

Storage Ring for Neutral Atoms

J. A. Sauer, M. D. Barrett, and M. S. Chapman

School of Physics, Georgia Institute of Technology, Atlanta, Georgia 30332-0430

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We have demonstrated a storage ring for ultracold neutral atoms. Atoms with mean velocities of 1 m/s corresponding to kinetic energies of ~ 100 neV are confined to a 2 cm diameter ring by magnetic forces produced by two current-carrying wires. Up to 10^6 atoms are loaded at a time in the ring, and seven revolutions are clearly observed. Additionally, we have demonstrated multiple loading of the ring and deterministic manipulation of the longitudinal velocity distribution of the atoms using applied laser pulses. Applications of this ring include large area atom interferometers and monochromatic atomic beam generation.

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Controlling the motional degrees of freedom of neutral atoms has emerged as a major theme in modern atomic physics. The development of laser cooling and related techniques to cool atoms down to the μK regime allows trapping and manipulation of the atomic motion using interactions with the relatively weak electric and magnetic fields available in the laboratory. Complementing the 3D trapping work, there has been considerable progress recently in developing 2D magnetic guiding structures for ultracold neutral atoms—so-called guided atom optics. Much of this work is motivated by the prospects of coherent de Broglie wave transport for applications including ultrasensitive atomic interferometers and quantum information processing. A variety of simple guides have been developed based on current-carrying wires [1–5], and extensions of these systems have been used to demonstrate atomic beam splitters [6,7], atom conveyors [8], and magnetic microtraps [8,9].

It is compelling to extend these techniques to a ring geometry, and there have been several proposals along these lines [10–12], as well as a recent demonstration confining fast polar molecules to an electrostatic ring [13]. These are motivated in part by the prospects of ring-based atomic interferometry and monochromatic atomic beam generation. Similar to optical ring interferometers, the ring geometry offers greater sensitivity through increasing the effective enclosed area of the interferometer both by straightforward enlargement of the ring as well as by employing multiple-orbit interfering trajectories. This is important because the sensitivity of many interactions (e.g., Sagnac rotational phase) is proportional to the enclosed area of the interferometer [14]. This geometry also provides new opportunities to create ultracold and monochromatic atomic beams. For example, the ring can be multiply loaded to increase the number of atoms in the ring, and both the longitudinal and transverse velocity distributions of the atoms can be manipulated and cooled in the ring. Finally, highly directional output beams can be created by using a coherent, variable output coupler.

In this work, we demonstrate the first storage ring for neutral atoms. Our ring consists of a particularly simple

two-wire magnetic guiding structure. We have developed a technique to successfully transfer atoms to the ring from an external magnetic waveguide directly loaded from a magneto-optic trap (MOT). We observe up to seven complete revolutions of the atoms in the ring, and we have also demonstrated multiple loading. Finally, we have performed simple manipulations of the longitudinal velocity distribution of the atoms in the ring.

Magnetic confinement of neutral atoms is based on the interaction of the atomic magnetic dipole projection μ_m with a spatially varying external magnetic field $\mathbf{B}(\mathbf{r})$. For slowly moving atoms, the dipole will adiabatically follow the field direction, yielding a trapping potential energy $U(\mathbf{r}) = -\mu_m |\mathbf{B}(\mathbf{r})|$. Hence, atomic states with spins antialigned with the local field (i.e., with $\mu_m < 0$, so-called weak-field seeking states) will be confined to regions in space with a minimum in the magnetic field magnitude.

To provide this minimum, we use a 2D quadrupole magnetic field produced by two nearly parallel wires carrying equal currents in the same direction. To the lowest order, the field between the wires is given by $\mathbf{B}(x, y) = 4\mu_0 I(y\hat{x} + x\hat{y}) (\pi d^2)^{-1}$ where μ_0 is the usual permittivity of free space, d is the spacing between the wires, and I is the current in each wire. A plot of the full trapping potential (ignoring gravity) is shown in Fig. 1c; the corresponding trap depth is $I\mu_0\mu_m/d\pi$, about 1/2 that of the more common 4-wire guide.

