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# Efficient 2D molasses cooling of a cesium beam using a blue detuned top-hat beam

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We have performed a 2D blue detuned Sisyphus collimation of a cesium beam. Compared to a red detuned Doppler transverse molasses cooling, the setup were found very advantageous because of its faster cooling time allowing a short (1 cm) cooling length and thus finally a denser atomic beam. A fibered laser was developed delivering up to 500 mW fiber coupled optical power. A 2D collimation was realized but this can be done only if the two cooling zone were not overlapping. A beam density enhancement of more than 10 was observed. We found that a simple top-hat beam was more efficient than a gaussian one. Similar cooling applies to other atom species and leads to a simple method to produce bright collimated atomic beams.

## I. INTRODUCTION

Among the techniques applied to collimate an atomic beam, transverse cooling exerted by optical molasses is widely used [1, 2]. These 2D molasses produce high-flux atomic beams [3, 4] that can be used for atom interferometry experiments [5], rapid loading of magneto-optical traps after a Zeeman-slower setup [3, 6] or to form electron or ion beams [7–9]. We stress that we do not discuss here the possible effect of a magnetic field which can compress an atomic beam [10–12], in a two-dimensional magneto-optical trap (2D MOT) for instance. We choose to address the cooling of an atomic beam, and more specifically, provided by an oven. Obviously the method presented in this article applied to a cooled atomic beam produced by a 2D-MOT as previously demonstrated in our group [13]. Nevertheless the drawback of this latter atomic source is that it creates a lower flux (and lower beam velocity), of  $< 10^{12}$  at/s/cm<sup>2</sup> [13, 14] compared to the  $10^{14} - 10^{16}$  at/s/cm<sup>2</sup> of an effusive oven [15, 16].

The standard cooling configuration uses a radiation frequency tuned near, but below, an atomic transition frequency. At sufficiently low intensity, the force on the atom is the sum of the forces from each individual traveling wave component of the standing wave and the atom will experience a net cooling force: the so-called Doppler force. However, at high intensity, the force is fundamentally altered. Stimulated processes involving both traveling waves become important and the force saturates.

By contrast, when the laser is blue detuned, another type of cooling known as “stimulated molasses cooling” does not saturate at high intensity [17, 18]. A stimulated redistribution of photons leads to a Sisyphus type of

cooling created by successive climbing of energy potential curves created by the dipolar potential in the dissipative lattice [19, 20]. We thus note that it is quite different from the Sisyphus cooling where the potentials are created by polarization interferences [21]. The pioneer work of this blue detuned Sisyphus cooling was performed on 1D and on a cesium beam [17]. It has then be used with other atoms such as, Li [22, 23], Ne [24], Na [25, 26], Ar [27].

We can wonder why the red detuned cooling scheme is still, by far, the most used in laboratories to create collimated atomic beams (to give only two examples see References [28, 29]), compared to the blue detuned one that does not saturate and therefore is able to catch and cool more atoms and thus form brighter atomic beam. We think that the reason is quite well summarized in [30] : “The Doppler-cooling schemes need only low laser intensity (of the order of the saturation intensity of the cooling transition) and have a wide velocity capture range, but require a rather long interaction region. The stimulated-cooling schemes require a short interaction distance, but need high laser intensity in order to have a relatively wide capture range”. Indeed, it was shown that with only 8 mW/cm<sup>2</sup> for Rb the red detuned cooling was more efficient than the blue detuned molasses [31]. For Cs, efficient blue detuned molasses has required build-up cavities to produce 0.18 W (20 W/cm<sup>2</sup>) in Ref. [32] or 3 W/cm<sup>2</sup> in Ref. [33]. Similarly, in the Ar case [27], a Ti:Sa laser with a beam diameter of 2.5 mm (defined by the  $1/e^2$  intensity level) produces a maximum electric field of the standing wave equivalent to a Rabi frequency of  $200\Gamma$  where  $\Gamma$  is the natural linewidth of the transition. A detuning near  $50\Gamma$  leads to a flux enhancement 6 times higher for blue detuning than for red detuning. We think that this justification to use red detuning instead of blue detuning is nowadays obsolete because the current laser sources can provide intensities which are much greater than the saturation intensities of

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many atomic transitions.

