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A continuous cold atomic beam from a magneto-optical trap

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Abstract. We have developed and characterized a new method to produce a continuous beam of cold atoms from a standard vapour-cell magneto-optical trap (MOT). The experimental apparatus is very simple. Using a single laser beam it is possible to hollow out in the source MOT a direction of unbalanced radiation pressure along which cold atoms can be accelerated out of the trap. The transverse cooling process that takes place during the extraction reduces the beam divergence. The atomic beam is used to load a magneto-optical trap operating in an ultra-high vacuum environment. At a vapour pressure of 10^{-8} mbar in the loading cell, we have produced a continuous flux of 7×10^7 atoms/s at the recapture cell with a mean velocity of 14 m/s. A comparison of this method with a pulsed transfer scheme is presented.

PACS. 32.80.Pj Optical cooling of atoms; trapping – 42.50.Vk Mechanical effects of light on atoms, molecules, electrons, and ions

1 Introduction

Slow and cold atomic beams have attracted increasing interest in recent years. They have proven to be very useful in a wide variety of experiments whose key feature is the long interaction time of atoms with the apparatus: applications in high resolution spectroscopy have contributed to the realization of high precision frequency standards [1]; intense beams of cold atoms have increased the performances of atom interferometers [2,3]; slow atom sources used to load atom traps are the starting point of recent experiments on Bose-Einstein condensation [4].

Using the effects of laser radiation on the atomic motion it is possible to control the velocity of an atomic beam in a wide range. However, all the techniques for decelerating atomic beams with laser light (Zeeman slowers [5], chirped cooled beams [6], etc.) generally suffer from a broad transverse velocity distribution that limits their brightness. To counteract this effect, it is necessary to cool the transverse degrees of freedom. The key element in many of these applications is the magneto-optical trap (MOT) [7]. In a vapour cell magneto-optical trap, atoms are trapped from the low pressure background gas contained in the vacuum cell and cooled to temperatures as low as tens of μK. This represents a good reservoir of cold atoms, suitable to be transferred into an atomic beam. There are different methods to extract a jet of cold atoms from a standard vapour-cell MOT. In the pulsed scheme, atoms are transferred after the capture vapour-cell MOT has been charged with a sufficient number of particles. A moving molasses scheme [8] or a short pulse of light [9,10] can be used to push atoms into the atomic beam. In the continuous scheme, the introduction of a leakage mechanism in the capture MOT produces a column of unbalanced radiation pressure along which a continuous flux of cold atoms can be extracted. In [11] a two dimensional magneto-optical trap (2D-MOT) allows to cool the transverse degrees of freedom of a thermal atomic beam. By using this scheme and adding a moving molasses configuration along the propagation direction of the atomic beam [12], it is possible to cool atoms in the moving frame and precisely control their velocity. In the 2D$^+$-MOT arrangement [13], a two dimensional MOT is used to compress and cool atoms in the transverse direction; this effect is combined with an unbalanced optical molasses in the longitudinal direction. The LVIS system [14] appears identical to a standard vapour-cell MOT with the difference that a narrow dark region in the center of one of the six beams is produced by using a mirror with a hole in the center. The unbalanced radiation pressure along this direction produces a continuous flux of cold atoms that are accelerated out of the trap. A different arrangement is used in [15]: the atomic beam is generated by a leaking MOT obtained by a pyramidal mirror with a hole pierced in its center.

In this work we produce and characterize a continuous, intense and slow atomic beam, extracted from a standard vapour-cell MOT using a novel scheme. A focused laser beam (forcing beam) crosses the capture vapour-cell MOT

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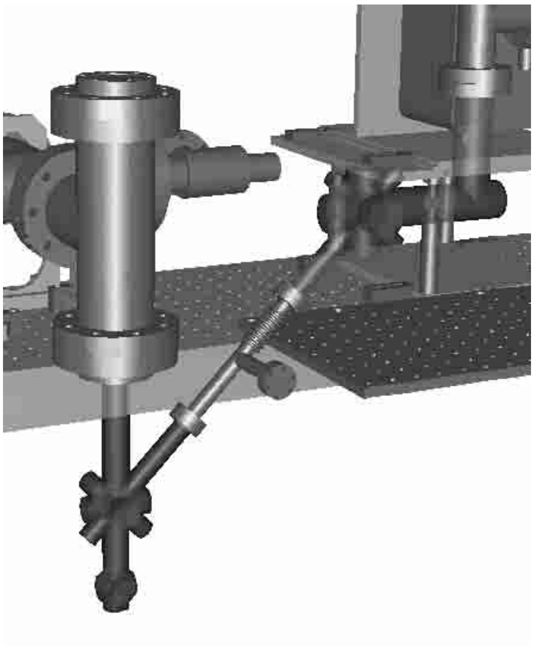

Fig. 1. Scheme of the two-chambers differentially pumped vacuum system. The two glass cells are connected by a transfer tube making a 45° angle with the horizontal plane. Atoms trapped in the loading vapour-cell MOT (upper cell) are pushed in the lower cell by a continuous laser beam directed along the transfer tube.

