diode lasers: a grating stabilized master laser for cooling and probing at 780 nm, a diode laser locked by injection to the master laser and a repumper grating stabilized diode laser at 795 nm. A modular buildup of the laser setup makes it possible to move or reconfigure separate parts. The master and amplifier lasers are placed together on a 75 × 90 cm² breadboard. A schematic drawing is shown in Fig. 3.12. The repumper assembly, not drawn here, fits on a 60 × 60 cm² breadboard and consists simply of a spectroscopy setup, electro-optical and mechanical switches and fiber couplers. All breadboards are placed in black cardboard boxes to prevent scattered light from reaching the main vacuum chamber. On the inside of the boxes egg-box-shaped foam damps acoustic noise. Sheets of sorbothane between the optical table and the breadboards provide for extra mechanical damping.

Master laser

The master laser is a commercial (Toptica DL100) external-grating-feedback diode laser that operates near the $^{87}$Rb D2 line (780 nm) and has 90 mW output power. Half of the available light is frequency-shifted and amplified by injection-seeding a second diode laser for cooling and probing. The other half is frequency-shifted and used for optical pumping.

FM lock

The master laser is frequency stabilized on the cross-over (co) line of the $F_g = 2 \rightarrow F_e = 1$ and the $F_g = 2 \rightarrow F_e = 3$ transitions as indicated in Fig. 3.11. This cross-over line is 212 MHz red-detuned with respect to the $F_g = 2 \rightarrow F_e = 3$ cooling transition. We perform saturated absorption spectroscopy in a 10 cm-long 1"-diameter cylindrical room-temperature Rb vapor cell. The spectroscopy beams are 10-times expanded to a diameter of 20 mm and effectively probe the whole cell. To lock our laser we use a frequency-modulation (FM) scheme [123]. We create frequency sidebands on the light signal with an Electro-Optic phase modulator (EOM)[Nova Phase EO-PM-R-020-C1]. The EOM’s electrical driving circuit is made resonant with the 20 MHz driving signal obtained from a “Pound Drever Driver” (Toptica PDD110). The low-voltage sine wave (2 V peak-to-peak) yields 4% modulation depth of the laser intensity. Subsequently the spectroscopy signal is recorded on a fast photo diode (PD in Fig. 3.12, Thorlabs DET110) and fed in the Pound Drever Driver where it is phase-shifted and mixed with the 20 MHz oscillator to obtain a dispersive lock signal. The lock signal finally enters a PID controller (Toptica
3.8 Lasers

Figure 3.11: Energy level diagram for $^{87}$Rb showing the relevant laser frequencies [122]: (1) probe, (2) master laser lock point, (3) optical pump, (4) MOT/molasses cooling, (5) repump.

PID110) that stabilizes the laser frequency on two channels: (i) fast feedback is achieved by direct modulation of the laser current; (ii) the external cavity grating angle is regulated with a Piezo-electric crystal to compensate for long-term drifts. We have abandoned the cheaper option of generating sidebands by direct modulation of the laser diode current because the sidebands, however small, end up in the light needed for the MOT. The presence of the sidebands appeared to be detrimental in the compressed MOT optical cooling stage probably because the red sidebands give rise to scattering and therefore heating.

Repumper

A second grating-stabilized diode laser (Toptica DL100) is locked to the $F_g = 1 \rightarrow F_e = 2$ transition of the $^{87}$Rb D1 line at 795 nm. This “repumper” light serves in the optical cooling process to pump atoms that have fallen in the dark hyperfine ground-state back to the $F_g = 2$ for further cooling. We again use an FM lock. In this case we directly modulate the laser current via a bias-T. This solution is cheaper than the use of an EOM. As mentioned above the disadvantage is that the frequency sidebands end up in the light used for the main experiment. The presence of the sidebands is not critical for the repumping process however.
Figure 3.12: Laser setup of the *master* laser with injection lock of a diode laser that acts as an amplifier. See text for a description of the various elements.

