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Formation of a beam of cold atoms by laser frequency tuning

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Abstract. **We report the possibility of producing a beam of slow atoms with a characteristic velocity of ~1 m s^{-1} by the 'chirp' method, namely, cooling by variable-frequency radiation. Method modifications are considered, which substantially reduce dimensions of the slower, the width of the longitudinal velocity distribution of the atomic beam, and the area of its cross section. The modified method of laser radiation frequency tuning for cooling rubidium atoms is mathematically simulated.**

Keywords: *laser cooling, beams of cold atoms, frequency standards.*

1. Introduction

Formation of beams of cold (slow) atoms has become possible due to the development of laser cooling methods [1–3]. Cold atomic beams are applied in various branches of science and technology, in particular, in atomic lithography. However, the main applications are ground- and cosmic-based frequency standards that are the most important part of global positioning systems.

The most promising devices utilising an atomic beam slower as a source of cold atoms are the optical frequency standards (OFS's), laboratory samples of which already demonstrate a unique (at the level of $10^{16}-10^{18}$) stability. Obligatory OFS components are optical resonators with super-high *Q*-factors and schemes for transferring stabilised frequency from the optical to the RF range based on femtosecond lasers. For this reason, OFS's in open space cannot be employed in the near future. In turn, cosmic-based devices impose stringent requirements on volume, mass, and energy consumption of constituent components and, thus, force developers to revert to relatively simple and compact, as compared to OFS's, solutions. First of all, these are RF frequency standards (RFS's) on the atomic beams cooled by laser radiation [4–7].

In a ground-based RFS it is possible to use gravity for further slowing and making zero the atomic beam velocity (frequency standards of 'fountain' type), whereas a cosmic-based RFS should employ atomic beams characterising a sufficiently low velocity and high density at the output from a slower. This is why the modified variants of standard laser cooling methods were suggested in [8–10], which provide a substantially lower velocity of the thermal beam and simultaneously reduce the volume and energy consumption of the slower. The radio-optical resonance in such a system should be detected by the Ramsey method of coherent population trapping [6].

In the present work, we theoretically consider a possibility of obtaining a beam of slow atoms with a longitudinal velocity of 1 m s^{-1} by linearly modulating the frequency of decelerating laser radiation. It is significant that the formation of such a beam by optical radiation is a challenging problem due to limitations pertaining to known schemes for atomic beam slowing. In the process of slowing, the Doppler shift varies in the atomic coordinate system; this variation should be compensated for along the entire path of the atomic beam; otherwise, atoms do not interact optimally with the cooling radiation. There are two methods for this compensation: the method of varying the frequency of cooling radiation (laser frequency chirp [1–3]) and method of varying the frequency of the atomic transition in a spatially inhomogeneous magnetic field (Zeeman cooling) [2, 3]. The chirp method can be only applied to pulsed beams, which implies a beam breaking system, whereas Zeeman cooling allows one to obtain a continuous beam of cold atoms. However, in practice neither of the schemes in their classical variants can slow atoms to velocities below 10–20 m s^{-1} with a required beam density because compression of the initial velocity distribution to a narrow peak takes considerable time, which results in an excess expansion of the atomic beam and the corresponding loss of its density.

Though our modifications are applicable to both methods, in the present work we will limit ourselves to modelling the chirp method, i.e., tuning of the optical radiation frequency. To prevent atoms from changing the velocity sing to opposite, we, in addition to cooling by a laser beam, employ an additional laser beam (so-called blanking field) with a frequency positively shifted from the atomic transition frequency, which propagates in the direction of the atomic beam. This approach as was first suggested in [7]. In addition, to make the duration of the atom interaction with laser radiation field shorter, we suggest taking the initial velocity of deceleration (cut-off velocity) lower than the average atomic thermal velocity in the beam. This will help make the duration of deceleration shorter and, finally, reduce dimensions and energy consumption of the slower. Obviously, a lower cut-off velocity will result in a loss of a certain number of cold atoms. However, from the practical point of view, the loss will be abundantly compensated for by a shorter duration of decel-

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eration, because the latter affects not only a linear dimension of the deceleration zone, but also the transverse cross section of the atomic beam at the output from the cooling zone. A reduction of the signal-to-noise ratio due to a smaller total number of cold atoms in the detection zone in the case of using the Ramsey method of coherent population trapping can be additionally compensated for by reducing the width of the longitudinal velocity distribution in the atomic beam. We have shown that a narrow (fractions of cm s^{-1}) width of the final velocity distribution can be realised if the intensity of decelerating radiation linearly falls as the atomic beam is cooled.