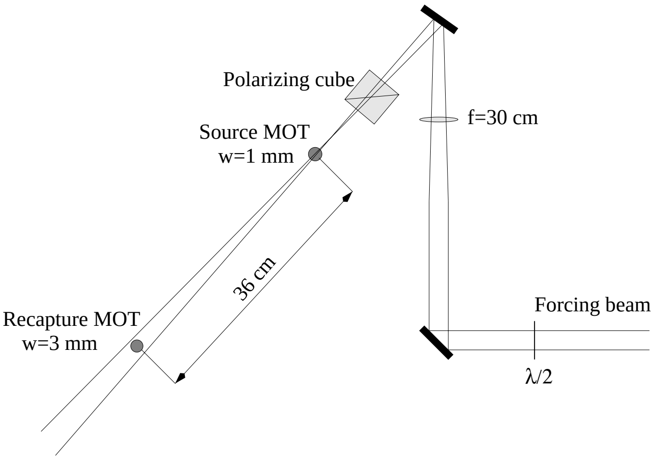

Fig. 2. The experimental set-up used to generate the cold atomic beam. The pushing radiation is spatially filtered by a single mode optical fiber and linearly polarized. A lens focuses the radiation so that it hits the loading vapour-cell MOT with a typical waist $w \simeq 1$ mm and the recapture MOT with a waist $w \simeq 3$ mm.

and creates the extraction column along which trapped atoms can escape. In the trapping region, atoms are efficiently cooled to sub-Doppler temperatures before being ejected. This mechanism reduces the velocity spread and provides a very efficient way to transfer trapped atoms into an intense and low-divergence atomic beam. The jet passes through a tube connecting two differentially pumped cells and is used to load a magneto-optical trap in an ultra-high vacuum chamber. Recapture of atoms into the trap provides useful information about the atomic beam characteristics and their dependence on pushing beam parameters. A comparison of this method with a pulsed transfer scheme is presented.

2 The experimental set-up

The experimental set-up is based on a two-chambers differentially pumped vacuum system (Fig. 1).

Two glass cells are connected by a 26 cm long transfer tube with a conductance of 0.9 l/s, at an angle of 45° with the horizontal plane. The upper cell (loading cell) is connected to a rubidium reservoir. Under the typical operating conditions the vapour pressures in the loading and the recapture cells are $\sim 10^{-8}$ mbar and $\sim 10^{-10}$ mbar respectively. The atomic beam leaves the loading cell and enters the ultra-high vacuum chamber where atoms are recaptured. The source of cold atoms is a standard vapour-cell MOT configuration with three pairs of orthogonal retro-reflected laser beams with opposite circular polarizations. Two anti-Helmholtz coils produce a magnetic field gradient of 15 G/cm along their symmetry axis. The trapping laser beam is obtained by optical injection of a 50 mW diode laser by a grating-stabilized diode laser. The frequency of the master radiation is stabilized on the dycroic atomic-vapour laser lock (DAVLL) signal [16] detected around the $5\,^2\mathrm{S}_{1/2}(F = 2) \rightarrow 5\,^2\mathrm{P}_{3/2}(F = 3)$ transition of ^{87}Rb. Before reflection, the three trapping beams have a power of ~ 5 mW and a spot size of ~ 1 cm^2. The repumping light is obtained by frequency locking a grating stabilized diode laser on the sub-Doppler line $5\,^2\mathrm{S}_{1/2}(F = 1) \rightarrow 5\,^2\mathrm{P}_{3/2}(F = 2)$ of ^{87}Rb. The repumping power on the loading vapour-cell MOT is ~ 2 mW. A further laser beam is added to the standard vapour-cell MOT to generate a direction of unbalanced radiation pressure along which a jet of cold atoms can emerge. Its frequency is locked on the DAVLL signal detected around the $5\,^2\mathrm{S}_{1/2}(F = 2) \rightarrow 5\,^2\mathrm{P}_{3/2}(F = 3)$ transition of ^{87}Rb. The scheme used to generate the forcing beam is shown in Figure 2. The radiation is spatially filtered using a single mode optical fiber and is linearly polarized. The beam is focused so that it hits the loading vapour-cell MOT with a typical waist $w \simeq 1$ mm and the recapture MOT with a waist $w \simeq 3$ mm. The recapture MOT is a standard magneto-optical trap with retro-reflected beams. Before reflection each beam has a power of ~ 5 mW distributed over an area of ~ 1 cm^2. A magnetic field gradient of 15 G/cm is generated by a pair of anti-Helmholtz coils. Transferred atoms are pumped by the forcing beam in the $5\,^2\mathrm{S}_{1/2}(F = 1)$ state. They can be efficiently trapped by the recapture MOT only if the repumping power is high enough. We use ~ 8 mW of repumping light on the second MOT. The confining volume of the two magneto-optical traps is monitored by two CCD cameras. The fluorescence radiation of trapped atoms is detected by two photodiodes. From the fluorescence signal of the recapture MOT we extract the information about the atomic beam properties. The maximum number of trapped atoms is given by the stationary fluorescence level and the initial capture rate provides the flux of transferred atoms. Observation of the time of flight signal (TOF) produced by the pushed atoms allows to measure the mean jet velocity.

