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The effect of laser beam size in a zig-zag collimator on transverse cooling of a krypton atomic beam

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Abstract. The effect of size of a cooling laser beam in a zig-zag atomic beam collimator on transverse cooling of a krypton atomic beam is investigated. The simulation results show that discreteness in the interaction between the cooling laser beam and atomic beam, arising due to finite size and incidence angle of the cooling laser beam, significantly reduces the value of transverse velocity capture range of the collimator. The experimental observations show the trend similar to that obtained from simulations. Our study can be particularly useful where a small zig-zag collimator is required.

Keywords. Transverse laser cooling; zig-zag atomic beam collimator; metastable Kr atoms.

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The advancement in the technique of laser cooling of atoms to manipulate atomic motion has opened many new and exciting areas of research and technology including high resolution spectroscopy, many-body physics, precision measurements, atom lithography, matter wave interferometry, quantum information etc. [1–3]. Intense and collimated atomic beams produced using laser cooling techniques can be very useful for some of the above applications as well as for efficient loading of a magneto-optical trap (MOT) [4]. The idea of using transverse cooling to collimate the atomic beam was proposed for the first time by Hansch and Schawlow [5]. Transverse laser cooling of atomic beams has been demonstrated by applying various techniques such as monochromatic standing wave [6,7], curved wave-front technique [8,9] and zig-zag method [10–13]. Among these techniques of transverse laser cooling, the zig-zag method is the most commonly used because of its easy implementation and low power requirement of the cooling laser beam compared to other methods. Moreover, Rasel *et al* compared these methods and found that the zig-zag method provides the best compression gain for an equal length of interaction with the cooling beam [14]. Recently, the zig-zag method was used to demonstrate direct laser cooling of a diatomic molecule by reducing the transverse velocity spread of a cryogenic beam of strontium monofluoride (SrF) [11]. Further, this method of transverse cooling has been used in experiments to measure the abundance of trace isotopes of Kr and Ca atoms [15,16]. The transverse laser cooling near the source chamber is important to achieve high number densities of trapped cold atoms [17,18].

In zig-zag method, the transverse component of velocity of a moving atom in atomic beam is reduced by a laser beam propagating at an angle with respect to the axis of the atomic beam. In this method, a zig-zag path for the cooling laser beam is generated after multiple reflections of laser beams between two nearly parallel mirrors. A drawback associated with this geometry is that atoms pass through certain path segments where there is no laser beam to interact with atoms. The length of non-interaction segments depends on the beam spot size and its incidence angle. In the present study, the effect of cooling beam size on transverse cooling of a Kr* atomic beam in a zig-zag collimator has been investigated. This aspect of the zig-zag technique seems to be overlooked in the earlier studies. Here, we report the effect of cooling laser beam size on the transverse cooling of metastable krypton (^{84}Kr*) atomic beam in a zig-zag configuration. We show that the cooling beam size governing the length of non-interacting path regions in zig-zag configuration significantly affects the transverse velocity capture range (i.e., range of initial transverse velocity for which the collimator can cool atoms) of the collimator. Thus, the size of the cooling laser beam plays a crucial role in the effective collimation of atomic beam. With improved collimation of atomic beam, a significant enhancement in the MOT loading has been reported earlier [19,20]. So, this study may be useful in enhancing the number of atoms in the atomic beam loaded MOT.

In a zig-zag collimator used for transverse cooling, as shown in figure 1, cooling laser beam is coupled to one of the mirrors of the zig-zag collimator at an angle β_0 with respect to the direction perpendicular to the axis of the atomic beam. For a pair of reflecting mirrors kept at a small angle α, the cooling laser beam keeps changing its angle from the atomic beam axis at each reflection from the mirrors. Therefore, after n reflections

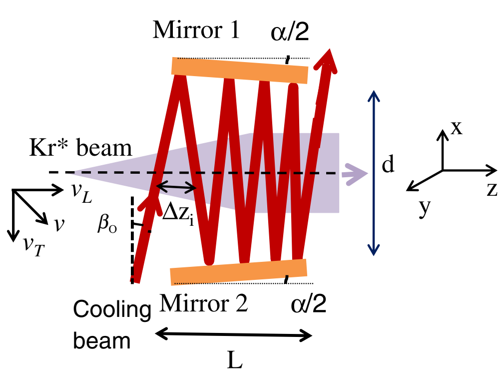

Figure 1. The zig-zag atomic beam collimator for a larger laser incidence angle showing discrete interaction of laser beam with Kr* atomic beam. Here, β_0 is the incident laser beam angle, α is the mirror angle, d is the separation between mirrors of length L and Δz_i is the length of non-interacting region.

