ac electric trapping of neutral atoms

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We study the dynamic behavior of ultracold neutral atoms in a macroscopic ac electric trap. Confinement in such a trap is achieved by switching between two saddle-point configurations of the electric field. The gradual formation of a stably trapped cloud is observed and the trap performance is studied versus the switching frequency and the symmetry of the switching cycle. Additionally, the electric field in the trap is mapped out by imaging the atom cloud while the fields are still on. Finally, the phase-space acceptance of the trap is probed by introducing a modified switching cycle. The experimental results are reproduced using full three-dimensional trajectory calculations.

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I. INTRODUCTION

The trapping of neutral particles has paved the way for remarkable achievements in atomic and molecular physics, culminating with the observation of degenerate Bose and Fermi gases [1, 2]. The ability to confine the ground state of neutral particles is becoming important for an increasing number of experiments, in particular for collision studies [3]. The ground state of any neutral particle is always attracted towards a point of maximum field, but it cannot be trapped in a static field, as static fields cannot possess a maximum in free space [4, 5]. Trapping in the ground state is therefore only possible when electrodynamic fields are used. For example, any sublevel of the ground state can be confined in the laser field maximum of a dipole trap [6], which has been successfully demonstrated for both atoms [7] and molecules [8]. Additionally, paramagnetic particles can be trapped using ac magnetic fields, as shown for ground-state Cs atoms [9].

Trapping by ac electric fields is a more versatile method, applicable to any ground-state atom or molecule. For polar molecules strong confinement can be achieved via the first-order Stark interaction. For atoms and nonpolar molecules, trapping is based on the second-order Stark interaction between an external electric field and the induced dipole moment. Similarly to trapping of ions in a Paul trap [10], three-dimensional confinement in an ac electric trap is achieved by alternating between two saddle-point configurations of the electric field. The first configuration has attractive (focusing) forces along one direction and repulsive (defocusing) forces along the other two directions, while in the second configuration the roles of the forces are reversed. Dynamic confinement of the particles is obtained by switching between these two configurations at the appropriate frequency.

The first demonstration of ac electric trapping was carried out for ammonia molecules using a cylindrically symmetric trap with a depth of several millikelvins [11]. Similar trap depths were later obtained for the same molecule with a linear ac trap [12]. In the meantime, Katori and coworkers achieved trapping of about 100 ground-state Sr atoms with a lifetime of 80 ms in a microstructured ac trap on a chip [13]. Recently, we demonstrated trapping of about 10^5 Rb atoms in a 1 mm^3 large and several microkelvins deep trap, with a lifetime of about 5 s [14]. Our trap is also based on the cylindrically symmetric geometry suggested by Peik [15]. It allowed for the first direct visualization of the dynamic confinement in an ac trap using absorption images taken at different phases of the ac switching cycle. Subsequently, trapping of ultracold Rb atoms was also obtained with a three-phase ac electric trap [16], as proposed by Shimizu and Morinaga [17, 18]. A recent paper describes in detail the ac trap geometries currently used to electrically confine neutral atoms and molecules [19].

In this paper, we present a detailed experimental investigation of the dynamics in the ac trap and study the dependence of the atom number on the switching-cycle parameters. Compared to our previous measurements [14], we have optimized the number of trapped atoms by introducing an evaporative cooling stage before loading the atoms into the ac trap. As the depth of the ac trap is small, the reduction in temperature helped increase the number of confined particles, which in turn improved the quality of our images. The experimental data are compared throughout the paper with results of numerical simulations based on classical trajectory calculations.

This paper is organized as follows. We start by describing the experimental sequence used to load the atoms into the ac trap in Sec. II. The ac trap is presented in detail in Sec. III and the theory model we use for the simulations is also briefly discussed. Next, we show how the atoms can be used to probe the electric fields in the trap in Sec. IV. The formation of a trapped cloud in the ac trap is studied in Sec. V by imaging the atoms after a gradually increasing number of switching cycles. This also leads to a measurement of the ac trap lifetime. Then, in Sec. VI, the dynamics of the atoms in the ac...
trap is visualized at different phases of the ac switching cycle. Additionally, the dependence of the trapped atom number on the trapping frequency and the symmetry of the switching cycle is measured. Furthermore, the mean kinetic energy of the atoms is determined at different phases of the switching cycle. In Sec. VII we study the phase-space acceptance of the ac trap by introducing a sudden change in the switching cycle. Finally, we summarize our results in Sec. VIII.