2. Laser cooling of the atomic beam

Consider the process of longitudinal deceleration of the atomic beam by a light wave [1–3, 11–13]. We assume that the atomic beam propagates in the positive Z direction, and the optical radiation passes in the negative direction. Then for obtaining a final velocity distribution one has to solve the spatially-homogeneous Liouville equation

$$\frac{\partial}{\partial\tau}w = \frac{\partial}{\partial\tilde{v}_z}(f_z w), \qquad (1)$$

where $\tau = (\hbar k^2/m_{\rm Rb})t = \omega_{\rm r}t$ and $\tilde{v}_z = k\tilde{v}_z/\gamma$ are the dimensionless variables of time and velocity;

$$f_z = F_z/(\hbar k\gamma) = \frac{G}{1 + G + (\Omega + kv_z + \alpha t)^2/\gamma^2} \qquad (2)$$

is the dimensionless light pressure force; $w \equiv w(v_z, t)$ is the one-dimensional distribution function of atoms over velocities; $G = 2g^2/\gamma^2$ is the saturation parameter (g is the Rabi frequency); $\Omega = \omega - \omega_0$ is the detuning of the laser radiation with a frequency $\omega = kc$ from the atomic transition frequency ω_0; and α is the rate of laser frequency tuning in the chirp regime. Model parameters of a two-level atom were chosen similar to those of the D_1 line of the rubidium (Rb) atom interacting with laser radiation at a wavelength of 780 nm. These are $2\gamma = 37.7$ MHz – the total radiation width of the upper atomic state and $\omega_{\rm r} = \hbar k^2/m_{\rm Rb} = 4.7 \times 10^4$ Hz – the recoil frequency. We assume that the initial thermal distribution of atoms in a beam is

$$w(\tilde{v}_z, \tau = 0) = (\tilde{v}_z^3/\langle\tilde{v}_z\rangle^4)\exp[-(\tilde{v}_z/\langle\tilde{v}_z\rangle)^2], \qquad (3)$$

where $\langle\tilde{v}_z\rangle$ is the average dimensionless velocity.

We employed the following procedure for deriving the final velocity distribution: at a first step, the entire velocity interval of the initial distribution is divided to a finite number of small intervals $[(\Delta\tilde{v}_z(t = 0))]$ and in each interval the part of atoms $N_i(t = 0) = \Delta\tilde{v}_{z,i}w(v_{z,i})$, $\tilde{v}_{z,i} \in \Delta\tilde{v}_{z,i}$ is calculated according to (3). At the next step, motion equations for a two-level atom with a characteristic light pressure force (2) are solved with the initial conditions corresponding to the boundary velocities for each of the velocity intervals. Then for instant t new velocity values are calculated $(\Delta\tilde{v}_z(t))_i$ because according to the Liouville theorem (conservation of the number of particles in a phase space volume) the number of atoms in the velocity intervals should not vary. In this case, new values of the density of atoms in each velocity interval can be obtained:

$$N_i(t) = N_i(t = 0)\frac{(\Delta\tilde{v}_z(t = 0))_i}{(\Delta\tilde{v}_z(t))_i}.$$

In this way, graphs of the velocity distribution evolution for rubidium atoms ^{87}Rb were plotted for longitudinal cooling by the oncoming laser field that employed the D_1 line for decelerating atoms.

Figure 1 shows the evolution of the velocity distribution of a thermal beam of rubidium atoms ^{87}Rb with the average velocity $\langle v_z\rangle = 400$ m s^{-1} (the temperature of the atomic source is 568 K) in the case of a constant laser radiation frequency ($\alpha = 0$). The frequency detuning corresponded to the optical radiation resonance for the atoms having an average beam velocity and was chosen from the condition

$$\Omega + k\langle v_z\rangle = \frac{\Omega}{\gamma} + \frac{k}{\gamma}\langle v_z\rangle = \Delta + \langle\tilde{v}_z\rangle = 0.$$

