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White light transverse cooling of a helium beam

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Abstract. We report a study of transverse laser cooling on a metastable helium beam using spectrally broadened diode lasers ("white light") to increase its flux. For this purpose, beam profile and atomic flux *versus* laser power and other parameters have been characterized. We have performed experiments to compare this technique with other transverse cooling methods using monochromatic light. Best results are obtained with a "ziz-zag" configuration using "white light".

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

1 Introduction

High atomic fluxes play an important role in the preparation of dense and cold atomic samples for many studies, for instance of cold collisions, quantum optics or metrology. New techniques based on the manipulation of atoms with light have been developed in the last years. They allow to modify all the essential features of an atomic beam such as its velocity, divergence and even play with the atomic coherence. Lasers permit to efficiently deflect, slow down and trap atoms with radiation pressure [1] or stimulated light forces [2].

We applied the radiation pressure force to obtain an intense and cold beam of helium 4 atoms in the 2^3S_1 metastable state. Our purpose is to investigate cold atomic collisions and quantum degeneracy of trapped helium. In order to achieve the required high densities in the trap, the loading beam has to have a flux of at least 10^9 to 10^{10} atoms/s. Even with an efficient discharge source, the metastable helium beam needs to be collimated to reach such a high flux.

One of the first approaches to collimate a metastable helium beam was implemented by Aspect *et al.* [3] using a monochromatic laser beam, and later successfully applied by Rooijakkers *et al.* [4] to generate a high flux beam. Its wave front was curved, which ensured that the atoms stay in resonance along their trajectory. Another method to keep the atoms in resonance is to broaden the frequency spectrum of the laser, so that it covers most of the atomic velocity distribution. This idea of "white light" cooling was first proposed by Hoffnagle in 1988 [5] for the deceleration of an atomic beam. Several experiments on longitudinal beam cooling based on white light followed [6–9].

In the present work, we used white light generated by a spectrally broadened diode laser to perform transverse cooling and thus reduce the divergence of an atomic beam. This method was combined with a so called "zig-zag" configuration [10], which implies a multi-pass interaction between the laser and the atomic beam. We studied the collimation by measuring the beam profile and the increase in the atomic flux as function of different parameters, such as the laser power. Finally, several techniques were applied to deflect the collimated beam, the main interest here being the separation of metastable 2^3S_1 helium atoms from other species.

In this paper, we will compare the results obtained with different techniques used both for compression and deflection.

2 Advantages of white light transverse cooling

Let us consider the case of a monochromatic plane wave radiation, with wave vector $\mathbf{k}$, crossing an atomic beam. In this case, the radiation pressure force modifies the atomic transverse velocity. In order to keep the laser always in resonance during the transverse velocity evolution, one could broaden the laser linewidth to consequently broaden the velocity capture range ΔV_t, in a plane wavefront configuration. We call this technique "white-light" cooling.

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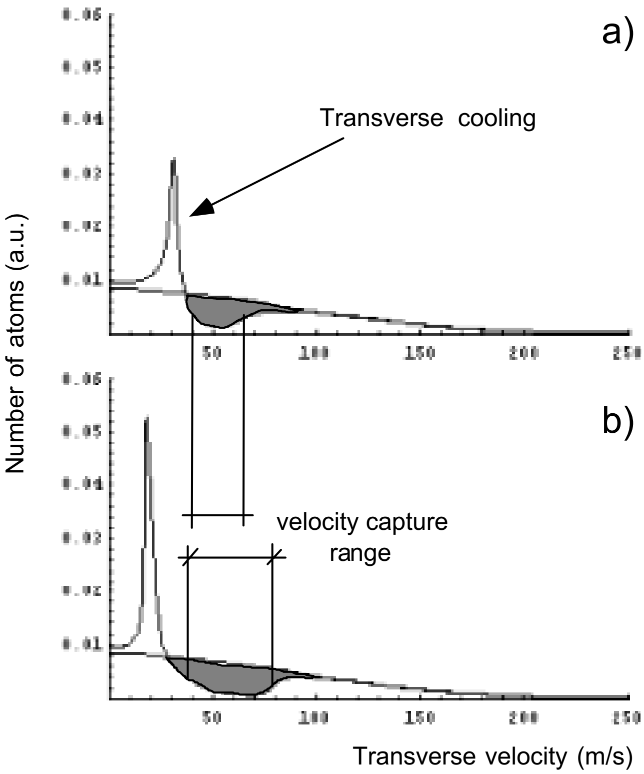

