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Loading mechanism for atomic guides

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We present a method of coupling laser-cooled atoms from a vapor-cell magneto-optic trap (MOT) into a magnetic atom guide. The axis of the four-wire quadrupole guide passes directly through the center of the MOT. The guide is tilted at a small angle with respect to the horizontal plane to facilitate the propagation of the atoms released from the MOT into the guide. We demonstrate the loading of 10^5 ^{87}Rb atoms into the guide and measure their propagation up to distances of 17 cm (limited by the guide length). The guide incorporates a tapered section in which the guide diameter reduces by a factor of about 3.

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The last few years have seen an increased interest in the design of both macroscopic and microscopic atom guides for transporting laser-cooled atoms. Atom guides have a large potential in atom-interferometric applications [1] and in integrated atom optics [2,3]. The success of evaporative cooling in reaching conditions for quantum degeneracy in a static magnetic trap has sparked theoretical interest in the feasibility of performing evaporative cooling of atoms propagating along atom guides [4].

Atomic transport via hollow optical fibers [5,6] confines atoms with the optical dipole force. Besides its poor accessibility, atoms confined in the fiber suffer from heating effects due to photon scattering. This can be avoided by confining atoms with magnetic forces produced by current carrying wires [7] or permanent magnets [8]. The trapping force that can be achieved in a magnetic trap is proportional to the field gradient $\nabla|\mathbf{B}|$. For wires that carry a current I and are separated by a distance s, the field gradient scales as I/s^2. Thus, the best trap performance is achieved by the use of moderate currents and small scale sizes. Magnetic atom transfer schemes using 1-cm to 10-cm-sized structures have been used in experiments with Bose-Einstein condensates [9,10]. On a small but still macroscopic scale, atom transport has been demonstrated using four wires spaced 1 mm apart [11]. Very steep traps are possible when one scales down to micrometer-sized conductors fabricated on substrates [3,12]. Such devices will eventually allow one to propagate cold atoms in a single mode of the atomic center-of-mass wave function, as desired for guide-based atom interferometry.

The transfer of cold atoms from magneto-optic traps (MOTs) [13] into small atom guides represents a problem because MOTs require a capture volume of the order 1 cm^3 and cannot be accommodated inside small atom guides. The coupling of cold atoms into a microscopic atomic waveguide has been accomplished by injecting fast moving atoms ($\sim$10 m/s) from a low velocity intense source (LVIS) [12,14]. While this approach allows for a high flux of atoms coupled into the atom guide, the large temperatures of the injected atoms pose a disadvantage for future atom-interferometric experiments. Alternatively, slower atoms can be coupled into an atom guide by placing the entrance of the guide vertically below a MOT and dropping the atoms into the guide using gravity [3,11]. In this approach, the expansion of the atom cloud during the free fall leads to a low coupling efficiency. A more complicated scheme involves the use of a mirror MOT [15] formed above a gold surface that is etched on a substrate. By varying a bias magnetic field, the MOT can be slowly shifted towards the chip surface [2,16] and eventually merged with an atom guide quadrupole potential.

In this paper, we demonstrate the loading of atoms from a cycled MOT into a tapered magnetic atom guide that directly overlaps with the MOT (see Fig. 1). This integrated loading strategy involves the formation of a MOT directly inside the atom guide. The guide can, in principle, always be on without spoiling the MOT operation. When the MOT beams and coils are turned off, atoms remain in the quadrupole atom guide and propagate downward with an acceleration determined by the tilt angle of the guide in the gravitational field.

Our design combines a number of desirable features. Because the atom guide can be permanently on, new batches of atoms can be collected in the MOT, while the ones that have been released into the guide earlier can still be used or processed further downstream. Since the atomic cloud produced by the MOT is directly transferred into the atom guide, there is no spatial spread associated with the transfer, and one can adjust the atom guide potential such that the atomic cloud does not excessively ''breath'' after the transfer. Breathing-mode oscillations are undesirable, because they carry energy and rapidly dephase due to the anharmonicity of the potential, thereby thinning the phase-space distribution (averaged over small cells). The tapered section of the guide, where the