Our experiment utilizes two pairs of such wires as shown in Fig. 1a—the “ring” that confines the atoms to a circular path, and the “guide” that couples atoms from the MOT into the ring. Both the guide and the ring consist of 280 μm diameter copper wires capable of sustaining a steady state current of several amps. The ring wires have a separation $d \sim 840 \mu\text{m}$, which, at a wire current of 8 A, provides a field gradient of 1800 G/cm, a mean trap frequency of 590 Hz, and a trap depth of 2.5 mK for the $F = 1$, $m_F = -1$ ground state of ^{87}Rb . The diameter of the storage ring is 2 cm. The spacing of the guide wires varies from 4 mm where the MOT is formed down to 840 μm where it overlaps with the ring.

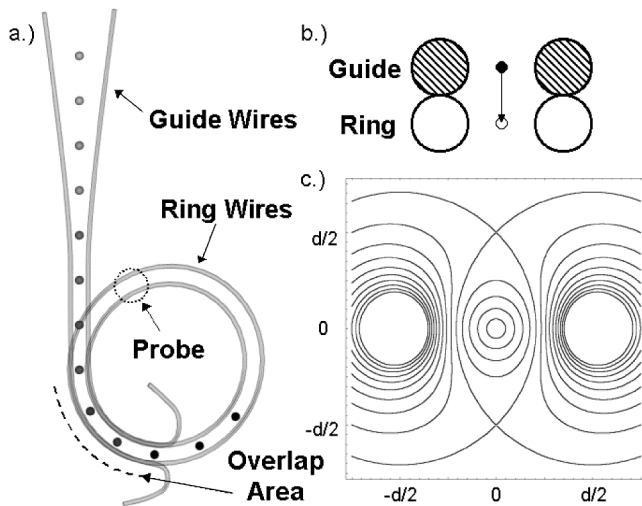


FIG. 1. (a) A schematic of the storage ring. (b) A cross section of the overlap region. The trap minimum is shifted from between the guide wires to the ring wires by adjusting the current. (c) A contour plot of a two wire potential. The contours are drawn every 0.5 mK for $d = 0.84$ mm and $I = 8$ A.

We begin the experiment by loading ^{87}Rb atoms into a MOT between the guide wires. The MOT is produced by 3 retroreflected laser beams, each having an intensity of 12 mW/cm^2 and a $1/e^2$ diameter of 1 cm. The trap lasers are tuned 17 MHz below the $5S_{1/2} - 5P_{3/2}F = 2$ to $F' = 3$ transition, while anti-Helmholtz coils generate a magnetic field gradient of 6 G/cm. An additional laser beam tuned to the $F = 1$ to $F' = 2$ transition with an intensity of 4 mW/cm^2 repumps the atoms decaying into the $F = 1$ state. The MOT is loaded directly from a thermal beam, and the trap typically contains $\sim 6 \times 10^6$ atoms after 2 s of loading. The presence of the guide wires directly in the path of the trap laser beams necessitates careful alignment of the MOT beams and coils—perhaps because the shadows of the wires reduce the effective loading volume of the MOT. Following loading, the MOT coils are turned off and the guide current is ramped on in 5 ms. A short interval of sub-Doppler cooling is performed, during which the trap laser detuning is ramped further to the red by 110 MHz over 2 ms and the repump intensity is lowered tenfold and finally shuttered off. At this point the atoms are all in the $F = 1$ ground state with a measured longitudinal temperature $3 \mu\text{K}$. From the extent of the cloud, we infer a transverse temperature of $57 \mu\text{K}$ after the guide current reaches its final value.