II. EXPERIMENTAL PROCEDURE

In the experiment, the $^{87}$Rb atoms are first collected in a six-beam magneto-optical trap (MOT) loaded from a Zeeman slower. After a short compression of the MOT, optical molasses cooling, and optical pumping, the atoms are transferred into a spatially overlapped quadrupole magnetic trap. About $5 \times 10^8$ atoms in the $F = 2, m_F = 2$ hyperfine sublevel at a temperature of $600 \mu$K are trapped in the magnetic trap which is characterized by a field gradient of $270$ G/cm along its symmetry axis. A short evaporative cooling stage is applied next by linearly ramping a radio frequency from 35 to 6 MHz in 8.3 s. At the end of the evaporative cooling stage, the field gradient is reduced to 65 G/cm. Approximately $2 \times 10^7$ atoms remain magnetically trapped at a temperature of $30 \mu$K. The quadrupole magnet is then moved horizontally in 3 s to a second quartz cell located 42 cm away [20]. This second ultrahigh-vacuum chamber houses the ac trap. The transfer is carried out using a precision translation stage allowing for accurate overlap of the cloud with the center of the ac trap. Altogether, the cooling, trapping, and transport of the atoms take about 25 s. At the final position, the magnetic field is switched off and, once it has completely disappeared, high voltage is applied to the ac trap electrodes. After a variable trapping time, the trap electrodes are switched back to ground and the confined atoms are detected by absorption imaging. In a typical experiment, the atoms are imaged 0.1 ms after the high voltage has been turned off, thereby reflecting the spatial distribution at the time of switch-off. The number of atoms is determined with an accuracy of about 5% using a two-dimensional Gaussian fitting procedure.

III. TRAP DESIGN

In the following, we give a description of the ac trap and briefly introduce our model for theory simulations.

The ac trap consists of two end cap electrodes and two ring electrodes as shown in Fig. 1. The inset is a schematic cross section of the cylindrically symmetric trap, while the photograph zooms in on the trap used in the experiment. The four electrodes are made of non-magnetic stainless steel and are mounted between two macor plates using macor spacers. The two ring electrodes are located between the end caps, but the ring opening is not visible in the photograph because the picture is taken from the side. As indicated in the schematic, the end caps have a hemispherical shape with a diameter of 7 mm and are separated by 6 mm. The ring electrodes are 3 mm thick, corresponding to an inner semicircular shape with a radius of 1.5 mm. They have an opening diameter of 6.7 mm and are separated by a 2 mm gap. All electrodes were highly polished before the trap was assembled and were subsequently conditioned to withstand increasingly high voltages.

A superposition of a static dipole field and an alternating hexapole field is used to switch between the two saddle-point configurations [15]. Because only the hexapole field is switched, the field strength remains constant at the center of the trap. Additionally, a dc quadrupole field is applied to counteract gravity. The two saddle-point configurations are referred to as $\rho$ and $z$ focusing. To alternate between these two configurations, two different voltage sets are applied to the four electrodes, as indicated in the photograph in Fig. 1. The ac switching frequency is given by $1/T$, where $T$ is the sum of the durations of the $\rho$-focusing and $z$-focusing phases, i.e., the duration of one full switching cycle.

The calculated fields that the atoms experience in the two different switching configurations are plotted in Figs. 2(a) and 2(b). For the $\rho$-focusing configuration in Fig. 2(a), the field has a maximum in $\rho$ and a minimum in $z$, and the highest field value is found at the top of the picture. For $z$ focusing the situation is reversed: the field has the maximum in $z$ and the highest fields are positioned symmetrically on the left and right sides of the picture. Note that the saddle points are displaced in $z$ due to the dc quadrupole field used for gravity compensation. The $z$-direction gradients for this field have the same value for both trapping configurations.

To describe the fields in the trap, we approximate the electric potential by a multipole expansion. Taking the
components are $\Phi_0$ trap geometry presented in Fig. 1, the multipole term shown in Eq. (1) is then fitted to these fields. For the (COMSOL). A multipole series up to the fifth term as terms represent undesirable nonlinearities in the system. The first term describes a constant potential, the $\Phi_0$ and $\Phi_0$ electrodes and the $\Phi_0$ decapolar field components. These last two higher-order terms represent undesirable nonlinearities in the system.