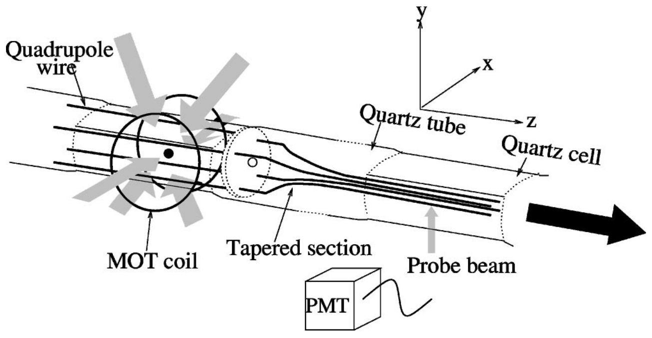

FIG. 1. Schematic of the experimental setup. A vapor-cell MOT created inside a tilted atom guide collects atoms and periodically releases them into the guide. A PMT measures the fluorescence of the propagating atoms.

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four wires forming the guide converge, acts as an integrating element between the large-scale loading section of the guide, the size of which is determined by the MOT, and a much smaller atom guide structure. The tapered region could be made more sophisticated than shown in Fig. 1 and reach μm-scale dimensions in the transverse directions (x and y in Fig. 1). As the atoms pass through the tapered region of the guide, they undergo transverse compression and experience a force in the $-z$ direction that increases with the transverse energy. The compression may become useful in achieving conditions favorable for evaporative cooling, which relies on a sufficient atomic density. The energy-selective repulsive force could be used to construct a filter that selectively transmits the atoms propagating in the lowest atomic waveguide modes. Such a mode filter could be useful in atom-interferometric applications.

Our quadrupole guide has a straight symmetry axis, which we define as the z axis (see Fig. 1). Four OFHC copper wires with 1.1-mm diameter are placed at the coordinates ($\pm a/2$, $\pm a/2$) with currents in adjacent wires running in opposite directions. In this configuration, the gradient of the guide field near the z axis is $4\mu_0 I/(\pi a^2)$. The separation a is dependent on the position z. It starts at 7.5 mm to allow the MOT beams to enter the atom guide and to collect cold atoms on the axis of the guide. Further down, the wire separation linearly tapers down to $a=3$ mm over a distance of 3.5 cm. After the tapered section, $a=3$ mm for the rest of the atom guide. The guide has a total length of 20 cm. Operating at a current $I=14$ A, the gradient of the guide field varies from 40 G/cm at the MOT location to 250 G/cm in the compressed region. The gravitational force on the ^{87}Rb $5S_{1/2}$ $|F=2,m_F=2\rangle$ atoms is equivalent to about 15 G/cm. Thus, even in the low-gradient section the trapping force is strong enough to prevent atoms from falling out. The earth's magnetic field has a z component of ~ 100 mG, which prevents trap loss due to Majorana spin flips near the guide axis.

The atom guide is accommodated in a vacuum chamber consisting of two rectangular quartz cells of dimensions $12.5\times 12.5\times 40$ mm^3 linked by a 1.3-cm-diam quartz tube. The Rb vapor pressure is regulated by cooling the Rb ampoule, which is connected close to the MOT, with a thermoelectric cooler. The vacuum chamber is pumped by a 20-l/s ion pump. The guide wires are held in place by thin Macor disks, which also aid in the differential pumping of the MOT and the narrow sections of the atom guide. The background vapor pressure near the pump is $<10^{-9}$ Torr; the MOT loading time with this pump pressure is 3 s. The MOT is operated with a 70-mW diode laser, which is stabilized by an external grating and detuned by 1.5Γ to the red of the $5S_{1/2}(F=2)\rightarrow 5P_{3/2}(F'=3)$ transition of ^{87}Rb (linewidth $\Gamma=2\pi\times 6$ MHz, $\lambda=780$ nm). A second diode laser tuned to the $5S_{1/2}(F=1)\rightarrow 5P_{3/2}(F'=2)$ transition provides light for repumping the atoms that fall out of the trap cycle.

While the MOT can be operated with the atom guide always on, in the following experiment the guide is cycled in order to maintain a low wire temperature and a low vacuum pressure. The experiment is performed in a pulsed mode with 4 s for the MOT loading and 500 ms for atoms to propagate along the guide. During the off phase of the guide, the MOT collects 2×10^6 atoms from the background Rb vapor. The MOT coils are then turned off and the detuning of the cooling beam increased to 3Γ to allow for 7 ms of cooling in an optical molasses. Just before the start of the guide on-phase, a shutter blocks the molasses beams. When the guide current turns on, the atoms are loaded directly onto the axis of the guide and start to accelerate down the guide, which is tilted at an angle of $\theta=18.5°$ from the horizontal.