of the laser beam from the mirrors in zig-zag geometry, the angle of the laser beam from transverse direction of atomic beam is given by

$$\beta_n = \beta_0 - n\alpha. \tag{1}$$

When β_0 is small and cooling laser beam spot size is large, the non-interacting regions denoted by Δz_i are negligibly small. In this condition, cooling laser beam can be considered as continuously interacting with the atoms. In this case, β can be approximately given as

$$\beta(z) = \sqrt{2\alpha\left(\frac{z_\mathrm{max} - z}{d}\right)}, \tag{2}$$

where z_max is the axial position when $\beta(z) = 0$ and the laser beam would turn in the opposite direction. For $\beta < 0$, the laser beam would heat up atoms and this would decrease the efficiency of the collimator.

Here, we note that if the incident angle β_0 is small, the laser beam will be interacting nearly continuously. For this case the variation in β with z is given by eq. (2). However, with increase in the incidence angle β_0, non-interacting regions where atoms do not interact with the cooling laser beam appear as shown in figure 1. We call this the discrete interaction case. In this case, the length of the non-interaction region (Δz_i) is dependent on the spot size (width) of the cooling laser beam as well as on angles β_0 and α.

In a zig-zag collimator, the Doppler shift in cooling laser beam frequency experienced by an atom, having velocity components (v_L, v_T) as shown in figure 1, is given as

$$\Delta_\mathrm{D} = -\vec{k}\cdot\vec{v} = -kv_\mathrm{L}\sin\beta + kv_\mathrm{T}\cos\beta \approx -kv_\mathrm{L}\beta + kv_\mathrm{T}, \tag{3}$$

where k is the magnitude of the wave-vector for cooling laser beam, and v_L and v_T are longitudinal and transverse velocity components, respectively.

For resonance condition, laser detuning ($\Delta_\mathrm{L} = \omega_\mathrm{L} - \omega_\mathrm{a}$) and Doppler shift ($\Delta_\mathrm{D}$) are related by

$$\Delta_\mathrm{L} + \Delta_\mathrm{D} = 0 \tag{4}$$

which gives $\Delta_\mathrm{eff} + kv_\mathrm{T} = 0$, where effective detuning parameter is given by

$$\Delta_\mathrm{eff} = \Delta_\mathrm{L} - kv_\mathrm{L}\beta. \tag{5}$$

To apply maximum force on an atom during the transverse cooling, the effective detuning should change with angle β such that the relation $\Delta_\mathrm{eff} + kv_\mathrm{T} = 0$ remains valid as v_T changes downstream through the atomic beam collimator. This will keep an atom with given initial v_T in resonance with the cooling laser beam throughout the interaction region and efficient cooling will be achieved. As expected in zig-zag geometry, transverse velocity component of an atomic beam is reduced by laser beam at an angle which changes at each reflection. For a small value of laser incident angle (β_0), though the laser beam can be assumed to be continuously interacting, only atoms with small transverse velocity can be cooled owing to eq. (5). To increase this transverse velocity capture range of the collimator, the incident laser beam angle has to be increased. But due to finite width of the cooling laser beam, increasing β results in increase in the extent of non-interacting regions (Δz_i). Thus, to reduce the non-interacting regions, the transverse cooling laser beam spot size becomes an important parameter.

