Appl. Phys. B 78, 49–52 (2004)
DOI: 10.1007/s00340-003-1355-8

Applied Physics B
Lasers and Optics

R.L. CAVASSO FILHO
D.A. MANOEL
D.R. ORTEGA
A. SCALABRIN
D. PEREIRA
F.C. CRUZ ✉

On-axis calcium magneto-optical trap loaded with a focused decelerating laser

Instituto de Física 'Gleb Wataghin', Universidade Estadual de Campinas, CP.6165, Campinas, SP, 13083-970, Brazil

Received: 23 April 2003/Revised version: 2 September 2003
Published online: 18 November 2003 •

ABSTRACT We report on a simple scheme to efficiently load an on-axis magneto-optical trap (MOT) from a decelerated atomic beam, which avoids perturbation by radiation pressure from the decelerating laser. This has been tightly focused near the MOT center, with a waist size much smaller than the atomic cloud. For comparison, and in order to test the efficiency of this non-optimum deceleration geometry we have employed a second, independent decelerating laser, with a profile mode matched to the atomic beam. Using a Calcium MOT, good performance has been achieved and for an oven temperature of 580 °C we loaded $1.2\,(2)\times 10^7$ atoms in 16 (1) ms. The technique described here has been essential for the sensitive detection of cold collisions, which represent minor losses in MOTs of alkaline-earth metal elements (R.L. Cavasso-Filho, A. Scalabrin, D. Pereira, F.C. Cruz: Phys. Rev. A, **67**, 021402(R) (2003)).

PACS 32.80.Pj, 39.25.+k, 39.10.+j

1 Introduction

Laser cooling and trapping of alkaline-earth atoms has been receiving increasing attention in the past years due for example to interest in optical frequency standards and clocks, investigation of cold collisions, or the possibility of extending the quantum degenerate regime to these elements, perhaps by all-optical means. Because of two electrons in the outer shell, these elements have series of singlet and triplet levels giving rise to strong transitions within these series and weak transitions between them. For example, the almost closed $^1S_0$–$^1P_1$ resonant transition, between the ground state and the first singlet state, has a large natural width (34.6 MHz for Ca), which makes it excellent for laser manipulation by radiation pressure. On the other hand, the spin forbidden $^1S_0$–$^3P_1$ intercombination transition, also departing from the ground state, has a low transition rate and consequently a narrow linewidth (408 Hz for Ca) [1].

In this paper we characterize an alternative technique to load an on-axis calcium MOT, operating on the $^1S_0$–$^1P_1$ transition at 423 nm. This element has been shown to be very attractive for experiments in high resolution and precision spectroscopy [2], atomic interferometry [3], optical frequency standards and clocks [4, 5], cold collisions [6], and new laser cooling and trapping strategies [7, 8]. In Sect. 2 we describe the experimental apparatus for the MOT loaded with a focused decelerating laser. This technique, which avoids perturbation of the atomic cloud by the decelerating laser, has been essential for the recent observation of cold collisions in a calcium MOT [9], where optical pumping effects dominate the trap losses. In fact, for alkaline-earth-metal elements cold collisions are difficult to observe because they represent only a small fraction of the total trap losses [10]. In Sect. 3 we explain how the number of trapped atoms is estimated when the atomic cloud is comparable to the laser waist sizes. An analysis of the number of trapped atoms when decelerating and trapping with the same laser, and when decelerating with a second, independent laser, is presented in Sect. 4. Temperature measurements are also included in this section. The conclusions are summarized in Sect. 5.

2 Experimental apparatus

Figure 1 shows a schematic diagram of the experimental apparatus. The atomic beam is produced in a stainless steel cylindrical oven with an exit aperture of 2 mm [11]. The oven chamber is connected to a 240 ℓ/s turbo pump and has two sapphire optical windows which allow saturation absorption spectroscopy in the high atomic flux environment near the oven. The atomic beam collimation is defined by another 2 mm aperture, 15 cm apart from the oven one. It connects the oven chamber with an all-glass chamber for the atomic beam and MOT.