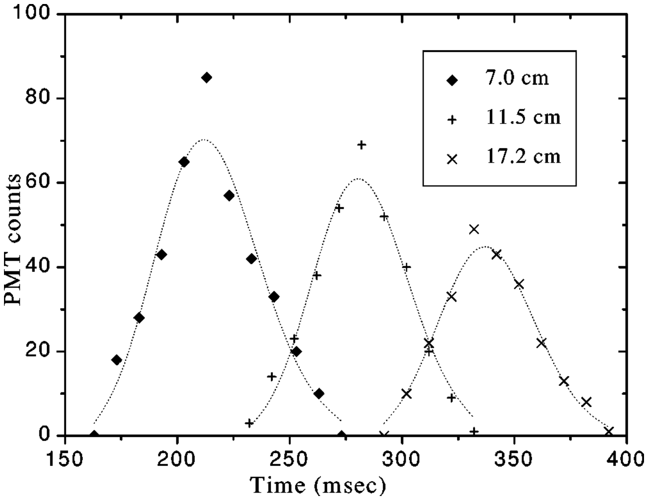

FIG. 2. Time-of-flight signal measured at $z_0=7.0$, 11.5, and 17.2 cm along the atom guide. The dotted curves are fits of Eq. (1) to the experimental data.

We perform time-of-flight (TOF) measurements of the atoms propagating in the guide by introducing a probe beam perpendicular to the atom guide at a distance z_0 from the MOT. The probe beam is at saturation intensity, has a duration of 500 μs, and is on resonance with the $5S_{1/2}(F=2)\rightarrow 5P_{3/2}(F'=3)$ transition. The fluorescence from the atomic cloud is measured with a calibrated photomultiplier tube (PMT). To prevent the **B** field of the atom guide from shifting the atoms off-resonance, the guide current shuts off during the time of the probe. The measured TOF signal $S(t,z_0)$ obtained for three values of z_0 is shown in Fig. 2.

The signal can be modeled by assuming that the initial atom cloud has a Gaussian velocity distribution with a constant longitudinal temperature T. All atoms start at $z=0$ and accelerate down the atom guide at a rate $g\sin\theta$ towards the probe beam (g is the gravitational acceleration). The initial width of the atom cloud released from the MOT and the probe beam diameter can be neglected, because they are small compared to the cloud spread at our observation times. Then, the fluorescence of the atoms approximately follows

$$S(t,z_0)\approx \frac{S_0}{t}\exp\left[-\frac{m}{2k_bT}\left(\frac{z_0}{t}-\frac{1}{2}gt\sin\theta\right)^2\right], \qquad (1)$$

where S_0 is a constant proportional to the number of atoms in the cloud. The $1/t$ factor in Eq. (1) reflects the spread of the atom cloud, which increases linearly with time.

By fitting the measured TOF data to curves of the shape $S(t,z_0)$ from Eq. (1), we deduce the longitudinal temperature

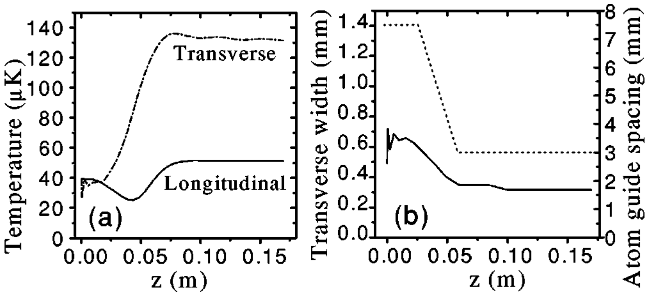

FIG. 3. Temperature (a) and transverse width (b) of the atom cloud as a function of z. The dotted curve on the right shows the separation between the wires along the atom guide.

of the atoms inside the atom guide to be 50 μK. The full width at half maximum cloud spread along z at $z_0=17.2$ cm is 5.5 cm, and the average longitudinal velocity 1.0 m/s. The three TOF curves do not exhibit a significant asymmetry relative to the fits. This observation indicates that over the ≈ 80 ms duration of the individual TOF curves at fixed z_0 the atom loss is minimal: if there were a significant loss over that time interval, the right (left) wings of the experimental data would be depressed (enhanced) relative to the fitted curves. Since the three TOF curves overlap, we can conclude that the atom loss between $t\approx 200$ msec and ≈ 350 msec is small. Further, the fits to the data in Fig. 2 yield three values for the normalization constant S_0 that vary by only 7%, i.e., the overall signal height for different z_0 approximately follows the $1/t$ behavior expected from Eq. (1). This observation provides a second indication that the atom losses between $t\approx 200$ msec and ≈ 350 msec are small. During that time interval, the atoms traverse the lower 2/3 of the atom guide, where the vacuum pressure is expected to be better than in the MOT region.