About 15% of the atoms in the MOT are transferred to the guide; this is comparable to other experiments using this technique [4,5]. We have found that the coupling efficiency increases with increasing guide current; however, our present setup is limited to a maximum current of 8 A. Once in the guide, the atoms fall 4 cm under gravity to the 15 mm overlap with the ring. To transfer the atoms from the guide to the ring, we ramp the current in the guide off while simultaneously increasing the current in the ring

to its final value. This process transfers the trap center from the guide to the ring (see Fig. 1b). Optimal transfer is achieved for equal currents in the guide and ring. The transfer efficiency to the ring is estimated to be $>90\%$ and is maximized by a transfer time of 16 ms. For longer transfer times, the cloud traverses the entire overlap region before transferring completely to the guide—for shorter times, we measure losses from the cloud, possibly due to heating.

To measure the evolution of the atoms in the ring, they are resonantly excited with a 1 ms laser pulse focused directly between the wires of the ring, and their fluorescence is imaged onto an intensified CCD camera (see Fig. 2). By repeating the measurement with different probe delay times, the complete trajectory of the atoms can be measured. A typical measurement of the atomic orbits in the ring is shown in Fig. 3. The different peaks correspond to complete revolutions of the ring, and 7 complete revolutions of the ring are clearly distinguished. The measured orbit time of 81 ms corresponds to an average velocity of 85 cm/s, which is consistent with a 4 cm free fall. The peaks fit reasonably well to a simple model incorporating only losses from the ring as well as the continued azimuthal free expansion of the atom cloud. From this fit, the $1/e$ lifetime of the ring is determined to be 180 ms, and the azimuthal temperature is measured to be $3.4(3) \mu\text{K}$, only slightly hotter than the temperature measured immediately after loading the guide. To obtain more satisfactory agreement with the data, the model was extended to include a term corresponding to a loss of atoms from the orbit to a diffuse background in the ring.

The lifetime of the ring is somewhat shorter than expected from losses due to background collisions alone. Although we do not have a reliable direct measurement of the vacuum at the ring, we infer a vacuum-limited lifetime of >800 ms from the MOT loading time constant.

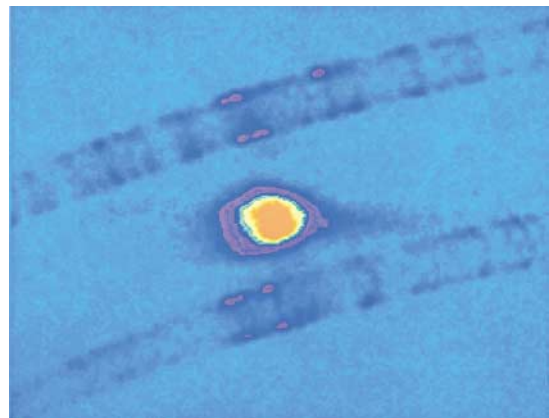


FIG. 2 (color). A false color image shows probing of the atomic cloud in the storage ring. These atoms have made 2 complete revolutions in the ring. The ring wires are visible above and below the cloud, and have a center to center spacing of $840 \mu\text{m}$.

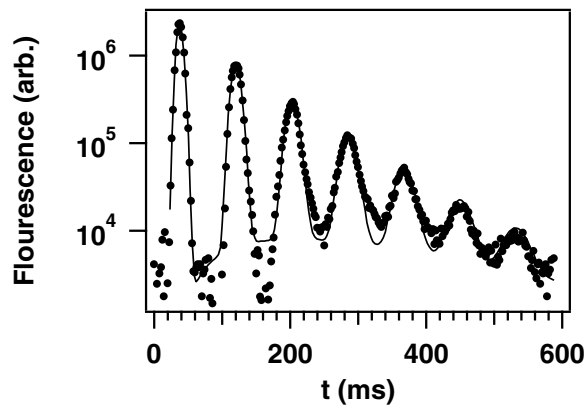


FIG. 3. Successive revolutions in the storage ring. The points represent experimental data, the curve is a theoretical model. The first peak corresponds to the first complete revolution in the ring.