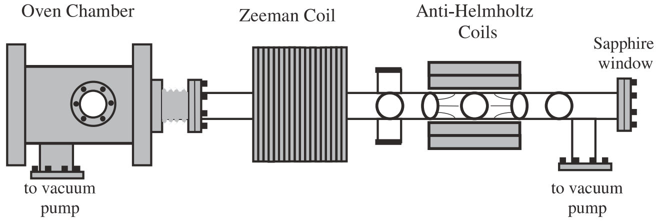

FIGURE 1 Schematic diagram of the atomic beam and MOT experimental apparatus. It shows, from *left* to *right*: the oven chamber, the slower and MOT glass chamber with 14 AR coated windows and one Sapphire window at the right end. Also shown is the 18 section Zeeman magnet and the anti-Helmholtz trap coils

✉ Fax: +55-19/3788-5427, E-mail: flavio@ifi.unicamp.br

The atomic beam slower and MOT chamber consist of a 90 cm long PIREX glass tube with AR coated windows for 423 nm and 657 nm, plus a Sapphire window at the tube end, for coupling the decelerating laser beam. The 22 cm-long Zeeman magnet produces a maximum magnetic field of 780 G. This allows deceleration of all atoms with velocities lower than 460 m/s, which corresponds to 13% of the velocity distribution when the oven is at 480 °C. After the Zeeman magnet, 47 cm downstream from the oven chamber collimation aperture, there are two pairs of windows that can be used for either 2-D optical molasses or spectroscopy. After these windows, we have the MOT chamber, 60 cm downstream from the collimation aperture. Two air-cooled anti-Helmholtz coils produce vertical and horizontal field gradients of 63 and 32 G/cm. At 13 cm from the MOT center we have an additional horizontal pair of AR coated windows, which can also be used for spectroscopy. After this, there is a connection to another turbo pump. At the tube end, we have a sapphire window, which is heated up to 250 °C to minimize deposition of calcium atoms from the atomic beam [12]. Typical background pressure in the MOT chamber is 5×10^{-8} mbar, when the oven is switched-off and 10^{-7} mbar when the atomic beam is on.

To generate coherent radiation at 423 nm, for deceleration, cooling and trapping, we are using a homemade frequency doubled and stabilized Ti:Sapphire laser [13]. The second harmonic beam is split into four beams of the same power. One of them is used for Zeeman deceleration and the other three are used in the standard retroreflected $\sigma_+ - \sigma_-$ 3D MOT configuration [14]. The six trap beams have equal waist sizes $w = 1.40\,(5)$ mm, where the transverse intensity is given by $I(r) = I_0 \exp\left(-r^2/w^2\right)$.

We have implemented an on-axis trap, where the MOT is located within the atomic beam, which has a diameter of 2 cm at the MOT position. Several configurations have been tested with similar results, with the MOT more or less centered with respect to the atomic beam. One of the problems of an on-axis trap, loaded from an atomic beam decelerated with the same laser, is that this very much disturbs the trapped atomic cloud and causes atom loss. One solution to this problem is to shift the slowing laser frequency far from resonance, for example with an acousto-optical modulator. An adjustment of the Zeeman slower magnetic field is then required to bring the outcome velocity of the decelerated atoms to the same value [15]. Another solution uses a slower laser with a central "dark spot" [16]. Both share the problem of laser power consumption. We have employed another approach, which consists of focusing the counterpropagating slower laser beam at the trap position, about 2 mm away in the transverse plane. The slower laser is focused by a telescope to a spot size of 20 μm at the MOT position. Therefore it has no effect in atomic clouds of nearly 1 mm diameter. This has been an essential feature for the recent observation of cold collisions in a calcium MOT operating without a repump laser [9]. In this case, atom losses are dominated by optical pumping mechanisms which also typically limit the lifetime to < 20 ms. Cold collisions thus represent only a small fraction of the total trap loss.

