MOT Loading Enhancement with Stimulated Light Forces

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***Abstract*—We demonstrate atom number enhancement in a magneto-optical trap (MOT) by use of bichromatic cooling to slow an atomic beam that is loaded into a MOT. Bichromatic cooling employs stimulated emission to apply strong cooling forces that are not limited by spontaneous emission. We demonstrate a factor of 3.5 increase in atom number captured from the atomic beam for a 1.5 cm cooling length. For a 1.5 cm effective cooling length, our technique yields MOT atom number enhancement that is about three times higher than the enhancement acheived via spontaneous emission.**

I. Introduction

While atom cooling and trapping have revolutionized atomic clocks and precision measurements, cold atoms are not yet used in commonplace technologies. The ability to create widely disseminated, high-performance compact atomic clocks and sensors based on cold atoms could revolutionize portable frequency standards. A fundamental difficulty in developing compact cold-atom devices is that the number of captured atoms in a conventional magneto-optical trap (MOT) scales as d^4, where d is the laser beam diameter [1]. Experiments performed with microfabricated pyramidal traps have demonstrated an $N \propto d^6$ scaling law, showing that the scaling can be even worse for small systems [2].

The strong dependence of the atom number on beam size is fundamentally set by the maximum spontaneous light force achievable in a MOT, $F_{spont} = \hbar k\gamma/2$ [3], where $\hbar k$ is the photon momentum, γ is the resonance linewidth, and $\gamma/2$ is the maximum spontaneous photon scatter rate. To overcome this limitation, we have employed stimulated emission forces to slow a ^{87}Rb atom beam and increase the atom number density at low velocities. In principle, the stimulated forces are limited only by the available laser power.

The stimulated forces are created by a bichromatic cooling technique. Experiments demonstrating use of the bichromatic force to slow an atomic beam were first done by Söding et al., who slowed a cesium beam over a distance of 10 cm with total laser power exceeding 100 mW [4]. Bichromatic cooling has also been studied for Rb atoms [5] and metastable He atoms [6]. A thorough review of laser cooling and trapping techniques that includes a review of bichromatic cooling can be found in Ref. [3]. To our knowledge, our experiment is the first to use the technique for MOT atom number enhancement.

The concept of bichromatic cooling is presented in Fig. 1, where a sample atom is moving with a velocity v_{atom} to the right. A light beam with two frequency components, $\omega = \omega_0 \pm \Delta - kv_{atom}$, strikes the atom from the right and a light beam with the frequency components, $\omega = \omega_0 \pm \Delta + kv_{atom}$, strikes the atom from the left, where $k = 2\pi/\lambda$ is the photon wavevector for light resonant with a cycling transition in the atom at resonance frequency ω_0. Due to the Doppler shift, the light from both the left and the right has frequency components of $\omega = \omega_0 \pm \Delta$ in the atom's frame of reference. For each bichromatic light beam, the two frequency components interfere to create a beat pattern with period $T = \pi/\Delta$. Tuning the intensity such that each frequency component has the Rabi frequency $\Omega = \Delta/4$ configures the light field into two counterpropagating traveling waves of pi-pulses. When the relative phase difference between the pulse trains is set such that an atom on average first absorbs a photon from the beams propagating opposite to its velocity, and is then de-excited due to stimulated emission into the other pulse train, the atom will be slowed with a $2\hbar k$ momentum loss per stimulated-emission cycle.

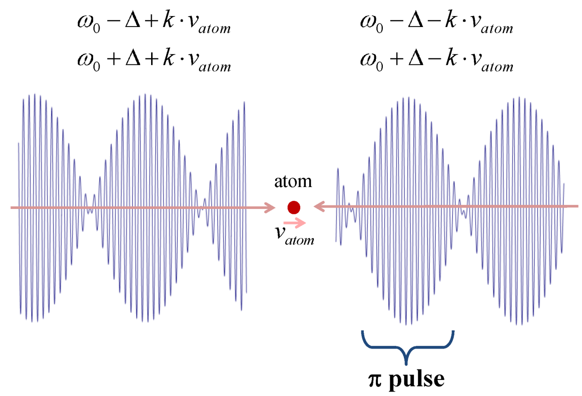

Fig. 1. The π-pulse picture of bichromatic cooling.

The relative phase of the beats from the two beams sets the preferred direction of photon momentum transfer. The optimum relative phase ϕ between the counterpropagating beat signals occurs at about $\phi \simeq \pm\pi/2$ ($+\pi/2$ for cooling, $-\pi/2$ for heating.) Spontaneous emission breaks the symmetry in the system. Since the atoms have more time after the second pulse to undergo spontaneous emission ($3T/4$), they are preferentially excited by the first pulse and de-excited by the second pulse that arrives a period $T/4$ later. The velocity over which the bichromatic force profile acts extends over a large class, $\delta v = \Delta/k$, centered on the velocity v_{atom}.

