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Master Thesis in Physics

submitted by

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born in Heidelberg

2021

Building a microdrop on demand system to load atom traps in ultracold quantum gas experiments

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 $29^{\rm th}$ of October 2021

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Evidence in physics, like in many other scientific fields, is backed by reliable and significant data. Starting with a prediction one often needs to take many measurements till the data reaches a significant state to underline the prediction or dismiss it. Producing data through measurements knows many limits. One limit is the time needed for one measurement which is ~ 2 seconds in our experiment. The first cooling step has the biggest share. Hence the goal of this thesis is to develop a technique to accelerate the cooling process by developing a new setup. The idea is to implement a drop on demand system which replaces the Zeeman slower. My goal is to produce $\sim 100 \mu m$ sized droplets from the element I want to experiment with. The next step, which lies beyond the goals of my thesis is to eject them into the vacuum chamber. There the droplets can be evaporated with a laser and a small amount of the evaporated atoms can be trapped by our MOT. In my thesis I will present a way to produce $\sim 100 \mu m$ sized microdrops at the rate of a few kHz, how to image them and how to hit them with a laser. All my experiments were done with water. Calculations and resulting estimations for rubidium are included as well as further ideas and suggestions on how to improve the setup to reach the final goal of implementing it into a vacuum chamber.

Bau eines micropdrop on demand Systems zum Beladen von Atomfallen in ultrakalten Quantengasexperimenten

Wissenschaftliche Beweise und Belege werden in der Physik, wie in vielen anderen Naturwissenschaften, gesichert durch verlässliche und signifikante Daten. Beginnend mit einer Vorhersage braucht es oft viele Messungen bis ausreichend Datenpunkte gewonnen wurden, um signifikante Ergebnisse zu haben, die sich mit der Vorhersage decken, oder diese verwerfen. Für statistische Signifikanz werden viele Messungen benötigt, sodass die Dauer eines Messzyklus ein limitierender Faktor sein kann. In unserem Experiment dauert ein solcher Zyklus aktuell $\sim 2s$ Dabei entfällt der größte Anteil auf den ersten Schritt im Kühlprozess. Deshalb ist das Ziel dieser Masterarbeit eine Technik zu entwickeln, um den Kühlprozess durch einen neuen Aufbau zu beschleunigen. Die Idee ist ein drop on demand System zu verwenden, welches den Zeeman-Slower ersetzt. Mein Ziel ist es, Tropfen aus dem Element, mit dem wir experimentieren möchten, im μm Bereich zu erzeugen. Der nächste Schritt, welcher nichtmehr zu den Zielen dieser Arbeit gehört, ist diese in die Vakuumkammer auszustoßen. Dort werden die Tropfen dann mit Hilfe eines Lasers verdampft und ein kleiner Teil der verdampften Atome kann durch unsere MOT gefangen werden. In meiner Arbeit werde ich eine Möglichkeit aufzeigen, Tropfen mit einer Wiederholungsrate von einigen kHz im μm Bereich zu produzieren, diese abzubilden und sie mit einem Laser zu treffen. Alle Experimente für mein Setup habe ich mit Wasser ausgeführt. Die Rechnungen und darauß folgenden Abschätzungen für Rubidium, sowie Ideen den Aufbau weiter zu optimieren, um das Ziel zu erreichen, kleine Tropfen in der Vakuumkammer zu verdampfen, sind ebenfalls enthalten.

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Introduction

1

A crucial component besides the precision of the system in our field of research, as in nearly every field of research is the resilience of data. Gaining statistical significance therefore is the main goal one wants to achieve. This gets possible when the measurements one takes can be replicated over and over again. As we deal with quantum states and hence always probability distributions it can sometimes take not only hundreds or thousands of runs but millions to produce statistically significant data. Depending on the experiment and the effect one wants to measure, this takes many iterations of the same process. This results in the time duration of one experimental cycle being a critical and limiting factor for the whole experiment. If for example one needs data from 10,000 experimental runs for valid predictions and one experimental run takes 10 seconds, the experiment needs to run for more than 24 hours straight without any interruptions. With 10 mio. experimental runs it would already take three years of continuous experimental cycles.

The goal of this thesis is to show a way to accelerate the current experimental cycle of our experiment. One cycle now takes roughly two seconds but could get as fast as one millisecond with the proposed technique resulting in an increase in efficiency of up to three orders of magnitude. Experiments that now would require millions of cycles and years of experimenting could be done in days. The longest process in one experimental cycle of our setup is the first cooling step, where the atoms are cooled with the Zeeman slower. Here hot atoms which are evaporated from the oven get slowed down with a combination of a counter propagating laser beam and a magnetic field gradient which generates a position dependent Zeeman splitting. This keeps the atoms resonant to the counter propagating laser beam forcing them to absorb photons and consequently an impulse in opposite direction of their trajectory.

The Idea is to directly shoot small amounts of the element we want to experiment with in the form of microdrops in the middle of the experimental chamber. With a laser these droplets can be evaporated and the fraction of atoms, which are slow enough to get caught by the MOT beams, can be used to do the experiment. This means the new limiting factor would be the frequency with which one can generate microdroplets and evaporate them in the experimental chamber.

This complete setup is to extensive for my thesis. This is why this thesis may reads a bit like

work in progress as it still is exactly that, because there are many steps one needs to think of and many methods one needs to develop. In this thesis I first concentrated on calculating and estimating if there is a realistic chance to make the setup work. Therefore I adapted some theory from Schäfer [1] on droplet formation and evolution. This included building a setup, which works for water at atmospheric pressure. Building this setup and controlling the necessary parameters was one of the main challenges. Furthermore I imaged the droplets with a CCD camera. It became clear, that the back pressure is a crucial parameter and needs to be as constant as possible. Therefore I build a small setup with a stepper motor and an arduino and as a last step I build a small laser setup to show that I am able to hit the droplets. I will make further suggestions at the end of my thesis on what to implement next in this setup to achieve the goal of replacing our MOT with a drop on demand system.

Idea / Theoretical background

In our current setup loading our MOT takes 2-4 seconds depending on the experiment. This process includes evaporating the atoms from our oven, transferring them through the Zeeman slower into the MOT and keeping them in the middle of our MOT with the MOT beams and the magnetic field. Hence running the experiment without any disturbances for a whole week would provide a bit over 300,000 data points, ignoring that issues might occur leading to interruptions in the experimental run. The goal of this thesis is to accelerate this process in the ideal case by many orders of magnitude replacing the Zeeman slower completely. As shown in chapter 5 this would not only fasten up our experiment cycles but also free some space on the experimental table as the Zeeman slower is quite large. However freeing space on the experimental table is not the main goal but more a pleasant side effect. Collecting 300,000 data points with a new setup loading our MOT with a microdrop on demand system and evaporating the droplets in the middle our trap could be done in less than a minute when the droplets are ejected at 7kHz. This would be an enormous improvement.

2.1 Droplet basics

In nature droplets occur in different sizes like rain drops or the water dust of very small droplets on a waterfall. When drawn or indicated in a comic, droplets often have a round bottom and a sharp tail. This imitates a falling rain drop, which due to its velocity and atmospheric friction deforms into this typical shape everyone thinks of when speaking about drops. In reality without external influences like air friction the shape of a drop is always spherical as it tries to minimize its surface energy. With decreasing droplet size this effect becomes even stronger since the surface-to-volume ratio increases. Keeping this in mind, I expect the generated droplets to be perfectly round spheres.

As our experiments even for many atoms experiments only need $\sim 10^9$ atoms, I want to create droplets as small as possible to avoid contaminating our vacuum chamber with more material than necessary. Therefore I want to eject droplets with diameters as small as possible. A very common and well known way to disperse liquid into micron sized droplets was used by Millikan in 1910 in his famous oil-drop experiment, where he precisely measured the electron charge. The technique he used was proposed in theory by Bernoulli. His principle states that an increase in the speed of a fluid occurs simultaneously with a decrease in static pressure or a decrease in the fluid's potential energy [2]. Millikan used this to to draw a liquid from a container along the way of the air current to subsequently spray it our in a fine mist. However in Millikans experiment the droplet significantly varied in size and charge and did not have well defined trajectories. Therefore this old but approved technique is not applicable for my project.

The first Idea I had to eject small droplets into our MOT was to use electrospray. Electrospray is a method to disperse liquid with the help of an electric field. The resulting spray contains small polarized droplets with a very narrow size distribution. High voltage is applied to a liquid supplied through an emitter. Ideally the liquid reaching the emitter tip forms a Taylor cone, which emits a liquid jet through its apex [3]. A Taylor cone forms, when a small volume of electrically conductive liquid is exposed to an electric field with the force F_{ef} on the liquid. Here the shape of the liquid starts to deform from the shape caused by the regular surface tension F_{st} alone. With increasing voltage the effect of the electric field dominates. As soon as $F_{ef} > F_{st}$, a cone shape begins to form with convey sides and a rounded tip. At a certain threshold voltage the slightly rounded tip inverts and emits a jet of liquid. This is called a con-jet and is the beginning of the electrospraying process [4]. On the way to the cathode the solvent evaporates and leaves charged droplets at the Rayleigh limit behind. Through strong coulomb forces the charged droplets split up in even smaller droplets with a trajectory, which is better defined, than at Millikans experiment. The electrospray is designed to produce very small but charged droplets. One challenge for this setup now would be to provide free electrons to get rid of any charges. This may be difficult but in the end was not the main issue why we decided not to pursue the electron spray idea.



Figure 2.1 Scheme of Electrospray setup from [5]. On the left one sees the nozzle and the formation of the Taylor cone. The solvent than evaporates and the droplets split up into more smaller droplets because of the Coulomb fission. Hence one ends up with very small, charged droplets.

The main problem for my setup comes with the solvent. From a chemical side of view one can dissolve lithium, which is used in our experiment, in ammonium and form a solution containing solvated electrons. With the free electrons, the problem of charged droplets we have, may already be solved. However the main problem is the evaporating solvent. Our chamber needs to maintain a very high vacuum at $\sim 10^{-12}$ mbar. An evaporative solvent would disturb our experiment dramatically as it hinders the laser and might even not evaporate completely from the droplet and form clusters with properties completely different to pure lithium. For this reason the idea was rejected even if it looked promising at first.

The second idea was to use a microdrop on demand system. This systems are for example used for printing or medical purposes. Commercial systems are available for regular liquids and atmospheric pressure. They can generate droplets with different sizes at different frequencies. Looking into the field it became clear that already available systems in the regime I want to work are very expensive and would need many modifications to work with a liquid metal and in high vacuum. Therefore we decided to build a setup ourselves. Thus we could gain our own experience and expertise in how this microdrop on demand systems work and customize the system the way we need it right from the beginning. The requirements are to eject droplets with a stable trajectory, constant size and repetition rate in the low kHz regime. The stable trajectory is needed to place the droplets reliable in the middle of the trap to evaporate them and afterwards catch the single atoms with the MOT lasers. As the waist of these lasers is < 1mm, high directional precision is needed. The constant size is important as I want to evaporate the droplets. For the evaporation I want to use a laser which will be continuously pulsed over a certain time with a certain energy. As the amount of energy needed to evaporate the droplet depends considerably on the diameter, the goal is to keep the variance of the diameter as low as possible. The frequency of the laser to evaporate the droplets, the other lasers to prepare the atoms and the imaging setup depend on the frequency the droplets are ejected with. Hence a constant repetition rate and distance between the droplets is crucial too. To see if one is able to build a setup which meets all the requirements, I built a test setup ejecting water droplets at atmospheric pressure.