Another reason why blue detuned molasses has not been widely used might be due to the fact that, to our knowledge, only 1D, but no 2D, transverse blue detuned cooling, has ever been reported. We have briefly mentioned in Ref. [34] our success in having performed a two-dimensional (2D) blue molasses and we would like here to give more details. The progress made compared to previous work on Cs [17, 32, 33] include the use of a more intense laser, a top-hat beam. Moreover we perform the first the 2D (in fact 2 times 1D) cooling. This article follows our almost decennial work to optimize the 2D transverse cooling of a cesium beam with the goal to ionize it to produce an intense (focused) ion beam [7, 13, 34–36]. We believe that this kind of testimony can be interesting for the laser cooling community. The article is therefore organized as follows. We first present the evolution of the experimental setup to a more and more efficient system, going from a red molasses using an amplified diode laser to the blue molasses using a Ti:Sa laser in a first step and an high power fibered laser [34] in a second step. We then discuss the experimental results. Finally we conclude that this blue detuned cooling is indeed very easy to implement and can be used for many atom or molecule species.

## II. EXPERIMENTAL SETUP

Our first attempt to collimate our effusive Cs atomic beam is summarized in the top panel of Fig. 1. A  $12\text{ cm} \times 1\text{ cm}$  elliptical red detuned gaussian beam was used to transversely cool the output of a candlestick recirculating oven [37]. The oven was heated typically to 425 K producing a Cs beam with an average longitudinal velocity around 250 m/s and a beam divergence of  $\sim 1/20$  rad corresponding to a radial velocity  $\sim 10$  m/s.

Using a simple DFB diode laser and a BoosTA (from Toptica) tapered amplifier we reach a maximum useful power of 1 W corresponding to an intensity of  $I = 2\text{ mW/cm}^2$  for each beam, leading to a saturation parameter (at resonance)  $s_0 \approx 2$  for the  $\sigma^+ - \sigma^-$  cooling configuration (saturation intensity  $I_{\text{sat}} = 1.1\text{ mW/cm}^2$ ). A 50 mW repumping laser tuned to Cs  $6s, F = 3 \rightarrow 6p_{3/2}, F = 4$ , was added to one arm with the same shape to cover all the collimation area. The Cesium atomic beam profile was measured by absorption measurement and by scanning spatially a probe laser beam located 26 cm downstream.

Even if the cooling was efficient the final atomic beam was large (see Fig. 1 b). The relative weakness of the red detuned cooling force implies a long interaction time and the optimal beam diameter is larger than several cm (our configuration includes 12.5 cm-long optics, including cylindrical lenses and gold mirrors for the retro-reflection). This is one of the main drawback of this method based on the friction force producing a cooling with a characteristic time of  $1/kv_r \approx 40\text{ }\mu\text{s}$  dur-

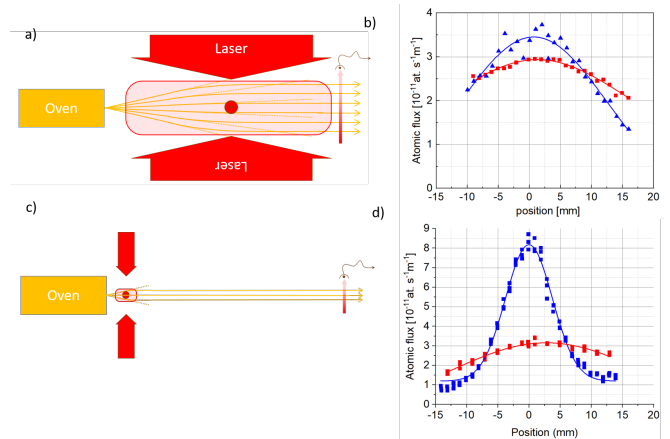


FIG. 1. Red (top) and blue (bottom) detuned molasses cooling. Schematic of the Cs oven, the collimation (on scale) and the absorption region: a) for the red molasses and c) for the blue one. Absorption beam profile with (blue curve) and without (red curve) the cooling laser: b) for the red molasses and d) for the blue one.

ing which the Cs beam travels along a distance  $\approx 1\text{ cm}$  and its diameter expands by an amount of  $\approx 0.5\text{ mm}$ .  $v_r = \hbar k/m = 0.35\text{ cm/s}$  is the recoil velocity, where  $k = 2\pi/852\text{ nm}$  the wave-vector of the cooling beams and  $m$  is the Cs mass [38]. The radiation force saturates at  $\hbar k\Gamma/2$ , when, on the contrary, the maximum force in a blue detuned Sisyphus cooling is on the order of  $\hbar k\Omega/20$ , and does not saturate ( $\Omega$  is the Rabi frequency).