To estimate the number of atoms in the guide, we numerically determine the average number of photons $\overline{N}$ detected by our PMT *per atom* in the whole guide. Since we probe the atoms using the practically closed $F=2\rightarrow F'=3$ transition, we can neglect optical pumping into the $F=1$ state. The spatial distribution $P(x,y,z)$ of the atoms in the waveguide at the time when the probe is turned on is calculated from the time evolution of the atom cloud inside the magnetic potential. The number of photons $N(x,y,z)$ that are scattered into the slit of the PMT detector by an atom that gets hit by the probe at location (x,y,z) is numerically obtained by trajectory calculations. These calculations take into account the probe parameters and the radiation pressure that the probe exerts on the atoms. The radiation pressure strongly accelerates the atoms while they are being probed, causing a time-dependent Doppler shift and a shift of the atom image that the imaging optics produces on the PMT slit. The radiation pressure has a strong influence on the values $N(x,y,z)$ returned by the trajectory simulation. The average number of photons detected per released atom $\overline{N}=\eta_{\mathrm{PMT}}\eta_{\Omega}\int\int\int P(x,y,z)N(x,y,z)dx\,dy\,dz$, where $\eta_{\mathrm{PMT}}=0.5\%$ is the PMT efficiency and $\eta_{\Omega}=1\%$ the fraction of the solid angle. We find $\overline{N}\approx 8\times 10^{-4}$ per atom at the maximum of the signal for $z_0=11.5$ cm. Considering that we have neglected reductions of the overall detection efficiency due to focusing errors and reflections, we estimate based on the maximum count of 70 obtained for $z_0=11.5$ cm (see Fig. 2) a number of 10^5 atoms per pulse propagating in the guide. This value corresponds to a transfer efficiency of 5% for the coupling of atoms from the MOT into the atom guide. The transfer efficiency can be enhanced by optically pumping the atoms into the magnetically trapped state $|F=2,m_F=2\rangle$. We also believe that background gas collisions in the vicinity of the MOT, where the pressure is higher, cause some losses. In the future, these losses will be controlled by an improved differential vacuum pumping design and by tools that cause the atoms to leave the MOT region faster.

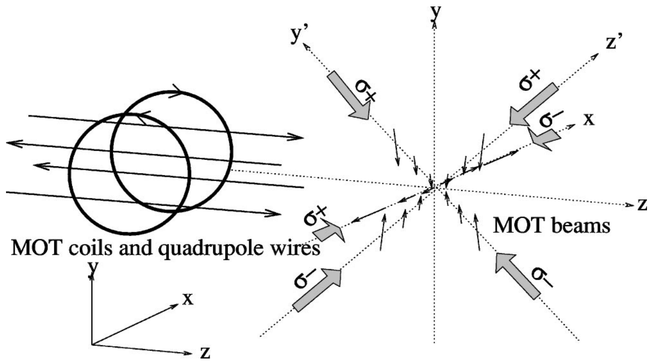

FIG. 4. MOT configuration for cw operation inside an atom guide. For clarity, we show the MOT beams and **B**-field vectors displaced to right of the coils.

The atom dynamics inside the guide can be described classically using the sum of the gravitational and magnetic-dipole potentials. For qualitative considerations, we assume a cylindrically symmetric trapping potential, i.e. we neglect the influence of gravity and deviations of the transverse magnetic field from a pure quadrupole field. The oscillation frequency of the atoms in the transverse atom guide potential increases from ~ 70 Hz near the MOT to ~ 500 Hz in the narrow part of the guide. The motion has two adiabatic invariants associated with the transverse oscillations of the atoms: one is the z component of the angular momentum, the other the radial action integral, $S_\rho=\oint_{\rho\,\mathrm{min}}^{\rho\,\mathrm{max}} p_\rho d\rho$, where $\rho=\sqrt{x^2+y^2}$. Since the transverse oscillation period is much smaller than the time the atoms take to move through the gradual taper, the adiabatic invariants are approximately conserved. Under our current conditions, the action of the transverse motion of the atoms is $\sim 20000h$, i.e., a classical treatment of the system is adequate. Our trajectory calculations indicate that for moderate symmetry breaking, as encountered in our system, the motion remains regular (with adiabatic invariants that are less obvious than in the symmetric case).