**Frequency shifter and amplifier**

Half of the laser light from the *master* laser is frequency shifted in a double-pass Acousto Optic Modulator (AOM) (Isomet 1205C-02) setup. The frequency of the laser light can thus be tuned between $+1\Gamma$ and $-13\Gamma$ with respect to the cooling transition where $\Gamma/(2\pi) = 6$ MHz is the natural linewidth. Two mW of frequency-shifted
light is amplified by injection-seeding a 120 mW diode (Sharp GH0781JA2C). The light is injected by sending it through the output polarizing beamsplitter cube of a 30 dB optical isolator (Linos), see Fig. 3.12. The slave laser is mounted and temperature-stabilized in a convenient commercially available mount (OFR PALTE-9.0-780). The free-running diode gives 120 mW of optical power at 784 nm. Operating at $T = 11^\circ \text{C}$ and $I = 139 \text{ mA}$ we get about 100 mW of injection-locked light out. We direct the light on two paths, one for probing and the other for cooling. Switching between the two with a bandwidth of 1 MHz is performed with a second EOM (Linos). Both probe and cooling light pass through mechanical shutters (Vincent Associates, Uniblitz, LS2T2) before entering single-mode polarization-maintaining fibers (coupler: Schäffer & Kirchhoff 60 SMS-1-4-A8-07).

**Optical pumping**

In order to trap the cold atoms magnetically, we pump them to the doubly polarized $F_g = 2; m_F = 2$ state. Optical pumping is performed by simultaneously illuminating the atoms with circularly polarized pump and repump light while the quantization axis is defined by a homogeneous magnetic field along the light axis. The pump light is tuned to the $F_g = 2 \rightarrow F_e = 2$ transition of the D2 line by shifting the master light 55 MHz to the red with an AOM (Isomet 1206C-02). Both pump and repump light beams are transferred to the vacuum chamber through polarization-maintaining fibers. The beams are re-collimated to a $1/e^2$ diameter of 10 mm with beam expanders (Shäffer & Kirchhoff 60FC-4-M60-10). Both beams have about two times the saturation intensity $I_0 = 1.67 \text{ mW/cm}^2$. Pump, repump and probe are made circularly polarized with separate $\lambda/4$-plates before they are overlapped with two non-polarizing beam-splitter cubes (Thorlabs).

**MOT**

For the MOT operation we couple 38 mW of cooling light and 7.5 mW of repump light from polarization maintaining fibers using beam expanders (Shäffer & Kirchhoff 60FC-T-4-M90-10) resulting in a $1/e^2$ diameter of 15 mm. After the cooling-light output coupler we place a polarizer (Melles Griot 03 PBS 015) to avoid polarization effects originating from temperature-dependent residual birefringence in the fibers. The cooling light is subsequently divided equally over 4 beams with central intensity $5I_0$. Cooling light and repump light are overlapped on a polarizing beam-splitter cube. The repump light has a total intensity of $6I_0$ divided over four beams.

**3.9 Imaging system**

A polarization-maintaining fiber transports the probe light to the main vacuum chamber. The diverging gaussian beam is collimated to a 10 mm $1/e^2$ diameter

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*The total cooling power was increased by 25% by replacing the 120 mW diode by a 150 mW type (Roithner RLT780-150GS) in 2007.*
with a beam expander (Shäfter & Kirchhoff). The light is made circularly polarized and overlapped with the pump and repump beams on a 50/50 non-polarizing beamsplitter (Thorlabs). The beams enter the vacuum system in the horizontal plane through a CF40 window that is anti reflection coated on both sides. The trap center is imaged with a three times magnifying (Mag=3) relay telescope onto a camera (Roper Scientific Coolsnap ES) see Fig. 3.13. Lens L1 with a diameter $d = 31.5$ mm and a focal length of $f = 100$ mm (Melles Griot 01 LAO 126/076) can be moved with a translation stage to select the object plane ($y$-direction) and to select the object area ($xz$-plane). Lens L2 with a diameter $d = 50$ mm and a focal length of $f = 300$ mm has a larger diameter to avoid vignetting. All imaging optics including the camera are rigidly mounted to the optical table using 1.5” posts or solid metal blocks. Fixing the translation stage after positioning lens L1 helped in reducing interference fringes in the images. The imaging beam travels through vacuum or is enclosed by lens tubes on most of its path to reduce the disturbing effect of air turbulence.