3 Number of trapped atoms

The number of trapped atoms was estimated by the scattered light power in the following way. In the presence of six laser beams of same intensity I, the scattered power by one atom is given simply by the product of the photon energy and the scattering rate [17]:

$$P_1 = h\nu\,\frac{\gamma}{2}\left[\frac{6I/I_S}{1+6I/I_S+4\delta^2/\gamma^2}\right], \tag{1}$$

where h is the Planck constant, ν is the photon frequency, γ is the angular natural linewidth, I_S is the saturation intensity and δ is the laser detuning. For the calcium resonant transition ${}^1S_0$–${}^1P_1$, $\nu = 710$ THz, $\gamma = 2\pi\times34.6$ MHz, and $I_S = 59.9\ \mathrm{mW/cm^2}$ [18]. Assuming that all atoms are subjected to the same total laser intensity $6I$, then the total scattered power is simply NP_1. This holds only when the laser waist size is large in comparison with the atomic cloud extension, in which case $I = I_0$. In a more realistic situation, the atoms spatial extent is not negligible with respect to the laser waist sizes and we have to take into account the Gaussian laser profile over the atomic density distribution $n(r)$. In other words, we have to consider an effective intensity as an ensemble average:

$$I_{\mathrm{eff}} = \frac{1}{N}\int I(r)\ n(r)\ d^3r\,. \tag{2}$$

In the case of alkaline-earth elements, for densities below $10^{11}\ \mathrm{cm^{-3}}$, the spatial distribution of the atomic cloud is Gaussian [19]. The MOT "spring constant" depends directly on the magnetic field gradient [18]. Therefore the cloud is smaller in the direction of the higher magnetic field gradient, z, and larger in the plane where the gradient is lower, plane xy. For moderated densities we can thus write:

$$n(r) = n_0 \exp\left(-z^2/a_z\right)\exp\left[-(x^2+y^2)/a^2\right], \tag{3}$$

where n_0 is the peak density, a_z is the width of the atomic cloud in the vertical direction and a is the width in the horizontal plane. In our case, we typically have a vertical field gradient of 63 G/cm and half of this value in the horizontal plane. Integration of (3) in an infinite volume give us the total number of atoms as $N = n_0\pi^{3/2}a_z a^2$. Assuming that all six laser beams have the same intensity and waist, we get from (1) the following effective total intensity:

$$I_{\mathrm{eff}} = \frac{2I_0}{\sqrt{1+a^2/w^2}}\left(\frac{1}{\sqrt{1+a^2/w^2}} + \frac{2}{\sqrt{1+a_z^2/w^2}}\right), \tag{4}$$

which for small atomic clouds goes to $6I_0$, as expected. The ensemble average power scattered per atom is then given by (2) by just replacing the term $6I$ by the effective intensity, I_{eff}.

4 Focused decelerating laser

To measure the number of trapped atoms, we used a calibrated photodiode and took into account the previous considerations. To get rid of the background signal due to the atomic beam fluorescence, we modulated the slower laser beam with a mechanical shutter. A peak number of $9\,(1)\times 10^5$ atoms was measured for a red detuning of 97 (5) MHz, or 2.8 (1) atomic linewidths. The uncertainty in atom number comes mainly from the uncertainty in the solid angle covered by the detection system. For a given laser power, the optimum detuning that maximizes the number does not change significantly with the field gradient, although the maximum atom number does, as can be seen in Fig. 2.

Keeping the power of the trapping beams constant, at 10 mW per beam, for a vertical field gradient of 63 G/cm, we changed the power of the slower beam and measured the variation in the number of trapped atoms, as shown in Fig. 3. The gain in trapped atom numbers from a slowing power of 2.5 mW to 5 mW is more than 100% while the gain from 5 mW to 10 mW is just 30%. Therefore it is not necessary to have large laser powers in the Zeeman slowing beam when using low oven temperatures and consequently a lower number of atoms.