To evaluate the transverse speed and position of an atom during its propagation in the collimator along z-direction in the above geometry, we numerically solve the following equations for Doppler cooling force on an atom:

$$m v_{\mathrm{L}} \frac{\mathrm{d} v_{\mathrm{T}}}{\mathrm{d} z} = hk \frac{\Gamma}{4\pi} \left[\frac{s}{1 + s + 4\left[(\Delta_{\mathrm{eff}} + k v_{\mathrm{T}})/\Gamma\right]^2} \right], \tag{6a}$$

$$m v_{\mathrm{L}}^2 \frac{\mathrm{d}^2 y}{\mathrm{d} z^2} = hk \frac{\Gamma}{4\pi} \left[\frac{s}{1 + s + 4\left[(\Delta_{\mathrm{eff}} + k v_{\mathrm{T}})/\Gamma\right]^2} \right], \tag{6b}$$

where m is the mass of ^{84}Kr* atom, k is the cooling beam wave-vector magnitude, Γ is the decay rate, $s = I/I_{\mathrm{s}}$ is the saturation intensity parameter, I_{s} is the saturation intensity (for ^{84}Kr* atom, $I_{\mathrm{s}} = 1.36\ \mathrm{mW/cm^2}$) and y is the transverse distance of atom from the beam axis (z-axis). To find transverse velocity and position of an atom at the exit of the collimator (figure 1), eqs (6a) and (6b) are solved for a known initial value of v_{T} and cooling beam parameters (wavelength $\lambda = 811.5$ nm) with natural linewidth $\Gamma/2\pi = 5.56$ MHz, laser beam angle $\beta_0 = 70$ mrad, mirror angle $\alpha = 5$ mrad and longitudinal velocity $v_{\mathrm{L}} \sim 300$ m/s. In these calculations, it is assumed that all atoms start from a single point at the beginning of the collimator (i.e., $z = 0$).

We have solved eqs (6a) and (6b) for two cases. First is the continuous case, where the laser beam is assumed to be interacting continuously with the atoms throughout the collimator. In this case, there is a negligible non-interacting region and the laser beam angle (β) varies with axial distance (z) as given by eq. (2). The second case is the discrete interaction case where the laser beam is assumed to interact over different segments of finite length during the propagation in the collimator. In these simulations, the values of various parameters correspond to those used in our experiments. In real cases, interaction is not continuous due to inherent discreteness in geometry as explained before. So, we have considered interaction in discrete segments whose length is dependent on laser beam width and angle β_0 for accurate analysis of the system. To find the velocity and corresponding trajectory of ^{84}Kr* atoms for this case, we have calculated transverse velocity and position by taking the laser beam angle (β) in discrete manner as given by eq. (1). Here, we have assumed cooling laser beam of uniform intensity and diameter w. For the laser beam of width $w = 7$ mm and initial transverse velocity of 12 m/s at the entrance of the collimator, the final transverse velocity at the exit of the collimator decreased to 10 m/s as shown in figure 2a with the dotted curve. As shown in figure 2a with the dashed curve, for the laser beam of width $w = 25$ mm, the final transverse velocity at the exit of the collimator (axial distance $z = 50$ mm) decreased to 4.9 m/s for an initial transverse velocity of 12 m/s at the entrance of the collimator. The solid line in figure 2a represents the continuous interaction case. If the final transverse velocity of atoms is reduced to ∼4.5 m/s for metastable ^{84}Kr* atoms, the Doppler width becomes approximately equal to natural linewidth, and as a result, one can observe a Doppler-free signal [4]. It is evident from the plot that atoms with transverse velocities $v_{\mathrm{T}} \leq 12$ m/s are transversely cooled over a distance of around 50 mm for a laser beam of width $w = 25$ mm and laser detuning $\Delta_{\mathrm{L}}/2\pi = +10$ MHz.

Figure 2b shows the atom trajectories for continuous (solid curve) as well as discrete cases of two different laser beam widths (for laser beam width $w = 25$ mm (dashed