Now, we present our method based on the blue Sisyphus cooling. Because the blue detuned force is higher for velocities on the order of  $\Gamma/3k \approx 1.5\text{ m/s}$  [18, 39] we decided to modify our Cs beam using a collimating tube with an aspect ratio of 50 (length over diameter) at the output of the Cs beam oven producing a maximal transverse velocity on the order of 1.5 m/s. The Sisyphus cooling stage was located as closed as possible to the output of the Cs beam oven. We first observed that, if a 1D blue detuned Sisyphus molasses was efficient, a 2D molasses did not work at all, and this for any attempt – modifications of lasers power and or polarization – we made. We think there is destructive cooling interference effect between the 2 lattices. It is worth mentioning that we did not try using different frequencies for the two different beam pairs that could suppress cross-dimensional stimulated scattering and may possibly restore the 2D cooling. Therefore, to perform 2D cooling, we switched to two subsequent non-overlapping 1D cooling steps and the result given in Fig. 1 d) indicates that the blue molasses cooling was more efficient than the red detuned one.

Our next tests were performed using a 1 W Ti:Sa laser (obviously a repumping beam is always added). At this time the Cs beam was transversally cooled then excited, ionized and coupled to a Focused Ion Beam column. It was thus impossible to repeat the probe laser scanning, neither the Doppler profiles of the atomic beam by scan-

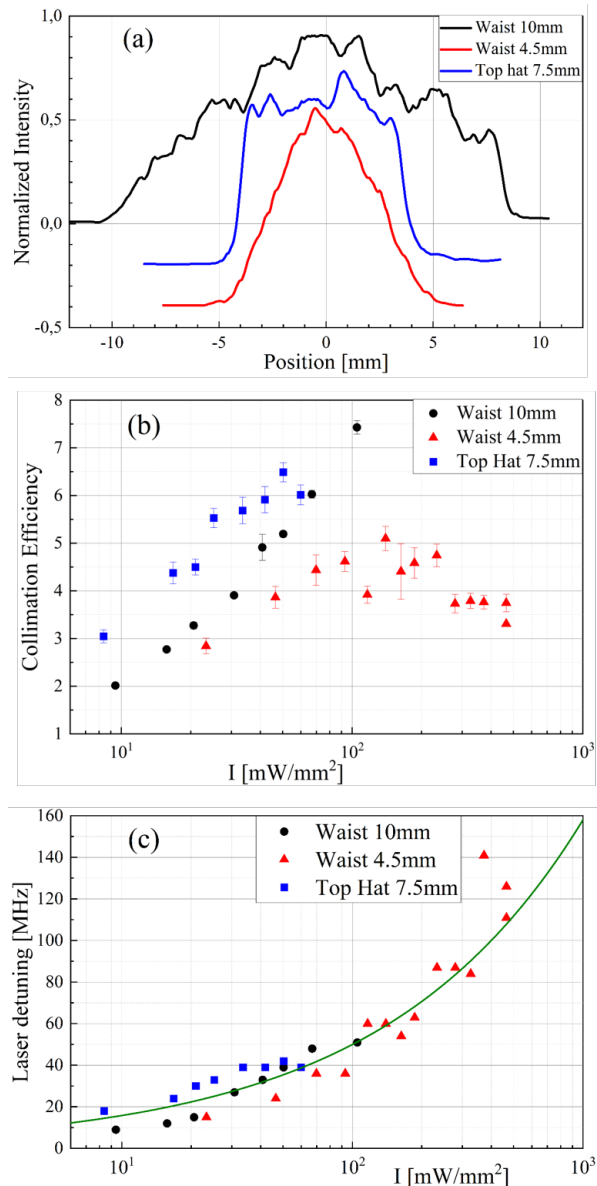


FIG. 2. Blue detuned cooling. (a): laser radial profiles in each configuration of the beam (a vertical offset is added for clarity). Cooling efficiency (b) and optimized detuning (c) for different laser intensities for each cooling arms and for the 3 laser profiles. In green: the curve  $\delta(\text{MHz}) = 5\sqrt{I/\text{mW cm}^{-2}}$