In order to test the efficiency of the focused slower laser technique we employed an independent laser to decelerate the atomic beam. This laser source is a frequency doubled diode laser in an alternative extended cavity, described elsewhere [20]. To measure the doubled diode laser detuning we beat its first harmonic with the Ti:Sapphire laser in a fast photodetector. The thermal drift of the diode laser was determined to be less than 5 MHz per minute, which enabled us to perform a series of measurements in a few minutes. The 8.5 mW 2nd harmonic output of the diode laser is beam shaped in a telescope to approximately match the atomic beam spreading. Keeping the detuning of the MOT beams constant, at −84 (10) MHz, and also the magnetic field of the Zeeman slower constant, we scan the slower frequency and the result is shown in Fig. 4. The maximum number of atoms occurs for a slower detuning of −438 (15) MHz. We note that the number of trapped atoms varies very little when the power in each MOT beam is changed from 1 to 11 mW, keeping the power and detuning of the slower laser. Therefore, relatively low power is needed to decelerate a calcium beam and trap the slowed atoms. Ten milliwatts at 423 nm is more than sufficient, with most of the power in the slower beam to assure adiabatic following during deceleration [15]. This is important for a practical and compact atomic clock based on cold atoms.

By raising the MOT field gradient, the ratio between the optimum number of trapped atoms, when slowing independently or with the focused laser beam, increases as shown in Fig. 5. For gradients below 80 G/cm, the ratio is about 25%. For a field gradient of 110 G/cm and an oven temperature of 580 °C we obtain a number of $1.2\,(2)\times 10^7$ atoms in our trap. The maximum field gradient is limited by heating of our air-cooled anti-Helmholtz coils.

Finally, we have measured the temperature of the trapped atoms by the size of the atomic cloud [18, 21]. In a MOT, when the Doppler and Zeeman shifts are small compared to the detuning, the radiation pressure force acting on the atoms are in good harmonic approximation [18]. The equipartition of energy implies that the velocity spread and the position spread are related by $m v_{\mathrm{rms}}^2 = \kappa r_{\mathrm{rms}}^2$, where κ is the MOT spring constant, given by:

$$\kappa = 8\hbar k\,\frac{\delta}{\gamma}\,\frac{I/I_{\mathrm{S}}}{\left(1+I/I_{\mathrm{S}}+4\delta^2/\gamma^2\right)^2}\,(2\pi\alpha_{\mathrm{B}}A)\ , \qquad (5)$$

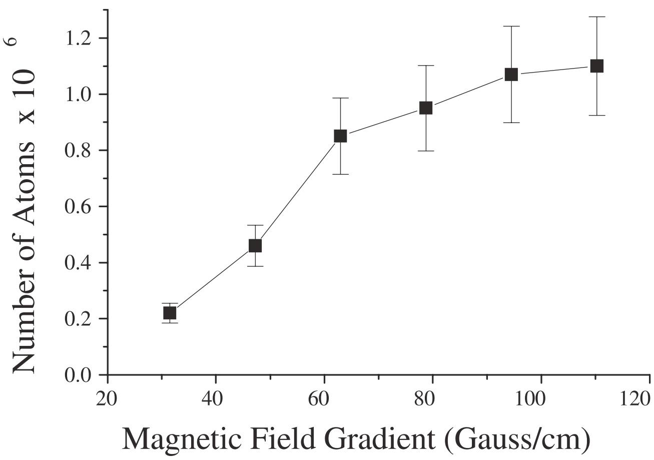

FIGURE 2 Number of trapped atoms as a function of gradient of the vertical MOT field, for an oven temperature of 480 °C. Horizontal gradient is half of the vertical