Simulations are carried out to model the experimental results. First, the electric fields for our trap geometry are calculated using a commercial finite-element program (COMSOL). A multipole series up to the fifth term as shown in Eq. (1) is then fitted to these fields. For the trap geometry presented in Fig. 1, the multipole term components are $\Phi_0 = 285 \text{ V}$, $\Phi_2 = 5992 \text{ V}$, $\Phi_2 = 604 \text{ V}$, $\Phi_3 = 3265 \text{ V}$, $\Phi_4 = 222 \text{ V}$, and $\Phi_5 = 737 \text{ V}$ for $\rho$ focusing, and $\Phi_0 = 232 \text{ V}$, $\Phi_2 = 5991 \text{ V}$, $\Phi_2 = 607 \text{ V}$, $\Phi_3 = 285 \text{ V}$, $\Phi_4 = 223 \text{ V}$, and $\Phi_5 = 687 \text{ V}$ for $z$ focusing. The forces acting on the atoms are then derived and trajectory calculations are carried out by numerically integrating the equations of motion. A fine grid in phase space is used to simulate the initial distribution of atoms. Throughout the paper, simulation results will be presented in conjunction with experimental data.

IV. MAPPING OF THE ELECTRIC FIELDS

We will now describe how the atoms can be used to sensitively probe the actual electric fields in the trap. This is important because small inaccuracies and misalignments of the electrodes can have a strong impact on the trapping fields.

To probe the electric fields in the ac trap, the usual experimental sequence is followed with the only exception that the electric fields are kept on while taking absorption images of the cloud. The atoms are confined in the ac trap for a short trapping time during the first switching cycle and the electrodes are switched to ground after obtaining the absorption images. To compensate for the resulting Stark shift, the absorption beam is detuned by several megahertz while the atoms are probed. We have already seen in Fig. 2 that the electric field strength varies significantly over the size of the atom cloud. Therefore, the position of an atom determines whether it is on resonance with the probing transition. Note that the absorption beam crosses the entire cloud and due to the cylindrical symmetry it can be thought of as passing once from left to right through the fields shown in the contour plots in Fig. 2.

In the electronic $5^2S_{1/2}(F = 2)$ ground state, the $m_F$ sublevels remain degenerate in an electric field. In the $5^2P_{3/2}(F = 3)$ excited state, however, the degeneracy is lifted due to the tensor polarizability [21], as seen in the inset of Fig. 3. This gives rise to four possible energy differences (Stark shifts) between the two states, which are plotted in Fig. 3.

In Fig. 4 the first two columns show images of the atoms in the $\rho$-focusing and $z$-focusing configurations, respectively. The third and fourth columns display simulation results. For the $\rho$-focusing pictures in the first column, the atoms are trapped for 9.83 ms, just before switching to $z$ focusing. For the measurements shown in the second column, the atoms are imaged immediately after switching to the $z$-focusing configuration, namely, after a trapping time of 9.84 ms. The difference in trapping times for the two configurations is tiny and ensures that the atom density distributions are identical. Additionally, for these short trapping times the atom cloud is dense, resulting in a good absorption signal. The experiment is repeated, varying the probe detuning from -22 to -38 MHz. Depending on the detuning, different electric field regions are visible, thus enabling direct probing of the field distributions shown in Fig. 2. For instance, the atom distributions in Figs. 4(c) and 4(g) look like an
hourglass, thereby resembling the shapes of the fields in Fig. 2, with the saddle points located at the waist of the hourglass. As expected, the waists are displaced in $z$ for the two pictures. The simulations, labelled with matching capital letters, agree well with the measurements.

Looking at the pictures in the first column, the lower fields corresponding to a small probe detuning are found in the center [Fig. 4(a)]. The higher fields at the top and at the bottom become visible for the larger detunings of -34 MHz in Fig. 4(d) and -38 MHz in Fig. 4(e). Note that the field strength is higher at the top than at the bottom, in agreement with Fig. 2(a). The trend is reversed for the $z$-focusing configuration shown in the second column. For a small detuning of -22 MHz [Fig. 4(f)] atoms at the top and at the bottom are on resonance. With increasing detuning only atoms at the center of the trap are visible, confirming that along the $z$ axis the highest fields are in the center of the trap as seen in Fig. 2(b). Additionally, in the case of $z$ focusing, the higher fields towards larger $\rho$ play a role. Nonetheless, the highest fields on the left and on the right side of the trap are not visible because the atom cloud is more dilute at larger $\rho$, and therefore the atom density is too low to image these trap regions.

