Crossed-Beam slowing to enhance narrow-line Ytterbium Magneto-Optic Traps

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We demonstrate a method to enhance the atom loading rate of a ytterbium (Yb) magneto-optic trap (MOT) operating on the narrow linewidth $^1S_0 \to ^3P_1$ intercombination transition. Following traditional Zeeman slowing of an atomic beam, two laser beams in a crossed-beam geometry frequency tuned near the broad $^1S_0 \to ^1P_1$ transition provide additional atom slowing immediately prior to the MOT. Using this technique, we observe an improvement by a factor of 6 in the atom loading rate of a narrow-line Yb MOT. The relative simplicity of this approach and its generality make it readily adoptable to other experiments involving narrow-line MOTs. We also present a numerical simulation of this two-stage slowing process which shows good agreement with the observed dependence on experimental parameters.

I. INTRODUCTION

Techniques for laser cooling of alkali atoms developed more than three decades ago have also been fruitfully applied to laser cooling of atomic species beyond alkalis over the last two decades. New scientific pursuits are afforded through the different electronic structure of such non-alkali atoms including optical atomic clocks for precision metrology and strong dipolar interactions for explorations of novel many-body phenomena. The different electronic structure can also lead to optical cycling transitions with linewidths far narrower than their alkali counterparts, leading to opportunities for narrow-line laser cooling and magneto-optical traps (MOTs) with correspondingly lower temperatures due to the reduced limiting value of the Doppler temperature.

This narrow linewidth however poses a problem for the atom loading rate of a MOT, since the laser cooling force is proportional to this linewidth. This problem can be circumvented by using a second transition with a broader linewidth as an intermediate “pre-cooling” MOT stage with protection from the correspondingly higher Doppler temperature being furnished by separating the broad- and narrow-line MOT beams either in time or in space. Such schemes involve Zeeman slowing of an atomic beam on the broad transition together with two sets of six MOT laser beams addressing the two transitions at the atom trap.

In this work we demonstrate a method to enhance the atom loading rate of a narrow-line Yb MOT fed by a Zeeman-slowed atomic beam by introducing only two additional laser beams on the broad transition. These additional beams are oriented in a crossed-beam geometry to provide additional cooling immediately prior to the MOT. Using this technique, which is readily adoptable to other atomic species, we observe an improvement by a factor of 6 in the MOT loading rate. We also perform a numerical simulation of this two-stage slowing process and find good agreement with the observed dependence on experimental parameters.

The rest of this paper is organized as follows. In Section II we discuss the basic idea of the cooling scheme and in Section III present its experimental demonstration in our apparatus. We compare our observations to the results of a numerical simulation of the laser slowing process in Section IV and present a summary and outlook in Section V.

II. CROSSED-BEAM SLOWING

In order to be captured by a MOT, an atom (i) must be located within the volume of the MOT beams (diameter $D$) and (ii) must be moving slower than the capture velocity $v_c$ of the MOT. A standard method in cold atom physics is to use the Zeeman slower technique to reduce the forward velocity of atoms in a beam emerging from an oven and bring a large fraction below $v_c$. This method allows for fine tuning of the exit velocity $v_f$ of the slowed atoms using the current flowing through the electromagnet generating the Zeeman slower field. In traversing the distance $d$ between the end of the Zeeman slower and the MOT beams, the finite transverse velocity $v_t$ of the atoms leads to a transverse displacement $v_t \times d/v_f$, which needs to be less than $D/2$ for capture.

There are several mechanical and optical access constraints common to such setups (see Fig. 1) that lead to a finite value of $d$. The slowing laser beam is set to counterpropagate with the atomic beam, which means that the beam must pass nearby or through the MOT region. To accommodate this close passage, an increasing field Zeeman slower is usually used so that the slowing beam detuning is sufficiently large to not affect the atoms in the MOT. This scheme requires some distance $d$ for the magnetic field to decay between the end of the Zeeman slower and the MOT region. In addition, the electromagnetic coils at the end of the Zeeman slower are often of sufficient size that they would block optical access to the MOT unless they are at least several inches away. In our experiment $d \approx 10$ cm, which is a typical value for such setups.

