Alkali vapor pressure modulation on the 100 ms scale in a single-cell vacuum system for cold atom experiments

Vincent Dugrain,1 Peter Rosenbusch,2 and Jakob Reichel1

1) Laboratoire Kastler Brossel, ENS, UPMC, CNRS, 24 rue Lhomond, 75005 Paris, France
2) LNE-SYRTE, Observatoire de Paris, CNRS, UPMC, 61 av de l’Observatoire, 75014 Paris, France

(Dated: 1 August 2014)

We describe and characterize a device for alkali vapor pressure modulation on the 100 ms timescale in a single-cell cold atom experiment. Its mechanism is based on optimized heat conduction between a current-modulated alkali dispenser and a heat sink at room temperature. We have studied both the short-term behavior during individual pulses and the long-term pressure evolution in the cell. The device combines fast trap loading and relatively long trap lifetime, enabling high repetition rates in a very simple setup. These features make it particularly suitable for portable atomic sensors.

I. INTRODUCTION

Magneto-optical trap (MOT) loading is a limiting factor to the repetition rate of cold atom experiments. Fast loading is crucial for practical applications of cold atoms, such as atom interferometry, as well as for experiments with high data volume, such as quantum state tomography of multiparticle entangled states. Ideally, the MOT loading time $t_{MOT}$ should be a small contribution to the cycle time, which means that it should be shorter than about 1 s in experiments involving evaporative cooling. The MOT loading rate $R$ is proportional to the partial vapor pressure of the element to be cooled (87Rb in this article). Consequently, this pressure should be high for fast loading, but low for long lifetimes after loading. A widespread approach is to use a two-chamber vacuum system with differential pumping. However, this considerably increases the complexity of the vacuum and optical systems. An interesting alternative is to temporally modulate the vapor pressure inside a simple, single-cell apparatus. Light-induced atom desorption (LIAD) from the cell surfaces has been investigated for this purpose. Although it performs well in some experiments, there can be reproducibility issues, at least for Rb. The pressure modulation factor and also the effective capacity of the surfaces (i.e., the number of pulses before depletion) vary by orders of magnitude between experiments. Strong dependence on material properties such as surface contamination is a possible explanation. Another, straightforward way to modulate the pressure of alkali vapors is to modulate the heating current in commercial alkali dispensers. A fast pressure rise is easily achieved by using elevated heating currents. However, the timescale of pressure decay is typically between 3 and 4, too long to achieve a significant reduction of the cycle time. Here we show that this decay can be accelerated by more than an order of magnitude without sacrificing the simplicity and safe operation of a dispenser setup, by optimizing the thermal contact of the dispenser to an outside heatsink. Our device achieves pressure decay constants on the 100 ms timescale as desired, well within the range of interest for high repetition rate experiments.

The long-term pressure evolution in a pulsed-source system is influenced by slow processes such as adsorption-desorption dynamics, which can introduce timescales as long as several hours. Therefore, we also investigate the long-term evolution of 87Rb pressure, background pressure and number of trapped atoms. As expected, the background pressure increases with the intensity of the dispenser pulses. We find evidence for both adsorption-desorption dynamics and slow heat-up of the vacuum apparatus. The latter effect is specific to our setup, which was not designed for this purpose, and we discuss straightforward improvements. In spite of these effects, we find that background pressure in our system remains lower than the pressure in a similar system with traditional, continuously heated dispenser, while the pulsed source accelerates MOT loading by more than an order of magnitude. This makes our system very attractive for many applications of cold alkali atoms.