As mentioned in Sec. III, our simulations are carried out using a finite-element program to determine the electric field in the trap. The probe beam attenuation by an atom cloud with a Gaussian density distribution is calculated for the simulated electric fields. The resulting theory plots are shown in Figs. 4(A)–4(J). In the magnetic trap only the $m_F = +2$ sublevel of the $5^2S_{1/2}(F = 2)$ state is populated, while in the electric trap there no longer is a preferred orientation axis and the atoms redistribute over the degenerate $m_F$ sublevels. However, the dipole component of the electric field is dominant at the trap center, and therefore the field points downwards along the $z$ axis across the whole imaging region. The probe beam is linearly polarized with its polarization vector almost parallel to this axis. In general, if linearly polarized light is aligned with the quantization axis, there are no circular polarization components. Therefore, the probe beam drives only transitions with $\Delta m_F = 0$, as indicated in the inset in Fig. 3. Hence, no transitions to the $m_F = \pm 3$ levels of the upper $5^2P_{3/2}(F = 3)$ state are possible. The strength of the allowed transitions varies as shown in the inset in Fig. 3 and is accounted for in the simulations by weighting the transitions accordingly. The natural linewidth of the transition is 6 MHz; therefore the beam can simultaneously excite transitions with different $m_F$, if the upper sublevels are close enough in frequency. The linewidth of the laser is in the submegahertz regime and thus has a negligible contribution.

From the simulations we determine that the actual fields in the $\rho$-focusing configuration are lower than expected for the ideal geometry presented in Fig. 1. In contrast, the simulations for $z$ focusing match well. These lower electric fields can be reproduced by moving the lower end cap electrode down by 0.25 mm in the simulations. The calculations with the retracted end cap electrode are shown in Fig. 4 and they agree remarkably well with the corresponding experimental images for both trapping configurations. The displacement of the end cap results in considerable changes only for the $\rho$-focusing fields. In the $z$-focusing configuration, it is the ring electrodes that are primarily important for creating the maximum along $z$, whereas the end cap voltages are relatively low.

By comparing the simulations with the measurements, we conclude that in-trap imaging of the atoms is a very convenient method to monitor the electric fields in the trap. Using the simulations we are able to verify the geometry of our trap and determine possible inaccuracies. All further simulations discussed in the paper are carried out using the fields associated with the retracted end cap geometry.

V. FORMATION OF THE TRAPPED CLOUD

We will now examine the onset of stable ac electric trapping by imaging cloud shapes after a small number of switching cycles. Figure 5 shows the gradual formation of a trapped cloud as an increasing number $N$ of full switching cycles is applied. The absorption images always show the 2 mm gap between the ring electrodes. In
are fit using a double exponential yielding a value of $9 \text{s}$

cycles at the switching frequency of $60 \text{ Hz}$. The data points up to $15 \text{s}$, which corresponds to $N$ seconds. We image the atom cloud at trapping times of

limited by the collisions with the background gas. Dis-

metastably trapped atoms leave the trap region within

ms. This can be attributed to the fact that most of the

switching cycles observed in the images can be fitted

to gravity. After $N = 2$ switching cycles, as displayed in

Fig. 5(a), the number of atoms is now much smaller and the cloud is almost pancake shaped. In Fig. 5(c) after $N = 3$ switching cycles, the cloud has taken a rounder shape. The "final" shape emerges only after $N = 4$ switching cycles, as can be seen in Figs. 5(d) and 5(e). However, most of the atoms are still metastably trapped and will finally escape from the trap. After $N = 5$ and $N = 10$ switching cycles, the cloud exhibits an asymmetric shape, which is visible in Figs. 5(e) and 5(f), respectively. This asymmetry can be attributed to possible misalignments between the center of the magnetic trap and the center of the ac trap. Even after $N = 30$ switching cycles [Fig. 5(g)] the shape is not as smooth as in Fig. 5(h) after $N = 60$ switching cycles. A small feature is still visible on the left side of the cloud. However, the shape remains unchanged at longer trapping times, as illustrated in Fig. 5(i) where the number of atoms has decreased due to collisions with the background gas.