3 Principle of operation

The loading vapour-cell MOT represents the source of cold atoms for the atomic jet. When an atom enters the trapping volume a strong damping force reduces its thermal velocity. As the particle approaches the trap center, sub-Doppler cooling mechanisms further reduce its temperature. The cooling takes place during all the extraction process. In the extraction column the unbalanced radiation pressure accelerates the atom out of the trap. As the forcing beam does not contain repumping light, the atom can scatter pushing photons only inside the trapping region. The cooling process in the vapour-cell MOT reduces the transverse velocities and limits the divergence of the extracted atomic jet. The beam flux is determined by the vapour-cell MOT capture rate R. In a standard vapour-cell MOT the stationary number of trapped atoms is $N = R/\Gamma_{\rm c}$, where $\Gamma_{\rm c}$ is the collisional rate. The forcing beam transfers most of the captured atoms into the jet. In this case, the beam flux Φ is given by $\Phi = R/(1+\Gamma_{\rm c}/\Gamma_{\rm t})$, where $\Gamma_{\rm t}$ is the transfer rate of atoms in the extraction column [14]. $1/\Gamma_{\rm t}$ is comparable with the atomic damping time which, for rubidium, is several tens of ms [14]. Typically $\Gamma_{\rm c} \sim 1$ s and $\Gamma_{\rm c} \ll \Gamma_{\rm t}$ so that $\Phi \simeq R$. In principle this allows to transfer the loading rate of a high pressure vapour-cell MOT to a magneto-optical trap operating into an ultra-high vacuum environment. However, the flux of recaptured atoms strongly depends on the collimation properties of the atomic beam and an efficient cooling process is fundamental to avoid high divergence losses.

4 Experimental results

In order to optimize the atomic beam flux it is necessary to maximize the capture rate of the source vapour-cell MOT. With a trapping beam power of 15 mW, equally separated over the three retro-reflected MOT beams, we observe a maximum capture rate of 1×10^9 atoms/s for a detuning of -15 MHz and a magnetic field gradient of 15 G/cm. These are the usual operating conditions of a standard vapour-cell MOT. Capture rate does not significantly change when the detuning is changed into an interval of 5 MHz around -15 MHz; at the same time, capture rate is insensitive to magnetic field gradient variations in an interval of 10 G/cm around the value of 15 G/cm.

We analysed the jet characteristics as a function of the pushing beam parameters. The flux is measured by trapping the transferred atoms into the recapture MOT. In Figure 3, the flux of recaptured atoms is reported as a function of the forcing beam power at a constant detuning from resonance of -20 MHz. For low power (< 50 μW) the forcing beam radiation pressure is not able to extract atoms from the vapour-cell MOT. As the power is increased over 50 μW, the beam intensity becomes comparable with the intensity of the vapour-cell MOT beams and atoms that enter the extraction column can be accelerated out of the trap. The beam flux reaches its maximum value at a power of 100 μW. The jet velocity can be measured by observing the TOF signal of transferred atoms. It increases with the pushing beam power from a minimum value of 14 m/s to a maximum of 18 m/s. This explains the flux decrease observed at a high forcing beam power: in fact, the short extraction time induced by strong accelerations reduces the effect of the transverse cooling and produces higher divergence losses. The flux dependence on the forcing beam detuning is reported in Figure 4 for a constant power of 100 μW. The experimental data show two pronounced peaks at a red detuning of -22 MHz and a blue detuning of 16 MHz. This behaviour can be qualitatively explained by looking into the extraction process. The forcing beam intensity is comparable with the vapour-cell MOT beams intensity. When