Fig. 1. The effect of laser cooling on the transverse velocity distribution in a beam of metastable helium atoms, with (a) a monochromatic laser, and (b) a "white light" configuration with a total spectral broadening of 45 MHz. In both cases, the laser detuning is 45 MHz, the laser power is 18 mW/cm^2 and the interaction length 8 cm.

The broadening of the laser linewidth can be obtained by means of superimposing sidebands, resulting from frequency modulation of the light. A quasi continuum spectrum can be obtained if the spacing between the sidebands is comparable with the laser linewidth.

We simulate the collimation process due to the transverse "white light" laser cooling by integrating the equation of motion in the interaction region. In this way, a final transverse velocity distribution can be obtained. The atomic transition we use is the 2^3S_1 to 2^3P_2 transition at 1083 nm, whose saturation intensity is 0.16 mW/cm^2 and width $\Gamma/2\pi$ equals 1.6 MHz. The advantage of broadening the laser spectral width is illustrated in Figure 1, which gives for a plane-wavefront configuration the compressed transverse velocity in two cases: (a) for a monochromatic laser and (b) for a spectrally broadened one with a total linewidth of 45 MHz. For the purpose of this comparison, a detuning of 45 MHz, larger than the half of the total broadening of case (b), has been chosen for both cases. Thus, the ideal situation for efficient cooling is not fulfilled, and the peak that appears in the velocity distribution is not centered around zero. Figure 1 shows that the number of compressed atoms is larger in case (b) than in case (a) and demonstrates clearly that the velocity capture range and the depletion region are smaller for the monochromatic case than for the broadened linewidth one.

3 Experimental apparatus

The measurements were performed with the helium beam apparatus shown in Figure 2.

We developed a new source based on the original Shimizu scheme [10,11] to efficiently excite the helium atoms in the metastable state 2^3S_1 from a continuous discharge.

When cooled at liquid nitrogen temperature, the source provides a continuous atomic beam with a typical flux of 10^{14} metastable atoms/s/sr. The velocity distribution peaks around 1000 m/s and shows a width of about 500 m/s (FWHM). These values can be deduced by time of flight measurements, obtained by pulsing the discharge.

The beam divergence of about 10^{-1} rad is fixed by the geometry of the source. In the horizontal direction, the divergence is reduced by laser cooling over an interaction distance of 8 cm. The interaction region starts at a distance $L_1 = 0.2$ m downstream the source. An additional optical access gives the possibility to deflect the atoms with a laser beam, similar to the one used for the collimation. For the study of deflection, we first laser collimated the atomic beam ("zig-zag" or curved wave front technique) and we placed an aperture ($\varnothing = 8$ mm) at a distance $L_2 = 0.36$ m from the source.

Two electron multipliers, a movable channeltron and a fixed channelplate are located downstream of the collimation and deflection zones. They are used to monitor the shape and intensity of the atomic beam. Metastable atoms are detected by means of electrons resulting from their de-excitation into the 1^1S_0 ground state (Auger de-excitation) when they hit the detector surface. The channeltron, mounted at a distance $L_3 = 1.3$ m from the source, is used to measure the time-of-flight spectrum of collimated or deflected atoms. We thus are able to study the effect of the light force as a function of the longitudinal atomic velocity, which is related to the interaction time with the lasers. The channeltron can be translated in the transverse direction across the atomic beam to measure the horizontal beam profile. The resolution in the horizontal dimension is defined by a vertical slit of about half a millimeter in front of the channeltron. The channelplate followed by a phosphor screen is installed at a distance $L_4 = 1.7$ m from the source. Thus, the profile of the collimated or deflected beam can be visualized in two dimensions, facilitating the beam alignment.