We also studied the atom loss from the trap more quantitatively by recording the number of atoms in the first $0.5 \text{s}$ of trapping. The fast decrease during the first ten switching cycles observed in the images can be fitted by an exponential yielding a $1/\epsilon$ lifetime of about $100 \text{ ms}$. This can be attributed to the fact that most of the metastably trapped atoms leave the trap region within the first few switching cycles.

Figure 6 illustrates the lifetime in the ac trap, which is limited by the collisions with the background gas. Displayed is the number of atoms versus the trapping time in seconds. We image the atom cloud at trapping times of up to $15 \text{s}$, which corresponds to $N = 900$ switching cycles at the switching frequency of $60 \text{ Hz}$. The data points are fit using a double exponential yielding a value of $9 \text{s}$ for the lifetime and a value of $1 \text{s}$ for the fast decay. Similarly to the $100 \text{ ms}$ decay in the previous paragraph, this fast decay accounts for metastably trapped atoms. These atoms, however, survive in the trap much longer, as they almost have the correct initial conditions to be stably trapped. The $9 \text{s}$ lifetime value is consistent with measurements of a magnetically trapped cloud, performed in the same vacuum chamber.

We therefore conclude that at least $60$ switching cycles have to be used in the experiment. Otherwise, the dynamics would be mainly guided by the behavior of metastably trapped atoms. Imaging the atoms after a trapping time of $1 \text{s}$ is a good compromise between stable behavior of the atoms and good signals, as longer trapping times suffer from atom loss due to background collisions.

VI. TRAP PERFORMANCE

In this section, we first visualize the dynamic confinement of the atoms in the trap by looking at the atomic distribution at different times within a switching cycle. From this we can qualitatively understand the motion in the trap. Next, we study the dependence of the number of trapped atoms on the switching frequency. Finally, we analyze the asymmetry of the switching cycle and present measurements on the mean kinetic energy of the atoms.

Characteristic for an ac trap is the fact that trapping is dynamic, i.e., the atoms are forced to move during the switching cycle, which is referred to as micromotion in ion traps. This can be seen in Fig. 7 where the images on the left show the atom cloud at different phases within the 61st switching cycle for a trapping frequency of $60 \text{ Hz}$. The corresponding phases $A−D$ are indicated on the switching cycle, which is asymmetric with $59\%$ of
ρ focusing followed by 41% of z focusing.

In Fig. 7(a) the atoms have just experienced z focusing and they are therefore moving inwards along z and outwards along ρ. Consequently, in the middle of ρ focusing, the cloud is focused in z and elongated in ρ, as shown in Fig. 7(b). However, the ρ-focusing forces have decelerated the motion along both axes and the atoms are now at the turning point of the micromotion before they change direction. Due to this motion, inwards in ρ and outwards in z, the cloud in Fig. 7(c) has a shape similar to that in Fig. 7(a). But as the atoms have just experienced the ρ-focusing phase, the velocity components are now pointing towards the center of the trap in ρ and outwards in z. This leads to a contraction in ρ and inwards in z. The cloud is imaged after a trapping time of 1016 ms, i.e., the distribution is tilted by 45°. As mentioned before, the atoms are at the turning point of the micromotion when they are in the middle of the focusing (defocusing) stage. The spread in position is maximal in the middle of the focusing stage, i.e., along ρ in B and along z in D, as also seen in the corresponding pictures in Fig. 7. On the other hand, the velocity spread is always minimal at these points, i.e., for ρ in B and for v_z in D. In the middle of defocusing, the cloud shape becomes round, as seen for ρ in D and for z in B. Note that the phase-space distributions shown are equivalent to the phase-space acceptance of the trap at that particular moment in the switching cycle. These phase-space distributions have been analyzed in detail for the case of molecules moving in the same trapping configuration [19].

To characterize the mean kinetic energy of the cloud, we perform ballistic expansion measurements of the trapped atoms. These time-of-flight (TOF) measurements are carried out at various trap phases within the 61st switching cycle at our standard switching frequency of 60 Hz. Figure 9(a) shows a typical TOF series where the cloud is imaged after a trapping time of 1016 ms, i.e., towards the end of the z-focusing phase. Plotted is the measured full width at half maximum (FWHM) of the cloud versus the TOF. The kinetic energy is determined from a fit to the measured FWHM, where the initial density and velocity distributions are assumed to be Gaussian. The fit yields a value of $E_\rho = k_B \times 38 \mu K$ in the radial direction (squares), and a value of $E_z = k_B \times 10 \mu K$ in the axial direction (circles) where $k_B$ is the Boltzmann constant.
the times A within the 61st switching cycle. The dashed lines indicate
standard deviations of the fit.