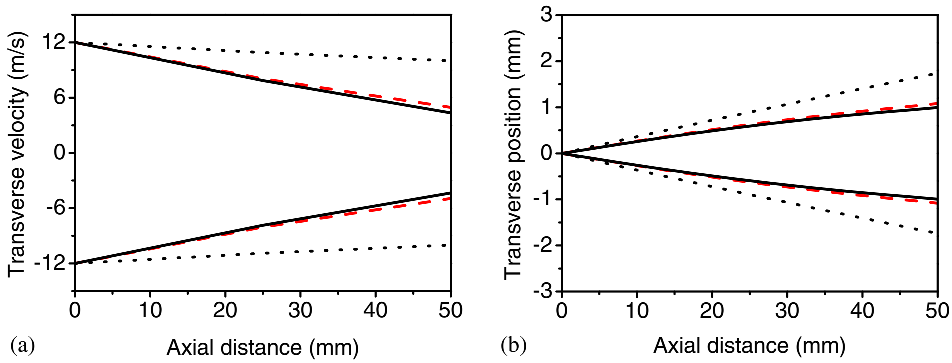

Figure 2. (**a**) Transverse velocity vs. axial distance and (**b**) transverse position vs. axial distance, for laser beam width of $w = 25$ mm (dashed curve) and $w = 7$ mm (dotted curve) ($\Delta_L/2\pi = +10$ MHz, $\beta_0 = 70$ mrad, $\alpha = 5$ mrad, $d = 120$ mm, $v_L = 300$ m/s and $\lambda = 811.5$ nm). The solid line represents the continuous interaction case.

curve) and $w = 7$ mm (dotted curve)) for an initial transverse velocity of ± 12 m/s. When $w = 25$ mm (dashed curve), atoms become collimated more effectively than when $w = 7$ mm (dotted curve). When the laser beam width $w = 25$ mm, the resulting width of the collimated atomic beam is estimated to be ~ 2 mm for initial velocity magnitude $v_T \le 12$ m/s, which is similar to the value obtained from the continuous interaction case. Figure 3 shows the transverse velocity at the exit of the collimator as a function of initial transverse velocity for different values of laser beam width. It is clear from this figure that the atoms having transverse velocity magnitude smaller than 12 m/s can be cooled effectively for the continuous interaction case. But for discrete interaction case, this velocity

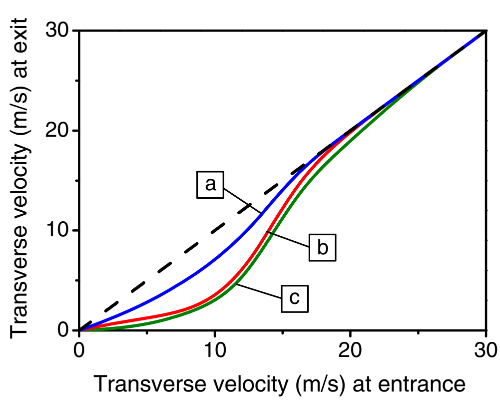

Figure 3. Transverse velocity of metastable Kr atoms at the exit of the collimator as a function of the transverse velocity at the entrance of collimator for (Curve a) laser beam width $w \sim 7$ mm, (Curve b) laser beam width $w \sim 25$ mm and (Curve c) continuous interaction case ($\Delta_L/2\pi = +10$ MHz, $\beta_0 = 70$ mrad, $\alpha = 5$ mrad, $d = 120$ mm, $v_L = 300$ m/s, $\lambda = 811.5$ nm). The straight dashed line represents the absence of transverse cooling.

magnitude range gets reduced to less than 4 m/s for $w = 7$ mm. As we increase the laser beam size from 7 to 25 mm, the transverse capture velocity magnitude increases from <4 to <12 m/s. It is evident from figure 3 that for a laser beam size of 25 mm, transverse capture velocity range is nearly the same as that for the continuous interaction case.

These results of simulation have been experimentally verified. The schematic of the experimental set-up used for our studies is shown in figure 4. This set-up is similar to that described in [21]. The metastable ^{84}Kr* atoms for this work were generated using RF discharge excitation (frequency $\sim$ 30 MHz, power $\sim$ 1.5 W) in a discharge tube (pressure $\sim 10^{-3}$ torr). These metastable Kr atoms propagated to the MOT chamber (pressure $\sim 5 \times 10^{-7}$ torr) at a distance of 180 cm from the Kr gas inlet chamber.