II. Experiment

We slow atoms from a thermal beam and then capture them in a MOT. We have deliberately used low cooling powers for the MOT beams to simulate the small capture velocity that would result from the use of small MOT beams. The MOT is formed from three pairs of retro-reflected cooling beams with a 7 mm diameter and approximately 0.9 mW of laser power per beam ($I/I_{sat} = 1.4$). Under these conditions, we calculate a MOT capture velocity of $v_c \simeq 15$ m/s, which is equal to the value for a MOT of 2 mm diameter with fully saturated beams.

To test how bichromatic cooling scales with miniaturization, we performed experiments over short cooling lengths and with low laser powers. We use laser powers of < 2 mW per bichromatic frequency component, which is $\sim 0.05\times$ as large as the powers used in Ref [4]. We achieve the high intensities required for stimulated emission by focussing the light through two apertures of 0.5 mm diameter that collimate the atomic beam ($I/I_{sat} \simeq 600$). Through simulations of the force profile, we calculate a maximum stimulated force $12\times$ larger than the spontaneous force limit, with less than 8 mW of total laser power. We set the central position of the force profile to sit at 70 m/s so that cooling force extends from atoms with velocities of about 15 m/s ($\simeq v_c$) out to about 120 m/s.

We vary the effective slowing distance by changing the total interaction period of the cooling light with the atomic beam. This is accomplished by rapidly chopping the bichromatic cooling light with a radiofrequency (rf) switch that controls the rf power applied to acousto-optic modulators. We switch the cooling light on and off on time scales as short as ten microseconds. To vary the cooling length, we change the duty cycle with which we pulse the light. The full distance that the atomic beam travels in our system before entering the MOT volume is 7.5 cm, and we typically test the cooling methods down to cooling lengths of about 0.4 cm (5 % duty cycle).

To test the effectiveness of bichromatic cooling for loading a small MOT, we compare the number of captured atoms loaded with an atomic beam slowed by spontaneous forces versus one slowed by stimulated forces. For spontaneous slowing, we apply a strongly saturated monochromatic light beam red-detuned from resonance by approximately $2\pi \times 100$ MHz. We optimize the intensity and detuning to maximize the number of captured atoms. We quantify the the effects of the beam slowing in terms of MOT number enhancement, which we define as the ratio of captured atoms in the MOT with and without slowing light applied to the atomic beam.

III. Simple Model

We have performed simple modeling of the bichromatic cooling process with which we compare our experimental results. When the phase and Rabi frequency are optimized for a selected value of Δ, the force profile is nearly rectangular in shape with a width of Δ/k (see, for example, Refs. [4], [5]). The bichromatic force is averaged across the Gaussian beam profile since the Rabi frequency varies with intensity. The force profile is further averaged over the full slowing length of our system, because the relative phase of the π pulse trains varies by about 20 degrees. This averaging broadens the range of velocities over which the force acts by about 50 % and lowers the maximum force by about a factor of 1/2. For simplicity, we have approximated the ideal force profile with a rectangular function of constant force that we fit to the force profile determined via numerical modeling of the optical Bloch equations. For the spatially averaged profile, we have decreased the maximum force and broadened the addressed velocity class to fit the spatially averaged force.

To estimate the fraction of captured atoms in a MOT, we have calculated an approximate "effective capture velocity," v_{max}. To find v_{max}, we set the work done on the atoms by the bichromatic force over the cooling distance L equal to the initial kinetic energy of the atoms with a velocity v_{max} and we solve for v_{max}. This gives $v_{max} = (2R_{scatt}Lv_{rc})^{1/2}$, where R_{scatt} is the photon scatter rate and v_{rc} is the recoil velocity. Note that this is the same equation that is often used for the MOT capture velocity with laser beams of diameter L [1]. For stimulated bichromatic forces, R_{scatt} is determined from numerical modeling to be about $10\times$ greater than what is achieved via spontaneous forces for the powers used in our experiment. To estimate the fraction of the atomic beam captured in the MOT, we integrated a normalized Maxwell-Boltzmann distribution out to v_{max} or the upper edge of the calculated force profile, whichever is smaller.

Fig. 2 is a plot of the simulated fraction of atoms captured in a MOT versus duty cycle for spontaneous and stimulated cooling processes. The fraction captured with the bichromatic cooling method saturates at low duty cycles (effective cooling lengths) because the atoms are cooled very quickly by the strong bichromatic force, and they stop interacting with the cooling light when their velocity is lowered below the edge of the force profile. The strongly saturated spontaneous cooling profile is weaker than the ideal bichromatic force by about an order of magnitude, but it acts over a much larger velocity range, which is why the fraction of captured atoms continues to rise for larger duty cycles, whereas the bichromatic fraction captured saturates.