The adiabatic conservation of the transverse actions entails a compression of the atomic distribution and an increase of the transverse temperature in the tapered region of the atom guide. We have simulated the classical motion of the atom cloud through the guide using the exact wire geometry and including gravity. Figure 3(b) shows that the atoms are compressed by a factor of about 2 (linear compression), while the temperature increases to about 130 μK. The oscillations at the beginning of the curves for the transverse motion reflect slight breathing-mode oscillations induced by the diabatic capture of the atoms into the magnetic trap.

Using the adiabatic approximation, one can further show that the taper in the atom guide induces a longitudinal repulsive force in the $-z$ direction, which depends on the transverse action. The repulsive force slows the atoms during their entry into the taper. Since atoms with initially large v_z arrive at the taper earlier than the slower ones, the fast ones are slowed first, resulting in a temporary compression of the longitudinal velocity distribution. This temporary compression causes a dip of the longitudinal temperature in the tapered region [see Fig. 3(a)]. The dip disappears once the atom cloud has completely moved past the taper.

To avoid an increase of the pressure in the chamber, we have mostly operated our guide in a pulsed mode. The atom guide could, however, be operated continuously in parallel with the MOT for several minutes before the wire heating affected the vacuum. The **B** field of the MOT coils superimposed with the guide field results in a field of the form $(2\beta+\alpha)x\hat{\mathbf{e}}_x-(\beta+\alpha)y\hat{\mathbf{e}}_y-\beta z\hat{\mathbf{e}}_z$, where α is the field gradient of the quadrupole and 2β the field gradient of the MOT coils along the MOT coil axis. In our setup, we have used $\alpha=40$ G/cm and $2\beta=20$ G/cm, resulting in a total field $\mathbf{B}=6\beta x\hat{\mathbf{e}}_x-5\beta y\hat{\mathbf{e}}_y-\beta z\hat{\mathbf{e}}_z$. The MOT beams are aligned along the x, y', and z' axes, where the primed axes are obtained by a 45° rotation of the y and z axes about the x axis. This configuration departs from the standard MOT setup [13] in that the beam directions, which define the light helicity, are not completely parallel to the magnetic field lines (see Fig. 4). We find that our MOT is still robust under that imperfect condition. We believe that this observation reflects the known robustness of standard MOTs against moderate deviations of the light polarizations from their ideal σ^+ and σ^- settings. In both cases, the imperfections increase the radiation pressure due to the beams pointing away from the trap center. This adverse condition does not spoil the MOT as long as the radiation pressure directed towards the trap center remains dominant. We further find that the atomic cloud in the described nonstandard MOT is thin but elongated along the guide axis. The aspect ratio appears in qualitative agreement with the large ratio between the field gradients in the transverse and the z directions. The observed deformation is cylindrically symmetric about the guide axis and is therefore compatible with the guide symmetry. This compatibility and the fact that the atom cloud in the MOT is predominantly spread along z allows one to transfer the atoms from the MOT into the atom guide potential such that there is a good matching of kinetic and potential energies, and that the total energy increase due to the transfer is small.

In conclusion, we have demonstrated a technique for direct on-axis coupling of cold atoms from a MOT into a magnetic atom guide. We have measured the gravitation-induced propagation of the atoms along the guide over 17 cm. The guide features a tapered section, which increases the transverse oscillation frequency and compresses the atoms. In miniature atom guide schemes, tapered sections could serve as mode selectors and as integrating elements connecting atom guides to macroscopic MOTs. In the future, control of the atomic motion along the atom guide axis can be obtained using guides that are curved in the gravitational field and/or employ auxiliary magnetic-dipole potentials generated by position-dependent bias fields. Our present setup uses four wires to form a quadrupole guide. The in-line MOT design we have presented can, however, be easily adapted to the two-wire quadrupole configurations that many existing miniature atom waveguides are based upon.

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