ning the probe frequency. We used the  $\text{Cs}^+$  ion current as a direct measurement of the collimation (or cooling) efficiency. We define the collimation efficiency as the ratio of the ion current with and without cooling. The ionization is produced, some tens of centimeter after the cooling section, at the intersection between two focused laser beams (spot slightly smaller than  $100\text{ }\mu\text{m}$ ) [35]. The collimation efficiency is thus directly proportional to the central Cs density. The collimation efficiency can also be seen as the geometrical ratio between the initial beam solid angle divergence and the final one. It is therefore a quite good diagnostic very similar to a Langmuir-Taylor, surface ion-

ization, hot wire detector, revealing what many experiments desire: a collimated beam with a large atomic density at the center. The distance between the source and the detector (laser of ionization) was comparable for all the experiments considered here (between 20 cm and 30 cm). We keep the same distance between the cooling region and the location where the atoms are used to make a fair comparison. Yet we notice that a larger distance will benefit more from our better cooling scheme.

The ratio between the blue detuned Sisyphus force and the red detuned scattering one is typically given by the square-root of the saturation parameter  $s_0 = \frac{I}{I_{\text{sat}}} = \frac{2\Omega^2}{\Gamma^2}$ . For our intensities on the order of  $\sim 100\text{ mW/cm}^2$ , we can thus expect a gain by a factor  $\sim 10$  in the cooling time, and a factor  $\sim 10$  in the interaction length as well. This is illustrated in Fig. 1 c). We therefore performed experiments with a beam size (twice the waist) of 9 mm and 20 mm. Results are given in Fig. 2 (black and red curves). As expected, the 4.5 mm waist is barely sufficient to cool the Cs beam with a saturation occurring around  $\sim 100\text{ mW/cm}^2$ . The efficiency then decreases for larger intensities. We believe this is due to a too hot final temperature leading to a slightly diverging beam. Indeed, when the waist is not big enough, increasing the intensity, and so the force, is not necessarily beneficial because the final temperature is typically given by the dipolar potential depth of the lattice  $k_B T \sim \hbar\Omega$  (to be compared to  $k_B T \sim \hbar\Gamma$  in standard Doppler cooling, leading again to the ratio  $\Omega/\Gamma$ ). The final temperature is thus  $\sim 3\text{ mK}$  and so the final velocity is still quite high ( $\sim 0.4\text{ m/s}$ ). The fact that the central Cs density of the beam is inversely proportional to the radial velocities squared leads to a simple explanation of the value (around 5 – 10) of the collimation efficiency. Results are thus better with a slightly bigger waist of 10 mm with an efficiency approaching 8. With this larger waist, we do not observe any saturation in the collimation efficiency because the intensity stays smaller than  $\sim 100\text{ mW/cm}^2$ . The optimized detuning  $\delta$  (see Fig. 2 c)) follows the evolution  $\delta \approx 1.4\Omega \approx 2\pi \times (\sqrt{\frac{I}{I_{\text{sat}}}} 5\text{ MHz})$ . At each  $\Omega$ , the optimal detuning is more than ten times the detuning where the force is maximum (the maximum force occurs for a detuning of  $\approx \Omega/10$  [18, 39]). This result may be due to the fact that our cooling is not as simple as idealized by a 1D cooling of a 2 level Cs atom. This may also be due to the fact that the collimating tube still produce (by Cs remission inside the tube [40]) transverse velocity bigger than  $1.5\text{ m/s}$  and illustrates that the force is efficient up to quite high velocities  $v$  because of the slow decay of the cooling force in  $1/v$  after this maximum force [39]. Finally, by simply cutting along the Cs beam propagation axis the tail of the Gaussian spatial spectrum, we found that, for the same intensity, a gaussian clipped-flat-top beam (of 7.5 mm size) was more efficient than the Gaussian beam (see Fig. 2 blue curves). This is again a clear indication that we do not saturate and that cooling acts along the whole Cs trajectory leading to a