The outline of this paper is as follows. We first discuss thermal coupling of the dispenser to the environment, motivate why an optimum range exists for this coupling, and estimate that the coupling found in usual experiments is too weak. Section II collects relevant facts about the mechanisms and time constants that govern the pressure evolution in the cell. In section III, we describe our setup, where the thermal coupling is improved by copper parts which embrace the dispenser shell and thermally connect it to an outside heatsink. Sections IV and V present and discuss the experimental results obtained when this dispenser is used as a pulsed source for a MOT. It is shown that a steady-state regime can be established and its characteristics are investigated. Finally, section VII investigates the features of this steady-state regime as a function of the alkali pulse intensity.
the dispenser temperature to be homogeneous. For cooling \((P = 0)\) from an initial temperature \(T(0) = T_1\), this equation leads to \(T(t) = T_0 + (T_1 - T_0) \exp(-t/\tau)\) with
\[
\tau = \frac{C_d}{h}.
\] (2)

Improving the heat conduction \(h\) has the desired effect of reducing \(\tau\). However, we also need to consider the undesired heat flow from the dispenser to the reservoir during the heating phase, which increases with \(h\). In our simple model, for heating with constant power and \(T(0) = T_0\), the temperature rise is \(T(t) = T_0 + \frac{P}{h}(1 - \exp(-t/\tau))\). The maximum temperature that can be obtained is
\[
T(\infty) - T_0 = \frac{P}{h}.
\] (3)

Therefore, as a first condition, \(P\) must be large enough to maintain \(P/h > T_1 - T_0\). The heat flow to the reservoir during the heating phase is \(\Phi(t) = P(1 - \exp(-t/\tau))\) and the total energy leaking to the reservoir during heating to \(T_1\) is \(\frac{P^2}{2h} \ln(\frac{1}{1 - (T_1 - T_0)/P}) - (T_1 - T_0)C_d\). It becomes negligible for \(P > h(T_1 - T_0) = \frac{C_d}{2}\). (This can also be seen by noting that \(\Phi(t)\) remains small for \(t \ll \tau\), and requiring that the heating time \(t_1\) be \(t_1 \ll \tau\).) This shows that reservoir heating during dispensing can be kept small even for large \(h\), by using a high heating power and a short heating time. Nevertheless, it would be wrong to conclude that \(h\) should be made as large as possible. First, larger \(h\) requires proportionally increased \(P\), and \(P\) is limited in practice. Moreover, an important practical limit comes from the fact that the required current exceeds the steady-state destruction threshold: when such a current is applied for too long, the dispenser melts like a fuse. The higher the current, the shorter the safety margin to destruction. With our holder described below, the required heating current is above 20 A. We have not made a systematic study of the destruction current, but we know from an unintentional experiment that a current of 40 A destroys the dispenser in less than 2 s. (A continuous current of 20 A is possible, though not desirable as it empties the dispenser in less than two days – another unintended experimental result.)

We conclude that an optimum regime exists for the thermal coupling \(h\). It is situated between the usual, undercoupled, slow-cooling regime and an overcoupled regime with strong reservoir heating and/or high likelihood of dispenser overheating. Our dispenser mount brings \(h\) into the optimum regime. Before proceeding, we note that the heat conduction model also provides an explanation for the slightly improved pressure decay in [13] and for the very fast decay observed in the laser-heated dispenser experiment [13] for low heating energies. In [13], the dispenser sleeves are attached to copper rods instead of wires, and the resulting pressure decay after dispenser turn-off has an initial decay constant of 1.8 s, about a factor of 2 faster than in experiments with wire-mounted dispensers [12]. In [13], the dispenser shell was attached...
to a ceramic plate over its full length, providing much higher h than wire mounting. Additionally, only a fraction of the dispenser surface was laser heated so that the rest of the dispenser effectively acted as a well-coupled reservoir. The authors place an upper limit of 100 ms on the switch-off time. From the schematic shown in the article, it seems that the ceramic plate itself did not have a substantial thermal contact to the outside, which would provide an explanation for the much slower decay they observed for high heating powers. Another possible explanation would be adsorption-desorption dynamics, treated below.

III. TIME CONSTANTS OF PUMPING AND ADSORPTION-DESORPTION DYNAMICS

Rapidly modulating the dispenser itself is not enough. Additionally, the timescale for evacuating excess alkali and dirt vapor after MOT loading must also be fast. If one considers the standard conductance formulas for the molecular flow regime, it seems easy to achieve a sufficiently fast pumping time constant, even with fairly small pumps. For our apparatus described below, the calculated pumping time constant (including tube lengths and angles) is 70 ms. However, these formulas describe an ideal gas and do not take into account the adsorption and desorption processes that occur for the highly reactive alkali vapor.