In my setup droplets form, when water seeps out of a thin tube. The adhesion to the tube material makes the liquid stick to the bottom edge. Over time it accumulates into a droplet increasing in size until it breaks of, when its weight, F_g , exceeds the retaining surface tension F_{σ} , at the outer tube circumference, $\sigma \pi d_{od}$. This means that even at a tiny orifice the droplet formation depends mainly on the outer diameter d_{od} of the tube. Considering the outer diameter of the capillary is $\sim 1mm$ one gets droplets with a diameter of roughly $\sim 3mm$. As the goal is to achieve droplets with a diameter of $\sim 100\mu m$ it is necessary to overcome the adhesion effect at the edge. This is done by pushing the water through the nozzle using back pressure. The results can be seen in fig. 2.2 illustrated as well as in reality. The liquid jet now has a diameter comparable to the orifice, but the splitting, if it happens at all, does happen randomly. The idea is to cut the stream into small portions, which will form spheres due to minimization of their surface energy. This can be realised by

pulling the jet back into the capillary through an abrupt decrease in back pressure. The jet will separate and the droplet forms through the inertia the little water volume has. If the change in back pressure is fast enough, the force is high enough to separate small volumes of water from each other. This is illustrated in fig. 2.2 and below one can see real droplets in my experiment. For the real droplets it seems like directly below the orifice there are several small droplets before they form into a big droplet. This is because the imaging for this picture was tuned in a way that one picture integrates over ten droplets, as discussed in chapter 5.4. In the beginning the droplets sometimes seem to overtake each other and do not keep a constant distance. After $\sim 2mm$ the droplets are always in the same spot and keep a constant distance. The diameter of the droplets in the picture is $\sim 250\mu m$. This is due to the slightly bigger orifice I worked with in the first test runs as capillaries with slightly bigger orifice are cleanable when they get clogged, which can happen regularly. This will be discussed in detail in chapter 5.



Figure 2.2 (a) Faucet-like droplet formation. The back pressure comes from the gravitational pressure of the water column. The droplet size depends on the outer tube diameter due to adhesion to the bottom of the capillary. (b) Applying manual back pressure results in a liquid jet. The jet has a diameter comparable to the size of the orifice. (c) Due to rapid back pressure variation the jet breaks up into small droplets. In the picture at the bottom right it seems like many droplets form into one droplet directly after getting ejected. This is an optical illusion and due to the shutter times from the imaging. In reality the droplets are just nearly perfectly overlapping. For better illumination at this example I choose to tune the shutter time in a way that it integrates over 10 droplets. In the beginning the droplets sometimes seem to overtake each other and do not keep a constant distance. After $\sim 2mm$ the droplets are always in the same spot and keep a constant distance. The graphical illustration is from[1]. The real pictures have been taken with my setup.

2.2 Theory

J. Schäfer[1] built a comparable setup to mine. Even if the purpose of his setup differs from mine, some fundamental parts of the theory behind the creation of microdroplets are comparable. That is why I adopted and adapted parts of his theory for my purpose.

With a simple model one can describe the parameters of the system needed to successfully generate μm sized droplets. One can assume that in a time period Δt the tube experiences a rapid increase of back pressure followed by a subsequent decrease back to equilibrium. This results in a liquid column, ΔV , pushed out of the orifice during the time $\Delta t/2$ at the average velocity $v_{av} = (\Delta V/A_{or})/(\Delta t/2)$. During the second half of the period the liquid column gets pulled back into the tube with the negative velocity $-v_{av}$ following the negative pressure gradient. Through the total deceleration from v_{av} to $-v_{av}$ during $\Delta t/2$ a droplet separates from the liquid column. The droplet contains almost all the liquid from the column ($\Delta V = V_{dr}$), if the break-off happens near the orifice when the deceleration is at its maximum. The inertial force acting on the droplet consists of its mass $m = \rho V_{dr}$ times the deceleration $-2v_{av}/(\Delta t/2)$. As soon as the restraining surface tension $\sigma \pi d_{or}$ with the orifice diameter d_{or} is exceeded, the droplet breaks off. For the droplet formation one can derive the following equation with F_{if} the inertial Force and F_{st} the restraining surface tension.

$$F_{if} < F_{st} \tag{2.1}$$

$$\sigma \pi d_{or} < \rho v_{dr} \frac{-2v_{av}}{\Delta t/2} \tag{2.2}$$

$$\sigma \pi d_{or} < \rho \frac{4}{3} \pi \left(\frac{d_{dr}}{2}\right)^2 \frac{-4v_{av}}{\Delta t} \tag{2.3}$$

$$\sigma d_{or} < \rho \frac{4}{3} \left(\frac{d_{dr}}{2}\right)^2 \frac{-4}{\Delta t} \frac{v_{dr}}{A_{or}(\Delta t/2)} \tag{2.4}$$

$$\frac{9}{8}\frac{\sigma}{\rho} < \left(\frac{d_{dr}^2}{d_{or}}\right)^3 \frac{1}{\Delta t^2} \tag{2.5}$$

Neglecting $\frac{9}{8}$ on the left hand side one gets

$$\frac{\sigma}{\rho} < \left(\frac{d_{dr}^2}{d_{or}}\right)^3 \frac{1}{\Delta t^2} \tag{2.6}$$

The term on the right hand side contains only properties of the liquid. To produce a droplet of sufficiently small size d_{dr} , the orifice diameter d_{or} and the time period of the pressure fluctuation Δt have to be small enough to satisfy the equation above. As the orifice can easily get clogged by impurities, it cannot be arbitrarily small. Furthermore it gets increasingly hard to overcome the surface tension induced pressure $p_{\sigma} \equiv F_{sigma}/A_{or} = 4\sigma/d_{or}$ preventing the liquid from being pushed out, when the orifice gets to small. Water for example has an outflow restraining pressure of 300mbar for an orifice size of $10\mu m$ [1]. The glass capillaries I got from Hilgenberg GmbH had an orifice size of $50\mu m$. The orifice size of the self made ones depend on the level of polishing. This will be discussed in chapter 5.1.1. It is safe to say that I was able to get the orifice to a diameter between $50 - 100 \mu m$ so I will assume $100\mu m$ as an upper limit. For this size the pressure has to fluctuate with a frequency in the kHz regime. To achieve very small but very fast motions moving volumes less than a nanoliter, piezoelectric transducers can be used. For my purpose the inverse piezo effect, a voltage transferring linearly into a mechanical deformation, is used. Therefore the piezo is attached around the capillary to induce radial contraction. The principles are explained in chapter 5.1.2. With the theoretical background of generating the droplets, I now want to discuss the liquid one wants to use. For my test setup I use distilled water, but as I want to load a MOT with this setup, it needs to work with an alkali metal. Currently we use Li6, an isotope of lithium which is a fermion, in our experiment. Lithium has many favourable properties, which in detail are discussed here [6]. The main deal-breaker why lithium can not be used in the setup designed by me is the high melting point. Lithium melts at 180 °C. At this temperature the PIB (see 5.1.2) I use as a glue liquefies as well as the solder joints on the piezo, as they do not tolerate temperatures this high very well. The high temperatures for lithium also were the main concerns from the scientific staff from the companies I asked to build a customized drop on demand system for lithium. Hence I decided to do the calculation and estimates with rubidium, which melts at around 50 °C. Rubidium also is an alkali metal. Unlike lithium, rubidium does not have a stable isotope which acts fermionic. Nevertheless many experiments in our field of research are done with bosons i.e. one can find many applications for a drop on demand system with rubidium, even if it probably will not work for the experiments we are doing.

2.2.1 Estimations for rubidium

As rubidium is very reactive with air and not too easy to handle especially in the first try and error phase, the experiments I did were not done with rubidium but with water. Nevertheless the estimations my setup will work with rubidium are important, to see, if there is a chance to succeed. The estimations and calculations were done with the values for rubidium in table 2.1.

Density	$\rho = 1.532 \text{ g/cm}^3$
Mass of one atom	$m = 1.419 \times 10^{-21} {\rm g}$
specific heat capacity	$c=0.363~{\rm J/gK}$
heat conductivity	$\kappa = 58 \text{ J/(s m K)}$
Enthalpy of vaporization	$\Delta Q_V = 887.46 \text{ J/g}$

Table 2.1 Relevant properties of rubidium for my experiment [7].

For my calculations I assume $d \simeq 100 \mu m$ for the diameter of my droplets. The diameter mainly depends on the orifice of the glass capillary. Hence it can be adjusted in the polishing process. Extrapolating the diameter of the nozzle one sees under the microscope, while polishing to the achievable droplet diameter is rather difficult. To get the final diameter the capillary has to be mounted into the setup and produce droplets which one needs to measure. As one will see later $d \simeq 100 \mu m$ is an adequate guess for the diameter of the droplets and my estimations.

The Volume V of one droplet with diameter d is

$$V = \frac{4}{3}\pi \frac{d^3}{2} \simeq 5 \times 10^{-7} \text{cm}^3$$
 (2.7)

and the mass

$$G = V\rho \simeq 8 \times 10^{-7} \text{g.}$$

Thinking about heating up my droplets till evaporation without producing a plasma, I am now interested in two quantities: The energy U_E to evaporate my droplet and the time t I have for my laser pulse to evaporate my droplet adiabatically. I want to evaporate them adiabatically, since I do not want to produce a plasma like in fig. 4.1. The energy U_E consists of two parts. The first part U_{E_1} is the energy needed to heat the droplet from ~ 320K to the boiling point. At nearly 0Pa it is < 114Kⁱ. Hence $\Delta T < 114$ K.

$$U_{E_1} = c\Delta TG \simeq 3.3 \times 10^{-5} J \tag{2.9}$$

ⁱFor 1Pa the literature value is 434K according to [7].

The used boiling point is the literature value for rubidium at 1Pa, i.e. $\Delta T < 114$ K is an upper limit as in ultra high vacuum the boiling point of rubidium will certainly drop even more. The second part is the enthalpy of vaporization U_{E_2}

$$U_{E_2} = \Delta QG = 7.12 \times 10^{-4} J \tag{2.10}$$

which is considerably bigger than U_{E_1} resulting in

$$U_E = U_{E_1} + U_{E_2} \simeq 7.45 \times 10^{-4} J \tag{2.11}$$

One can now calculate with the heat conductivity κ the time one needs to heat up one droplet by $\Delta T < 114K$ and evaporate it

$$t = \frac{(U_{E_1} + U_{E_2})d}{\pi (d/2)^2 \kappa \Delta T} \simeq 6.6 \times 10^{-7} s \tag{2.12}$$

To estimate if one has $6 \times 10^{-7}s$ when hitting the droplets with the laser, one needs to know the velocity of the droplets after leaving the capillary. This can be done theoretically like Schäfer [1] did. For my setup this calculation does not hold, since I applied a back pressure to eject the droplets which is not comparable to Schäfers setup. For further estimations I therefore will take $v_{dr} \approx 5m/s$. This is the velocity I measured for a frequency of 7 kHz. This measurement was of course only done with water, but the approximation should also be valid for rubidium. If one focuses a laser to a waist size of $\sim 200\mu m$, one gets that the droplet needs $\sim 4 \times 10^{-5}s$ to pass through the focus of the beam, two orders of magnitude more then the $\sim 6 \times 10^{-7}s$ one needs to heat it up adiabatically. One can also estimate the power the laser needs to provide. As we have $\sim 4 \times 10^{-5}s$ max. one will need a laser with > 10W power. This power is only needed for a short period of time, why one can use a pulsed laser, which can easily supply a peak power in the 100W regime for short periods. After heating up the droplet till it evaporates, the velocity distribution of the atoms in the gaseous phase is given by the Maxwell-Boltzmann distribution

$$F(v_a) = 4\pi \left(\frac{m_a}{2\pi k_B T}\right)^{\frac{3}{2}} v_a^{\ 2} \exp^{\frac{-m_a v_a^2}{2k_B T}}$$
(2.13)

with v_a the velocity of the atoms, $m_a = 1.42 \times 10^{-25} kg$ the mass of one atom, $T \simeq 434 K$ the evaporation temperature and k_B the Boltzmann constant.