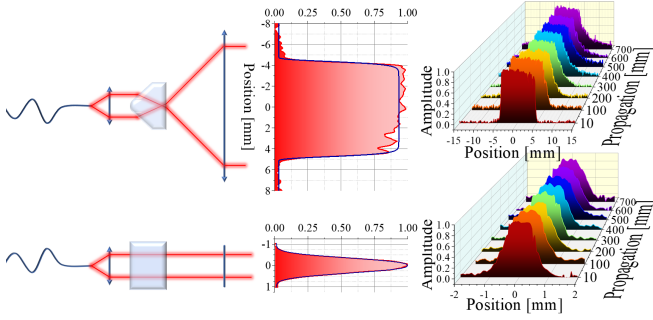


FIG. 3. Laser beam propagation produced by the Powell lens. Top panel: Top-hat laser propagation. Lower panel: gaussian laser propagation.

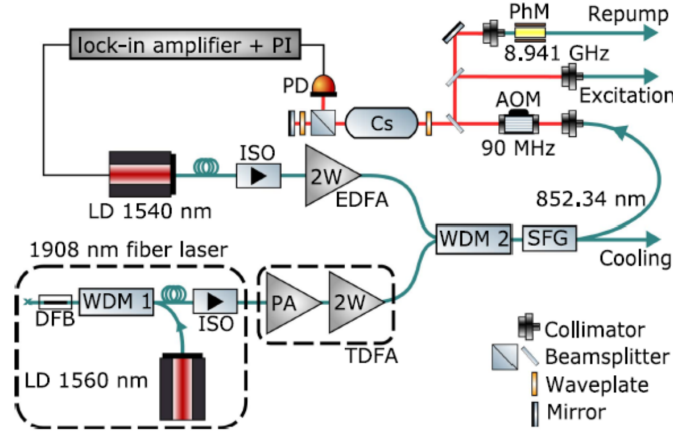


FIG. 4. Architecture of the 852 nm laser source. LD, laser diode; DFB, distributed feedback; ISO, isolator; EDFA, erbium-doped fiber amplifier; PA, pre-amplifier; TDFA, thulium-doped fiber amplifier; WDM, wavelength-division multiplexer; SFG, sum frequency generation; Cs, cesium vapor; PD, photodiode; PI, proportional integrator; AOM, acousto-optic modulator; PhM, phase modulator

better collimation.

In conclusion in a gaussian beam the tails are of little help for the cooling because of the low intensity. Therefore, a 10mm gaussian beam can be less efficient than a 7.5mm top-hat beam because in the first case the effective cooling region is probably near 5mm (where the intensity is sufficient for an efficient cooling) whereas the effective cooling region is 7.5mm in the top-hat case.

Finally we present our optimized setup. The first modification was to optimized the useful optical power by forming a collimated top-hat beam (not to be confounded with the most used top-hat beam at focus) along the Cs beam propagation axis. There are several solutions to produce such propagating top-hat beam, we can cite for example commercial beamshapers from Asphericon Company (model TSM-25-10-S-B) or from AdlOptica (model  $\pi$ Shaper) [41–43]. Our solution was a cheaper and simple Powell's lens. we choose a lens with a fan angle of 20° for

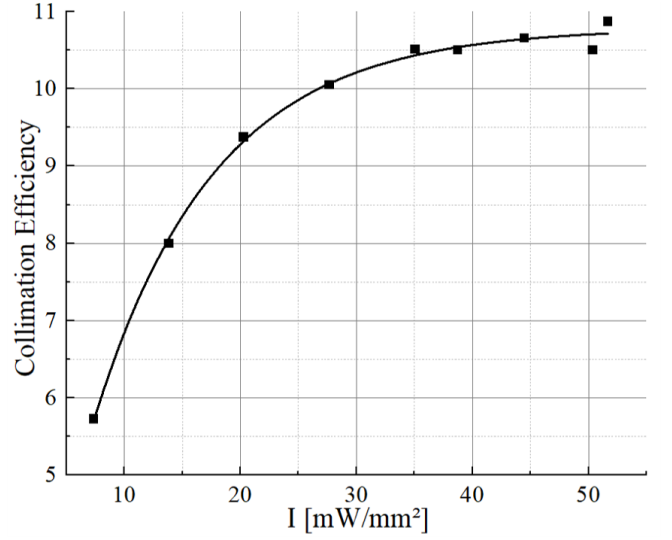


FIG. 5. Blue detuned cooling with the laser described in Fig. 4 and the top-hat beam in Fig. 3. In square black is the collimation efficiency (left axis) versus the laser power. The black exponential is guide for the eye.

a 1mm input beam <sup>1</sup>.