Even for an atomic beam that is initially perfectly col-
eliminated, transverse velocity at the end of the Zeeman slower will arise from “blooming” of the atomic beam due to interactions with the slower beam. This happens because atoms absorb photons from the slower beam (and receive a momentum kick counter to their motion), and then re-emit these photons in a random direction. Summed over many such events, the average momentum change from emitted photons is zero. However, the distribution of net momentum transfer from emission events has some width, meaning that many atoms do end up with non-zero momentum from emission. Modeling the emission in the transverse direction as a random walk, we expect \( v_t \) to scale as \( \sqrt{Nv_r} \), where \( N \) is the number of scattering events in the Zeeman slower and \( v_r \) is the recoil velocity.

We can estimate \( v_c \approx \sqrt{\frac{\hbar k_B T}{m}} \), where \( \Gamma_0 \approx 2\pi \times 128 \) kHz is the linewidth of the \( ^1S_0 \rightarrow ^3P_1 \) 556 nm (green) atomic transition, \( k_B \) is the corresponding laser wavenumber, and \( m \) is the mass of ytterbium. It is clear from this expression that a narrow-line MOT will feature a correspondingly small capture velocity \( v_c \). For Yb this is \( 9.7 \text{ m/s for } D = 2 \text{ cm} \). The transverse velocity is \( v_t \approx 1.5 \text{ m/s for our system} \); for an atom traveling at \( v_c \), this then converts to a transverse displacement which is larger than \( D/2 \). These estimates already suggest that loading a narrow-line Yb MOT with a Zeeman slowed atomic beam is less efficient than with a broad-line MOT as in alkali systems. For comparison, in alkali Rubidium with a large natural linewidth, \( v_c \) is an order of magnitude larger.

The dual constraint on \( v_c \) and transverse position on a conventional Zeeman slower is lifted by the addition of a second stage of cooling. The crossed beam slower is designed to provide a final stage of slowing immediately before the MOT, so that the Zeeman slower exit velocity \( v_f \) can be set higher than \( v_c \). This allows the condition \( v_t \times d/v_f < D \) to be satisfied for larger values of \( v_t \). The crossed beam slower consists of beams near the strong dipole transition \( ^1S_0 \rightarrow ^1P_1 \) at 399 nm that are set to propagate parallel to two of the MOT beams, intersecting each other in the atomic beam path just upstream of the MOT, as shown in Fig. 1. The transverse forces (vertical in figure) from the crossed slower beams cancel each other by symmetry, leaving a longitudinal force (horizontal and to the left in figure) that accomplishes the final stage of slowing down to the MOT capture velocity.

### III. CROSSED-BEAM SLOWER PERFORMANCE AND CHARACTERIZATION

We demonstrate the performance of the second-stage slower on an apparatus which can produce \(^{174}\text{Yb} \) Bose-Einstein condensates of \( 10^9 \) atoms with cycle times as short as 10 seconds. Details of other aspects of the apparatus relevant to cooling Yb can be found in Ref. 10. We now summarize the details relevant for the second-stage slowing.

The magnetic field profile of the slower consists of an offset field of \( B_0 \approx 110 \text{ G} \) and an increasing field with the total field reaching a maximum value of \( B_f \approx 475 \text{ G} \) at the exit of the slower. The maximum initial forward velocity that can get slowed by the slower is then \( \mu_B (B_f - B_0)/(\hbar \kappa_0) \approx 200 \text{ m/s} \), where \( \mu_B \) is the Bohr magneton and \( \kappa_0 \) is the laser wavenumber of the \( ^1S_0 \rightarrow ^1P_1 \) 399 nm (blue) transition. In practice, atoms starting with even higher forward velocity from the oven can be slowed by our apparatus due to the slowing laser beam also interacting with the atoms in the space between the oven and the start of the Zeeman slower. \( B_f \) is adjustable with the current supplied to the electromagnet generating the increasing field. The slowing laser beam addresses the 399 nm transition and is detuned by \( \delta = -2\pi \times 807 \text{ MHz} \approx -\mu_B B_f/\hbar \) from the transition with an average intensity approximately equal to the saturation intensity of 59 mW/cm².

The two crossed laser beams forming the second-stage slowing (see Fig. 1) are positioned to intersect at a distance \( d = 10 \text{ cm} \) beyond the end of the Zeeman slower coils and \( d_M = 1 \text{ cm} \) before the MOT. The crossed beams are elliptical, with the long axis oriented in and out of the page with respect to Fig. 1, and with the short axis having an approximately Gaussian horizontal profile of \( 1/e^2 \) width 1.5 mm. The dimension of the ellipse long axis is set to make the height of the crossed beam slowing region approximately match the diameter of the MOT beams. The beam is made narrower on the other axis so that the crossed region could be placed as close to the MOT as possible without disturbing the atoms trapped in the MOT. The frequency of the crossed beams was experimentally optimized to be \( \delta_X = -2\pi \times 42 \text{ MHz} \) detuned...
from the 399 nm transition.