We probe our polarized atomic samples with circularly polarized light on- or near-resonance with the $F_g = 2 \rightarrow F_e = 3$ cycling transition while defining the quantization axis with a weak (2 G) homogenous magnetic field in the propagation direction of the light (except for in situ measurements, where the quantization axis is defined by the IP magnetic field that points perpendicular to the propagation direction of the light). The number of scattered photons when probing with light with intensity $I$ at a detuning $\delta$ from resonance for a duration $\tau$ can be found from

$$N_{\text{scat}} = \frac{\tau s \Gamma}{s + 1}$$

and

$$s = \frac{I/I_0}{1 + 4\delta^2/\Gamma^2},$$

where the saturation parameter $s$ is related to the saturation intensity $I_0$. The probe light intensity $I$ is 0.3 mW/cm$^2$. With an exposure time $\tau$ of 70 $\mu$s we find from equation (3.7) $N_{\text{scat}} = 200$ for the number of scattered photons at resonance. During illumination atoms are displaced by the recoil of the scattered photons. We can estimate the root mean square displacement transverse to the line of sight with $v_{\text{rec}} \tau \sqrt{\frac{N_{\text{scat}}}{3}}$. Inserting the recoil velocity of $v_{\text{rec}} = 5.9$ mm/s we find that 200 recoils give a displacement of 3 $\mu$m. This displacement is smaller than the optical resolution limit of 4 $\mu$m (see below) and of the order of the effective pixel size in the object plane of $6.45$/Mag = 2.15 $\mu$m (see below).

**Imaging camera**

We have chosen an interline transfer CCD camera (Roper Scientific Coolsnap ES). It contains a Sony ICX285 CCD chip, data is read out via dark lines between the rows of illuminated pixels. A matrix of micro lenses directs most of the light to the

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9An aberration occurs if part of the light that enters the optical system is truncated further along its path.
pixels. In this way a quantum efficiency of 30% at 780 nm is obtained. The "interline transfer" technique commonly used in consumer cameras has reached a sensitivity that is not much less than with the frame transfer technique widely applied in cold atom experiments. In the frame transfer CCD’s typically all pixels in the top half of the chip are illuminated, followed by readout that is done by first transferring all charges all the way to the covered lower chip half before the collection of charges in horizontal direction. This transfer scheme slows down the readout rate. The Sony ICX285 CCD chip has 1392 × 1040 = 1.5 × 10^6 pixels with 6.45 μm square size. The AD converter generates 12-bit digital data. At the probing light level we saturate about 60% of the full well of 16000 electrons in one pixel, staying nicely in the regime of linear response of the camera. The pixel readout rate is 20 MHz with a RMS readout noise of 8 electrons per pixel. With a dark current of one electron per pixel per second at room temperature cooling is not required for our purpose. The readout time per image is 1.5 × 10^6/20 × 10^6s^{-1} = 75 ms. It is possible to read out only pixels within a predefined region of interest (ROI). The readout time is reduced proportional to the fraction of vertical lines in the ROI. We typically use a ROI extending over all 1392 pixels horizontally and only 300 pixels vertically resulting in a readout time of less than 30 ms. Keeping the time between the absorption image and the "flat field" normalizing image short reduces the effect of interference fringes in the resulting images.