Furthermore one can calculate the average velocity of the atoms in the gas

$$\bar{v}_a = \sqrt{\frac{8k_BT}{\pi m_a}} \simeq 328 \text{ m/s}$$
(2.14)

As our MOT is only able to capture atoms with a velocity up to 50 m/s, the average atom is an order of magnitude faster than what we can capture and will not be resonant with the trapping beams of the MOT. Hence all atoms above a velocity of 50 m/s will be lost to the experiment.

Integrating over the Maxwell-Boltzmann distribution from $0 \le v_a \le 50$ gives the percentage of atoms our MOT can capture.

$$\int_{0}^{50} 4\pi \left(\frac{m_a}{2\pi k_B T}\right)^{\frac{3}{2}v_a{}^2} \exp^{\frac{-m_a v_a{}^2}{2k_B T}} dv = 0.38\%$$
(2.15)

This result means that ~ 99.6% of the atoms are too fast for our MOT. At first sight this looks like all atoms are gone. Considering that a $100\mu m$ droplet consists of $G/m = 5.65 \times 10^{14}$ atoms, one is left with $\simeq 2.1 \times 10^{12}$ atoms. This is 2-3 orders of magnitude more than the amount of atoms we now have in our trap, when we are doing many particle experiments. Of course one than has to deal with the ~ 99.6% of atoms that cannot be used. This will be discussed in the section Next steps.



Figure 2.3 Here the Maxwell-Boltzmann distribution is visualized for the given parameters. Green is the amount of atoms our MOT can catch. Red is the amount of atoms that are to fast for our MOT. The orange dashed line in middle is at the most probable velocity.

From the estimations and calculations one can see that in theory loading a MOT with a microdrop on demand system is possible and promising. Implementing such a setup in a vacuum chamber and operating it nevertheless will be a difficult task and lies beyond the goal of this master thesis. I still will suggest some ideas for improvements on my setup which can be implemented but were not implemented by me because of the limited time frame.

2.3 Cooling through expansion

Until now, I have not considered the cooling through expansion in my setup. For the number of atoms we end up with in our trap, two factors are important. The first one is the energy the laser transfers into the droplets and hence their vapour pressure. As one does not only want them to boil a bit but expand fast, one will likely heat them up to a higher temperature, to increase the inner pressure and hence let them expand faster. If for example one heats the droplets not only to the boiling point of 434K but to 769K where the vapour pressure is 10kPa, one initially ends up with only 8.4×10^{11} atoms slower than 50 m/s and therefore slow enough for our MOT. In this first calculation I neglected any cooling effects through expansion. Through the sudden expansion of the droplet when heated up, all atoms dispense. This expansion costs the droplet a lot of energy which is taken from the kinetic energy of the atoms in the droplets resulting in a velocity loss and therefore a reduction in thermal energy. One can imaging this process as a gaseous sphere with a density gradient. In the middle the density is maximal and with growing radius one gets less and less atoms in the outer "shells". The cooling happens, because the atoms must perform work as they are accelerated away from the centre of the sphere. The work they need to perform is represented by the collisions with atoms in an outer shell which are slower and need energy for their acceleration away from the centre. This only happens, if the mean free path length of the atoms is way smaller than the droplet itself. One can estimate the mean free path length considering the Maxwell-Boltzmann distribution to

$$\lambda = \frac{1}{\sqrt{2\pi n d^2}} \simeq 10^{-20} \ll d$$
 (2.16)

with the diameter $d \simeq 100 \mu m$ and the number of particles $n \sim 3 \times 10^{28}/\text{cm}^3$. I estimated the the cross section σ with πd^2 as this is the geometrical cross section for the collision of two spherical particles. The factor $1/\sqrt{2}$ comes from equilibrium considerations including the Maxwell-Boltzmann distribution. The mean free path length is way smaller than the diameter of the droplet, meaning the assumption is valid. We now wanted to know how big the cooling effect through expansion can become. For the gaseous sphere one can assume $VT^{f/2} = \text{const.}$ with f = 3. As the Volume V is anti proportional to the density n (I will define the density here in particles/cm³) one gets

$$n \propto T^{f/2}.\tag{2.17}$$

Hence one can directly correlate the loss in temperature to the loss in density. For the ideal case one can assume that the density in the beginning is the density of our droplet.

The underlying assumption is, that the droplet changes from the liquid to the gaseous phase in an infinitesimal short time and then expands. The density in the beginning for this assumption is $n_{si} \sim 10^{28}/\text{cm}^3$. In reality, this will not happen instantaneously and the droplet starts to evaporate atoms before the centre is in the gaseous phase and one will get a pressure gradient along the radius. For an upper limit, I will assume now, that the distance between each particle needs to be three orders of magnitude higher to have the whole sphere in the gaseous phase. This means, one loses nine orders of magnitude in density and $n_{sul} \sim 10^{19}/\text{cm}^3$. This is only a rough estimate and the truth will lie in between but it helps to get an idea if it is worth to pursue this proposal. I now want to consider two possible outcomes. For the first one I assume that there is a MOT that can cool the atoms further down. For the second one the atoms get directly transferred into a dimple trap without further cooling through a MOT.

With a MOT

When one has a MOT after the expansion of the gaseous sphere, one can capture atoms around ~ 10K. Assuming one can start with a droplet of temperature ~ 1000K one wants to lose two orders of magnitude in temperature and therefore will lose three orders of magnitude in density considering (2.19). Starting with $n_{si} \sim 10^{28}/\text{cm}^3$ one will end up with $n_{fi} \sim 10^{25}/\text{cm}^3$. This would be ~ 10^{22} atoms for a millimetre sized MOT. Starting with $n_{sul} \sim 10^{19}/\text{cm}^3$ one will end up with $n_{ful} \sim 10^{16}/\text{cm}^3$. Heating up the droplet to ~ 1000K will of course change the results from (2.15). Though if cooling through evaporation would work as described, the amount of atoms one can capture with the MOT would be higher than predicted in (2.15).

Without a MOT

Without a MOT one needs to cool the atoms down to ~ 1mK. Starting with 1000K one now wants to lose six orders of magnitude in temperature, ending up with twelve orders of magnitude less in density and hence starting with $n_{si} \sim 10^{28}/\text{cm}^3$ one will end up with $n_{fi} \sim 10^{16}/\text{cm}^3$. Starting with $n_{sul} \sim 10^{19}/\text{cm}^3$ we end up with $n_{fi} \sim 10^7/\text{cm}^3$. Assuming a trap size $< mm^3$, in the upper limit scenario one has $n_{fi} < 10^4/\text{mm}^3$. This will not be enough for many particle experiments but can still be sufficient for few particle experiments. Because of the Maxwell-Boltzmann velocity distribution one will not be able to capture every atom contained in that space but it gives a rough estimation if the cooling through expansion would be sufficient to for example trap atoms that are not resonant to a MOT. One can conclude that, if everything works in the limits of my assumptions, it would be possible to load the trap for few particle experiments even without a MOT.

Zeeman slower & Magneto-optical trap

In this chapter I want to give a brief overview about the tools we currently use, which are planed to be replaced or connected to. The Zeeman slower and the Magneto-optical trap (MOT) are both essential in slowing the atoms down and therefore reducing their temperature after they evaporate out of the oven. As already mentioned the goal of my thesis was to develop a new setup in which the Zeeman slower could be replaced and the atoms can be directly loaded into the MOT. This could not only accelerate the experiment but also save a lot of space on the experimental table. Certainly there are many more stages one has to go through to get a well behaved and controllable fermi gas like we have in our experiment. A more detailed overview on how this is done can be found in the PhD Thesis of Friedhelm Serwane *Deterministic preparation of a tunable few-fermion system* [8].

3.1 Zeeman slower

The process of controlling the atoms starts with an oven. There the element one wants to experiment with is heated up until atoms evaporate and a cloud of atoms leave the oven. The thermal velocity directly correlates with the temperature

$$v_{th} = \sqrt{2\frac{k_B T}{m}}.$$
(3.1)

This equation holds for three dimensions and defines the most probable speed. Hence the atoms leave the oven with ~ 1000m/s and need to be slowed down. Therefore the Zeeman slower is the main tool of the first stage one has to complete in order to slow down atoms. This is done with a magnetic field gradient and a counter propagating laser beam. The tube, the atoms travel through, is wrapped with thin copper coils, which generate a magnetic field. The number of windings directly correlates with the strength of the magnetic field. In the beginning the magnetic field acting on the atoms is quite strong and gets gradually weaker with the distance the atoms travel. This magnetic field induces a Zeeman splitting in our atoms which makes them resonant to the counter propagating laser light. Their transition frequency becomes Doppler shifted by $\delta_v = -kv$ with k the wave vector of the laser beam. As they travel towards the laser beam, they see the laser light blue-detuned so the frequency

of the light matches the transition frequency. This leads to an absorption of photons with the net momentum \hbar/λ with $\lambda = 671nm$ in our experiment and therefore they decelerate. This photon is then emitted again in a random direction. Hence the atom gains back the lost momentum but as the momentum from absorption is always lost in the direction of flight and the emission happens randomly in every direction, over many iterations statistically there is no change in velocity through emission but only through absorption. This results in the atoms no longer being resonant to the laser light as they see the laser less blue detuned. Hence the Zeeman splitting has to be reduced, resulting in the atoms being resonant again. This process inside the Zeeman slower slows the atoms down from 800m/s to around 60m/s[9].



Figure 3.1 Sketch of a Zeeman slower. On the left is the oven where in our case Li6 is evaporated. The Li6 than travels in the gaseous phase through the Zeeman slower where we hit the atoms with a counter propagating laser. The atoms absorb momentum from the photons. To maintain resonance between the photons and the transitions from ground state to excited state, we apply a magnetic field which induces a Zeeman splitting. Due to the magnetic field gradient the atoms can absorb the energy of the photons during the whole process.

3.2 Magneto-optical trap

The Magneto-optical trap (MOT) is the second step of cooling the atom beam further down. This time the atoms are not slowed down from only one direction but from six different directions. This is done with three lasers and three mirrors reflecting the laser beams resulting in six counter-propagating laser beams which are not resonant for atoms sitting in the middle of the trap. If atoms which increase their velocity through collision, the laser appears blue detuned for them and they get resonant. This happens since we again have a magnetic field inducing a Zeeman splitting and making the atoms resonant. This way the atoms absorb photons resulting in a damping force proportional to their velocity. This adds spatial confinement as the force driving the atoms back into the middle of the trap now is not only velocity but also position depending. The magnetic field has the same effect as in the Zeeman slower as it increases the Zeeman shift proportional to the distance of the atoms from the middle of the trap. This of course only works for atoms which are in the

right regime to be resonant with the laser beams. Atoms which are too fast will just leave the trap without interacting with the laser enough to get slowed down and pushed back to the middle of the trap. This is an important aspect considering the amount of atoms one can catch when a drop of for example rubidium is evaporated as the velocities of many atoms will beyond the regime a MOT can trap. One will later see that only a small part of the atoms are slow enough for the MOT to catch them. As I explained beforehand in (2.3) there can be a way where one can even replace the MOT if the atoms are cooled down enough through expansion and the density is still high enough to capture enough atoms directly in a dimple trap. Even if this could work in theory, there is still much work to be done. Thus I will not pursue this as a goal here.