If several models of flat-topped beam profiles exists (super-Gaussian, flattened Gaussian, super-Lorentzian, ...) [44] we find out that our beam is quite close to a collimated super-Gaussian beam with a flatness parameter  $p = 12$  leading to a 1D intensity (irradiance) distribution proportional to  $e^{-\left(\frac{2x^2}{w^2}\right)^p}$  (edges at  $w/\sqrt{2}$  on every axis, so the beam size is  $\sqrt{2}w \approx 9.2\text{mm}$ ). Our 1D cooling setup up using the top-hat profile along the atomic beam propagation axis is illustrated in Fig. 3 where the laser propagation has been checked by imaging a beam on a camera. This 1D system is duplicated and the second one is shifted by 1 cm for the other cooling axis to produce a 2D cooling. The second modification concerns the improvement of the cooling laser. It has been described in details in Ref. [34] and is presented in Fig. 4. The architecture is based on the sum-frequency generation of 1540 nm and 1908 nm laser, realized through a periodically poled lithium niobate waveguide with a conversion efficiency of 40%. It produces a 1 W all-fibered polarized beam at 852 nm. In addition to the high optical power, the main strength of our laser source is the narrow sub-MHz linewidth. This is an important parameter because we have observed that a linewidth bigger than 1 MHz leads to a strong degradation of the cooling efficiency. The final cooling results are presented in Fig. 5 for a maximal power of 500 mW. The cooling efficiency is saturated at a value higher than 10.

<sup>1</sup> www.altechna.com reference 1-PL-1-B9201

### III. CONCLUSION

In conclusion, we found that the simplest, and more efficient way, to produce an dense collimated Cs atomic beam, was the use of a blue detuned molasses cooling. The collimated flux per transverse area is  $\sim 1 \times 10^{13} \text{ at s}^{-1} \text{ cm}^{-2}$  making it an interesting source for experiments in atom optics [5], atom lithography [3, 45] or to form electron or ion beams [7–9]. The blue detuned molasses is extremely simple to realize and therefore compares favorably to other Sisyphus, stimulated or adiabatic type of cooling (see [46–52] and references therein). Therefore, experimental comparison with these methods would be interesting to be performed to compare efficiencies and adding a magnetic compression before or after the cooling stage can also improve further the performances.

One of the biggest advantage of the blue molasses, compared to the red one, is its strong force over a large velocity range making the cooling zone smaller and the capture velocity much higher. However, the drawback is the final temperature, that is typically in the mK regime compared to the 100  $\mu\text{K}$  for the standard red detuned molasses cooling. However, once the bright atomic beam has been produced by a blue molasses, it is always possible to add an extra cooling like a red, gray or Raman sideband cooling ([53] and references therein) to increase the brightness further. We believe that this technique has an interest for instance in front of a Zeeman slower. Another possible application is atom interferometry when a high atom flux is required, such as atomic gyroscopes

[5, 43, 54].

Among the practical implementation of the blue molasses we found that:

- a 2D collimation is possible but can be realized only in a 1D+1D configuration where the two cooling zones do not overlap.
- Only hundreds of mW of narrowband ( $\lesssim 1 \text{ MHz}$ ) laser power is required, which, nowadays is easily commercially reachable using simple diode lasers. It can also be achieved by more robust fibered laser systems as we presented in this article.
- Top-hat beams were found to perform better than Gaussian ones. Powell lenses, which produce such top-hat laser beam profile, don't seem commonly used in laboratories; even if, for many type of atomic, molecular, and optical physics experiments having a uniform intensity would be very interesting.

Therefore, this method applies to other atoms or to some molecular species and we hope that this work will stimulate other ones.

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