The binding energies and sticking times of alkali metals on UHV cell surfaces vary widely depending on the surface material and on the amount of coverage. It is difficult to obtain reliable data on the time constants and the situation appears to be particularly obscure for Rb, perhaps because its melting point is so close to room temperature. Nevertheless, some experimental facts are well established. First, there is the phenomenon sometimes called “curing”: when alkali vapor is first introduced from a reservoir into a freshly baked cell, it takes a long time, often several days, until a substantial vapor pressure can be created throughout the cell. This is most clearly observed in long UHV tubes or elongated cells, but the phenomenon is general and we have observed it in all our experiments. Once a significant vapor pressure has been reached in the cell, it can then be adjusted on a much shorter timescale (tens of minutes) by adjusting the source rate, via a reservoir valve for example. The curing phenomenon suggests that clean surfaces form strong bounds with the impinging alkali atoms, whereas binding is much weaker once the surface has adsorbed a certain amount (often suggestively called a “monolayer”). The main consequence of the curing phenomenon in our context is that data should only be taken after the transitory curing phase has ended. All data presented below has been taken after several months of dispenser operation and fulfills this condition.

The cured surface still has a memory effect for its recent alkali exposure. It is well known, for example, that a small MOT can still be loaded for many hours after the source has been turned off. These timescales are too long to be explained by dispenser cool-down and suggest that some fraction of the alkali atoms stick to the cell walls and thus spend an average time \( \tau_s \) (on the order of hours) inside the cell before being pumped away. To estimate the consequences of this effect, consider the following very crude model.

Two effects contribute to the alkali pressure in the cell \( p(t) \). The dispenser releases atoms at a rate \( r_d(t) \), and the cell walls can both release and capture atoms, changing the number of adsorbed atoms \( N_w \):

\[
p(t) = \alpha (r_d(t) - N_w).
\]

Here, \( \alpha \) is a constant that depends on the pumping speed. \( N_w \) is governed by a rate equation,

\[
N_w = -N_w \tau_s^{-1} + \beta r_d(t),
\]

where \( \tau_s \) is the mean overall sticking time that an atom spends on the cell walls before being pumped out, and \( 0 \geq \beta \geq 1 \) is the total probability for an atom to stick to the cell walls rather than being pumped away directly. In an experiment with constant alkali release rate \( r_d(t) = \bar{r}_d \) (“cw” experiment), \( N_w \) will reach a steady state \( N_s = \tau_s \beta \bar{r}_d \) which balances desorption and adsorption. Once this steady state has been reached, pressure no longer depends on the adsorption properties and remains constant at \( p_c = \alpha \bar{r}_d \). In a pulsed experiment, the cycle time is typically less than a minute, while \( \tau_s \) is expected to be much longer. Consequently, \( N_w \) in the pulsed case will undergo only small oscillations about a steady-state value \( N_s' = \tau_s \beta \bar{r}_d' \), where \( \bar{r}_d' \) is the release rate averaged over one cycle. For the purpose of this model, we will neglect the dispenser time constant and take \( \bar{r}_d'(t) \) to be square pulses, with a constant high value during the MOT loading phase of duration \( T_M^p \) and \( \bar{r}_d'(t) = 0 \) during the “science” phase of duration \( T_s' \). The pressure during the science phase is then

\[
p_s' \approx \alpha N_s' \tau_s^{-1} = \alpha \beta \bar{r}_d'.
\]

Now we can compare a cw and a pulsed experiment which both use the same MOT setup (beam diameters, detunings, field gradients etc.) and load the same number \( N \) of atoms into the MOT. For simplicity we assume that the alkali pressure dominates over other gases, so that the required release rate during MOT loading is inversely proportional to the MOT loading time (see below for a discussion of MOT loading). In the cw case, this release rate is kept constant, so that \( \bar{r}_d = \gamma T_M^{-1} \), where \( \gamma \) is a constant depending on \( N \) and on the MOT setup. The constant steady-state pressure is then

\[
p_c = \alpha \gamma \frac{1}{T_M}.
\]