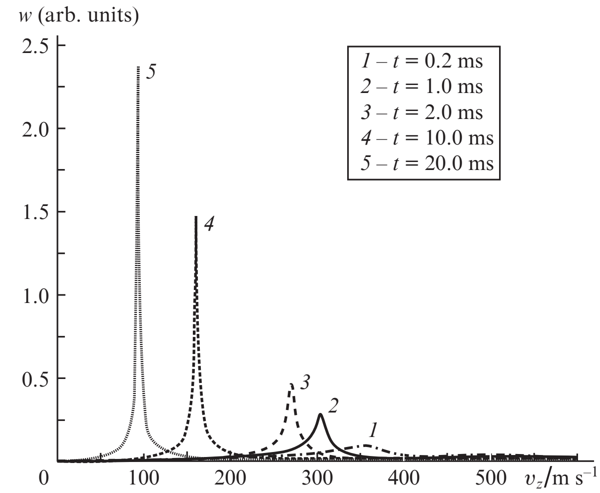

Figure 1. Stationary slowing of the rubidium atomic beam in the field of a counterpropagating light wave at various durations of slowing. The laser radiation is matched in resonance with atoms having the longitudinal velocity equal to the average velocity of the thermal beam (400 m s^{-1}); the saturation parameter is $G = 100$.

As one can see in Fig. 1, initially a mono-velocity peak arises rapidly (in ~1 μs). The peak shifts to zero atomic velocities at a reducing rate as the action of force (2) falls [12, 13]. In the result, in a time interval of deceleration $t = 20$ ms the velocity peak of cold atoms shifts to only ~100 m s^{-1}; the interaction domain reaches the length of several meters. Hence, radiation of constant frequency cannot principally be used for slowing an atomic beam in on-board frequency standards. In order to reduce the length of interaction between the atom and the laser field, the frequency should be tuned in such a way that the resonance condition between atoms and the optical radiation holds true as atoms are decelerated [1–3].

Correspondingly, we have modelled deceleration of a rubidium atomic beam by laser radiation with the frequency varying as $\omega + \alpha t$. Then the resonance condition depends on time as follows:

$$\frac{\Omega + kv_z + \alpha t}{\gamma} = \frac{\Omega}{\gamma} + \frac{k}{\gamma}v_z + \frac{\alpha}{\gamma\omega_{\rm r}}\omega_{\rm r}t = \Delta + \tilde{v}_z + \tilde{\alpha}\tau = 0,$$

where $\tilde{\alpha} = \alpha/(\gamma\omega_{\rm r})$, and at $t = 0$ the initial detuning is taken equal to the cut-off velocity $\tilde{v}_0$ and $\tilde{\alpha} = 1$. In the considered case, the cut-off velocity v_0 equals the initial average thermal velocity: $v_0 = \langle v_z \rangle = 400$ m s^{-1}.

In the case of employing a single light field adjusted in resonance with the initial average velocity, a narrow mono-velocity peak of atoms rapidly arises and shifts in the direction of zero velocities (Fig. 2). The employment of the chirp regime can provide in the deceleration time of $t \sim 1$ ms a fast shift of the intense monochromatic peak of atoms to the velocity range of ~100 m s^{-1}; in this time interval atoms cover a distance of at most 25 cm. However, an increase in the interaction duration to 1.8 ms sharply reduces the number of cooled atoms (see Fig. 2): cold atoms interacting with the oncoming light field change the direction of the velocity vector to the opposite one and start acceleration, that is, atoms are blown out backward to the source of the atomic beam by laser radiation.