Figure 3.2 [8]

Laser

4.1 Hitting the droplets

Evaporating the droplets in the middle of the vacuum chamber can be done with a high power laser pulse as suggested in 2.2.1. In this chapter I want to especially take care about the waist size of the laser compared to the size of the droplets, the material properties of the droplets, the time frame for the laser pulse and the requirements the laser setup needs to fulfil to evaporate atoms to load our MOT.

4.1.1 Waist size of the laser

In the thesis of Alexander Klein [10] the impact from different waist sizes to water droplets is carefully probed. Figure 4.1 shows the experiments he carried out. Even if the diameter d_D of the droplets is roughly 20 times bigger than the diameter of the droplets I want to dispense, the results are partly conferrable. One can see that a tightly focused beam with $\omega_0 \ll d_D$ leads to an explosion of the droplet with a bright light in the centre of the explosion. Klein describes the laser impact leading to optical breakdown in the water with the resulting plasma emitting a white glow and driving the fluid dynamics. In the first picture after $30\mu s$ one can even see a spherical shock wave emitted from the location of the laser impact. It is intuitively clear that the droplet in this case is not even close to being heated adiabatically to the boiling point of water. Therefore it becomes impossible to capture a sufficient amount of atoms because they are either too hot and thus too fast or not completely in the gaseous phase and still joint together. For setup (b) $\omega_0 \simeq d_D$ the drop deforms in a liquid shield, which is propelled through the evaporated water that can be seen in the form of a nebular between the laser and the droplet. The nebular already comes closer to our application but still a lot of the material is wasted in the form of the liquid sheet the droplet is deformed into. (c) with $\omega_0 > d_D$ is quite comparable to (b). In (b) and (c) one can see that a bigger waist size leads to less plasma and the droplet does not explode into clusters of microdrops but evaporates a nebular. Nevertheless we want to avoid producing a plasma at all. Note that the pulse duration of the laser used here from Klein is rather short too and his explicit goal was to reach a plasma. So the results cannot

be directly transferred to my application but it gives a good impression that just focusing down a laser as far as one can go and shooting at the droplets will not necessarily deliver the expected results.



Figure 4.1 scheme of setup from [10]

As stated I do not desire to produce a plasma and instead want to heat up the droplets as slow as in the quite short time frame possible. I first need to determine the time frame I am operating in. Here the material properties are involved. I did the experiments with the current setup only with water but as one wants to switch to an alkali metal that can be used in our experiments I also did the theoretical calculations for rubidium. It turned out that rubidium is much more suited for laser-induced evaporation than water.

	Water	Rubidium
Diameter drop [cm]	100×10^{-4}	100×10^{-4}
Density [g/cm]	0.997	1.532
Specific heat capacity (c_p) [J/gK]	4.19	0.36
Thermal conductivity $(k) [J/(s m K)]$	0.6	58
Enthalpy of vaporization(ΔQ_V) [J/g]	2088	887
Mass of one atom [g]		141.877×10^{-23}

Table 4.1Material properties of water and rubidium [7].

The calculations for rubidium can be found in 2.2.1. Hence I will now only calculate the necessary energy for water. The goal is to calculate the time and energy one needs for the droplet to be adiabatically heated up by the laser. With that one can estimate the waist of the laser and the energy it needs to supply in during the pulses. I calculate the volume of the water droplet V_W at the given diameter with

$$V_W = \frac{4}{3}\pi \left(\frac{d}{2}\right)^3. \tag{4.1}$$

With ρ_W being the density of water the mass of one droplet is

$$M_W = V_W \rho. \tag{4.2}$$

The energy U_{W1} necessary to heat the droplet from around room temperature to the boiling point ($\Delta T \simeq 80K$) with c_p being the specific heat capacity can be calculated to

$$U_{W1} = c_p \Delta T M_W = 1.75 \times 10^{-4} J. \tag{4.3}$$

The second important energy U_{W2} is the enthalpy. This is the amount of energy ΔQ_V necessary to achieve the transition between liquid and gaseous phase to evaporate the droplets.

$$U_{W2} = \Delta Q_V M_W = 1.09 \times 10^{-2} J \tag{4.4}$$

One can directly deduce that the energy necessary to heat the droplet is only a fraction of the enthalpy. It is now interesting for me to know how much time I have to evaporate the droplet. Limiting factors for this part of the experiment are the thermal conductivity of the droplet, as one does not want to generate a plasma and explode the droplet, and the time the droplet is in the centre of the focused laser. With the help of the total energy calculated above and the thermal conductivity, one can now calculate the time to heat the droplet adiabatically

$$t = \frac{(U_{W1} + U_{W2})d}{\pi (d/2)^2 k \Delta T} = 0.46ms.$$
(4.5)

One now needs to compare this time to the time our droplet is in the focus of the laser. From chapter 2 one knows that the droplets need $\sim 4 \times 10^{-5} s$ to pass through the focus of our beam. This means for water one needs ten times more time to evaporate the droplets adiabatically than there is available. Luckily as I calculated in chapter 2 this is not the case for rubidium as the thermal conductivity is significantly better.

4.2 Setting up the optics

As calculated beforehand one does not have enough time to heat up the water droplets adiabatically. Nevertheless I wanted to set up a pulsed laser to at least hit the water droplets. Unfortunately the parts did not arrive yet so I can only sketch the idea. The LEDⁱ I ordered can provide 75W with a pulse width of 100ns. With an operating voltage of 9V this means one roughly needs 8A. This can be achieved with the help of capacitors. If one uses capacitors between the power source and the laser and builds in a switch, a current much higher than the current provided by the power source can be released for a short period. If one wants to limit the voltage drop ΔV to 0.5V, one can calculate the necessary capacity C to provide the current wit Q = It.

$$C = \frac{Q}{U} = \frac{8A \times 100ns}{0.5V} = 1.6\mu F$$
(4.6)

If one wants to use a higher current one can simply operate more capacitors parallel to each other. The LED I ordered can be operated with up to 40A. The more limiting factor here is the pulse width of 100ns. More power will be necessary if one wants to make use of the cooling effect through expansion as the vapour pressure of the droplet needs to be high as discussed in 2.3.

ⁱ720-SPLPL90-3 Mouser

$\mathbf{5}$

Setup

The technique of producing droplets in the size of $\sim 100 \mu m$ is not new at all and many companies offer solutions specialised for medical and biological research and commercial production. The main problem with the commercial available setups for our application is that they are designed only for common liquids like water or other solutions and not for liquid metals like lithium or rubidium we had in mind. The setup we want to implement in the experiment not only needs to reach the melting points of the used metal, which for lithium at $\sim 180^{\circ}$ C is quite high and will strain the glass and the piezo (especially at the soldering points) quite a lot. An even bigger requirement is the functionality in vacuum as the experiments in our MOT are carried out at very high vacuum. It soon became clear that reconstructing a commercial drop on demand system will not be easier than building one ourself from scratch.

The main components for this tool are the capillary and the piezoelectric crystal around the capillary, a high voltage source to control the piezo and an imaging setup to see if I am really able to produce droplets with the required size.

5.1 Capillary

For the first attempt we bought capillaries from Hilgenberg. They are made of borosilicate glass with a polished tip. The exact properties are shown in table 5.1.

Length	L = 130 mm
Outer diameter	$D_o = 1 \pm 0.025 \text{ mm}$
Inner diameter	$D_i = 0.722 \pm 0.05$
Tip	S = 0.139 mm
Outer diameter tip	$S_{D_o} = 0.5 \pm 0.02 \text{ mm}$
Inner diameter tip	$S_{D_i} = 0.05 \pm 0.0005 \text{ mm}$

 Table 5.1
 Properties of the borosilicate capillaries from Hilgenberg.



Figure 5.1 Side view of the capillaries we got from Hilgenberg.

I was already able to receive good results, but the capillaries kept breaking and clogging as I was improving the setup permanently. Given that the capillaries from Hilgenberg cost more than $50 \in$ per capillary, we decided to contact our own glass workshop at the Zentralinstitut Neuenheimer Feld. Ms Scheurich drew some capillaries for me. The outer diameter here is not as precise as from the Hilgenberg capillaries, but this is not too important for my setup. As long as the piezo fits around the capillary in the lower third, I could work with the self made capillaries. Making a tip with an inner diameter small enough for me to produce droplets with the required size was the main challenge. Therefor Ms Scheurich melted and twisted one side of the capillary down until she got a small tip. As they were handmade, not all capillaries turned out the same and some were just too big or too small diameter wise in order to work with them. Still, the self made versions were much cheaper.

To produce droplets with my own capillaries, I had to polish the tip, because melting the capillary down to a tip made the tip round. A round nozzle would cause strong wetting effects, making it unsuitable for stable microdrop generation. Hence it has to be polished to a smooth and even surface with successively finer grades. This was done with four grades of fiber polishing sheets from Thorlabs with grades between $30\mu m$ to $1\mu m$ and a bit of distilled water preventing the glass from slivering. In order to get the droplets as straight as possible out of the capillary, it is crucial to avoid an angle on the nozzle surface. To maintain a plane surface and prevent the capillary from breaking during polishing, I let the workshop manufacture a device to support the polishing process. The device has a broad base roughly

the size of a coin and twice the thickness. On top is a cylinder with a hole a little bigger than the outer diameter of the glass capillary and a height of 3*cm*. This acts as a handle. The device is made of stainless steel, preventing it from rusting and losing small particles during the polishing process which will eventually clog the nozzle. To get a uniform surface the capillary in the steel cylinder should be guided in the form of an "8" over the polishing sheets. The duration of polishing determines the inner diameter of the capillary. That is why one should always have a microscope nearby to check the progress regularly.

Figure 5.2 shows nine polished tips horizontally oriented and on the bottom the mechanically manufactured capillary from Hilgenberg vertically oriented for comparison. The length of the tip differs significantly. This does not affect the droplet production decisively as they depend mainly on the inner diameter of the nozzle. Observing figure 5.2 one can clearly see the sediments in the capillary at the bottom left. These particles got detached from the polishing sheets and sucked into the capillaries because of the capillarity. Some of them can be cleaned with distilled water but others get useless. Nevertheless producing our own capillaries with nozzle diameters comparable to the mechanically manufactured one from Hilgenberg was a huge success and helped a lot during the test runs, since many capillaries broke or got clogged.



Figure 5.2 Side view of the capillaries the glass workshop made for us. The diameter is $1.00 \pm 0.05mm$. The inner diameter of the tip depends on the polishing. If more glass is polished off, the diameter gets bigger. The vertically oriented capillary on the bottom is the mechanically manufactured capillary from Hilgenberg with a nozzle diameter of $50\mu m$ for comparison.

5.1.1 Piezo

As already described in the introduction, I want to produce small water droplets. One way to achieve this is to squeeze small water portions out of the capillary. Therefore one would like to displace small volumes of water, such they get ejected and form droplets caused by the surface tension of water. I want to realize this with the help of the piezo effect, which I will now discuss in more detail. It describes the occurrence of an electrical charge as a response to mechanical stress.

Piezoelectric materials, a subset of ferroelectric materials, exhibit the formation of a local charge separation known as electrical dipoles due to their non-centrosymmetric crystal structure. The electrical charge, which accumulates in certain solid materials (for example crystals and some ceramics) responses to mechanical stress. Inversely, if one applies a voltage and forces the electrical charges to react, they respond through a mechanical deformation of the material. The reason is that dipoles close to each other tend to be aligned in regions called Weiss domains. Applying a strong electric field across the material, the usually randomly oriented domains can be aligned, which is called polarizing.

Three main quantities are important for the piezoelectric effect. First, the orientation of the change of polarization within the piezoelectric material. Second, the symmetry of the material and third the applied mechanical stress. The change in polarization appears due to a variation of the electric field on the surface of the crystal caused by a change in dipole density. This effect is reversible and can also be shown the other way around when an applied voltage causes a structural deformation. The structural deformation is rather small (below 1%) and most of the time not visible with the naked eye.