Additionally, we have measured that the lifetime of the storage ring decreases by 20% if the current in the ring is ramped from 8 to 5 A over 40 ms after the atoms are loaded. Possible additional loss mechanisms from the ring include nonadiabatic spin flips (so-called Majorana transitions) and ergodic mixing from the azimuthal motion to the transverse motion. Adiabatic following of the magnetic field requires the time rate of change of the field direction to vary slowly compared with the precession frequency, $d\theta/dt < \mu_m|B|/\hbar$ [15]—where the field goes to zero, this condition cannot be met and hence atoms passing within a minimum radius of the guide center are likely to be lost from the ring. Following the model given in [16], the loss radius for our guide is $b_0 = 0.6 \mu\text{m}$, which, together with the cloud size and transverse temperature, leads to an expected $1/e$ lifetime of 300(100) ms. However, we would expect that the loss rate would increase with increasing ring current, which is contrary to our observations. In any case, this issue can be readily avoided in future rings by adding a single axial wire to the ring, which would provide a small azimuthal field.

The losses could also be the result of ergodic mixing due to imperfections in the ring. A likely suspect in this regard is the junction in the ring where the current is fed in and out. We estimate that the nonuniformity in the current distribution at this location produces a 20% ripple in the potential over a $250 \mu\text{m}$ distance. This perturbation in the magnetic potential could transfer some of an atom's azimuthal energy into transverse energy and cause it to leave the trap. From the extent of the cloud inside the ring, we infer a transverse temperature of 1.35 mK after one revolution, about two times greater than expected from adiabatic heating alone. The average orbital kinetic energy of the atoms is about twice the trap depth at 8 A, and hence an atom need transfer only 15% of its azimuthal energy to transverse energy to be lost from the trap in two revolutions. This mixing could also explain the slowly changing diffuse background mentioned above. Furthermore,

we would expect that this loss mechanism would decrease with increasing current as the trap becomes deeper, while the atoms are compressed to the center of the guide where the perturbation is weakest. In future rings, the field irregularity can be greatly minimized with additional trim wires.

Even with this ring lifetime, it is noteworthy that the total guided distance in the ring is ~ 0.5 m and if this system was used in a ring interferometer configuration, the enclosed area would be $\sim 4400 \text{ mm}^2$, 200-fold larger than the most sensitive atomic gyroscope demonstrated to date [17]. Furthermore, with straightforward modifications to the ring discussed above, together with improved vacuum conditions, it should be possible to increase these values by another 100-fold (corresponding to a ring lifetime 20 s), yielding an intrinsic sensitivity 10^4 larger than in [17]. Of course, maintaining atomic coherence over these time scales is a significant technical challenge, and would most certainly require guiding in a single transverse mode; however, the ring geometry offers important advantages. In particular, by using complete revolutions of the ring for the interfering counterpropagating trajectories, we can ensure that each interfering amplitude acquires the same dynamical phase from the guiding potential (to the extent that the ring current and dimension remain constant), which will be important to cancel out effects of inevitable irregularities in the guiding potentials. This advantage, together with the recent demonstrations of fast, compact techniques for making atomic Bose condensates in optical [18] and magnetic microtraps [19] makes the prospects of single-mode guided atom interferometry quite promising.