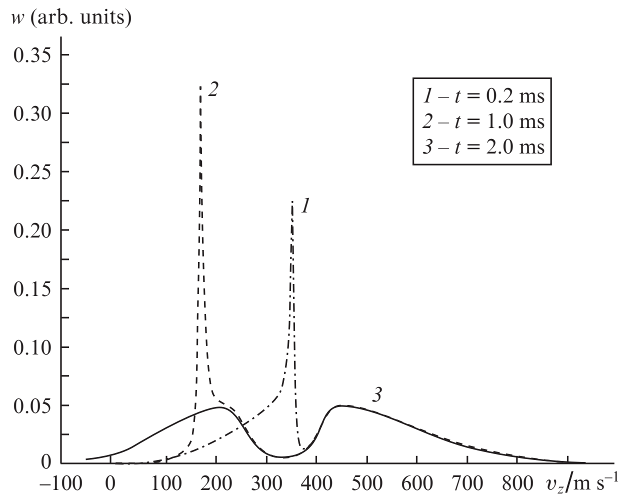

Figure 2. Evolution of the velocity distribution of a thermal beam of rubidium atoms with $\langle v \rangle = 400$ m s^{-1} in the case of a linear frequency variation of laser radiation $\alpha = \gamma\omega_r$. Initially, a mono-velocity peak of atoms is rapidly formed [(*1*); $t = 0.2$ ms], then the peak shifts to zero velocities [(*2*); $t = 1.0$ ms] and its intensity sharply falls [(*3*); $t = 2$ ms] due to a change in the atomic motion direction.

To prevent this effect, we, in addition to the slowing laser beam, introduce laser radiation (blanking field) that propagates in the direction of the atomic beam and has a positive frequency mismatch relative to the atomic transition frequency [7]. By varying the value of blanking field detuning one can provide an action of this positive force on atoms having a small negative velocity. Thus, atoms will slow down but would not change the direction of the velocity vector to the opposite one. We have tried various laws of changing the frequency detuning for the cooling field, and the best results have been obtained with the linear frequency variation at $\tilde{\alpha} = 1$.

Figure 3 presents the evolution of the velocity distribution for the initial thermal beam of rubidium atoms in the case of the blanking field. Note that the employment of the blanking field not only substantially increases the peak of cold atoms, but also controls its position. This opens a possibility of forming in a time interval of 2 ms an intensive velocity distribution peak with an average velocity of less than 1 m s^{-1}. In this case, the length of the slower is still substantial; in our case, it is 34 cm.

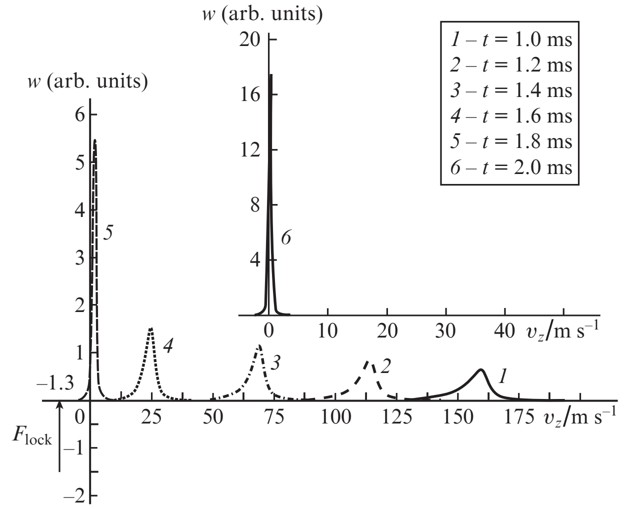

Figure 3. Evolution of the velocity distribution of rubidium atoms in the case of chirped radiation at the same parameters as in Fig. 2 with the additional blanking field $E_{\rm lock}$ having a saturation parameter $g = 3$ matched in resonance with the atoms having a longitudinal velocity of -1.3 m s^{-1}. Final atomic distribution in the inset was obtained by the chirp method at the duration of slowing $t = 2$ ms (*6*).

The transverse divergence is defined as the ratio of a transverse velocity to a characteristic thermal velocity of the atomic beam. At the initial beam divergence of ~10^{-2}, the transverse beam dimension after cooling will be ~2 cm, if a point source of atoms is considered. To avoid reduction of cold atomic beam density one should either employ additional transverse cooling or make the interaction time shorter.

3. Decrease in the interaction time

As mentioned above, in atomic beam cooling, it is possible to cool atoms with arbitrary velocity distributions, in which case the cut-off velocity should be taken above the average thermal beam velocity. In this case, an intensive beam of cold atoms will be obtained, but a considerable time of interaction will increase the slower dimensions and the transverse beam divergence. Also, one can use for cooling the atoms that have initial velocities below the average thermal velocity. In the latter case, the beam intensity reduces, which can be partially compensated for by a small transverse divergence of the beam; therefore, dimensions of the slower domain are smaller. If v_0 is the cut-off velocity, then a distance to the atom full stop is $z_0 = v_0^2/2a$, where a is the deceleration of the atomic beam regardless of the adjustment method (chirp or Zeeman cooling). The length of the deceleration domain is proportional to the square of the initial velocity; hence, if the initial velocity falls twice (from 400 to 200 m s^{-1}), then the distance L covered by atoms to stop will be four times shorter and equal to ~8 cm. In this case, the number of atoms at the slower output will fall by approximately 20 times; nevertheless, other factors being the same, the area of the beam transverse cross section will reduce by 4 times.