We assessed the performance of the crossed-beam slower by comparing the MOT loading rates for various parameters of crossed-beams and slower beam. Representative “loading curves” are shown in Fig. 2. Such loading curves were obtained by monitoring the fluorescence of the MOT using a photomultiplier tube and are fitted by a function of the form \( N(t) = N_0 (1 - e^{-Lt/N_0}) \), where \( L \) is the initial atom loading rate and \( N_0 \) is the equilibrium number at long times. When utilizing the crossed beams, we see a marked improvement in both the MOT loading rate and overall MOT population.

To further explore the performance of the crossed beam slower, we mapped out the behavior of the loading rate in the two-dimensional parameter space of slower current and crossed beam intensity \( s_X \) (see Fig. 3(a)). The success of the technique is gauged by observing that the peak occurs at a finite value of \( s_X \) and that the loading rate at the peak is significantly greater (by a factor of about 6) than the largest loading rate along the \( s_X = 0 \) axis. Furthermore we see that the location of the largest loading rate for a given \( s_X \) moves towards lower currents as \( s_X \) is increased. This is expected because by increasing the slowing power of the crossed beams, the atoms may have a higher velocity coming out of the Zeeman slower and still be captured by the MOT.

FIG. 2. Fluorescence signals (black lines) showing the atom number growth in a narrow-line Yb MOT for optimized arrangements with and without the crossed-beams. For each of the two data curves, the slower current was adjusted to maximize the loading rate and \( s_X = 0.3 \) for the with-crossed-beams data. The data are fit to exponential curves for both with crossed beams (blue line) and without crossed beams (red line) cases. The loading rates are given by the initial slopes which are different by a factor of 6.

IV. NUMERICAL SIMULATION

To provide a theoretical model for our experimental results, we numerically simulate the trajectories of atoms subject to laser cooling forces through the experimental apparatus. Within the Zeeman slower, an atom experiences a position- and velocity-dependent average scattering force from the slower beam with acceleration given by:

\[
a_S(v, z) = -\frac{\hbar k_b \Gamma_b}{2m} \left[ \frac{s}{1 + s + \frac{4}{\Gamma_b^2} \left( \delta + k_b v + \frac{\mu_B B(z)}{\hbar} \right)^2} \right] \tag{1}
\]

where \( k_b = \frac{2\pi}{399 \text{ nm}} \) is the wavenumber, \( \Gamma_b = 2\pi \times 29 \text{ MHz} \) is the transition linewidth, \( m \) is the atomic mass, \( \delta \) is the slower beam detuning, \( s \) is the saturation parameter of the slower beam (intensity in units of the saturation intensity 59 mW/cm\(^2\) of the transition), and \( B(z) \) is the value of the Zeeman slower magnetic field at position \( z \) along the longitudinal direction. \( B(z) \) is calculated using the Biot-Savart law for the coils which compose our Zeeman slower, and it has been verified that the measured field is in excellent agreement with the calculated field.\(^{16}\) It is implicit that \( v \) is also a function of \( z \).

In the region of the crossed beams, the slower beam is far off resonance with the atoms that are moving slow enough to be eventually captured by the MOT. The relevant average scattering force that comes from the two-crossed beams is given by:

\[
a_X(v, z) = -\frac{\hbar k_b \Gamma_b}{2m} \left[ \frac{2}{\sqrt{2}} s_X(z) \right] \tag{2}
\]

where \( s_X(z) \) is the saturation parameter of the crossed beams at position \( z \) and \( \delta_X \) is the detuning of the crossed beams. The factor of \( 2/\sqrt{2} \) in the numerator accounts for the two crossed beams each contributing \( 1/\sqrt{2} \) of its force to oppose the atomic motion (to the left in Fig. 1), since in our setup each of the crossed beams intersects the atomic beam at an angle of 45 degrees. The force components for the two beams in the orthogonal direction (up/down in Fig. 1) cancel each other out. The factor of \( 1/\sqrt{2} \) in the velocity-dependent Doppler term in the denominator is also from the crossed beams propagating at 45 degrees with respect to the longitudinal velocity of the atomic beam. The spatial dependence of \( s_X \) arises from the Gaussian transverse profile of the crossed beams.