The piezoelectric effect can be described mathematically combined through the electric flux density \mathbf{D} , the permittivity ϵ and the electric field \mathbf{E}

$$\mathbf{D} = \epsilon \mathbf{E} \to D_i = \sum_j \epsilon_{ij} E_j \tag{5.1}$$

and the linearised strain ${f S}$ with ${f s}$ is the compliance under short-circuit conditions and the stress ${f T}$

$$\mathbf{S} = \mathbf{sT} \to S_{ij} = \sum_{k,l} s_{ijkl} T_{kl}.$$
(5.2)

Interesting for me, to determine the coupling efficiency between the piezo and the glass capillary, is the second part, which can be written in the following matrix equation

$$\{S\} = [s^E]\{T\} + [d^t]\{E\}.$$
(5.3)

The relative deformation $\{S\}$ is caused by the mechanical stress $\{T\}$ and the electric field $\{E\}$. $\{S\}$ and $\{T\}$ are rank-2 tensors but are conventionally expressed as 6 component

vectors partitioned in two parts where the second part with the last three indices represent shear forces. Therefore $[s^E]$ is a 6x6 matrix including the elastic and piezoelectric material coefficients reading

$$[s^{E}] = \begin{bmatrix} s_{11}^{E} & s_{12}^{E} & s_{13}^{E} & 0 & 0 & 0\\ s_{21}^{E} & s_{22}^{E} & s_{23}^{E} & 0 & 0 & 0\\ s_{31}^{E} & s_{32}^{E} & s_{33}^{E} & 0 & 0 & 0\\ 0 & 0 & 0 & s_{44}^{E} & 0 & 0\\ 0 & 0 & 0 & 0 & s_{55}^{E} & 0\\ 0 & 0 & 0 & 0 & 0 & s_{66}^{E} \end{bmatrix}.$$
(5.4)

 $\{E\}$ is the electric field vector and therefore has three components, which means the strain matrix $[d^t]$ is 6x3 and reads

$$[d^{t}] = \begin{bmatrix} 0 & 0 & d_{31} \\ 0 & 0 & d_{32} \\ 0 & 0 & d_{33} \\ 0 & d_{24} & 0 \\ d_{15} & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}.$$
 (5.5)

This helps us to estimate whether the given piezo has the right geometry and can achieve a mechanical deformation high enough to overcome the stiffness of the capillary underneath and compress the capillary enough to create droplets with the desired diameter. The following calculation in [1] gives a good estimate of the radial contraction we can expect. The geometry and material properties of the glass capillary and the piezo are shown in fig. 5.3.

As explained the piezo has the form of a cylinder with a vertical hole. It is poled radially with electrodes on the inner and outer walls. Therefore applying a voltage between the electrodes results in an average radial electric field

$$\overline{E} = \frac{1}{\delta_p} \int_{r_i}^{r_o} E(r) \mathrm{d}r = -\frac{U}{\delta_p}.$$
(5.6)

This leads to three perpendicular displacements for a free piezo without capillary. One is the longitudinal contraction $\Delta \delta_p / \delta_p = d_{33}\overline{E}$ and the two transversal expansions along the circumference $\Delta (2\pi \bar{r})/(2\pi \bar{r}) = d_{31}\overline{E}$ and the length of the tube $\Delta l/l = d_{31}\overline{E}$. The effective radial strain $S_{r2}^{(3)}$ at the inner radius of the piezo tube is caused by the superposition of the tangetian contraction at r_p and the increase in wall thickness δ_p . This can be calculated with the effective displacement d_{eff}

$$d_{eff} = -\left(d_{31}\frac{r_p}{r_2} + d_{33}\frac{\delta/2}{r_2}\right) = -430\frac{pm}{V}$$
(5.7)

 $S_{r2}^{(3)} = \frac{\Delta r_2}{r_2} = d_{eff}\overline{E}$ (5.8)

with the values given in fig. 5.3. This yields a radial contraction of $r_c \sim 86 \frac{nm}{100V}$. Considering we want to produce microdrops with a diameter of $\sim 100 \mu m$ one can calculate the displaced volume at 100V

$$V_d = \pi l_p (r_2^2 - (r_2 - r_c)^2) = 0.03 mm^3.$$
(5.9)

This is circa seven times more than the volume of one droplet. It is still necessary, as the flexibility of our adhesive and the stiffness of the glass reduces the net contraction significantly. The stiffness of the glass can be described through the restraining stress $T = s_g^{-1}S$ which occurs when the piezo contracts around the capillary. With (5.3) in mind we can derive the net radial strain at the interface r_2

$$S_{r_2}^{(3)} = \frac{d_{eff}\overline{E}}{1 - \frac{s_p}{s_q}}.$$
(5.10)

I do the same estimation in [1] for the radial compliances of the glass tube, s_g , and the piezo tube, s_p , from the material properties. If one assumes equal lateral strains $S_{\overline{r}}$ and S_{δ} for the glass tube, one can approximate the effective compliance at the interface with roughly $s_g \simeq -\mu/E_M$. For the radial piezo compliance one can approximate $s_p \simeq s_{33}$. The last part of my estimation is that the assumption of equal lateral strains in the glass tube also holds to deduce that the radial strains at inner and outer glass walls are equal $S_{r_1}^{(3)} = S_{r_2}^{(3)}$. With this estimations one gets a rough approximation for the radial deformation of the inner glass wall for a given voltage: the effective radial electro-mechanical coupling coefficient of our setup ζ

$$\zeta \simeq \frac{r_1}{\delta_p} \left(\frac{d_{eff}}{1 + s_{33} \frac{E_M}{\mu}} \right). \tag{5.11}$$

For our given parameters we get $\zeta \approx 8 \frac{nm}{100V}$. This radial contraction Δr_1 results in a volume displacement ΔV_1 to either side of the tube, resulting in a column with a volume

$$V_{col} = 1/2\Delta V_1 \simeq \pi r_1 l_p \Delta r_1 \tag{5.12}$$

From (5.9) we can now estimate the droplet size assuming the ejected second half of our column forms a droplet

$$d_{dr} \simeq \sqrt[3]{6l_p r_1 \xi U_V}.$$
 (5.13)

This means our droplet size actually scales with the cube root of the voltage U_V . Hence, even for a fixed nozzle geometry, the droplet size is slightly tunable by the piezo voltage. With this equations one can now estimate, whether our goal of roughly $d_{dr} \simeq 100 \mu m$ is

 to
achievable. To produce a $100\mu m$ droplet, the piezo has to displace a volume of 1 nl. This corresponds to a radial contraction of roughly 5nm. For the effective radial contraction we have $\zeta \approx 8 \frac{nm}{100V}$. This means the contradiction can be 1.5 times as high as needed if a good mechanical coupling between the piezo and the glass tube is achieved.



Figure 5.3 Geometry of the capillary in the piezo. The room between the piezo and the glass capillary is minimal. Here we put the adhesive (see next section). The dimensions and material parameters were either provided by the manufacturer or measured by ourself. For the capillary I had to assume small deviations as the inner as well as the outer diameter are not perfectly constant.

ⁱWe got this values for the piezo directly from PI Ceramic. The derivation can be found in *Determination* of a Complete Set of Piezoceramic Coefficients by Dr. Ing. Timo Scholehwar and the value from Material coefficients PIC255. It is a numerical value for simulations. Its variance is 10 %.

ⁱⁱTER Group [https://www.tergroup.com/]



Figure 5.4 Schematic of the piezo we got from PI Ceramic.

5.1.2 Adhesive

With the capillary and the piezo set up and ready to go, the challenge was to stick the piezo to the capillary. To fulfil this task, one has to consider two things. The obvious one is, that the coupling between the piezo and the capillary needs to be strong as the deformation is only 2kV/mmⁱ. Many adhesives available would be able to deliver a strong connection. One can here for example think of instant adhesives or even UV adhesives. Both would give a strong bonding. The UV adhesive could even work quite well in vacuum if applied correctly and the capillary can conduct UV light so the UV adhesive can harden. Unfortunately, first tests with UV adhesives and a UV light showed that this does not work as well as expected, which could be due to the rather weak light source. Considering the setup in the vacuum, UV adhesives could still be an option because compared to instant glue they would not evaporate as much resolvent. For our first attempts both adhesives are not suitable because of another less obvious reason: The capillary gets clogged rather easy and one needs to change the capillaries because of this clogging or breaking on a regular basis. Throwing away a capillary and a piezo together as they cannot be separated any more would be rather pricey, particularly because of the piezo, since we are able to produce capillaries ourselves.

The requirements for the adhesive now are to give a strong connection with as little damping as possible and simultaneously be easily removable. Schäfer [1] proposed polyisobutylen (PIB) which lead, mixed with some paraffin and heated up slightly, to good results in

ⁱValue provided by PI Ceramic.

his setup. From the TER Groupⁱⁱ I got a 1kg sample of TER_PIB KMW 60 with a low molecular weight resulting in it being rather viscous. After a few attempts it became clear that even without paraffin this works quite well. To process the PIB, I heated it up with a hot air gun until it liquefied more and more. Then I applied very little of the PIB to the capillary and pulled the piezo over the capillary. It is important, if the piezo was already in use, to note that there still is some glue inside and one should pull the piezo over the capillary from behind and not tip first to avoid clogging. To keep it processable the piezo and the capillary were heated up with the hot air gun from time to time. Care has to be taken that the applied heat does not loosen the solder connections on the piezo. To make sure the PIB is distributed evenly beneath the piezo, twisting the capillary while pushing it through the piezo helps a lot. After cooling down for a few minutes the setup is ready.

To remove the piezo from the capillary one can again use the hot air gun and liquefy the PIB. One again needs to be careful not to apply too much heat, so the soldering connections will not break. When the PIB is warm enough the capillary can be removed. If the capillary should be reused, it is important not to cover the tip with glue and just push the capillary through completely.

5.1.3 Mounting

In order to mount the capillary with the piezo, I used posts and clamps from our regular optical mounting and a special 3D printed cylinder which can be seen in fig 5.5. On the left is the 3D model with the capillary and the piezo inside and on the right a picture of the real setup. The capillary is not glued to the printed cylinder but a small halved cylinder is pressed against the piezo with the screw in the middle of the right picture. The only point where the capillary is glued to the printed cylinder is on the top because there a needle is inserted to the capillary and glued together with instant glue to make it leak-proof.

ⁱTER Group [https://www.tergroup.com/]



Figure 5.5 3D model of mount on the left and real mount in experiment on the right.

5.2 High Voltage Source

The idea behind my setup is to emit droplets with a diameter of $\sim 100 \mu m$ at a frequency of a few kHz. Hence we need to drive the piezo with the desired voltage at the frequency we want our droplets to be emitted. The voltage necessary can be calculated as in 5.1.1. This is only the minimum needed. Taking the damping from the glue into consideration it becomes clear: the higher the voltage we can supply, the better the separation of the droplets, as the calculated minimum voltage will not be transferred completely to the glass. On the other hand, with a higher voltage, at least in theory, the volume of the droplet grows as well. This leads to the conclusion that a normal function generator with around $10V_{pp}$ will not be able to supply enough voltage. Therefore I took some old experimental controls from our neighbour lab, namely a power supply unit with a potentiometer and a high voltage switch. The power supply unit can supply over $100V_{pp}$, which is sufficient to operate our piezo. Since the supply unit can only supply constant power, I needed to implement an high voltage (HV) switch. The HV switch takes the signal from a normal frequency generator with $5V_{pp}$ as an input and the constant high voltage from the power supply unit. The HV switch maps the signal from the frequency generator onto the HV input and provides an output with the frequency tunable at the frequency generator and the voltage from the power supply. This output is directly connected to the piezo. Operating the droplet generator with such high voltage can be quite dangerous, which is why I took some safety measures. Between the power supply unit and the wall socket I installed a circuit breaker, so if by accident a voltage builds up somewhere, no one gets hurt. Between the output of the power supply unit and the HV switch I built in a microfuse as a second protection measurement against deadly currents. This can be seen in fig 5.6. The last safeguarding is to switch on the power supply unit last and only switch it on directly before one experiments. One should never adjust the setup in any way while the power supply unit is on.