Final distributions $w(v_z)$ are presented in Fig. 4 for the initial atomic velocities of 500, 400, 300 and 200 m s^{-1}. The interaction time corresponds to the deceleration duration for atoms with the initial velocity of 200 m s^{-1}. Thus, in a time interval of ~0.8 ms at the initial velocity of 200 m s^{-1} in the

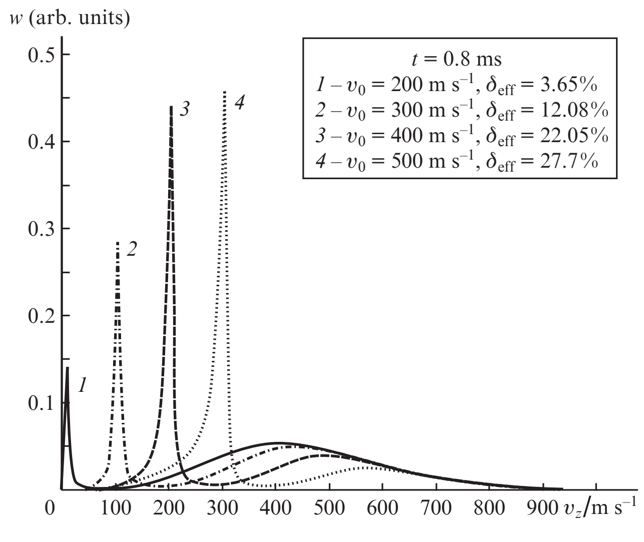

Figure 4. Position of the final atomic distribution at various cut-off velocities v_0 for $t = 0.8$ ms in the case of chirped radiation and the blanking field having the parameters similar to those in Figs 2 and 3; δ_{eff} is the effective number of slowed atoms.

case of frequency chirp and at the slower length of ~8 cm it is possible to form an intensive peak of cold atoms with velocities below 1 m s^{-1}.

4. Reducing the width of the final velocity distribution

A substantial problem that hinders obtaining the required stability is a finite width of the velocity distribution for cold atoms, because it affects the signal-to-noise ratio in the case of optical detection by the Ramsey method of coherent population trapping. Figure 5 shows the formation of a narrow atomic beam at constant (Fig. 5a) and reducing intensities by the law $G = 100 - 0.2\omega_r t$ (Fig. 5b). Blanking field parameters are similar to those in Fig. 3. From comparison of Figs 5a and 5b it follows that at the same duration of deceleration the final width of the atomic velocity distribution in the second case (Fig. 5b) is narrower, and the peak intensity is higher. Also, the velocity corresponding to the peak intensity of cold atoms in the case of a constant laser radiation intensity is lower than in the case of a variable intensity. This is explained by a reduction of the average energy spent on cooling. By varying the saturation parameter in time one can substantially reduce the width of the beam velocity distribution and increase the beam density by making the deceleration duration slightly shorter (cf. Figs 5a and 5b).

Note that in the calculations we did not take into account the width of the laser emission line. This is reasonable, because the Rabi frequencies are large and only at the end of the slowing process they become comparable to unity.

Dependences of the FWHM of the cold atom final distribution on the saturation parameter in the range of zero velocities are shown in Fig. 6 for the cut-off velocities of 400 and 200 m s^{-1} and for the interaction duration of 2 ms. The blanking field parameters are similar to those in Fig. 3. One can see that there is an optimal value of the saturation parameter, at which the width of the final distribution is minimal. At greater saturation, the width increases due to field broadening of the transition line; at smaller saturation it occurs due to a small coefficient of dynamic friction in a wing of the light pressure force profile. In this case, even at a cut-off velocity of 400 m s^{-1} the width of the final distribution is 50 cm s^{-1} in a sufficiently wide range of saturation parameter variation. At the cut-off velocity of 200 m s^{-1}, the minimal width is ~10 cm s^{-1}, which is only possible in the dynamic cooling regime. In other words,