plotted together with the associated error bars, which are the
particular switch-off time. Then, the cloud FWHM in-
cause the atoms are moving towards the center at this
direction first decreases to a minimum value at 5 ms, be-
constant. Note that the size of the cloud in the axial
direction first decreases to a minimum value at 5 ms, be-
from the beginning of the next cycle. For the axial direc-
cycle wraps around, i.e., the end of one cycle coincides

FIG. 9: (a) Ballistic expansion measurements of the ac
trapped cloud after a trapping time of 1016 ms at 60 Hz. Plotted
are the measured FWHM of the cloud in the ρ (squares) and
z (circles) directions versus the TOF. The solid lines show
the corresponding fits. (b) Mean kinetic energies $E_\rho$ (squares)
and $E_z$ (circles) of the atoms for various ac trapping times
within the 61st switching cycle. The dashed lines indicate
the times A–D in the switching cycle. All data points are
plotted together with the associated error bars, which are the
standard deviations of the fit.

Figure 9(b) shows the mean kinetic energy in the ra-
dial and the axial directions, $E_\rho$ and $E_z$, for various ac
trapping times within the same 61st switching cycle. The error bars indicate the standard deviations of the fit. The dashed lines correspond to the phases A–D of the switching
cycle. As expected from Fig. 8, the velocities in the
radial direction (squares) are higher than the velocities in the axial direction (circles) which is confirmed by our
measurements. We also expect that the kinetic energy is minimal in the middle of the focusing phases, i.e., at
the turning points of the micromotion, B and D. Only at these phases of the switching cycle can we exclude the contribution of the micromotion to the kinetic energy.
From measurements at point B and close to point D, we obtain minimum values of about $k_B \times 10 \mu K$ for the mean kinetic energy.

As the atoms do not have well-defined Gaussian ve-
locity distributions across the entire switching cycle, the
FWHM fits of the expanding cloud can have large error
bars. This is primarily the case for ac trapping times
where the motion of the atoms is governed by the de-
foosing forces, i.e., from the middle of the defocusing
phase to the middle of the next focusing phase. There-
fore, as seen in Fig. 9(b), in the radial direction we obtain
larger error bars for trapping times between D and B via
A. Here we take into account the fact that the switching
cycle wraps around, i.e., the end of one cycle coincides
with the beginning of the next cycle. For the axial direc-
tion, the error bars are largest for trapping times between
B and D, that is to say for the complementary part of
the switching cycle.

Figure 10 shows the number of trapped atoms versus the
applied switching frequency after a 5 s trapping time. Two different sets of voltages are used. The frequency
scan plotted with squares was obtained using the volt-
ages indicated in Fig. 1. For the measurement plotted with circles, the applied voltage set results in an elec-
tric field that is a factor of 1.2 higher. The solid curve is a simulation carried out using the lower-voltage set
which is in excellent agreement with the experimental
data. For the lower voltages, trapping works in a rather
narrow range between 54 and 75 Hz with a maximum of
$2.5 \times 10^5$ atoms trapped at 61 Hz after 5 s. No trapping is observed below the 54 Hz threshold. For the higher volt-
ages, trapping occurs at higher switching frequencies, as
expected. As with the lower voltages, there is a strong
increase in signal above the threshold frequency of 64 Hz,
and a slowly decreasing signal for the higher frequencies.
Here, the range of working frequencies is broader. De-
spite the deeper trapping potential at higher voltages,
the recorded number of trapped atoms is smaller, which
we attribute to tiny discharges that we did not observe
for the lower voltages. These discharges lead to a local
increase in pressure which reduces the number of trapped
d atoms due to a higher rate of background collisions.

In Fig. 11 the relative switching time of ρ versus z fo-
cusing is varied, while the duration of the switching cycle is
held constant at 16.7 ms. The first data point refers to a
symmetric switching cycle with 50% of ρ focusing and 50%
of z focusing, where no signal is observed. The num-number of trapped atoms increases with increasing ρ-focusing
time. The maximum atom number after 1 s of trap-
ping is $4.5 \times 10^5$ and is found for a switching cycle with
60% of ρ focusing. For longer ρ-focusing times the num-number of atoms quickly decreases with no signal observed

\begin{align*}
E_\rho &= k_B \times 38 \mu K \\
E_z &= k_B \times 10 \mu K
\end{align*}
from 64% onwards. The solid curve is the corresponding theory prediction and shows the same trend as the experimental data. There is a clear shift, however, between theory and experiment, with the theoretical maximum at a smaller value of the \( \rho \)-focusing fraction. The asymmetry of the switching cycle is partly explained by the need to compensate for differences between the ideal trapping geometry and the actual experimental configuration. The experimental misalignments are likely more complex than the already mentioned retracted end cap geometry, which is taken into account in our simulations.