Figure 5.6 Microfuse behind high voltage source, which can be exchanged easily. Behind the fuse is the power supply for the TTL. This was done with our E-Lego. Documentation can be found in our group wiki or on the Axion. All it does is supply unusual quantities of power a plug-in power supply cannot supply (like 3.6V). With the E-Lego this is not done with a potentiometer but with a system similar to a letterbox. As it just supplies power for our HV switch, I will not explain this in detail here.

5.3 Keeping constant pressure

Keeping a constant back pressure is essential to reach our goal of loading a MOT with a fixed frequency at a fixed position inside the MOT. First experiments with the capillary and the piezo where done with a syringe directly attached to the capillary. One can then apply pressure manually. This works well to test if one can eject microdrops but as we will see later, the pressure can not be kept constant enough by hand. The small deviations will lead to variations of the ejection angle and therefore the position where the droplets move and variations of the distance between the droplets because of the varying velocity depending on the back pressure. This variance is very small and barely visible in the majority of my measurements but we need to know precisely when and where our droplet will be. To evaporate the droplet with the laser, one needs to consider and take care of these variances. Figure 5.7 shows an example of the effect a varying back pressure can have. The droplets were produced with 7kHz at 100V and imaged with 0,147 ms shutter time. The only difference is the applied back pressure. The back pressure was applied manually by pushing the forcer into the syringe. The picture does not represent the regular variance in my measurements as I intentionally applied different pressures to show the effect. In the next chapter one will see, that the difference is not that big, but noticeable. The ejection angle also differs a bit but only marginally.



Figure 5.7 This picture was taken with 7kHz, 0,147ms shutter time and 100V to demonstrate the effect of varying back pressure. The angle only has minor variations, but the velocity and therefore the distance varies quite a bit. It is important to note that this picture does not represent the average variance depending on the manually applied back pressure but I intentionally applied different pressure to demonstrate the effect. Usually the variance, even with manually applied back pressure is much smaller as one will see in the next chapter.

The problem could not be solved completely during my thesis, which is why many measurements were done with manually applied pressure. As already explained, the effect is not very well visible for the naked eye, which is why I exaggerated it for fig. 5.7. Nevertheless it sometimes can be noticed. In a long term view for loading the MOT, we want to have a very stable pressure and droplet output and of course can not have someone standing in the experiment pushing alkali metals through a syringe. This is why I will present an option I started working on to get a constant back pressure. Therefor I used an arduino and a step motor. The step motor is controlled via a driver chip which is connected to the arduino. The syringe and the step motor are fixed to a 3D printed mount. A gear wheel is attached to the motor. This gear wheel drives a bar with sprockets, which is attached to the forcer. Triggering the motor now from the arduino it pushes the water out of the syringe and through a hose into the capillary.



Figure 5.8 The step motor is connected to the arduino via a driver chip. It takes 12V power. The setup the motor was built in is 3D printed. As the motor slowly rotates it slowly moves the forcer into the syringe. In this setup the motor moves constantly. One idea to improve the setup is using a pressure sensor which controls the motor steps depending on the pressure needed to produce microdrops at a constant rate.

Unfortunately this did not lead to a pressure as constant as I wanted it to be, so further improvements are necessary. Hence we had the idea to build in a pressure sensor which monitors the pressure and triggers the motor directly. Due to time constraints this could not be implemented in this thesis. In long term view one probably needs to think of another way to achieve constant back pressure because experiments with liquid lithium or rubidium can not be done with plastic syringes surrounded by air as they will react with both of them. Nevertheless the pressure sensor could be implemented using a noble gas which does not react with the alkali metal. Another way could be using the regular gravitational force instead of back pressure. These ideas will be discussed in a little more detail in the last chapter.

5.4 Imaging

Ejecting microdroplets at a kHz rate with a velocity of a few meters per second is quite fast. Hence I need some supporting mechanisms to see, if I really do produce microdroplets with my setup. Since the droplets are tiny, the contrast between the droplets and the background needs to be accentuated. One way is to illuminate the background to image the droplets as little shadows (fig. 5.9). This was the first method I tried, inspired by [1]. With our camera I could not achieve a good contrast between the surface of the droplets and the background. This could maybe be improved with coloured water and blacked droplets. Therefore the colour needs to be very fine and filtered to a grain size below $\sim 2\mu m$. To avoid this procedure I changed the imaging to a completely dark background and illuminated droplets. This can be seen in figure 5.10.



Figure 5.9 On the left an image done through shadow imaging by [1]. The nozzle and the droplets have a high contrast and can be seen nicely. On the right my first attempt to visualize the droplets with an illuminated background. One cannot distinguish the droplets very well from each other. There is no good contrast between the droplet surface and the background. The stream of droplets has quite a big angle in this picture. This is a result of an inconstant back pressure and the nozzle geometry which I could improve during the experiment as will be seen in the next picture.



Figure 5.10 This picture was taken at 7kHz ejection speed and 100V. One can still see that the droplet stream has a small angle. This is mainly due to the geometry of our capillaries. As they are all drawn by hand, the nozzle is not necessarily completely straight. This effect needs to be considered for further development of the setup but does not inhibit the first tests with my setup.

The imaging here is done with a simple white LED with a nominal voltage of 5V working as a stroboscope. In my setup the LED is powered with 18V but only for a very short time. It is directly connected with a transistor and a resistor. The transistor is operated from a signal generator at the frequency I produce my droplets with but with a duty cycle of only 5%. Hence we can use more power for extremely short but bright light pulses. With the light pulses synchronized with the frequency the piezo is operated with, one gets a steady picture as the droplets are always illuminated on the same spot. This illumination technique nevertheless still has one downside: It is quite hard to determine the diameter of our droplets. As one can see in figure 5.11 on the left, it is tempting to assume that the bright spot is our illuminated droplet. Measuring the diameter of the bright spot leads to a droplet diameter of $\sim 70\mu m$, which would be even smaller than our goal of $\sim 100\mu m$. Looking at the picture on the right, which was taken with the same settings but recorded at another recording cycle, one clearly sees something looking like a shadow, implying that only little more than half of our droplet is illuminated. Here the measurement of the diameter yields ~ $120\mu m$, more than our goal but still in a good regime. Nevertheless, since the volume increases proportional to the diameter cubed, small deviations in the diameter can have significant influence on our further proceeding. Looking into the imaging proposed in [1] with an illuminated background could solve this problem. Hence one probably needs a better camera than the one I used, even if this model already has a quite small pixel size of $3.75\mu m^{-1}$. Since for future applications one wants to replace the water with rubidium, rubidium may reflect the light as well as water and will definitely be less transparent than water. Therefore the imaging technique with an illuminated background may be more suitable for rubidium.



Figure 5.11 Pictures taken at 7kHz and 100V at two different recording cycles. Through slightly varying angles the droplets get illuminated differently. The green circle shows the visible part of the droplet at the first glance. On the left picture one does not assume that there is a dark part of the droplet, which is not visible. On the right picture the green circle has nearly the same size but the picture indicates that only half the droplet is illuminated and the other half lies in the shadow of the bright half. Together the dark and bright part form a perfect sphere which is exactly what we expect because of the high surface tension.

 $^{^{\}mathrm{i}}\mathrm{I}$ used the Chameleon CM3-U3-13S2M-CS

5.4.1 Camera settings

For the experiment I used the CM3-U3-13S2M-CS from Chameleon together with the FlyCapture2 software. The camera can take pictures at 30 FPS. That is way slower than the frequency with which we produce droplets. Hence we used the stroboscopic LED as explained in the last section. The main parameters I want to control when taking pictures are the shutter time and the gain. Even if the camera could only do 30 pictures per second, with the help of the shutter time we still can take a picture of one single drop. Therefore the shutter time needs to be as long as the illumination of one droplet. For example, if droplets are produced at 7000 kHz the shutter time is 0.143 ms. In figure 5.12 one can see the settings for this measurement. There the shutter time is 0.147 ms. That is because we cannot choose our shutter times arbitrarily small. The next smaller possible shutter time would have been 0.113ms. This does not have a big effect as this difference does not add up over time, because we only take up to 30 pictures per second.



Figure 5.12 Settings of the FlyCapture Software. The most important parameters for my experiment are Shutter and Gain.

To compensate the small shutter time, the gain needs to be quite high, collecting as much light as possible for this short amount of time. If one wants to reduce the gain, the shutter time can be set to for example 1.43 ms. This is an order of magnitude more than before. Now we do not image single droplets but the overlap of ten droplets. In theory this should work better as we collect more light from the droplets and less noise from the surrounding as the gain can be reduced. In practice though, one will see that the droplets seem to be a bit bigger than they really are, as they are nearly in the same spot as the droplet before but not every droplet out of 10 droplets is in the exact same spot when the LED flashes as the droplet before and afterwards. To achieve exact overlapping positions, the back pressure needs to be perfectly stable. Nevertheless the overlapping is very good, as I will show in the next chapter.



Figure 5.13 Scheme of my experimental setup with the high voltage power supply and the HV switch on top connected to the piezo. Bottom left is the LED and th the right the camera. In fig. 6.8 one can find a picture of the setup in reality, as this is only a simplified scheme.

Measurements

In this chapter I want to present my measurements. After assembling the setup for the first time, many pictures have been taken and I have made many improvements. Nevertheless there still is a lot of work to be done. I will point out the suggestions I have for further developments in the different sections and will give a bigger overview of the work that needs to be done at the end of my thesis.

6.1 Frequencies

As mentioned in section 5.3, the back pressure is not perfectly constant. This will also be the case for the following measurements. Hence the distance between the droplets may be less meaningful, than one might assume at first sight, because with the pressure the velocity and therefore the distance between the drops changes. In the following figures I measured different voltages for different driving frequencies. For all pictures the shutter time was 1/fwith f the frequency I operated the piezo with. The different frequencies are 3, 7, 10 & 15kHz. From left to right the measurements were done with 50, 100 & 130V. As already explained the distance between the droplets depends on the back pressure and must be interpreted with caution. What can be interpreted is the form and volume of the droplets and if the distance varies between different droplets in the same picture.

In the first figure (6.1) one can see droplets ejected with 3kHz at 50, 100 and 130V. On the left is the measurement with 50V. Here one can see that the droplets are smaller than on the right picture, but the distance between the droplets varies drastically. It looks like with lower voltages I was able to produce smaller droplets but the cut between single droplets is not as clear as for higher voltages. This makes sense as the volume the piezo compresses depends on the applied voltage. Less voltage means less compressed volume and therefore smaller droplets but also less backward pressure when the piezo relaxes and the water column segregates into small droplets. For 50V I could achieve a diameter of ~ $100\mu m$ while for 130V the droplets had ~ $250\mu m$ and for 100V in the middle ~ $180\mu m$. One can also see, that for 130V the distance between the droplets is nearly constant compared to 50V and 100V. At 100V the droplets smaller dout a bit. This could be because of the angle they are emitted with, as it can also vary back and forth .

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Figure 6.1 Droplets ejected with 3kHz at 50, 100 and 130V. One can see that not only the size of the droplets depends on the voltage but also the precision of the frequency generating them.

