Efficient production of a narrow-line erbium MOT with two-stage slowing

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We describe an experimental setup for producing a large cold erbium (Er) sample in a narrow-line magneto-optical trap (MOT) in a simple and efficient way. We implement a pair of angled slowing beams with respect to the Zeeman slower axis, and further slow down atoms exiting from the Zeeman slower. The second-stage slowing beams effectively increase the capture velocity of the narrow-line MOT. This scheme is particularly useful when the Zeeman slower is operated at low power without the transverse cooling in the system, wherein we significantly improve the loading efficiency into the MOT and are able to trap more than $10^8$ atoms in the narrow-line MOT of $^{166}$Er atoms. This work highlights our implementation that greatly simplifies laser cooling and trapping of Er atoms and also benefits other similar elements.

Ultracold magnetic atoms (e.g. dysprosium and erbium isotopes) has offered a tunable atomic system where unprecedented quantum states can be explored. Various remarkable many-body phenomena have been observed in those dipolar quantum gases based on the dipole-dipole interaction, including quantum droplet states [1–3], roton excitations [4, 5], the extended Hubbard model [6] and supersolid phases [7–9]. For cooling those atoms, a narrow-line magneto-optical trap (MOT) has popularly been employed using the narrow optical transition with the sub-MHz linewidth [10–12]. This cooling scheme has an advantage to pre-cool trapped atoms to the lower Doppler temperature limit in the $\mu$K or sub-$\mu$K regime and has been successfully employed for cooling atoms that contain transitions with relatively narrow natural linewidths [13–16].

However, lanthanide elements with the high melting point are still elusive with laser cooling and trapping although several research groups have successfully realized quantum degenerate gases with Dy [17] and Er [18]. Inspired by earlier works [10], decelerated lanthanide atoms in a Zeeman slower using a broad optical transition are loaded into a narrow-line MOT, but it still remains challenging to fully optimize the transfer of slowed atoms from the Zeeman slower into the narrow-line MOT due to the small capture velocity of the MOT. Moreover, the slowed atoms below the capture velocity often suffer from transverse heating when exiting from the Zeeman slower, which further limits the effective atomic flux into the MOT region. Several methods have been implemented to increase the effective capture velocity of the MOT by combining broad and narrow-line MOTs in a temporal [19] or spatial manner [20]. Here, we describe a simple and efficient method to increase the loading efficiency into the narrow-line MOT by adding second-stage slowing beams. It results a large number of $^{166}$Er MOT at the temperature of $<20$ $\mu$K (after the compression of the MOT), similar to the recent realization in Yb [21] and Dy [22] experiments.

In Er experiments, the large mean velocity of atoms necessitates relatively high slower power to supply enough atomic flux into the MOT. However, the high-intensity slower light often induces the optical pumping and/or the radiative force in the weak narrow-line MOT. In the previous works with Er, such an effect was avoided by displacing the MOT during the loading stage [23, 24]. This method, however, may require a large volume of the vacuum chamber for MOT loading, which limits broad applications, for example, high-resolution optical microscopy. Here, we highlight an alternative way to achieve a large sample of cold Er atoms in the narrow-line MOT without such displacement. With a pair of near-resonant slowing beams implemented between the exit of the Zeeman slower and the MOT, we successfully trap $1.1 \times 10^8$ $^{166}$Er atoms in the MOT with a significantly enhanced loading rate by more than one order of magnitude. An important figure of merit of our apparatus is the efficient production of a cold Er sample without using a transverse cooling stage and separate spectroscopy cells.

The schematic design of the experimental apparatus is shown in Fig. 1. The apparatus consists of an effusive atomic oven, an intermediate chamber for laser spectroscopy, a Zeeman slower and a science chamber. A high temperature effusion cell at 1200°C generates an atomic beam with the mean velocity of 500 m/s from a 4.5 cm crucible containing 25 g Er pieces (Alfa Aesar 99.9%). The atomic beam is then collimated by a 13 mm-diameter nozzle that consists of 22 pieces of 5 cm micro-capillary tubes with the inner diameter of 1.4 mm. The nozzle is kept at 1250°C. Additional 4.5 cm long differential pumping tubes are located before and after the intermediate chamber. The pressure of the oven and intermediate chamber is $4 \times 10^{-11}$ and $1 \times 10^{-10}$ mbar, respectively, maintained by ion getter pumps (Gamma vacuum, 45L/s). The pressure of the science chamber is $5 \times 10^{-11}$ mbar.