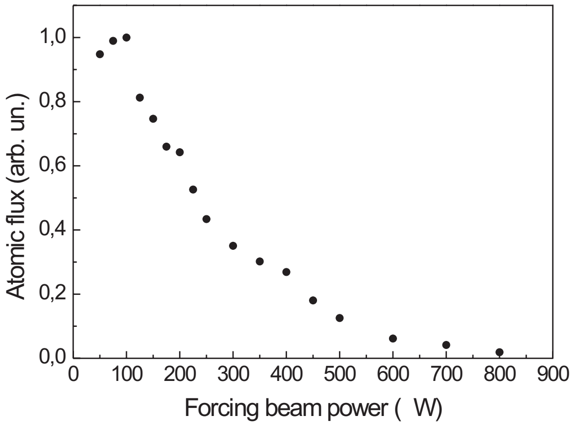

Fig. 3. The flux of recaptured atoms as a function of the forcing beam power at a constant detuning from resonance of -20 MHz. The maximum value corresponds to 7×10^7 atoms/s.

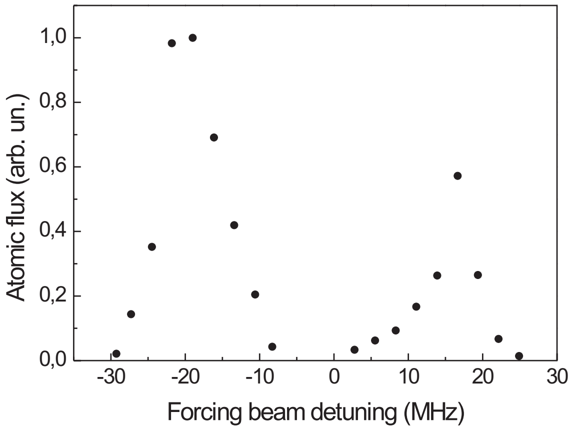

Fig. 4. Dependence of the flux of recaptured atoms as a function of the forcing beam detuning at a constant power of 100 μW. The maximum value corresponds to 7×10^7 atoms/s.

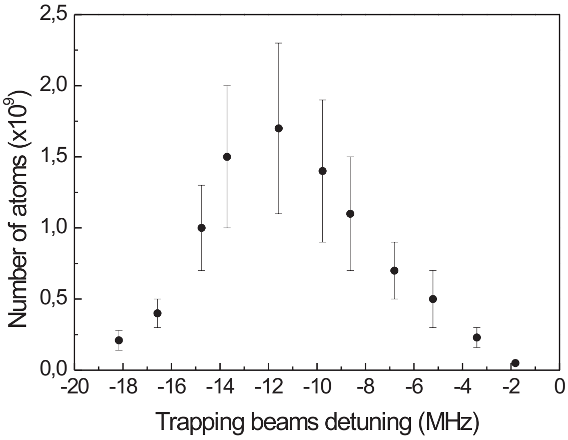

Fig. 5. Dependence of the steady state number of trapped atoms in the recapture MOT as a function of the MOT beams detuning.

the forcing beam detuning is much less than the vapour-cell MOT trapping beam detuning, the radiation pressure is not able to push the atoms out of the magneto-optical trap and the source vapour-cell MOT has no leakage. The beam flux reaches its maximum value at a red detuning of −22 MHz. In this case, the slightly unbalanced radiation pressure accelerates atoms out of the trap and produces a low divergence jet. When the pushing beam detuning gets closer to resonance, higher jet velocities can be measured. As in the case of high power, the transverse cooling process is not efficient and the beam divergence induces higher losses. This is the reason for the very low (in the actual experiment not measurable) transfer efficiency near resonance. We observe a high flux of atoms at a blue detuning of 16 MHz. In this case, both the forcing beam and the vapour-cell MOT beams are almost resonant with the two Zeeman sub-levels $5\,^2\mathrm{P}_{3/2}(F = 3, m_F = 3)$ and $5\,^2\mathrm{P}_{3/2}(F = 3, m_F = -3)$. In the moving frame the atoms interact with both laser beams and the transfer takes place as in a moving molasses scheme based on the Doppler effect. In this case, the low velocity in the extraction column and the efficient transverse cooling process produce a low divergence jet. For a blue detuning much higher than the trapping beam detuning, the forcing beam is not able to extract the confined atoms and the source vapour-cell MOT is stable.