Most earlier experiments on laser cooling of helium at 1083 nm (transition 2^3S_1–2^3P_2) were performed with a LNA ring laser pumped by an argon ion laser [12]. In our new experimental set-up, we apply a new laser scheme to obtain a more powerful source at this wavelength. We combine a DBR-Laser diode (SDL-6702-H1), serving as master oscillator, with a commercial fiber amplifier (IRE-POLUS GROUP YAM-1083-500) [13] providing more than 600 mW of power in the TEM_{00} mode at the output.

After passing two optical isolators and a polarization control consisting of one quarter and one half wave plate, the diode laser beam is injected into the fiber amplifier. An injection power of a few mW is sufficient to saturate

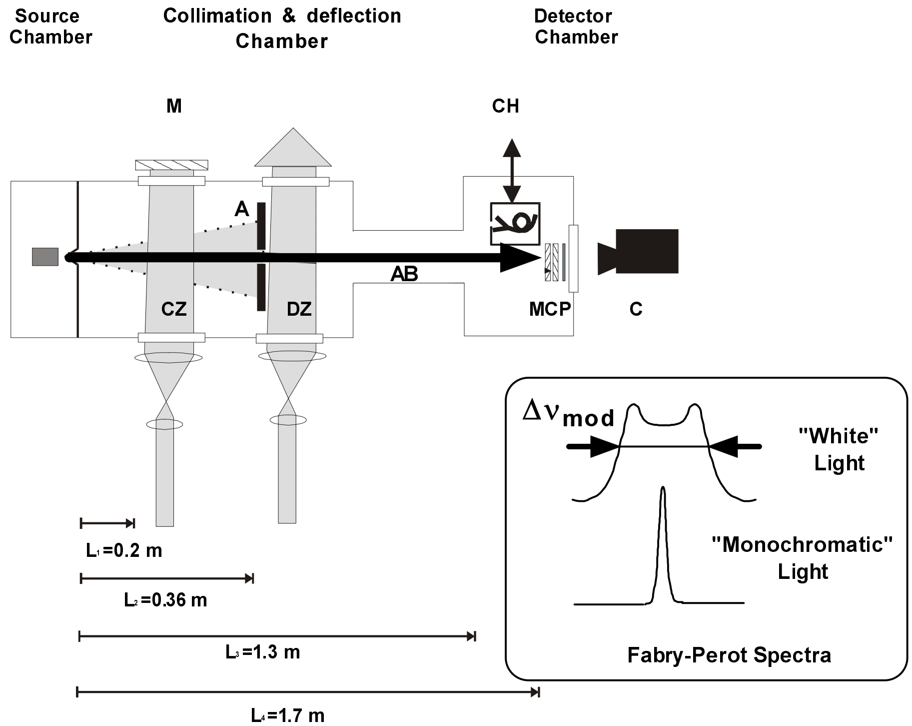

Fig. 2. Scheme of the helium collimation and deflection experiment. AB atomic beam, CZ collimation zone, DZ deflection zone, CH movable channeltron, MCP channelplate plus phosphorscreen, C camera, A removable aperture and M mirror. Inset: scheme of the laser beam frequency spectrum observed with a Fabry-Perot for the case of "monochromatic" and "white" light, used in the present work.

the amplifier. Behind the amplifier, an additional optical isolator is placed to reduce perturbations from the following optics. The initial waist of the laser beam at the fiber output ($\varnothing = 0.4$ mm) is expanded by a spherical telescope to a size of about 8 mm. The beam waist must be further extended to a width of about 7 cm so that the interaction between atoms and laser lasts sufficiently long. In height, the laser beam is enlarged to 1.5 cm to guarantee enough overlap with the atomic beam. This is realized by two telescopes made out of a large spherical lens and two crossed cylindrical lenses.

The diode laser is stabilized on the helium line by saturation spectroscopy. A small fraction of the laser beam crosses twice a glass cell where helium atoms are excited by a RF-discharge.