For laser cooling and trapping Er atoms, two optical transitions at 401 nm and 583 nm have been
used in this work. The broad transition \((4f^{12}6s^2 \, 3^6H_6 \rightarrow 4f^{12}(3^6H_6)6s6p(3^1P_1))\), at 401 nm with the natural linewidth of \(\Gamma_{401}=2\pi \times 29.7 \text{ MHz}\) is used for the Zeeman slower, angled slower beams and absorption imaging while a MOT is formed with the narrow transition \((4f^{12}6s^2 \, 3^6H_6 \rightarrow 4f^{12}(3^6H_6)6s6p(3^1P_1))\) at 583 nm with \(\Gamma_{583}=2\pi \times 190 \text{ kHz}\). The 401 nm laser light is generated by an external-cavity diode laser (Toptica DL-pro 120 mW total output) as well as a homemade injection-locking setup. The 583 nm laser light is generated by a Toptica TA-SHG system (740 mW total output).

To stabilize laser frequencies in a simple way, we perform laser spectroscopy with the collimated atomic beam in the intermediate chamber. For the broad 401 nm transition, the laser is frequency stabilized by a standard fluorescence spectroscopy with a 2 mW probe beam with a diameter of 0.8 mm. We stabilize the 583 nm laser using saturation fluorescence spectroscopy, where the fluorescence signal is obtained from a 15 mm-diameter probe beam (with 10 mW) by pre-amplifying photodiode current. We note that the laser spectroscopy does not reduce the atomic flux into the Zeeman slower.

The slowed Er atoms are generated by a spin-flip Zeeman slower using the broad optical transition at 401 nm. In contrast to alkali atoms, Er isotopes require relatively high slower laser power due to the large saturation intensity \(I_{s,401} = 56 \text{ mW/cm}^2\) and the high melting temperature \((1522^\circ \text{C})\), in order to produce sufficiently enough atomic flux into the MOT. However, a high intensity Zeeman slower beam may cause off-resonant pumping and/or atomic loss in the Er MOT [23][24]. This detrimental effect has been alleviated by displacing a MOT below the center of the MOT quadrupole field [23][24]. For this, the detuning of the MOT is increased so that atoms are displaced by gravitational sag. In our work, however, the trapped atoms are difficult to be displaced due to the recessed viewport being only \(\sim 6.5\) mm away from the center of the chamber. To overcome this limitation, our Zeeman slower is designed to operate at relatively low intensity and minimize the above-mentioned detrimental effect.

Now, we discuss the Zeeman slower used in our work. The 400 mm-long spin-flip Zeeman consists of five separate parts of coils wrapped around a thin brass tube with a 1” outer diameter. The coils are built with insulated square hollowed copper tube. The square tube has an edge length of 1/8” and an inner hole diameter of 1/16”, and are water-cooled [25]. The 22 mW slower light is red-detuned by 540 MHz from the singlet transition \((4f^{12}6s^2 \, 3^3H_6 \rightarrow 4f^{12}(3^3H_6)6s6p(3^1P_1))\) corresponding to 18.2 \(\Gamma_{401}\), resulting in the capture velocity of \(\sim 200 \text{ m/s}\). The residual magnetic field (around 3 G) at the MOT position is compensated by the compensation coil between the Zeeman slower and the MOT. We note that the Zeeman slower can be operated by a single external-cavity diode laser in our system.

In the chamber, a narrow-line MOT is formed by three pairs of 50 mW retro-reflected 583 nm laser beams, resulting in a saturation parameter of \(s \approx 340 (I_{s,583} = 0.13 \text{ mW/cm}^2)\). During the loading process, MOT beams are detuned by -21 \(\Gamma_{583}\) from the narrow transition with the magnetic field gradient of 3.5 G/cm. To increase the MOT capture velocity, we broaden the laser linewidth up to 2.0 MHz with an acousto-optic modulator (AOM) being modulated with a 200 kHz frequency. The science chamber is equipped with recessed viewports for high-resolution imaging setup (see Fig. [1]), wherein a narrow-line MOT is formed at the center of the chamber without noticeable gravitational sag. Note that we optimize the Zeeman slower at low optical power and therefore minimize possible off-resonant optical pumping caused by the slower light, which potentially reduces the loading effi-