With a forcing beam power of 100 μW and a red detuning from resonance of −22 MHz we measured a flux of 7×10^7 atoms/s for a loading time of 1.4 s in the source vapour cell MOT. Compared with the capture rate of the loading MOT we observed a 7% transfer efficiency. This measure is related to the recapture process in the second magneto-optical trap. In order to optimize the detection method we measured the steady state number of atoms trapped into the recapture MOT as a function of the trapping beam parameters. The behaviour with the MOT beams detuning is shown in Figure 5. The maximum value corresponds to $\sim 2 \times 10^9$ atoms limited by the laser power and the size of the trapping beams.

5 Comparison with a pulsed transfer scheme

We compared the flux of the continuous jet with that produced by a pulsed transfer scheme [9]. In this case, the pushing beam is derived from the vapour-cell MOT trapping beam by using a variable Pockels cell; the trapping radiation is switched off and a few ms light pulse pushes the atoms from the upper to the lower cell. During the transfer this laser is tuned close to the cycling transition $5\,^2\mathrm{S}_{1/2}(F = 2) \rightarrow 5\,^2\mathrm{P}_{3/2}(F = 3)$ of ^{87}Rb. A lens focuses the beam near the recapture MOT so that it has a cross section of 0.6 cm^2 on the vapour-cell MOT center. The radiation is circularly polarized and a small axial magnetic field is applied when the pushing light is on. The atoms, pumped in a weak-field-seeking state, can be guided along the transfer tube in the radially confining harmonic potential generated by a hexapole magnetic field. This is provided by six strips of uniformly magnetized rubber surrounding the transfer tube in the form of a hexagonal prism. Magnetic guiding increases the collimation properties of the pulsed atomic beam. We optimized the transfer efficiency with respect to all the variables in the experiment. The dependence of the transfer efficiency from all the pushing beam parameters (push detuning, length and intensity of the pulse) is related to the mean velocity of atoms in the pulsed jet. The maximum beam flux is obtained for a jet velocity of 18 m/s. We measured a recapture rate of 6×10^7 atoms/s for a loading time in the source vapour cell MOT of 3.7 s. This value can be compared with the one obtained with the continuous transfer scheme. Indeed, in the low pressure regime ($< 10^{-7}$ mbar) the interparticle interactions can be neglected and the continuous beam flux linearly depends on the loading cell pressure. If we scale the recapture rate of 7×10^7 atoms/s obtained in the continuous transfer experiment by the ratio of the pressures in the loading cell, we obtain a flux of 3×10^7 atoms/s. In the low pressure regime, the recapture rates are comparable in the two cases. The continuous transfer system is expected to give better results at higher pressure. In fact, by using the pulsed transfer system, as the pressure in the vapour-cell increases, the saturation of the number of atoms that can be observed in the source MOT does not lead to an optimized loading rate and to an increase of the flux of particles in the atomic beam.

6 Conclusion

We demonstrated a new scheme to produce a continuous beam of cold atoms from a leaking vapour-cell MOT. Among all methods, our scheme offers different advantages. Indeed, pulsed systems have to follow a well defined transfer cycle making more elaborate the timing of the experiment. After loading the source vapour-cell MOT, atoms are pushed into the atomic beam. Using this scheme, the source vapour-cell MOT operates in a high density regime, where the loading time is not optimized. During the transfer it is necessary to switch the vapour-cell MOT off to allow the pushed atoms to leave the trapping volume. When this time interval is comparable with the vapour-cell MOT loading time, the flux of the atomic jet can be strongly reduced. Moreover, if the atoms are pushed by simply using a short pulse of laser light, spontaneous scattering of photons can induce a broadening of the velocity distribution in the moving frame. In this case it is necessary to use magnetic guiding to reduce the jet divergence and to achieve high transfer efficiencies. The moving molasses scheme is a complex but more versatile method that gives an efficient way to precisely control the velocity of transferred atoms.

Continuous transfer systems does not suffer from these problems. They work in a low density regime and, by means of the transverse cooling process, the atomic beam divergence can be efficiently controlled. As for other continuous transfer schemes, the system we have described allows us to obtain a flux of cold particles slightly smaller than what was reported in [12–14]. However, the main characteristic is the simplicity of the experimental set-up. A single laser beam determines a direction of unbalanced radiation pressure along which the atoms confined in the source vapour-cell MOT can escape. The set-up is extremely flexible and, unlike the 2D$^+$-MOT and LVIS systems, does not require optical parts inside the vacuum chambers.

A work similar to the one presented in this paper was performed in the group of Dalibard [17]. Stimulated by the results of our work, the method of continuous transfer was also used to achieve simultaneous operation of a double MOT for ^{87}Rb and ^{40}K [18].

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