Optical resolution

A theoretical resolution limit for imaging with a lens can be given by the Rayleigh criterion: two point sources are resolved if the center of the Airy disc of one overlaps with first dark ring of the other. In formula: $d_{\text{min}} = 1.22\lambda f/d$, where $\lambda$ is the
wavelength of the light, \( f \) is the focal length and \( d \) the diameter of the lens [124].
The numerical aperture \( NA \) and its inverse, the F-number, are given by \( 1/F = NA = f/d \).
In our setup lens L1 (see Fig. 3.13) has an F-number of 3.17 resulting in a resolution limit \( d_{\text{min}} = 3 \ \mu m \).
We measure a minimal \( 1/e^2 \) radius feature size of 5.6 \( \mu m \). This corresponds to a minimal second-order moment of an intensity distribution of 2.8 \( \mu m \) and an \( 1/e \) radius of 4 \( \mu m \).

**Magnification**

To determine the magnification of our imaging system we have used the accurately known dimensions of our chip patterns. We have trapped two clouds of atoms in steep potential wells created with a single chip wire with a separation of 1034\( \pm 10 \) \( \mu m \).
In an absorption image the cloud separation was 485\( \pm 4 \) pixels. Inserting the pixel size of 6.45 \( \mu m \) we find a magnification of 3.03\( \pm 0.04 \).

**Absorption imaging**

The probe beam travelling in the \( y \)-direction with initial intensity distribution \( I_0(x, z) \) passes an atomic cloud and casts a shadow on the camera. The light is absorbed by the atoms following Lambert-Beer’s law

\[
I(x, z) = I_0(x, z)e^{-D(x, z)}. \tag{3.9}
\]

The optical density profile is the integrated atomic density along the line of sight multiplied by the absorption cross section \( D(x, z) = \sigma \int dy \ n(x, y, z) \) where \( \sigma = 3\lambda^2/(2\pi) \) for circularly polarized light and polarized atoms. We find \( D \) in Eq. (3.9) from the ratio \( I(x, z)/I_0(x, z) \) by taking a sequence of three images. First the absorption image \( I_{\text{abs}}(x, z) \) secondly a “flat field” image \( I_{\text{ff}}(x, z) \) without atoms and finally a dark background image \( I_{\text{bg}}(x, z) \). The background corrected ratio is \( I/I_0 = (I_{\text{abs}} - I_{\text{bg}})/(I_{\text{ff}} - I_{\text{bg}}) \).

### 3.10 Experimental control

The experiment is controlled with the help of a single PC in combination with analog and digital cards. Images from the CCD camera are read out and processed directly using the same computer. We give a brief description of the used components and the functionality of the control device here. A more detailed description of the experimental control including the software written in LabView (National Instruments) will appear in [115]. During each experimental cycle of 10 to 20 seconds atoms are trapped and cooled and subsequently a series of digital images is collected. The control involves two tasks: first the programming of digital and analog outputs and second the image processing.
### Table 3.4: Overview of used hardware for experimental control (AI= Analog Input, AO= Analog Output, DI=Digital Input, DO= Digital Output).

<table>
<thead>
<tr>
<th>device</th>
<th>type</th>
<th>manufacturer</th>
<th>connections</th>
</tr>
</thead>
<tbody>
<tr>
<td>Industrial PC</td>
<td>IPC-535</td>
<td>Spectra</td>
<td>12 PCI slots</td>
</tr>
<tr>
<td>digital card</td>
<td>DIO-64</td>
<td>Viewpoint Systems</td>
<td>64 DO</td>
</tr>
<tr>
<td>Analog output 1</td>
<td>PCI-6713</td>
<td>National Instruments</td>
<td>8 AO</td>
</tr>
<tr>
<td>Analog output 2</td>
<td>PCI-6713</td>
<td>National Instruments</td>
<td>8 AO</td>
</tr>
<tr>
<td>Analog output 3</td>
<td>PCI-6713</td>
<td>National Instruments</td>
<td>8 AO</td>
</tr>
<tr>
<td>Analog input</td>
<td>PCI-6014</td>
<td>National Instruments</td>
<td>8 AI</td>
</tr>
<tr>
<td>Camera card</td>
<td>PCI</td>
<td>Roper Scientific</td>
<td>Camera control</td>
</tr>
</tbody>
</table>