By frequency modulating the laser, an error signal is generated, which reacts on the diode laser current through a lock loop. The spectral profile of the laser diode and of the amplified light are analyzed with a Fabry-Perot. The spectral width of the stabilized diode laser is typically 3 MHz. For such a frequency width of the injected light, the fiber amplifier broadens the spectrum to about 5 MHz by introducing additional noise [14].

Frequency broadening of the laser line needed for the experiments on "white light" cooling is realized by modulating the current of the diode. In the frequency spectrum, this generates sidebands separated by the modulation frequency. The number of sidebands depends on the modulation amplitude of the diode current. By choosing a modulation frequency of the order of half the laser linewidth (FWHM), one generates a quasi continuous spectrum. In the following, we will call "modulation broadening" the difference between the total spectral width and the laser intrinsic linewidth.

Various cooling schemes have been compared by their effect on the atomic beam profile. Both collimation as well as deflection bend the atomic trajectories in their characteristic ways and thus, produce a particular beam shape. The number of atoms at a given position of the channeltron is obtained by integrating the portion of the time of flight signal corresponding to the metastable atoms. Repeating this measurement at different positions of the channeltron, we obtain the flux profile for the collimated and the non collimated beams (see Fig. 3). Note that the non collimated beam profile is uniform over a large angle.

For quantitative comparison of the profiles, we define the gain due to the collimation as the ratio between the number of atoms within an angle of about 10^{-2} rad with and without collimation. For a distance between the source and the detector of 1.3 m, the gain is calculated by integrating the normalized transverse profile for the detector positions between -5 mm and $+5$ mm (see Fig. 3). The origin refers to the center of the collimated beam.

In this experiment, the width of the collimated beam is rather large (3 to 5 mm FWHM depending on the techniques and power). In the present setup, the collimation region starts 20 cm away from the source in a zone where the atomic beam has already considerably expanded. For example, an atom with a 1000 m/s longitudinal velocity and a 10 m/s transverse velocity enters the collimation zone 2 mm off axis. This results in a given width of the beam, even if perfectly collimated. Clearly, it is necessary to start the collimation as close as possible to the skimmer to obtain a width as small as possible. From the intensity gain that we measure, we can extract

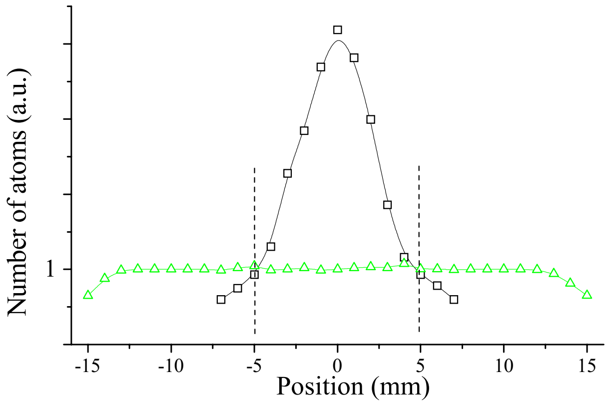

Fig. 3. Example of collimated beam profile. The number of atoms detected with the channeltron at each position is plotted. The squares and the triangles refer to the collimated beam and the non-collimated beam respectively. The decrease at positions larger than 12 mm for the non-collimated beam is due the size of the vacuum chamber. The collimated beam was obtained using "white light" collimation. The gain, defined as the ratio between the number of atoms detected between −5 mm to +5 mm with and without collimation, is 2.5.

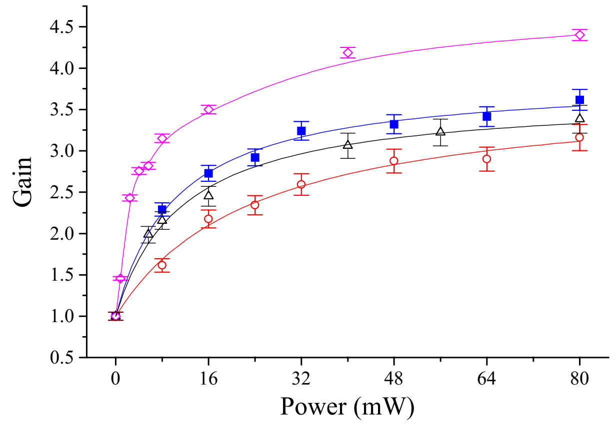

Fig. 4. Gain in the number of atoms as a function of the laser power for different compression techniques. The error bars take into account fluctuations of the atomic beam flux during the measurements. Open circles correspond to the monochromatic plane wave, open triangles to the curved wave front, squares to the "white light", and diamonds to the "zig-zag" configuration with "white light".

a velocity capture range and estimate the expected width. The widths that we measure are compatible with a maximum residual transverse velocity of the order of 1 m/s.