For the pulsed case, a rate \( \gamma T_M^{-1} \) is applied during the MOT loading phase, but the rate drops to zero during the science phase. The average rate is then

\[
p_s' = \gamma / (T_M + T_s')
\]
and the pressure during the science phase is

\[ p'_s = \alpha \gamma \frac{\beta}{T'_M + T'_s}. \]  

(7)

The pressure during the science phase in the pulsed experiment is related to the constant pressure of the cw experiment by

\[ p'_s = \frac{\beta}{T'_M + T'_s} p_c. \]  

(8)

The relation depends on the sticking probability \( \beta \). Even for the worst case \( \beta = 1 \), \( p'_s \) is lower than \( p_c \) as long as the cycle time \( T'_M + T'_s \) of the pulsed experiment is no shorter than the MOT loading time of the cw experiment. The ratio \( T_M/(T'_M + T'_s) \) reflects our assumption \( \tilde{r}_d \propto 1/T_M \) for a given \( N \), which means that a constant fraction of the released atoms ends up in the MOT, independently of the rate \( \tilde{r}_d \) at which the MOT is loaded. If factors such as non-alkali background pressure change this relation, the ratio will change. Nevertheless, the qualitative trends predicted by eq. 8 should still be correct: In a pulsed experiment, for a given \( N \), the pressure in the science phase increases for higher sticking probability and for shorter cycle time. Compared to a cw experiment with the same \( N \), we expect that one can always achieve either a faster cycle or a reduced pressure in the science phase, even in a cell with unfavorable sticking properties. Achieving both improvements at the same time may also be possible, but requires the sticking probability to be significantly below 1.

IV. EXPERIMENT

A. Setup

In order to improve the heat flow out of the dispenser, we have mounted it in copper clamps on the top surface of massive copper bars, as shown in Figs. 1 and 2. The clamps provide a much better thermal contact than the spot-welded or crimped wires that are usually employed. The bars (cross section \( \sim 1 \text{ cm}^2 \)) provide the thermal connection to a low-temperature reservoir outside the vacuum system. Ideally, they should be very short in order to keep their thermal resistance negligible. Our system is quite far from that ideal (Fig. 2) because we have reused an existing glass cell which had a particularly long glass-to-metal transition, so that the rods had to have a total length of 22 cm. This reduces the overall thermal conductivity and leads to a significant temperature rise in the upper part of the rods, contributing to the long-term behavior described below in sec. VI. In a purpose-built vacuum system, this length could be made much shorter. Heat-sinking from the copper bars is achieved by a copper flange that has the diameter of a standard CF copper gasket, but a thickness of several centimeters. The copper bars are screwed to the inside of this flange, while passive heatsinks or optionally water cooling can be attached to its outer surface. The quartz cell of volume 290 ml is pumped with a 25 l/s ion pump via a 35CF cross, tube (length 20 cm), and an angle valve. Taking into account the tubes and angles, the calculated pumping speed at the cell entrance is 41 l/s and the pumping time constant about 70 ms. The base pressure as indicated by the ion pump current is below \( 10^{-9} \text{ hPa} \).

The MOT is a standard setup with six independent beams. The axial gradient of the magnetic quadrupole field is \( 11 \text{ G/cm} \) in all experiments reported here. In our test setup, the \( 1/e^2 \) beam diameter (1.2 cm) and the power per beam (1.6 mW) are both small, which limits the trapped atom number. This should be taken into account when comparing our atom numbers to other experiments: atom numbers can be expected to increase by several orders of magnitude if the same dispenser assembly is used with the larger beam diameters and laser powers that are typical in state-of-the-art quantum gas
experiments.

B. Measurement methods

As mentioned above, all the experiments described here were carried out after several months of operation, i.e. long after the system had cured. Fluorescence light from the atoms in the beam intersection was collected by a 2 in diameter, \( f = 40 \) mm lens outside the glass cell, followed by an amplified photodiode. Unless otherwise indicated, the fluorescence was measured during MOT loading. Because of the uncertainties in solid angle and in the average dipole strength of the fluorescing atoms, the absolute values of our atom number and loading rate measurements are beset with a large systematic error.