3.10.1 Output control

The hardware used in the experimental control is listed in table 3.4. We use an industrial computer (Spectra IPC-535) with 12 available PCI slots in a 19" housing. It runs on Microsoft Windows XP and has a 2.8 GHz pentium 4 processor. The PCI cards involved are: Viewpoint DIO-64 for digital control and timing, three National Instruments PCI-6713 analog output cards and one analog input card (National Instruments PCI-6014). We program 18 bipolar analog outputs (±10 V) and 31 TTL outputs with sub-µs time precision in steps of 10 µs. An overview of the control lines involved is listed in table 3.5. Before the start of each cycle a timing sequence of typically $10^4$ steps is loaded into the memory of the Viewpoint DIO-64 card. During an experimental cycle the clock on the DIO card governs the timing and triggers the analog output cards guaranteeing reliable timing precision undisturbed by other processes that run on the PC. The TTL signals from the DIO card are shaped with line drivers and connected to a BNC break-out box with twisted pair flat cables to avoid reflections and cross-talk.

3.10.2 Radio frequency source

We generate a radio frequency (RF) signal for forced evaporative cooling with a direct digital synthesis (DDS) evaluation board (Analog Devices). The DDS board is programmed using 8 parallel data lines, 6 address lines and 6 other lines. In this way the RF amplitude and frequency can be controlled with the same 10 µs timing precision as the rest of the control signals. The frequency resolution was set to 24 bits corresponding to 12 Hz. A more detailed description of the DDS system will appear elsewhere [115].

Image processing

Three images of maximally $1.5 \times 10^6$ pixels are collected in $\approx 75$ ms per image. Subsequently the two dimensional optical density is calculated and displayed in real time. Two simple gaussian fits are performed separately to estimate atom number and cloud size “on the fly”. The set of three images is stored in the lossless 16 bits pgm format for further analysis.
Table 3.5: Overview of used analog and digital control lines.

<table>
<thead>
<tr>
<th>analog</th>
<th>digital</th>
</tr>
</thead>
<tbody>
<tr>
<td>cool/probe EOM</td>
<td>camera trigger</td>
</tr>
<tr>
<td>cool/probe AOM</td>
<td>probe shutter</td>
</tr>
<tr>
<td>pump AOM</td>
<td>cool shutter</td>
</tr>
<tr>
<td>repump EOM</td>
<td>repump 1 shutter</td>
</tr>
<tr>
<td>dispenser</td>
<td>repump 2 shutter</td>
</tr>
<tr>
<td>miniwire 1</td>
<td>pump shutter</td>
</tr>
<tr>
<td>miniwire 2</td>
<td>MOT coils on/off</td>
</tr>
<tr>
<td>miniwire 3</td>
<td>RF on/off</td>
</tr>
<tr>
<td>miniwires 4, 5 and 6</td>
<td>DDS 1-8 data</td>
</tr>
<tr>
<td>compensation coils 1</td>
<td>DDS 1-6 address</td>
</tr>
<tr>
<td>compensation coils 2</td>
<td>DDS 1-6 other</td>
</tr>
<tr>
<td>compensation coils 3</td>
<td>AO trigger 1</td>
</tr>
<tr>
<td>MOT coil 1</td>
<td>AO trigger 2</td>
</tr>
<tr>
<td>MOT coil 2</td>
<td>AO trigger 3</td>
</tr>
<tr>
<td>Y bias coils</td>
<td></td>
</tr>
<tr>
<td>chipwire Z</td>
<td></td>
</tr>
<tr>
<td>chipwire box</td>
<td></td>
</tr>
<tr>
<td>RF amplitude</td>
<td></td>
</tr>
</tbody>
</table>

3.11 Concluding remarks

The described setup forms a state of the art machine for cold atom experiments that is especially suited for studying the 1D regime. In the design emphasis was put on simplicity and compactness, resulting in a reliable and stable setup for BEC production. The design and thermal analysis of the novel microtrap are discussed in some detail forming a basis for improvements and more general applications. The next chapter describes how this setup is used. One elementary cycle that leads to the production of a BEC every 10 seconds is detailed.