4 Results

First we use the standing wave formed by two counter propagating laser beams to compress the atomic beam (1D optical molasses). The laser frequency is red detuned. The Gaussian shaped beam is expanded to a size of 8 cm × 1.5 cm, aligned perpendicularly to the atomic beam, and retro-reflected on a silver coated mirror. We measure the gain for several values of the laser power, ranging from 0 to 80 mW. The results are shown as open circles in Figure 4. For each power, the red detuning is set to the value that optimizes the number of atoms detected at the center of the collimated beam. The gain keeps increasing with the laser intensity, as one is able to slow down higher and higher transverse velocities.

For the "white-light" technique, we used the same optical set-up and alignment as for the molasses. The laser current is modulated at a frequency of 2 MHz. The spectral width resulting from the overlapping sidebands is enlarged by about 8 MHz, corresponding to a widening of the capture range to about 8 m/s. The gain as function of power is shown as squares in Figure 4. As expected, it is larger, but has the same behavior as the gain achieved with the standard plane wave configuration. At higher power, the velocity capture range is enlarged also due to power broadening.

The gain depends on the spectral width of the "white light" (see Fig. 5a). Starting with no modulation (1D molasses), the gain grows when the modulation broadening is increased up to 7 MHz. Beyond this value, the power is shared between many sidebands resulting in a decreasing gain. It is important to note that the red detuning of the laser had to be adjusted for each value of the modulation broadening.

In a third step, we collimated the atoms with a light beam whose wave front was curved by slightly focusing the beam. As for the 1D molasses, the laser beam was retro-reflected by a mirror. For correct collimation, both light beams have to be aligned in such a way that at the end of the interaction region their wave vectors are perpendicular to the final atomic beam direction. In the curved wave front configuration, the atoms follow the curvature of the field if the radiation pressure is sufficient to balance the centrifugal force. An optimum gain was found for a radius of curvature of 10 m. The corresponding results are shown as triangles in Figure 4. One can see that the collimation gain is better than with the plane wave with a monochromatic laser, as expected and already demonstrated in [3]. One the other hand, it shows rather similar behavior as for the "white light" in a plane wave configuration, with slightly smaller values.

Finally, we used the "zig-zag" geometry to collimate the beam. This technique, without white-light, has already been used very efficiently to collimate and deflect a beam of metastable neon [10], and to collimate a beam of metastable helium [15]. We create such a "zig-zag" configuration with a 8 mm wide laser beam, whose angle of incidence is chosen so that the multiple beams are nearly overlapping, giving an effective interaction length of 8 cm. In addition, the "zig-zag" configuration is combined with frequency broadening the light. The gain is measured as a function of the laser power, knowing that we choose the optimum modulation broadening for each laser power. The results are shown as diamonds in Figure 4. The resulting gain is clearly much better than with the three other methods already discussed and particularly at low laser power.