To deduce the Rb pressure from the fluorescence during MOT loading, we use the well-established loading rate analysis (see for example Reference 9, 21, 22). In our regime of moderately low trapped atom number \( N \), MOT loading and decay are well described by

\[
\frac{dN}{dt} = R - \frac{N}{\tau_{MOT}}.
\]

(9)

\( R = \alpha_R p_{Rb} \) is the MOT loading rate, \( p_{Rb} \) the partial pressure of \(^{87}\)Rb and \( \alpha_R \) is a constant that depends on the parameters of the MOT setup (beam diameter, detuning and intensity and magnetic field gradient). \( \tau_{MOT} \) is the decay time constant due to collisions with the background gas. It is proportional to the sum of the partial pressures of \(^{87}\)Rb and of all contaminants \( i \) present in the vacuum chamber, each weighted with the relevant collisional cross section \( \sigma_{Rb-i} \). We separate loss due to thermal Rb atoms from the loss that is independent of Rb pressure:

\[
\tau_{MOT}^{-1} = \beta_{Rb} p_{Rb} + \tau_b^{-1},
\]

(10)

When pressures are constant, eq. (9) leads to

\[
N(t) = N_f (1 - e^{-t/\tau_{MOT}})
\]

(11)

with

\[
N_f = R \tau_{MOT} = \frac{\alpha_R p_{Rb}}{\beta_{Rb} p_{Rb} + \tau_b^{-1}}.
\]

(12)

\(^{87}\)Rb pressure is proportional to \( R \). The background pressure is roughly proportional to \( \tau_{MOT}^{-1} \) because the collisional cross-sections of background gas constituents are all comparable\[22\]. Thus, both quantities can be deduced from \( N(t) \). During the dispenser pulse, where pressures vary too fast for this solution to be valid, \( R \) can still be measured from the initial linear rise in \( N(t) \).

V. RESULTS: PRESSURE MODULATION

In a first experiment, we measure \(^{87}\)Rb fluorescence emanating from the beam intersection while applying short current pulses to the dispenser. The MOT magnetic field remains off. Therefore, the photodiode signal
is proportional to the instantaneous pressure of room-temperature $^{87}$Rb in the cell (with some integration due to a short-lifetime optical molasses created by the beams). Applying 1 s pulses with various currents $I_d$, we find that the threshold for $^{87}$Rb emission lies around $I_d = 18$ A. Fig. 4 shows the fluorescence for $I_d = 20.2$ A. The rubidium pressure decay after the end of the pulse is well described by an exponential decay, yielding a time constant of $\tau_f = 112$ ms. This decay time is at least 20 times shorter than the values reported for bare dispensers\cite{13,14}, confirming the validity of our approach. We have checked that the time constant depends only weakly on the value of $I_d$ and on the system temperature (see section VI below). We also observe that very little $^{87}$Rb is emitted during the first 0.7 s: the dispenser heats up, but has not yet reached emission temperature. After this delay, the pressure rises very quickly to very high values. It would be possible to further accelerate the emission by using a higher current until emission starts and then lowering it, instead of the simple square pulses we use here.

Next, we have used these rubidium pulses to load the MOT. In Fig. 3(a), we use again $I_d = 20.2$ A and 1 s pulse duration, and the MOT coils are turned on together with the current pulse at $t = 0$. Full loading takes about 1.2 s, including the 0.7 s heating time where no $^{87}$Rb is emitted. As can be seen in the figure, most of the loading takes place during the final 0.5 s. It may be possible to further accelerate the cycle by starting the heating before the end of the preceding cycle. (We have not attempted to do this here.)