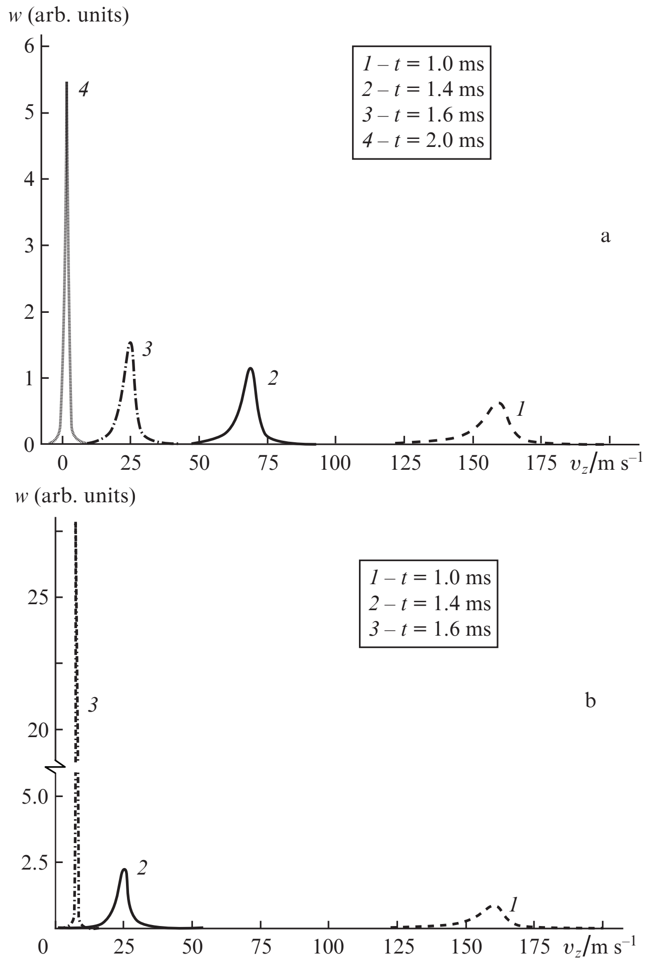

Figure 5. Evolution of the velocity distribution of rubidium atoms in the case of chirped radiation and the blanking field with the parameters similar to those in Figs 2 and 3 at $t = 0.8$ ms and $v_0 = 400$ m s^{-1} (a); the same at the saturation parameter of the cooling field linearly falling in time, $G = 100 - 0.2\,\omega_r t$ (b).

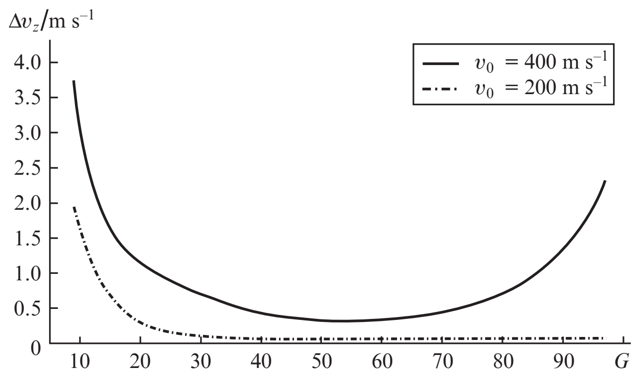

Figure 6. FWHM of the final velocity distribution for cold atoms vs. the saturation parameter G of the cooling field at $t = 2$ ms and various cut-off velocities. The rest parameters are similar to those in Figs 2 and 3.

the employment of the dynamic cooling regime allows one to noticeably reduce the influence of pulsed diffusion. It also provides sufficiently narrow widths of the atomic beam velocity distribution at the end of the slowing process. In this case, the operation regime of such a source of cold atoms is principally pulsed.

In Fig. 7 one can see dependences of the number of atoms (Fig. 7a), the duration of deceleration down to the velocity of 1 m s^{-1} (Fig. 7b) and the length of slowing (Fig. 7c) on the cut-off velocity. Comparison of curves in Fig. 4 demonstrates the advantage of reducing the cut-off velocity down to 200 m s^{-1}. For example, the duration of slowing reduces to 1 ms, the length falls to 8 cm, which makes real the possibility of employing such a scheme for forming cold atomic beams in cosmic-based frequency standards. In this case, the number of interrogated atoms $\delta_{\rm eff}$ is about 4% of the total beam intensity. The latter circumstance is not an obstacle in employment of this slowing scheme because its drawbacks are mainly compensated for by a smaller beam transverse divergence.