In order to simulate the slowing in the cross-beams, we also need a model of the velocity distribution entering the region. For this we first simulate the trajectory of atoms through the Zeeman slower using Eq. (1). We record the longitudinal velocity \( v_{\text{center}} \) of atoms at the end of the Zeeman slowing region for a fixed \( s \) and slower current. This provides a conversion between slower current and the center of the slowed atom distribution \( v_{\text{center}} \) entering the crossed-beam region. Since the modeled Zeeman slower is ideal, the atoms captured by the slower beam emerge with a very narrow longitudinal velocity distribution in our simulation. In practice however, the longitudinal velocity distribution is broadened by the natural linewidth \( \Gamma_b \) of the transition and non-ideal effects such
as the finite laser linewidth, irregularities in the slowing beam profile, and fluctuations in current to the Zeeman slower coils. We approximate these effects in our simulation using a Gaussian distribution with standard deviation of 12 m/s, which is the measured value from earlier Doppler spectroscopy characterizing the Zeeman slower in our apparatus. This value is consistent with \( \Gamma_b/k_b \) for this transition.

To produce the parameter space map, for each \( s_X \) and slower current value, we simulate the trajectories of 3000 atoms with initial longitudinal velocities selected at random from a normal distribution with mean \( v_{\text{center}} \) and standard deviation of 12 m/s to approximate the flux of slow atoms produced by our Zeeman slower. The atoms begin with random initial transverse velocities and positions picked from a distribution that is estimated from the results of the Zeeman slower simulation. For both Eqs (1) and (2), we use a time step of 20 \( \mu \)s to model the effect of the average scattering force from photon absorption in the direction of laser light propagation.

To model the effects of spontaneous emission in random directions, the number of photons scattered during each time step, \( N_{ph} \), is calculated and the atom is numerically made to do a 3-dimensional random walk in velocity space of \( N_{ph} \) steps of length \( v_{rec} \), the recoil velocity of ytterbium (5.7 mm/s). As photons are scattered in random directions, the transverse velocity of an atom is increased and it travels transversely as well as longitudinally, resulting in the blooming effect. For an atom that reaches the MOT capture region, its capture is determined by two conditions: (i) its transverse distance from the center is less than the 1 cm radius of the MOT beams and (ii) its total final velocity \( v_{\text{tot}} = \sqrt{v_l^2 + v_t^2} \), where \( v_l \) is the longitudinal velocity, is less than \( v_c = 9.7 \) m/s. The fraction of atoms that meet both of these criteria is recorded for each pair of values of slower current and crossed beam intensity \( s_X \).

Fig. 3 shows how these simulations compare to our experimental data. We see that optimal capture for our experimental parameters occurs at around slower current of 30 A and \( s_X = 0.3 \). The simulations demonstrate good agreement with the experimental results, with the peak locations differing by less than 3% of the slower current.

Our simulations indicate that under optimum condi-
tions, 24% of the atoms that are slowed by the Zeeman slower are slowed adequately by the crossed beams to be captured by the MOT. We also find that of the atoms which satisfy condition (ii) above, only about 15% do not satisfy condition (i). This indicates that the crossed beam method has largely solved the blooming problem for narrow line MOTs. The remaining limiting factor is the width 12 m/s of the slowed longitudinal velocity distribution, which is larger than the MOT capture velocity $v_c$ of 9.7 m/s. With sufficient laser power, this issue could be addressed by using larger MOT beams and thus increasing $v_c$.

V. SUMMARY AND OUTLOOK

We have described a method to improve the performance of a narrow-line Yb MOT by a factor of 6 using a crossed arrangement of two additional slower beams immediately prior to the MOT. We have assessed the performance of our method by observing its effect over a large parameter space of slower magnetic field and crossed beam intensity. The results of a numerical model for the behavior of our system show good agreement with our experimental observations.

A notable feature of the method is the relative simplicity of the setup, which involves only two additional laser beams beyond a traditional laser cooling apparatus. Our results can be adapted to other experimental efforts which use laser cooled Yb, an atom with various applications in atomic clocks.[17] Preparation of quantum degenerate systems,[18] precision atom interferometry,[19] quantum simulation,[20] and quantum information processing,[21] the method is also applicable to narrow-line MOTs of other elements and has been very recently demonstrated in Dy.[22] and Er.[23]

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DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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