We have measured the number of trapped atoms as a function of dispenser current $I_d$. As before, current pulses were 1 s long and the MOT coils were turned on at the start of each pulse. Because the photodiode also receives fluorescence from untrapped background $^{87}$Rb atoms (visible as a peak before MOT switch-on visible in fig. 4b), $N$ was measured 200 ms after the end of the pulse. (This time is long enough for background fluorescence to become small, while being shorter than MOT lifetimes at these pressures.) $N$ increases with $I_d$ and shows no saturation up to the highest currents that we dared to apply (Fig. 5). This suggests that the pressure of elements other than rubidium remains non-negligible even at the highest currents, but rises more slowly than $p_{Rb}$. The absolute numbers of $N \sim 2.5 \cdot 10^7$ for the highest currents compare favorably to those of steady-state MOTs with similar beam diameters such as the TACC experiment in our lab\cite{23}.

Measuring the initial linear slope of MOT loading curves provides an alternative and more sensitive way to measure $p_{Rb}$. We use a dispenser pulse duration of 1 s as before. We record fluorescence curves for various delays $t_0$ between the end of the current pulse and the start of MOT loading, which is initiated by switching on the coils. After each loading cycle, MOT coils are switched off for 0.3 s to purge all cold atoms. The measurements are analyzed by performing a linear fit to the fluorescence curve in a 100 ms time interval at the start of the MOT loading. Its slope yields the loading rate $R$ at $t_0$. To avoid measurement errors due to the background fluorescence mentioned above, we limit our analysis to times after the dispenser switch-off, where we have checked that the variation of background fluorescence is only a small contribution to the measured slope. (To obtain loading rates for earlier times, it would be possible to subtract
First, we examine the long-time stability of the pressure decay time constant \( \tau_f \). As the Rb release from the dispenser is a very nonlinear function of temperature, \( \tau_f \) might have a strong dependence on the temperature of the copper bars, which would be problematic because this temperature is difficult to control precisely. In this respect, our long copper bars represent a worst-case scenario: due to their length which limits heat evacuation, the temperature of the copper structure rises slowly during operation, and with it the mean dispenser temperature will rise as well. Therefore, we have repeated the decay time measurement of Fig. 3 every 5 s over a duration of 4 hours, using a current \( I_d = 21.2 \, \text{A} \) and 1 s duration for \( I_d = 20.2 \, \text{A} \). None of these variations will cause major perturbations for fast trap loading.

Another quantity of interest is the long-time evolution (over many pulses) of the peak \(^{87}\text{Rb}\) pressure reached during the pulse. This determines the long-time evolution of the MOT loading rate and of the total number of trapped atoms per cycle. To measure it, we again apply a 1 s current pulse every 5 s over a long time (several hours to days). The MOT is switched on at the start of each pulse, and switched off for 300 ms before the next one to purge all cold atoms. We record the MOT fluorescence and deduce a mean loading rate during each pulse by di-

\[ \tau = 10^8 \, \text{ms} \]

This time constant is in good agreement with the value obtained by the simple fluorescence measurement above. It then reaches a plateau, from which it decreases by at least another order of magnitude on a much slower time scale. Doubly exponential decay was observed in LIAD experiments. In our case, the slow decay is not well approximated by an exponential. Its timescale is roughly 200 s. We attribute it to a combination of cell heating and adsorption-desorption dynamics. (If the wall temperature was constant, it would allow us to estimate the sticking time \( \tau_s \) of sec. III.) The long-term pressure evolution is studied in more detail in the next section.

VI. RESULTS: LONG-TERM BEHAVIOR

To summarize these results, the rapid pressure drop by a factor of 50 in about 100 ms demonstrates the usefulness of this source for high-repetition-rate experiments. It confirms that dispenser cooldown was the limiting process for the slow pressure decay in previous pulsed-dispenser experiments, which used bare dispensers. In other words, in those experiments, source shut-off was much slower than the pumping processes. Although the pressure plateau reached after the fast decay is above the base pressure in the cell, the pressure modulation provides a significant advantage over the unmodulated dispenser. This becomes clear when comparing to a single-cell experiment with unmodulated dispenser, such as TACC. TACC has somewhat larger MOT beam diameters (1.8 cm), a similar base pressure, and its constant Rb pressure is similar or higher than the pressure plateau observed here (loading rate \( R \approx 3 \times 10^6 \text{at/s with } \tau_{\text{MOT}} = 4.8 \, \text{s} \)). Yet, full MOT loading takes more than 10 s in TACC instead of 1.2 s here, and achieves an atom number that is at best comparable, and typically lower than observed here.