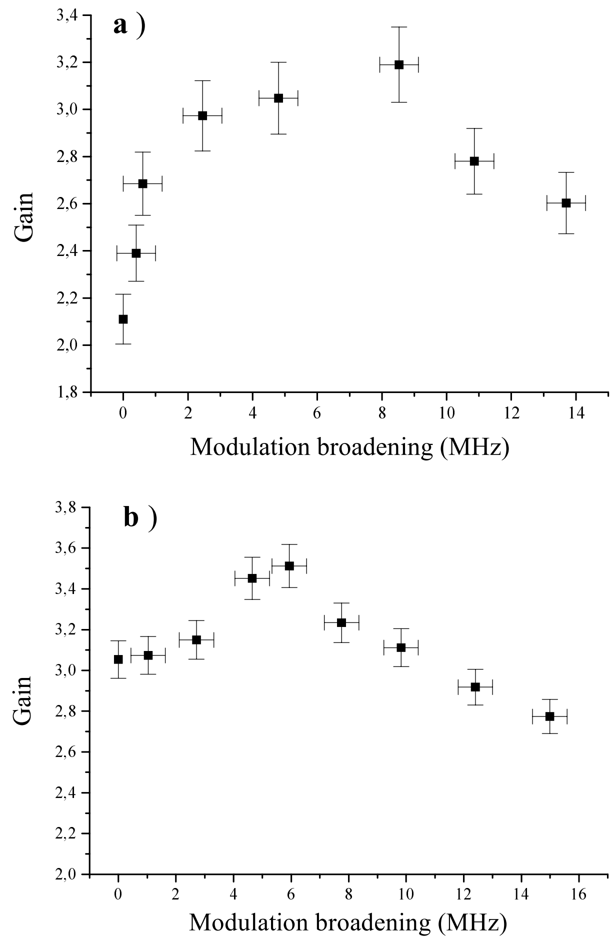

Fig. 5. (a) Compression gain *versus* modulation broadening in the plane wave configuration. The laser power is 30 mW. (b) Similar results in the "zig-zag" configuration. The laser power is 15 mW.

As before, for a fixed power of 15 mW, we varied the modulation broadening (see Fig. 5b). An optimal modulation broadening is obtained around 6 MHz. The advantage of the "white light" is an increase of at most 15% compared to the use of a "zig-zag" without "white light" (which corresponds to 0 MHz modulation broadening).

Dealing now with the deflection of atoms [16] the light force is supposed to act only from one direction on the atoms. To obtain a sufficient spatial resolution, we first collimated the atomic beam, either with the "zig-zag" or the curved wave front technique. In addition, we decreased the beam diameter with a diaphragm to prevent the non collimated part of the beam from reaching the detector.

The deflection angle was measured either with the channeltron or with the channelplate followed by a phosphor screen. Most of the measurements were done with the channeltron, since the size of the MCP detector was not sufficient to detect large deflections.

Figure 6 summarizes the horizontal beam profiles obtained with the different techniques. Figures 6a and 6b show the effect of a 8×1.5 cm running plane wave without and with frequency broadening of the laser respectively. One can see that the deflection angle increases with the laser power in both cases. As expected, one obtains that, for a given deflection angle, the required power is less for "white light" than for a non broadened laser. For instance, a deflection angle of 8×10^{-3} rad, corresponding roughly to a deflected position of 8 mm in Figure 6, requires a power of 75 mW in case (a) and 40 mW in case (b).

As expected from the collimation studies, the "zig-zag" scheme proved to be the most efficient technique for deflection. Here, the atoms enter the "zig-zag" with an adjustable angle with respect to the direction perpendicular to the light beams. They are deflected if this angle lies within the angular capture range of the "zig-zag" arrangement. The force they experience comes mostly from one direction. As they are resonant with only half of the beams, the situation is very similar to the deflection by a curved wave-front. A 8 mm deviation can be achieved with a power of less than 3 mW (see Fig. 6c). We were able to deflect the beam by about 20 mm (about 20×10^{-3} rad), with no significant loss of atoms, with more laser power.

5 Discussion

In this article we presented studies and a comparison of several laser techniques to transversally cool and to deflect an atomic beam. We first explained and showed the advantage of broadening the laser frequency while keeping the plane wave geometry for the light beams. For each laser power, an optimal collimation is achieved for a particular spectral width in combination with an adequate red detuning of the laser. This method is an alternative one to the curved wave-front technique. Its advantage is that it requires no geometrical adjustment and is very simple to use with a diode laser.