Figure 6.2 was taken with 7kHz at 50, 100 and 130V. One can see that doubling the frequency improved the quality of the droplets. Not only did they get smaller but also the distance between them is more constant compared to 3kHz, even at 50V. Testing my setup, I did the majority of test measurements with 7kHz. I choose 7kHz after driving the piezo with different frequencies and acoustically measuring its noise. I expected the most noise from it at the resonant frequency, which I discovered to be \sim 7 kHz. As one can see, the droplets are getting smaller compared to 3kHz but the difference between the different voltages is not as big as for the 3kHz measurement. The reduction of size is because the time the voltage is applied is shorter for 7kHz than it is for 3kHz.



Figure 6.2 Droplets ejected with 7kHz at 50, 100 and 130V. With 50V the droplets are not always perfectly separated. With higher voltage the separation improves and the distance between the droplets varies less.

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Figure 6.3 was taken with 10kHz at 50, 100 and 130V. Again the distance between the droplets diminished. The size of the droplets now varies on a scale one can not determine with sufficient certainty any more. All droplets are $100 - 120\mu m$ in diameter. One notices that for 100V in the middle the distance between the droplets is bigger than for 50V and 130V. Also there is no ejection angle to the nozzle. I observed that for some of the self made capillaries there seems to be some kind of threshold pressure. This means the angle sometimes changes abrupt at a certain pressure and not continuously. One can also note, that the pressure must have changed looking at the distance between the droplets compared to 50V and 130V.



Figure 6.3 Droplets ejected with 10kHz at 50, 100 and 130V. Between the three measurements the distance between the droplets varies. This is because of the variation in back pressure between the three measurements since the pictures were not during the same measurement. There is no ejection angle to the nozzle for the 100V measurement. I observed that for some of the self made capillaries there seems to be some kind of threshold pressure. This means the angle sometimes changes abrupt at a certain pressure and not continuously.

Figure 6.4 was taken with 15kHz at 50, 100 and 130V. The droplets do not get much smaller compared to 10kHz. It looks like the droplets are sharper at 50V and 100V but as explained beforehand the droplets always form perfect spheres because of the high surface tension. For 130V the droplets probably just reflected the light slightly different. This can happen when the angle changes a bit with changing back pressure. Experimenting at 15kHz became a little more difficult, as I got further away from the resonance frequency. This resulted in the ejection being more sensitive to pressure change than for the frequencies around 7kHz.



Figure 6.4 Droplets ejected with 15kHz at 50, 100 and 130V. There is no directly noticeable difference between 10kHz. With a completely constant back pressure, there will be a noticeable difference between 10kHz and 15kHz since with higher frequencies the distance between the droplets will decrease.

As explained for figure 6.3 sometimes the ejection angle changes abrupt when pressure changes a bit. However this is not the only effect I observed. Not experimenting for some days, for example the weekend, sometimes also changes the ejection angle. This does not happen with every capillary, but I have seen this effect for some capillaries. I assume that very small dust particles settle at the tip of the capillary. Sometimes they get washed away when one starts the experiment again, but sometimes they stay at the nozzle. Both effects, the dust and the varying pressure will be eliminated though when one puts the experiment into vacuum and implements a way to maintain constant back pressure. Nevertheless they played a role for my test setup. An option to avoid dust would have been to do the experiment in a clean room. We decided to forego this option, as this would have been much more time consuming.

6.1.1 Improvement: Resonant circuit

Looking back at fig. 6.2 I talked about the resonance frequency of the piezo. At its resonance frequency the ejection of droplets was very stable and resistant to smaller pressure changes. The same could be witnessed for higher voltages. As the power supply output is limited at 130V one could build a resonant circuit with the piezo and an inductor. The piezo will then act as a capacitor. With

$$f_0 = \frac{1}{2\pi\sqrt{LC}}\tag{6.1}$$

one can calculate the needed inductor. The piezo has a capacity of 3nF. If one now wants to operate the resonant circuit between 7-10kHz one needs 100-200mH. This is quite a lot considering standard inductors, but one can still buy inductors with this specifications. With a free tunable inductor one could easily eject droplets at different frequencies changing the inductivity respectively.

6.2 Exposure time

As explained in the section 5.4.1, the camera settings are an important part of the measurement. Since droplets are ejected in the kHz regime and the camera can only image 30 frames per second, I used a stroboscopic flash light to illuminate the droplets. As one cannot increase the number of pictures the camera takes, one needs to find another option to image single droplets. This can be done by tuning the shutter time. The shutter time is the time the CCD chip is accessible to light. The maximal possible shutter time for the camera is 33ms. During that time, the shutter is open. This is the maximum if one operates at 30 frames per second as one picture takes 1/30s = 33ms. Ejecting microdrops at for example 7kHz in a period of 33ms more than 200 droplets fly by. With the help of the stroboscopic flash light in the ideal case, all droplets are illuminated at certain points and one droplet is illuminated the second time when it is exactly at the position the droplet before was. In reality, very small velocity variations will ruin this effect as droplets will not align perfectly. To get images with single droplets, one needs to adjust the shutter time to $t_s = 1/f$ with f in my example being 7kHz. This calculates to 0.143ms. To image the droplets with such short shutter times the gain needs to be adjusted. In fig. 6.5 one can see the result of such a measurement for 7kHz and 100V. The picture on the left was taken with $t_s = 0.143$ ms ⁱ. Every droplet in the picture represents a single droplet. The picture on the right was taken with $t_s = 1.43$ ms. The droplets look brighter but also bigger. That is because the overlap is not 100% accurate. With the bare eye one can not see an overlap because the

ⁱIn reality it was 0.147ms. See section 5.4.1 for explanation.

droplets look quite sharp but measuring them reveals that they are a little bit bigger than the droplets taken with $t_s = 1/f$. Nevertheless this picture shows impressively how good the alignment of the produced droplets actually is. Only at the start and the very end one can see that there are > 1 droplets overlapping. In the middle the overlap is nearly perfect. This demonstrates that my setup has the ability to produce droplets at a fixed frequency, which always appear at the same spot after the same time.



Figure 6.5 Pictures taken at 7kHz and 100V. On the left the shutter time was 1/f, on the right 10/f with f=7kHz. One can see that the last droplets tend to smear out a bit. If one looks closely one can also spot that some of the droplets do not overlap at all with the other droplets and are imaged as single droplets. Nevertheless this effect can only be seen at the start and the very end. In the middle the droplets overlap nearly perfectly, which shows the precision of the setup I built.



Figure 6.6 Pictures taken at 7kHz and 100V. Both shutter times are 10/f, but on the right picture one sees what happens, when the droplets do not align. This is the case for pressure changes at very short time scales. Even with pressure applied by hand this happens very rarely and is completely eliminated when one implements constant back pressure. I had to actively change the pressure by hand to get results as bad as in the right picture. This means that the setup in general is quite robust.

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6.3 Micropdrop Motion

As I want to keep my setup as small as possible, it is desirable to hit the droplets with the laser nearly directly after they emerge out of the nozzle. At first sight it should be possible to move the laser as close as possible to the nozzle but in reality this is not possible. In theory all droplets should have the exact same speed when emerging the nozzle and therefore the exact same distance to the droplet in front of them. In our experiment this is not necessarily the case as one can see in Fig. 6.7. Comparing my setup to the setup in [1], I do not have a big reservoir with a steady back pressure due to gravitation (a big, high reservoir is unfavourable as the long term goal is to implement the setup in a vacuum chamber) but I need to press the liquid, in my case now water, through the capillary and through the nozzle. The piezo works as a partitioning device, slicing off small portions of water which form into droplets because of surface tension. Due to their small size the surrounding air damps the droplet motion down to a much lower speed. One can estimate this from a simple force evaluation. As soon as the droplets are ejected, only the gravitational force $F_g = mg$ and the decelerating air damping force F_d acts on them. The nature of the damping force depends on the Reynolds number, $Re = (\rho/2\nu)vd_{dr}$, which marks the border between laminar and turbulent flow. A $100\mu m$ spherical droplet moving with 1 m/s through atmospheric air has a Reynolds number of 3.3 [1]. This is well in the laminar range ($Re \ll 100$), which can be assumed for all the microdrops. In this range the damping is dominated by the viscous Stokes force, $F_{St} = -3\pi\nu v d_{dr}$, which is proportional to the droplet speed, leading to the following equation of motion for the vertical coordinate

$$\ddot{y} + \frac{1}{\tau}\dot{y} - g = 0; \ \tau \coloneqq \frac{\rho d_{dr}^2}{18\nu}.$$
 (6.2)

The solutions for the droplet path y(t) and velocity v(t) can be obtained:

$$y(t) = \tau (v_{y0} - v_{y\infty})(1 - e^{-t/\tau}) + v_{y\infty}t$$
(6.3)

$$v(t) = (v_{y0} - v_{y\infty})e^{-t/\tau} + v_{y\infty}$$
(6.4)

with $v_{y\infty} \coloneqq \tau g$. One can see that the velocity v_{y0} of a droplet is reduced after ejection to a constant final speed $v_{y\infty}$. To get an estimation how the droplet velocity changes along its path one cannot find a direct expression for v(y) but an inverse function y(v) can be used to model the behaviour:

$$y(v) = \tau \left[v_{y0} - v - v_{y\infty} \ln \left(\frac{v - v_{y\infty}}{v_{y0} - v_{y\infty}} \right) \right].$$
 (6.5)

The distance a microdrop travels until it relaxes into steady state can now be approximated as $z_{\tau} = v_{y0}\tau$. Hence an 80 μm droplet in air is decelerated from 1.0 to 0.2 m/s after ~ 40mm. The effect of this can nicely be seen in fig. 6.7. It is a picture of droplets I generated at 7kHz. On the top of the picture on can see the nozzle and the bright spot to the left is the stroboscopic light source. The picture was taken with an exposure time ten times longer than the generation of one droplet takes. Hence one droplet here actually is the overlap of ten droplets in reality. The stroboscopic light source only illuminates them at the same frequency they are generated but with a duty cycle of only 5%. For the first few millimetre (a)) on can see that the droplets do not overlap and one sees many droplets with very small distance between each other. In addition the droplets seem to be less bright in the beginning, which comes from the exposure time being ten times longer than the generation of one droplet. Overlapping ten droplets in one picture gives a brighter spot but as the droplets in region a) are not perfectly overlapping because of their different velocity, one gets several less bright droplets very near to each other. Over time they reach $v_{y\infty}$ and begin to overlap perfectly what can be seen in region b).



Figure 6.7 Picture of the droplets moving through air. On top is the nozzle and the bright spot to the left is the stroboscopic light source. The picture was taken with an exposure time ten times longer than the generation of one droplet takes. Hence one droplet here actually is the overlap of ten droplets in reality. The stroboscopic light source only illuminates them at the same frequency they are generated with, but with a duty cycle of only 5%. For a) one sees that some droplets are faster than other droplets. After a certain distance x_{τ} they all have the same speed. This can be seen in b).

6.3.1 Improvements: back pressure

Since we do not want to experiment with rubidium at normal pressure but in vacuum the damping factor will not be seen, when we move the experiment into vacuum. If one now moves into vacuum one has two options.

One Option is to optimize the back pressure so it is perfectly stable. That way the droplets should all have the exact same velocity and therefore fixed trajectory and constant distance. In my setup with water constant distance can not be achieved as gravity plays a role again. Therefore the distance between the droplets will grow over time. Still the growing distance can probably be neglected, since the variation will not be very significant over such a small distance. If the distance grows over time because of gravity the droplets nevertheless will occur at exactly the same position for every cycle. This happens because the distance does not increase randomly but by fixed amounts caused by gravity. Hence aiming a laser at this position will not be different for a setup in vacuum. The second option would be to rotate the setup 180 degrees and eject the droplets upwards. This way the droplets would be slowed down by gravity. Nevertheless for the second option back pressure still is an issue as well because the "rubidium fountain" cannot be arbitrarily high, since one has limited space in the vacuum chamber. To evaporate the droplets, one can then aim the laser at the turning point of the droplets with v = 0. This might be advantageous as one gains more time to evaporate the droplets. Though the new time limit is not given through the droplets levitate but the time till the next droplet arrives. Therefore the turning point in their trajectory needs to be inside of the vacuum chamber. This is probably not the case, since the vacuum chamber is small. Therefore the second option is only a theoretical option and probably cannot be used for our setup.