A Zeeman slower (ZS) was connected between the pumping and the MOT chambers to slow down the Kr* beams before cooling and trapping in the MOT chamber. The collimation of Kr* atomic beam was achieved by a one-dimensional zig-zag collimator consisting of a pair of plane mirrors located at 30 cm downstream from the source chamber. The two mirrors each of 50 mm length were separated by a distance of 120 mm and were kept nearly parallel with a small interplanner angle $\alpha = 5$ mrad. The transverse cooling laser beam was made incident at an angle $\beta_0 = 70$ mrad. The cooling laser beam detuning $\Delta_L/2\pi = +10$ MHz was used for effective transverse cooling. For metastable ^{84}Kr* atoms, the transition $4p^5 5s[3/2]_2 \rightarrow 4p^5 5p[5/2]_3$ with a linewidth of $\Gamma/2\pi =$ 5.56 MHz was used for cooling at a wavelength of $\lambda = 811.5$ nm. The cooling laser was locked at 10 MHz blue detuned to the $4p^5 5s[3/2]_2 \rightarrow 4p^5 5p[5/2]_3$ transition. The power in cooling beam was 25 mW. For the experimental conditions mentioned above, we have calculated the expected change in transverse velocity and the position of metastable ^{84}Kr* atoms. To measure the transverse velocity of an atomic beam, a nearly resonant probe beam of 10 mm diameter and 10 mW power was made incident perpendicular to the atomic beam propagation direction. The fluorescence was collected from the atomic beam on a photodiode and the generated signal is shown in figure 5.

The fluorescence signal in the absence of transverse cooling laser beam is shown as Curve a in figure 5. In the presence of cooling laser beam, there is no effective transverse cooling for laser beam width $w = 7$ mm, as shown in Curve b of figure 5. As we increased the cooling laser beam width from 7 to 25 mm, transverse cooling became more effective. As shown in Curve c of figure 5, increase in size resulted in the reduction of the non-interacting gaps. The narrow peak in the signal for $w = 25$ mm in Curve c of figure 5 indicates an effective transverse cooling by the collimator for this laser beam size.

To conclude, we have investigated the effect of cooling laser beam size on the transverse cooling of a metastable ^{84}Kr* atomic beam. The transverse capture velocity was found

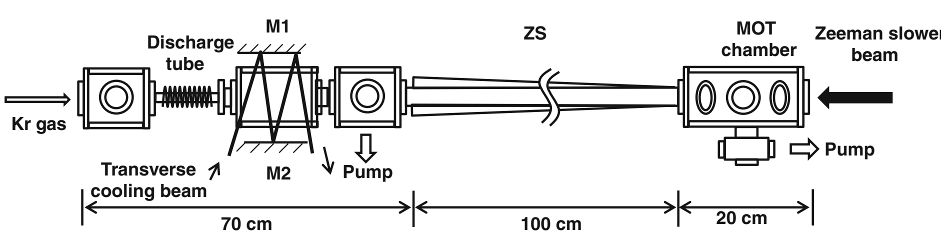

Figure 4. The schematic of the experimental set-up used for cooling Kr* atoms.

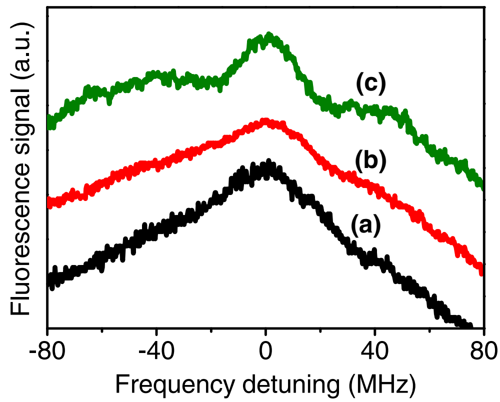

Figure 5. Effect of cooling laser beam width (w) on the transverse cooling of the metastable ^{84}Kr* atomic beam. (Curve a) Transverse cooling beam is absent, (Curve b) $w = 7$ mm and (Curve c) $w = 25$ mm ($\Delta_L/2\pi = +10$ MHz, $\beta_0 = 70$ mrad, $d = 120$ mm, $v_L = 300$ m/s, $\lambda = 811.5$ nm and $\alpha = 5$ mrad).

to increase with the cooling laser beam size. Our results suggest that, it is important to consider the discrete interaction between the cooling laser and atomic beams in the zig-zag method for determining the capture velocity range of the collimator. Apart from increasing the cooling laser beam spot-size to counter the effect of non-interacting gaps, another possible way could be to use multiple cooling laser beams at different incidence angles and frequency detunings. This, however, may result in handling more lasers for the atomic beam collimator.

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