Figure 1: Schematic of experimental apparatus for cooling and trapping Er atoms. An effusive oven at 1200°C generates an Er atomic beam into the intermediate chamber wherein laser spectroscopy is performed for 401 nm (blue) and 583 nm (yellow) transitions. The 400 mm-long spin-flip Zeeman slower decelerates atoms followed by the second-stage angled slowing beams (not shown). Two recessed viewports are used in the science chamber.
Figure 2: Schematics of two-stage slowing, the science chamber, and the level diagram (a) Layout of two-stage slowing scheme near the narrow-line MOT. Two 401 nm beams intersect 20 mm ahead of the MOT position, wherein atoms exiting from the Zeeman slower are further decelerated along the x direction. (b) View of the narrow-line MOT and the recessed viewports. In the science chamber, the diameter of the MOT beam is fully maximized up to 12 mm. The gap between two recessed viewports is 13 mm. (c) Broad singlet and narrow triplet transitions are used for two-stage slowing and narrow-line MOT loading.

To alleviate the low MOT loading, we implement second-stage slowing with two angled beams being circularly-polarized and red-detuned by 34 MHz (\(-1.13 \times 10^8\)) from the 401 nm beams. Those 401 nm beams intersect at 20 mm away from the narrow-line MOT position, as depicted in Fig. 2(a). Before entering the science chamber, atoms are slowed by the conventional Zeeman slower along the longitudinal direction (x direction in Fig. 2(a)). Inside the chamber, angled slower beams further decelerate the slow atoms exiting from the Zeeman slower along both the longitudinal and transverse directions, and effectively reduce the transverse velocity distribution at the MOT position, increasing the MOT population significantly (see Fig. 3). The angled slowing beams are generated from the injection-locked slave laser, resulting 21 mW and 7 mW for beam 1 and 2, respectively. We optimize the power distribution and detuning of these two beams based on the MOT atom number. The net scattering force along the y direction is balanced by the power imbalance of angled slower beams.

In Fig. 3, we monitor the trapped atom number in a \(^{166}\)Er MOT with and without the angled slower beams at the 1200°C oven temperature. We observe that the MOT loading rate is significantly enhanced by more than one order of magnitude, from \(R = 3.5 \times 10^8 s^{-1}\) to \(R = 2.3 \times 10^9 s^{-1}\), which produces the saturated atom number of \(1.1 \times 10^8\) within two seconds. The atom number is consistently calibrated both by fluorescence detection and absorption imaging. Without the angled slowing beams, the total MOT atom number is around \(\sim 3 \times 10^7\) with experimental parameters being separately optimized. It is worthwhile to note that the saturated atom number in the MOT increases up to \(2 \times 10^8\) at the 1250°C oven temperature with angled slower beams. The two-stage slowing scheme also works for other isotopes such as \(^{168}\)Er with similar performance.

We attribute the enhanced atom number to the improved capture velocity of MOT as described in Fig. 4. In Fig. 4(a,b), we numerically calculate the trajectories of atoms with various initial velocities from the effusive oven to the MOT in the chamber with and without the angled slowing beams, respectively. Taking a sample of atoms with a given velocity distribution, the full trajectory is simulated by stepping their positions in small time steps. For each case, experimental parameters being employed in our experiment are used for the calculation. It suggests that the effective capture velocity of the MOT is enhanced by angled slowing beams. We speculate that
Figure 4: **Enhanced capture velocity with two-stage slowing** Velocity of Er atoms along the Zeeman slower with angled slower beams off (a) and on (b). Magnetic fields in the Zeeman slower is separately optimized by MOT loading at each cases (a,b). For example, final velocities of Er atoms with initial longitudinal speed of 200m/s is 3.8 m/s and 7.6 m/s in (a) and (b), respectively. The insets show the zooms of the velocity in the range between -15 cm and -11 cm. The MOT is located at 0 cm. The grey dashed lines in insets indicate 5.0 m/s. (c) Maxwell-Boltzmann distribution of Er atoms at 1200°C. Colored lines show different initial velocities.

this enhancement of the capture velocity alleviate the transverse heating for atoms during the flight from the slower exit to the MOT.

In conclusion, we have demonstrated a simple and cost-effective method to produce a large number of Er atoms in a narrow-line MOT. We apply a two-stage slowing scheme, for the first time in an Er experiment, which significantly enhances the loading efficiency into the MOT. Our experiment suggests that the near-resonant angled slowing beams in front of the MOT further slow down atoms exiting from the Zeeman slower and therefore enhance the capture velocity of the MOT. This method can be easily applied to laser cooling and trapping other similar elements with high melting points. Therefore, our method may not only greatly simplify the current approach for producing ultracold magnetic atoms, but also pave the way for the broad search of quantum degenerate gases of elements that have never been explored as far.

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