6.4 Laser

To evaporate the atoms, the method currently in use in our experiment is a small oven, which heats up the lithium to the gaseous phase. Counter propagating lasers are then used to slow down the atoms through resonant photon absorption. For my setup, I want to use the laser to evaporate the droplets in the centre of the trap. This could not be done during my measurements, since the thermal conductivity of water is to low to get into a regime where one can adiabatically evaporate the water droplets. Nevertheless I wanted to try at least hitting the water droplets with a laser. For this purpose I ordered a laser diode from mouser ⁱ with 75W output power at a pulse width of 100ns. The maximal frequency for the diode is 1kHz which is a bit slow for our purpose but one could still hit one out of seven or out of ten droplets. Unfortunately my order could not be processed as already explained in 4.2 and did not make it in time to be implemented in my setup. Nevertheless I want to shortly sketch how the setup could have looked like. One knows from figure 4.1 I do not

 $^{^{}i}720$ -SPLPL90-3



Figure 6.8 Picture of my final setup. On the left in the back is the LED for the stroboscopic imaging. In front of the LED is the mount for the piezo and the capillary. In front of that mount is the CCD camera and to the right the laser with the lenses build into a cage system

want to have a perfectly focused laser but collimate the beam down to a certain waist. The waits should be around $\sim 200 \mu m$ but tunable, since one needs to find the perfect waist for the rubidium droplet once the setup is implemented into a experimental chamber. Therefore the second lens should be mounted on a translational state. This of course means, that the laser will not be perfectly collimated when moving the lens. As one is only interested in the waist size in the plane of the droplets, this however is no problem for my setup. As explained I was not able to built this setup so I used a low power green laser for some first runs to see the effect of the laser illuminating a droplet. With the lenses mounted to the stage mounting, the waist could easily be tuned. As the tuning was done by hand it was quite rough. That is why I suggested to use a translational stage when implementing the lenses to a real experiment.



Figure 6.9 Picture taken at 7kHz. The laser is a green laser with little power. Though the droplets do not get evaporated and just reflect the laser light. This image was taken to illustrate that the droplets can be hit with a laser.

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Next Steps

It was clear when I started my thesis that the goal behind the idea of implementing such a setup and the work that needs to be done exceeds the time and work I was able to invest during the time of my master thesis. Hence there still are many open questions one needs to think of and implementations that need to be realized. Therefore in this section I want to briefly summarize all work in progress and the questions that occurred as I already talked about most of the possible improvements in the correspondent chapters.

Back pressure

The back pressure has been discussed in the previous chapters. This is the biggest and most important challenge in my opinion. For water the solution might be easily obtained with the suggested pressure sensor and some coding in one of the arduino libraries, but for rubidium it is more difficult An important decision here will be if one wants to have the droplets ejected from the top, so they will gain velocity through gravity but never change direction or if one wants them to be ejected from the bottom of the trap so they will be decelerated through gravity. Though the required back pressure might be so high that the droplets do not have a point of return as the vacuum chamber is to small and they just hit the inner top of the vacuum chamber. The next step will be thinking about a setup that can maintain constant back pressure. This will be rather tricky as rubidium interacts with air where it oxidizes and ignites. This means the rubidium needs to be implemented in the setup without having any contact to the air. This could be done with the help of a noble gas. It will not damage any pressure sensors and will not react with rubidium (see section "Rubidium"). However if one builds a system with external back pressure, there needs to be a pressure difference between the vacuum chamber and the reservoir. This can be done with a small amount of noble gas, which will not react with the rubidium. The chamber with the ultra high vacuum will pull the rubidium inside if the pressure in the reservoir is higher. For this case one needs to think about an interruptor to switch the back pressure on and off.

Contamination of the vacuum chamber

Another problem is the contamination with rubidium in our chamber. As explained only 0.4% of the droplet will be used in the experiment and the other 99.6% goes to waste. At this rate the MOT will be full of condensed rubidium rather fast. Since we cannot clean up our MOT easily without breaking the vacuum which requires subsequent baking, one wants to reuse the rubidium which is lost in the process. One idea here is to distil the rubidium back into a reservoir. This would have the advantage that we do not have to filter the rubidium any more as it is already distilled. The problem is, that gravitational pressure is not enough to gain a back pressure high enough to eject our droplets. If one uses a back pressure system with external back pressure, it needs to be sealed perfectly from the vacuum chamber when it is switched of. If not, the chamber will get contaminated with for example noble gas or what ever is used for the back pressure system.

Laser

In chapter 2 and 4 I already talked about the requirements a laser needs to fulfil. As explained it is way easier to fulfil the requirements for rubidium than it is for water. One could use a pulsed laser with a pulse width of around $10\mu s$ as calculated in (2.12). For this pulse width one would need ~ 75W as we need 745μ J (see (2.11)). Considering that one has ~ 40μ s to hit the droplet, if one expands the pulse over 30μ s one only needs ~ 25W peak power. The calculated limits leave some room for tuning the parameters to longer pulses than the lower limit, which is the adiabatic limit and therefore decreasing the peak power. Considering the possibility of cooling the atoms without using a MOT as discussed in 2.3, the laser power, one wants to evaporate the droplets with, needs to be higher. As explained it is favourable to have a high vapour pressure to get a fast expansion and high effective cooling. Hence using a MOT there are less requirements to the laser setup, as we need less power from the laser, than without a MOT, since the laser setup needs to be optimized more.

Camera

The camera in my setup is necessary for two things. On the one hand it gives one a good impression of the distance between our droplets and the position. For this purpose the CCD camera used in my setup was sufficient as can be seen in the pictures in the chapters beforehand. On the other hand one wants to resolve the droplets as detailed as possible to measure them. This was quite difficult with my camera as already explained in chapter 5.4. A camera with a even smaller pixel size would help to resolve and measure the droplets more accurate. As the volume increases with the third power of the diameter, little variations have a huge effect on the number of atoms in our drop and therefore on the energy necessary to evaporate the droplet. One idea I pursued was to implement a Raspberry Pi camera.

Raspberry Pis have cameras with only half the pixel size ($\sim 1.7 \mu m$) of my CCD camera. The encountered problem here was that one could change the shutter time but not the gain manually. Therefore the gain always adapted automatically to the shutter time. If one finds a way to manually change the gain, this could help to achieve a better resolution.

Raspberry Pi

A Raspberry Pi could not only be used for the camera but also to control the complete experiment. In the moment this is done with two function generators. One controls the LED by switching a transistor. The other one controls the piezo. It therefore operates the high voltage switch, which toggles the power from the high voltage source with the frequency I apply through the frequency generator. With the second output of the frequency generator I can control the laser. The outputs all have a duty cycle between 30% for the piezo and 5% for the LED and an output power of 5V. They have been operated between 1-10kHz. All this could be done with an Raspberry Pi and save a lot of space. One also would not need to change the frequency at two devices and could tune the LED, the piezo and the laser in perfect synchronisation with each other.

Rubidium

Rubidium is an alkali metal and therefore has an atomic structure close to hydrogen with one free electron. As hydrogen is the only element we can calculate the structure analytically, one wants to use elements which are similar and make ones life easier in understanding the interaction. One problem many alkali metals have is their reactivity with normal air. For our purpose this makes it quite difficult to get the rubidium into our reservoir on top of the capillary. It can be handled in specific mineral oil or surrounded by noble gas, which does not react with the rubidium. Using mineral oil can cause contamination of our rubidium to a very small degree, but enough to get interactions with the oil and the laser one cannot foresee. The best way would be distilling the rubidium into the reservoir. This way one could make sure that only rubidium atoms find their way into the reservoir and the rubidium we are experimenting with is 100% clean.

8

Outlook

In my Master thesis I adapted and customized a basic droplet generation mechanism from [1]. The idea behind this project is to load a MOT orders of magnitude faster than it is now possible by substituting the Zeeman slower with a drop on demand system. Droplets with a diameter of $\sim 100\mu m$ at a steady frequency with a fixed trajectory can be produced with a glass capillary, a piezo and a corresponding adhesive connecting the two. I also showed with my calculation that it is theoretically possible to produce rubidium droplets and evaporate them with a laser. With my thesis I have done the groundwork for further developing this drop on demand system. I am quite confident, that it is possible to realize the setup working with rubidium in vacuum. It could even be possible with this setup to not only replace the Zeeman slower but also the MOT as explained 2.3. This will be more complex as there is not much room tuning the necessary parameters. Nevertheless it seems to be an option one can pursue.

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Acknowledgements

Ich möchte mich bei Selim und der ganzen Arbeitsgruppe für die insgesamt 3,5 Jahre, die ich Teil der Gruppe sein durfte, bedanken. Ich hatte viel Spaß an der Umsetzung dieses spannenden Projekts, sowie an den gemeinsamen Mittagessen, Ausflügen, Feuerzangenbowlen und anderen Aktivitäten. Besonderer Dank gilt allen, die obwohl sie inhaltlich nichts mit meinem Projekt zutun hatten, sich doch hin und wieder meine Ideen angehört haben und mir mit Nachfragen und Anregungen bei der Umsetzung geholfen haben. Besonders hervorheben möchte ich hier Frau Scheurich von der Glaswerkstatt, die trotz anfänglicher Skepsis gegenüber meiner Idee die Kapillaren selbst zu ziehen, sich darauf einließ und mir schnell und zuverlässig Kapillaren nach meinen Vorgaben gezogen hat, was viel Zeit und Geld gespart hat. Auch Gerhard, der mich bei der technischen Umsetzung der Steuerung unterstützt hat, sowie Philipp, der zu Beginn viele Ideen mit mir diskutiert hat möchte ich hier danken. Außerdem möchte ich Lauriane Chomaz danken, die sich bereit erklärt hat als Zweitkorrektorin für meine Arbeit zu fungieren.

Des Weiteren danke ich allen aktiven und ehemaligen Mitgliedern der Fachschaft MathPhys-Info, mit denen ich einen großen Teil meines Studiums verbracht habe. Egal ob fachliche Themen, Hochschulpolitik, oder Fachschaftspartys, mir hat die Zeit mit euch an der Universität großen Spaß gemacht und ich werde immer gerne daran zurück denken.

Zum Schluss möchte ich meiner Familie und meiner Freundin danken, die mich während meinem ganzen Studium immer unterstützt haben und sowohl Verständnis während der sehr stressigen Semester zu Beginn hatten, als auch als ich gegen Ende meines Studiums die Zeit noch etwas ausgenutzt und dieses nicht in der kürzest möglichen Zeit beendet habe. Ich freue mich, dass ich mir meinen Kindheitstraum, an der Universität Heidelberg Physik zu studieren, erfüllen durfte und ihr mich dabei unterstützt habt.

Ich hoffe, dass meine Masterarbeit eines Tages fortgeführt wird und möchte die Personen, die an dem Projekt weiterarbeiten werden ermuntern, mich auf dem Laufenden zu halten.

Erklärung

Ich versichere, dass ich diese Arbeit selbstständig verfasst habe und keine anderen als die angegebenen Quellen und Hilfsmittel benutzt habe.

Heidelberg, 29. Oktober 2021

5.34 .

(Sebastian Blänsdorf)