Studying transverse cooling of the beams with "white light", we compared two configurations based on different geometrical arrangements: first a retro-reflected laser beam expanded to a large dimension in 1D, second a non expanded laser beam reflected several times between two plane mirrors across the atomic beam (so called "zig-zag" configuration). For an equal length of interaction, the "zig-zag" geometry gave the best compression gain. Its advantage is most significant for small laser powers. This method is rather versatile, because it does not require large optics to expand the beam. In addition, the mirrors for the multiple reflections of the light beam can be placed inside the vacuum chamber, which avoids power losses by absorption in the windows and restriction on the length of the interaction region.

In summary, we found that the best method for collimating the helium atomic beam is to use a "white light" laser in the "zig-zag" configuration. For instance, with such a set-up, a laser power of 40 mW and a horizontal interaction length of 9 cm, we measured that the atomic beam at 1 m from the source is concentrated over a length of roughly 0.5 cm in the horizontal direction, with a gain of roughly 4 as compared to the case with no compression. This method can be easily extended to two dimensions. For 2D, the gain in flux is expected to be approximately

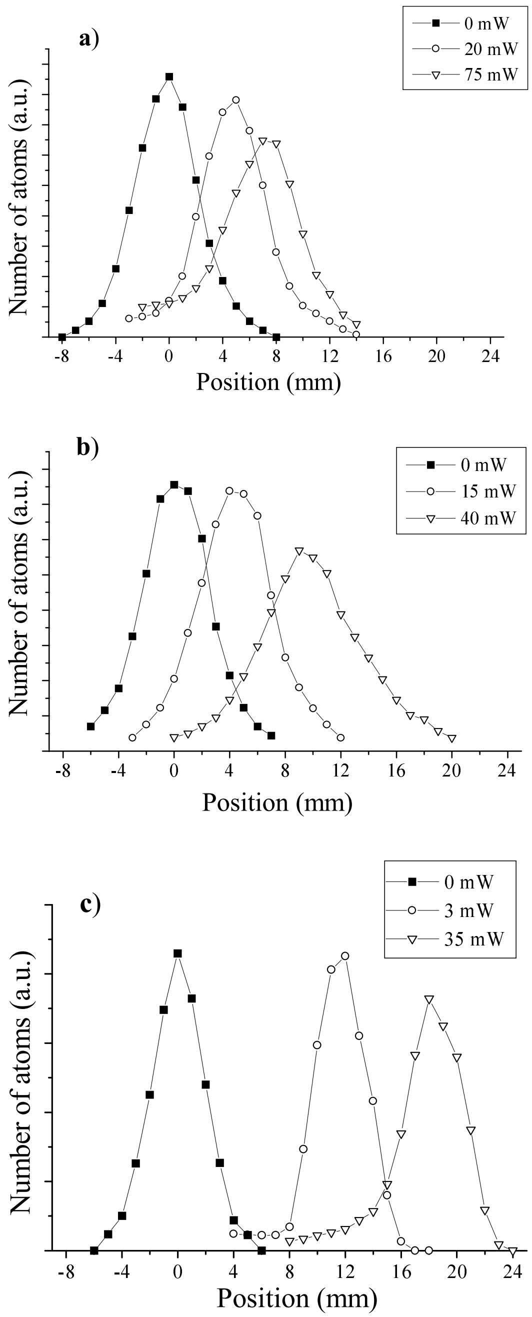

Fig. 6. Deflection of the collimated atomic beam with increasing powers using (a) a plane wave, (b) a plane wave with "white-light", (c) a "zig-zag" configuration.

the square of the gain in 1D. Such a gain should allow to produce a beam at least as intense as in [4], where the intensity of the collimated beam was reported to be 10^{10} at/s/mm^2.

Finally, we applied the above mentioned techniques to deflect the atomic beam in order to separate the metastable 2^3S_1 atoms from majoritary ground state helium atoms (ratio: 1 to 10^4). The atoms are pushed either by an expanded running laser beam or by a narrow beam in the "zig-zag" configuration. For instance with a laser power of 35 mW, the transversely compressed beam could be pushed by about 2 cm at 90 cm away from the deflection zone with no significant loss of atoms.

All the discussions presented here on the collimation and the deflection of an atomic beam by laser light have been illustrated on a beam of metastable helium, for which these techniques are crucial to reach high densities of trapped atoms. However, all these results can easily be transposed to any other heavier element.

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