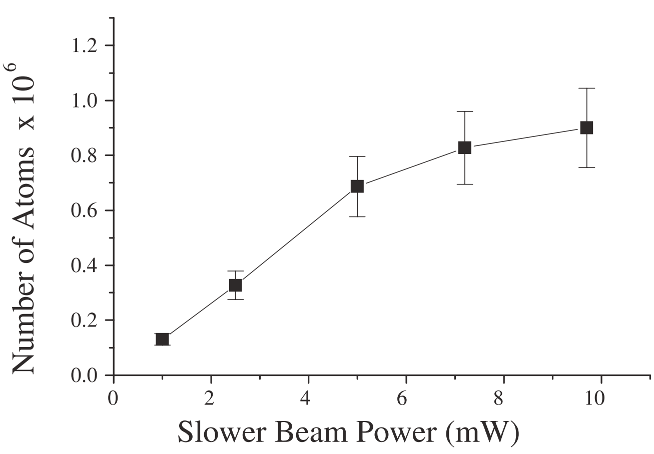

FIGURE 3 Atom number as a function of slower laser power, for the same conditions of Fig. 2

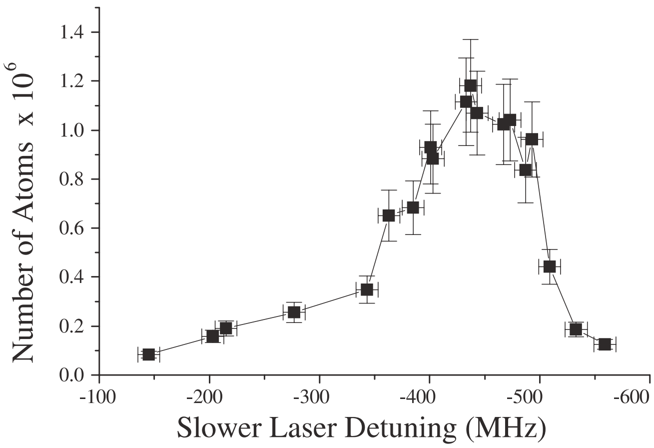

FIGURE 4 Number of atoms for MOT beams detuning of −84 (10) MHz

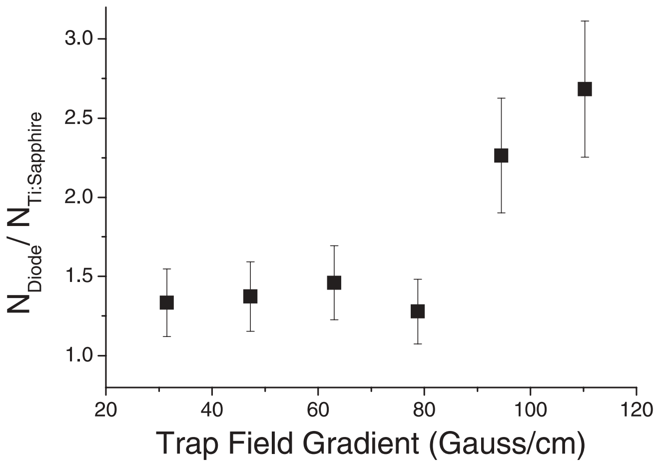

FIGURE 5 Ratio between the number of trapped atoms when decelerating the atomic beam with an independent laser (diode laser) or with the same laser (Ti:sapphire) used for the MOT

where I is the intensity of the MOT laser beam in the direction considered, α_B is the Zeeman splitting of the excited level and A is the magnetic field gradient. Although the number and the lifetime are not critically dependent on the precise MOT alignment, this temperature determination by the cloud size r_{rms} is. With careful alignment of the MOT beams, we estimate for the horizontal Gaussian spread of the atomic cloud, a root mean square velocity of 136 (12) cm/s, corresponding to a temperature of 9 (2) mK. As already observed for strontium [21], this is much higher than the limit given by Doppler cooling theory (831 μK). The observed trap lifetime of 16 ms is consistent with the loss mechanism of optical pumping into the metastable $^1D_2$ level.

5 Conclusion

We characterize an on-axis magneto-optical trap for calcium atoms loaded from a decelerated atomic beam. The decelerating laser is tightly focused near the trap region, so that the trap is perturbed as little as possible. This has been an essential feature of a recently demonstrated technique, where small cold collision effects in a calcium MOT have been observed by comparing the trap load and decay curves [9]. Independently decelerating the atomic beam with another laser shows that the focused slower laser technique has an efficiency very close to optimum. From our atom number measurements, we also conclude that a total power of 10 mW at 423 nm, generated by a single laser, is enough to implement a calcium MOT loaded from a decelerated atomic beam. This is an important practical feature, relevant for a compact optical clock based on cold calcium atoms.