In the next section, we will try to get a better understanding of the plateau, and of the long-term evolution of the pressures in general.
FIG. 8. Long-term evolution of the mean MOT loading rate during the dispenser pulse. For \( t < 0 \), the dispenser was permanently off for several hours (“cold start” at \( t = 0 \)). Starting from \( t = 0 \), 1 s pulses with \( I_d = 24 \) A were applied every 5 s.

FIG. 9. Timing sequence for measuring long-term evolution.

...
erating the plateau – wall adsorption and heating – the steady-state plateau pressure depends on the amount of $^{87}{\text{Rb}}$ released per pulse, and thus on the dispenser current $I_d$. Using again the measurement pattern of Fig. 9 we have measured the total and $^{87}{\text{Rb}}$ plateau pressures, as well as the loading rate during the pulse, for different values of $I_d$. For each $I_d$, measurements were performed over many hours to obtain the steady-state value. The results are shown in Fig. 11. As expected, both the loading rate during the pulse and the plateau pressures increase with the pulse intensity.

The figure also shows the product of atom number and lifetime, which is a figure of merit for evaporative cooling. This figure grows for loading rates up to $5 \times 10^7$ at/s and saturates for higher rates.

Let us use Fig. 11 to compare again to a cw experiment. As above, we will compare to the TACC experiment ($R \approx 3 \times 10^6$ at/s, with $\tau_{\text{MOT}} = 4.8$ s and $N = 1.4 \times 10^7$, achieved after 10 s of loading). With the pulsed dispenser, using an intermediate loading rate of $5 \times 10^7$ at/s, the atom number is increased by more than a factor 2 and the lifetime by 1.5, while reducing the loading time by a factor of 10.

VIII. CONCLUSION

The pulsed dispenser device demonstrated here provides alkali pressure modulation by more than an order of magnitude on the 100 ms timescale in both directions. While fast pressure rise with pulsed dispensers has been demonstrated before, the important new feature of our device is fast pressure decay after the pulse. Although the plateau pressure reached after this decay is above the base pressure, it is lower than the cw pressure in a similarly-sized unpulsed MOT, while loading is at least an order of magnitude faster. This performance is achieved in a single-cell setup with only marginal added complexity over a standard MOT setup. These features make our device attractive for many applications of ultra-cold atoms, including single-cell Bose-Einstein condensation experiments with sub-second repetition rate and cold atom sensors for field use.

Several further improvements are possible. Our test setup had small beam 1/e beam diameters of 1.2 cm. Increasing this beam size would dramatically increase the number of trapped atoms for the same alkali pressure, without any changes to the dispenser device itself. Using current pulses with an initial “boost” instead of square pulses would reduce the delay before alkali emission, further reducing the loading time. Total loading times below 300 ms are realistic with this improvement alone (cf. Fig. 3). As discussed in sec. IVA, shortening the copper holding bars should significantly reduce their temperature rise and the associated transient behavior. Furthermore, having shown that adsorption dynamics is an important factor for the plateau pressure, we expect that this pressure can be further reduced by improving the cell geometry and possibly by a suitable choice of cell materials. Our pulsed dispenser can also be combined with a nozzle such as described in ref[18] to direct atoms more efficiently towards the capture region. This may reduce the overall amount of alkali vapor released in every pulse. Finally, the pulsed dispenser can be combined with light-induced desorption (LIAD) to further increase the peak pressure and reduce the surface coverage during the low-pressure intervals. In a first test, we have observed a reduction of the $^{87}{\text{Rb}}$ pressure in the science phase by roughly 1/3 when applying LIAD pulses simultaneously with dispenser pulses.