VII. PROBING THE PHASE-SPACE ACCEPTANCE OF THE TRAP

The phase-space acceptance can be probed by introducing a sudden change in the switching cycle. Most of the atoms have the wrong initial conditions to survive this change and they will be lost from the trap. Only the few atoms that reside in the accepted part of the phase-space distribution will remain trapped if more switching cycles are applied afterwards.

For this experiment, a truncated switching cycle is applied to the stably trapped atom cloud. We will refer to this modified switching cycle as a 'phase jump'. First, 60 switching cycles with the usual 59% of \( \rho \) focusing and switching frequency of 60 Hz are applied. This ensures that most of the metastably trapped atoms have escaped from the trap. Then comes a cycle with reduced durations for both the \( \rho \)- and the \( z \)-focusing phases. This is illustrated in Fig. 12. In the first column, a phase jump is applied where the \( \rho \) focusing is reduced to 1/4 and the \( z \) focusing is reduced to 3/4 of their usual durations. For the measurements in the second column, a symmetric phase jump is applied, i.e., a 1/2 \( \rho \)-focusing phase is followed by a 1/2 \( z \)-focusing phase. In the third column, the measurements are again taken for an asymmetric phase jump with 3/4 of \( \rho \) focusing and 1/4 of \( z \) focusing.

In the first row of Fig. 12, the cloud is imaged directly after the phase jump. From left to right, the radial extent of the cloud decreases while the cloud becomes larger in \( z \). In Fig. 12(a) the atoms have been exposed to \( z \)-focusing longer than to \( \rho \) focusing, which keeps the cloud tightly together in \( z \), whereas the atoms spread out in \( \rho \). In Fig. 12(k), due to the short \( z \)-focusing phase, the cloud is spread out in \( z \) and confined in \( \rho \). In Fig. 12(f) the phase jump is symmetric and the cloud shape is intermediary between the situations in Figs. 12(a) and 12(k). The pictures in the second row show the atoms after the application of an additional, full \( \rho \)-focusing phase. As a consequence, from Fig. 12(b) via Fig. 12(g) to Fig. 12(l), the atoms are more focused in the \( \rho \) direction. In Fig. 12(f) the cloud density is very low making the atoms barely visible. In Fig. 12(g) the cloud is fairly well confined because the atoms are not as perturbed as in Figs. 12(b) and 12(l) due to the symmetric switching. In Fig. 12(l) the
the jump. In Fig. 12(c) the density has increased due to now experienced one full switching cycle after the phase

full space distributions, where the modified cycle. Figure 13 shows the calculated phase-focusing and the first half of focusing is mapped onto the distribution in the middle therefore the phase-space acceptance in the middle of truncated switching cycle is applied, the distribution and final 30 cycles will be discussed in the following. If this

ing cycles. Note that only the atoms that survive these phase jump and the subsequently applied 30 full switching procedures in Figs. 12(e) and 12(o) few atoms have followed the phase jump. For the asymmetric switching, the atoms remain confined in the trap.

As discussed for Fig. 8, the trap acceptance varies with the phase in the switching cycle. To visualize how the motion of the trapped atoms is perturbed by the symmetric phase jump (i.e., 1/2 \( \rho \) focusing) and the subsequently applied 30 full switching cycles. In (a), the phase-space distribution after the \( \rho \)-focusing stage of the phase jump (orange) is plotted, along with the distributions already shown in plots B (black) and D (magenta) of Fig. 8. In (b), this distribution (orange) is shown again, along with the distributions after the entire phase jump [blue, corresponding to Fig. 12(f)], and after an additional \( \rho \)-focusing stage [red, corresponding to Fig. 12(g)].