The ring geometry also provides unique capabilities for the generation of intense, cold atomic beams. Although linear guides are already promising in this regard [20], the ring geometry allows for convenient multiple loading [21,22]. Furthermore, the ring could be combined with a very selective output coupling mechanism (employing laser induced Raman transitions, for example) to provide

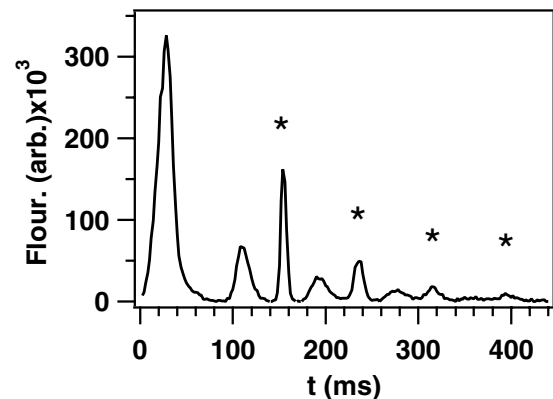


FIG. 4. Double loading into the ring. Those peaks marked with a "*" are from the second loading. The clouds are 180° out of phase, with a spacing of only 40.5 ms between successive peaks.

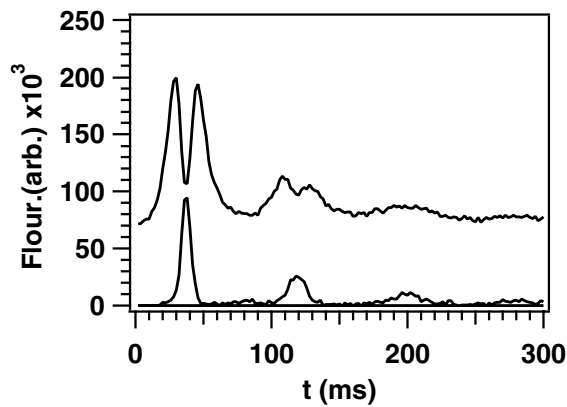


FIG. 5. Deterministic pulse shaping. The upper graph corresponds to a cloud with its center removed. The lower graph has everything but its center removed. The upper graph has been offset for clarity.

a very bright extracted beam. Here, the ring configuration can provide efficient “recycling” of the unextracted atoms, which can then be further manipulated in the subsequent revolutions. We have taken first steps toward these goals by demonstrating multiple loading of the ring and simple manipulation of the azimuthal atomic momentum distributions.

To multiply load the ring, we immediately begin to reload the MOT after the ring is initially loaded. After a 0.2 s loading time, these atoms are loaded in the guide and fall down to the ring. To load them into the ring without releasing the originally loaded atoms, the ring current is first ramped down to 2 A to allow the reloaded atoms into the overlap region. Then the ring current is increased while the guide current is decreased just as in the original transfer. Figure 4 depicts a typical double loading trajectory. The additional loading of the ring appears as a second set of peaks orbiting 180° out of phase with the original loading. The second loading results in additional losses of 28% in the initial cloud. Most of these losses (70%) are due to scattered trapping light and magnetic fields from the MOT coils—these losses can be easily avoided with appropriate isolation of the ring.

In our final experiment, we used a resonant beam to alter the azimuthal velocity distribution of orbiting atoms. The original azimuthal velocity distribution has a width $\Delta v \sim 2$ cm/s corresponding to a speed ratio $v/\Delta v \sim 50$ in the ring. Because of the free expansion of the atomic cloud along the guide direction, the initial velocity distribution is mapped onto the azimuthal spatial distribution of the atoms in the ring. Hence the velocity distribution can be modified by selective temporal or spatial removal of portions of the cloud. Two such modifications are shown in Fig. 5. In both cases, the velocity distribution has been modified in the previous orbit (not shown)

and traces show the evolution for subsequent orbits. In the bottom trace, only the central 40% of the FWHM has been preserved, corresponding to an increase of the speed ratio to 125. In the top trace, the central 40% of the FWHM has been removed, leaving a double-peaked distribution. In both cases, the subsequent evolution and broadening of the peaks occur at the expected rate.

In summary, we have demonstrated a magnetic storage ring for neutral atoms, together with an efficient loading method. We have also demonstrated that the ring can be multiply loaded, and we have manipulated the velocity distribution of the atoms in the ring. Extensions of this work to ring-based atom interferometry and cold-beam generation hold much promise for the future.

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