ACKNOWLEDGMENTS

We thank Fabrice Gerbier for fruitful discussions. This work was supported in part by the Agence Nationale pour
FIG. 11. The currents of the pulses are $I_d = 22.8\,\text{A}, 23.4\,\text{A}, 24.0\,\text{A}, 24.7\,\text{A}, 25.3\,\text{A}$.

la Recherche under the “CATS” project.

1A. D. Cronin, J. Schmiedmayer, and D. E. Pritchard, Rev. Mod. Phys. 81, 1051 (2009).

2M. F. Riedel, P. Böhi, Y. Li, T. W. Hänsch, A. Sinatra, and P. Treutlein, Nature 464, 1170 (2010).
3F. Haas, J. Volz, R. Gehr, J. Reichel, and J. Estève, Science 344, 180 (2014).
4B. P. Anderson and M. A. Kasevich, Phys. Rev. A 63, 023404 (2001).
5W. Hänsel, P. Hommelhoff, T. W. Hänsch, and J. Reichel, Nature 413, 498 (2001).
6S. N. Atutov, R. Calabrese, V. Guidi, B. Mai, A. G. Rudavets, E. Scansani, L. Tomassetti, V. Biancalana, A. Burchianti, C. Marinelli, E. Mariotti, L. Moi, and S. Veronesi, Phys. Rev. A 67, 053401 (2003).
7S. Du, M. B. Squires, Y. Imai, L. Czaia, R. A. Saravananan, V. M. Bright, J. Reichel, T. W. Hänsch, and D. Z. Anderson, Phys. Rev. A 70, 053606 (2004).
8C. Klempt, T. van Zoest, T. Henninger, O. Topic, E. Rasel, W. Ertmer, and J. Arlt, Phys. Rev. A 73, 013410 (2006).
9E. Mimoun, L. De Sarlo, D. Jacob, J. Dalibard, and F. Gerbier, Phys. Rev. A 81, 023631 (2010).
10D. Z. Anderson, (2012), private communication.
11C. Wieman, G. Flowers, and S. Gilbert, Am. J. Phys. 63, 317 (1995).
12J. Fortagh, A. Grossmann, T. W. Hänsch, and C. Zimmermann, J. Appl. Phys. 84, 6499 (1998).
13U. D. Rapol, A. Wasan, and V. Natarajan, Phys. Rev. A 64, 023402 (2001).
14J. Fortágh, H. Ott, K. Günther, and C. Zimmermann, Appl. Phys. B 76, 157 (2003).
15C. Bartalini, I. Herrera, L. Consolino, L. Pappalardo, N. Marino, G. D’Arrigo, and F. Cataliotti, Eur. Phys. J. D 36, 101 (2005).
16D. R. Scherer, D. B. Fenner, and J. M. Hensley, J. Vac. Sci. Technol. A 40, 061602 (2012).
17B. Grüner, M. Jag, G. Stibor, M. Visanescu, M. Häffner, D. Kern, A. Günther, and J. Fortágh, Phys. Rev. A 80, 063422 (2009).
18D. McDowall, T. Grünzweig, A. Hilliard, and M. F. Andersen, Rev. Sci. Instrum. 83, 055102 (2012).
19P. F. Griffin, K. J. Weatherill, and C. S. Adams, Rev. Sci. Instrum. 76, 093102 (2005).
20I. Ma, A. Kishinevski, Y.-Y. Jau, C. Reuter, and W. Happer, Phys. Rev. A 79, 042905 (2009).
21C. Monroe, W. Swann, H. Robinson, and C. Wieman, Phys. Rev. Lett. 65, 1571 (1990).
22T. Arpornthip, C. A. Sackett, and K. J. Hughes, Phys. Rev. A 85, 033420 (2012).
23C. Deutsch, F. Ramirez-Martínez, C. Lacroûte, F. Reinhard, T. Schneider, J. N. Fuchs, F. Piéchon, F. Laloe, J. Reichel, and P. Rosenbusch, Phys. Rev. Lett. 105, 020401 (2010).
24M. H. Anderson, W. Petrich, J. R. Ensher, and E. A. Cornell, Phys. Rev. A 50, R3597 (1994).
25K. Gibble and S. Chu., Metrol. 29, 201 (1992).