cloud is spreading out along \( z \) as it has experienced only a short \( z \)-focusing phase. In the third row a subsequent, full \( z \)-focusing stage is applied so that the atoms have by now experienced one full switching cycle after the phase jump. In Fig. 12(c) the density has increased due to the \( z \) focusing, and a very dilute cloud is now visible. In Fig. 12(b) the cloud is pretty well confined. In Fig. 12(m) atoms have escaped from the trap along the \( z \) direction, the additional defocusing in \( \rho \) during the \( z \)-focusing phase leading to a dilute cloud. In the fourth row an additional \( \rho \)-focusing phase is applied. For both asymmetric phase jumps the atoms now form a small cloud. Very interesting is the pancake shape in Fig. 12(n), elongated along \( \rho \) and focused in \( z \) due to the prior phase of \( z \) focusing. Looking at the series in Figs. 12(l)–12(n), we notice that the cloud changes dramatically, being \( \rho \) focused in Fig. 12(l) and dilute in Fig. 12(m) because of the reshaping. The last row shows the atoms after 30 full switching cycles have followed the phase jump. For the asymmetric switching procedures in Figs. 12(e) and 12(o) few atoms survive, whereas in the case of symmetric switching more atoms remain confined in the trap.

As discussed for Fig. 8, the trap acceptance varies with the phase in the switching cycle. To visualize how the motion of the trapped atoms is perturbed by the symmetric phase jump (i.e., 1/2 \( \rho \) focusing followed by 1/2 \( z \) focusing), we carried out simulations which include the phase jump and the subsequently applied 30 full switching cycles. Note that only the atoms that survive these final 30 cycles will be discussed in the following. If this truncated switching cycle is applied, the distribution and therefore the phase-space acceptance in the middle of \( \rho \) focusing is mapped onto the distribution in the middle of \( z \) focusing. This happens because the second half of \( \rho \) focusing and the first half of \( z \) focusing are missing in the modified cycle. Figure 13 shows the calculated phase-space distributions, where \( v_z \) is displayed versus \( z \). The phase-space distribution after the \( \rho \)-focusing stage of the phase jump is presented in Fig. 13(a), along with the distributions already shown in plots B and in D of Fig. 8. Only those atoms that are in a region of phase space where the distribution after 1/2 \( \rho \) focusing (black) overlaps with the distribution after 1/2 \( z \) focusing (magenta) will remain trapped. Therefore, after the \( \rho \)-focusing stage of the phase jump the accepted phase space has reduced to this overlap region (orange). In Fig. 13(b), this reduced distribution is again illustrated, along with the distributions after the entire phase jump [blue, corresponding to Fig. 12(f)] and after an additional \( \rho \)-focusing stage [red, corresponding to Fig. 12(g)]. At the end of the phase jump and therefore at the beginning of the next switching cycle, the distribution has rotated clockwise by 45°, as we expect from plot A in Fig. 8. While this distribution is narrow in both velocity and position, the distribution after an additional \( \rho \)-focusing stage starts to spread out thereby gradually refilling the whole accepted area in phase space.

It becomes clear from these simulations and the associated measurements that the overlap of the accepted areas in phase space is optimal for a symmetric phase jump. For asymmetric phase jumps, more atoms are located in the unaccepted region of phase space and will therefore be lost from the trap. This is also visible in the last row of Fig. 12.

VIII. CONCLUSIONS

In this paper, we have presented a detailed study on trapping of rubidium in an ac electric trap. First, we showed that the atoms can be used to probe the electric fields in the trap, and we reproduced our results with simulations. By studying the gradual formation of a trapped cloud, we observed that most of the atoms that are not stably confined leave the trap within the first second. In a typical experiment, \( 3 \times 10^5 \) atoms are stably trapped with a lifetime of about 9 s, limited by collisions with the background gas. One of the nice features of our ac trap is the ability to directly visualize the atom dynamics at different phases of the switching cycle using absorption imaging. Trajectory calculations were carried out to confirm this dynamic behavior and to understand the corresponding phase-space distributions. Additionally, the mean kinetic energy of the trapped cloud was observed to vary across the switching cycle, as it is dominated by the micromotion in the trap. Values of about 10 \( \mu \)K were measured at the points where the micromotion does not contribute. We have also studied the dependence of the trapped atom number on the switching frequency and the symmetry of the switching cycle. Stable trapping occurs for a narrow frequency range around 60 Hz and for an asymmetric switching cycle. Finally, when a modified switching cycle is applied, the motion of the atoms in the ac trap can be readily understood from simulations of the phase-space acceptance at various phases of the
switching cycle.

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