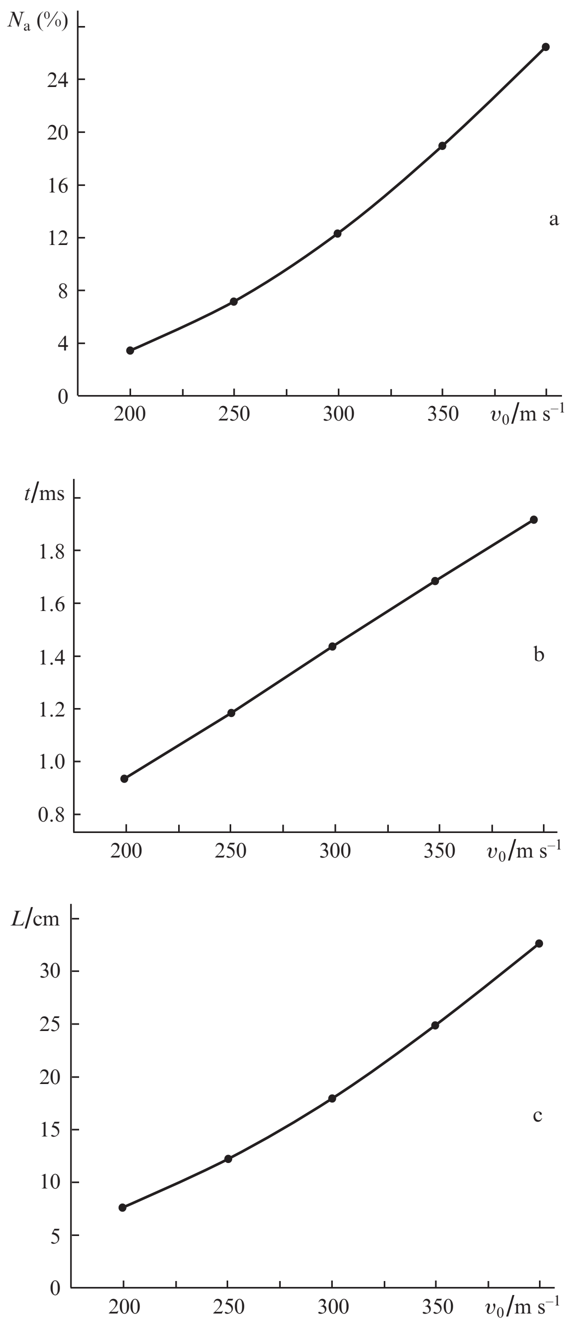

Figure 7. Dependences on the cut-off velocity in the case of the chirped radiation and blanking field with the parameters similar to those in Figs 2 and 3: the number of atoms in the final distribution in percent from the total number of atoms in a beam (a); duration of interaction upon reaching the final velocity of 1 m s^{-1} for the peak of the cold atom distribution (b); the length of the slowing zone (c).

5. Conclusions

Thus, from our calculations follows that, first, for efficient cooling it is reasonable to use laser radiation with a frequency linearly varying in time. Second, for obtaining an intensive peak of cold atoms not only a cooling laser beam directed towards the atomic beam is needed, but also an additional beam directed similarly to the atomic beam, which provides the effect of the blanking field. Third, for reducing dimensions of the slower, the initial velocity of decelerated atoms (the cut-off velocity) should be reduced down to at least 200 m s^{-1}. Finally, for reducing the width of the final atomic distribution one should use the laser radiation intensity linearly varying in time. Such configurations will give a possibility to obtain the number of cold atoms sufficient for detection. The latter is an important argument in favour of the methods suggested for cooling atomic beams in frequency standards.

The scheme considered above, in addition to obvious advantages, has also some technological drawbacks: impossibility of operation in an instantaneous regime, and hence, a need for a unit to overlap the atomic beam; a complicated scheme for introducing the blanking laser beam along the atomic beam axis; a risk of atom deposition on the window through which a slowing laser beam is introduced. Nevertheless, there exist solutions for all these technological problems and employment of the scheme suggested for atomic beam slowing seems promising for realising small-dimension frequency standards on atomic beams.

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