IV. Results

A detailed paper on our experimental results is currently in preparation [7]. By use of bichromatic forces, we have demonstrated an increase in atom number captured from an un-cooled atomic beam by a factor of about 3.5 for a 1.5 cm effective cooling length, and by up to a factor of 5.5 for longer cooling lengths. Consistent with Fig. 2, the technique yields MOT atom number enhancement that is about $3\times$ higher than the enhancement achieved with spontaneous forces for a 1.5 cm effective cooling length.

Fig. 3 shows example data for MOT number enhancement versus duty cycle achieved with and without an applied

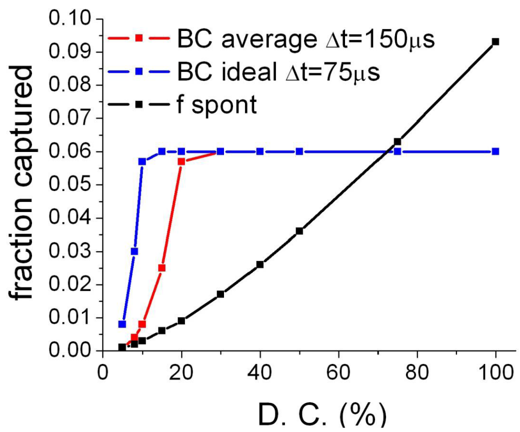

Fig. 2. Simulations of the fraction of captured atoms versus duty cycle for spatially averaged and ideal bichromatic force profiles as well as for a spontaneous force profile. To convert from duty cycle to effective cooling length (in centimeters), multiply the x-axis by 0.075. $\Delta t = m\delta v/F$ is the time required to slow an atom from the upper to the lower limit of the force profile of width $\delta v = \Delta/k$. The fraction captured in the MOT without any slowing of the atomic beam is 0.0002.

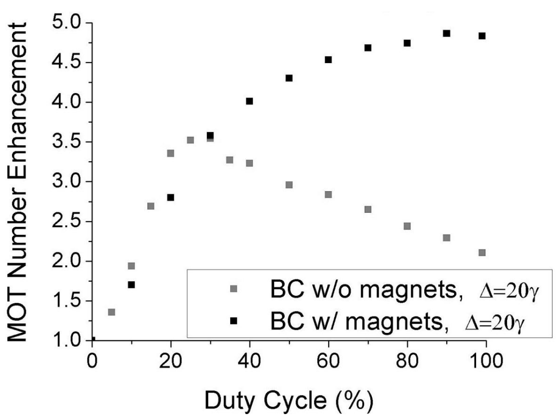

Fig. 3. Measurements of the MOT number enhancement versus duty cycle with (black squares) and without (gray squares) a magnetic guiding potential between the apertures.

magnetic guiding field. The unguided data are qualitatively similar to Fig. 2, but the enhancement actually decreases for the higher duty cycles after a maximum of 3.5× is reached for a 20 % duty cycle (1.5 cm effective cooling length). In other experiments, the MOT number enhancement actually *increased* when the bichromatic force was made *weaker* – particularly for the higher duty cycles (data not shown).

We attribute these dependencies on force magnitude and cooling length to cold-atom loss. Consistent with this, the MOT number enhancement that we observe is about 60 times smaller than what we would expect. We suspect that the main loss channel is transverse spreading of the atomic beam. The divergence angle of the uncooled atomic beam is set by the aperture geometry in the atomic beam collimator to approximately 10 mrad. The divergence angle for a given atom is equal to its transverse velocity divided by its longitudinal velocity. When an atom is slowed, its divergence angle increases and it is less likely to emerge from the second pinhole in the collimator.

One of the data sets in Fig. 3 was measured with a linear quadrupole field applied between the collimator apertures by two permanent magnets. The magnetic field gradient was $\sim$ 20 G/cm, which is strong enough to guide atoms with transverse velocities of up to 0.1 m/s through the second collimator aperture. Since the maximum transverse velocity for the atoms addressed by the cooling light is ~ 1.2 m/s, we would not expect to guide all of the atoms with the quadrupole field, but we would expect to increase the enhancement for the proper cooling-light polarization. With the guiding field, we increased the MOT number enhancement for the higher duty cycles from about 2× to about 5× (Fig. 3). As expected, the increase in MOT atom number enhancement was only observed for the proper cooling-light polarization.

V. Conclusion

By use of bichromatic cooling, with our current experimental parameters we should be able to slow 6 % of the atoms in an atomic beam to MOT capture velocities in distances of under 1 cm.

We are currently working on experimental design changes that will alleviate the problem of cold atom loss, after which we will try the method in a compact system with trapping volumes of order 1 mm^3. Ultimately, we expect to optimize our system to be able to load an optical molasses with 1 mm diameter beams with 100× more atoms than if loaded from a background vapor.

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