ACKNOWLEDGEMENTS This work was supported by FAPESP, CAPES, CNPq, and FAEP-UNICAMP, Brazilian government agencies. Support for RLCF was through CAPES graduate research scholarship and for DAM and DRO through FAPESP graduate and undergraduate scholarships respectively.

REFERENCES

1 T. Kisters, K. Zeiske, F. Riehle, J. Helmcke: Appl. Phys. B **59**, 89 (1994)
2 T. Kurosu, G. Zinner, T. Trebst, F. Riehle: Phys. Rev. A **58**, R4275 (1998)
3 F. Riehle, H. Schnatz, G. Zinner, K. Zeiske, B. Lipphardt, J. Helmcke: Laser Phys. **6**, 237 (1996)
4 P. Kersten, F. Mensing, U. Sterr, F. Riehle: Appl. Phys. B **68**, 27 (1999)
5 C.W. Oates, F. Bondu, R.W. Fox, L. Holberg: Eur. Phys. J. D **7**, 449 (1999)
6 G. Zinner, T. Binnewies, F. Riehle: Phys. Rev. Lett. **85**, 2292 (2000)
7 T. Binnewies, G. Wilpers, U. Sterr, F. Riehle, J. Helmcke, T.E. Mehlstaubler, E.M. Rasel, W. Ertmer: Phys. Rev. Lett. **87**, 3002 (2001)
8 E.A. Cutis, C.W. Oates, L. Hollberg: Phys. Rev. A **64**, 1403 (2001)
9 R.L. Cavasso Filho, A. Scalabrin, D. Pereira, F.C. Cruz: Phys. Rev. A **67**, 021 402(R) (2003)
10 J. Grünert, A. Hemmerich: Appl. Phys. B **73**, 815 (2001)
11 J.V.B. Gomide, G.A. Garcia, F.C. Cruz, A.J. Polaquini, M.P. Arruda, D. Pereira, A. Scalabrin, Brazilian J. Phys. **27**, 266 (1997); G. Woehl, G.D. Garcia, F.C. Cruz, D. Pereira, A. Scalabrin: Appl. Opt. **38**, 2540 (1999)
12 J.A. Neuman, P. Wang, A. Gallagher: Rev. Sci. Instrum. **66**, 3021 (1995)
13 H.J. Onisto, R.L. Cavasso Filho, A. Scalabrin, D. Pereira, F.C. Cruz: Opt. Engin. **41**, 1122 (2002)
14 E.L. Raab, M. Prentiss, A. Cable, S. Chu, D.E. Pritchard: Phys. Rev. Lett. **59**, 2631 (1987)
15 R.J. Napolitano, S.C. Zílio, V.S. Bagnato: Opt. Commun. **80**, 110 (1990)
16 S.G. Miranda, S.R. Muniz, G.D. Telles, L.G. Marcassa, K. Helmerson, V.S. Bagnato: Phys. Rev. A **59**, 882 (1999)
17 P.D. Lett, W.D. Phillips, S.L. Rolston, C.E. Tanner, R.N. Watts, C.I. Westbrook: J. Opt. Soc. Am. B **6**, 2084 (1999)
18 H.J. Metcalf, P. van der Straten: *Laser cooling and trapping* (Springer-Verlag NY, Inc. 1999)
19 T.P. Dinneen, K.R. Vogel, E. Arimondo, J.L. Hall, A. Gallagher: Phys. Rev. A **59**, 1216 (1999)
20 D.A. Manoel, R.L. Cavasso Filho, A. Scalabrin, D. Pereira, F.C. Cruz: Opt. Commun. **201**, 157 (2002)
21 X. Xu, T.H. Loftus, M.J. Smith, J.H. Hall, A. Gallagher, J. Ye: Phys. Rev. A **66**, 011 401(R) (2002)