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How to reach the collisional regime on a magnetically guided atomic beam

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Abstract. In this paper, we report our progress towards the realization of a continuous guided atomic beam in the degenerate regime. So far, we have coupled into a magnetic guide a flux of a few 10^8 atoms/s at 60 cm/s with a propagation in the guide over more than 2 meters. At this stage, the collision rate is not high enough to start an efficient forced evaporative cooling. Here we describe a new approach to reach the collisional regime. It is based on a pulsed feeding of the magnetic guide at a high repetition rate. The overlap of the packets of atoms occurs in the guide and leads to a continuous guided beam. We discuss different ways to increase the collision rate of this beam while keeping the phase space density constant by shaping the external potential.

1. INTRODUCTION

A spectacular challenge in the field of Bose-Einstein condensation is the achievement of a continuous beam operating in the quantum degenerate regime. This would be the matter wave equivalent of a CW monochromatic laser and it would allow for unprecedented performance in terms of focalization or collimation. In [1], a continuous source of Bose-Einstein condensed atoms was obtained by periodically replenishing a condensate held in an optical dipole trap with new condensates. This kind of technique raises the possibility of realizing a continuous atom laser. An alternative way to achieve this goal has been proposed and studied theoretically in [2]. A non-degenerate, but already slow and cold beam of particles, is injected into a magnetic guide where transverse evaporation takes place. If the elastic collision rate is large enough, an efficient evaporative cooling leads to quantum degeneracy at the exit of the guide. This scheme transposes in the space domain what is usually done in time, so that all operations leading to the condensation are performed in parallel, with the prospect of obtaining a much larger output flux. In the present paper, we report our progress along those lines, and outline our strategy to reach the required collisional regime in the magnetic guide.

2. EXPERIMENTAL REQUIREMENTS

The condition for reaching degeneracy with the latter scheme can be formulated by means of three parameters: the length ℓ of the magnetic guide on which evaporative cooling is performed, the collision rate γ at the beginning of the evaporation stage, and the mean velocity v_b of the beam of atoms. Following the analysis given in [2], one obtains

$$N_\mathrm{c} \equiv \frac{\gamma\ell}{v_\mathrm{b}} > 500 . \qquad (1)$$

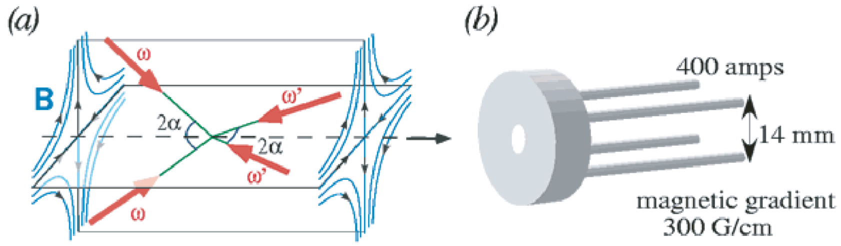

Figure 1. (*a*) Laser configuration of the injector magneto-optical trap. (*b*) Entrance of the magnetic guide. The cylindrical hollow metal piece allows for the connection of the electrical currents and cooling water circulating into the four copper tubes.

If the collision rate γ is constant over the cooling process, which is approximately the case for realistic conditions, this means that each remaining atom at the end of the guide has undergone N_c elastic collisions during its collisional propagation through the magnetic guide.

Some conclusions can already been drawn from the inequality (1). One needs to operate in a long magnetic guide, at very low mean velocity, and the collision rate should be as high as possible at the beginning of the evaporation. The criterion (1) suggests to start with a large incoming flux at low velocity and at very low temperature.

3. CONTINUOUS INJECTION

3.1. Injector

In our experiment, we produce a slow atomic beam with a magneto-optical trap called the *injector* that has been described in detail elsewhere [3]. It is based on four laser beams in a tetrahedral configuration, superimposed with a two-dimensional magnetic quadrupole field (see Fig. 1*a*). The transverse gradient is typically 10 G/cm, and each beam has a power of 25 mW and a waist of 15 mm. This geometry is dictated by the requirement of a free axis (no confinement) needed for the propagation of the beam. This kind of trap provides trapping in two dimensions and cooling in three dimensions. The absence of trapping along one direction makes this trap very sensitive to local imbalance of intensity, and one has to use intensity stabilized and spatially filtered beams. The frequency of one pair of beams is adjusted with respect to the frequency of the other pair in such a way so as to perform the cooling in a longitudinally moving frame with an adjustable velocity v_b ranging from 0 to 3 m/s. This technique is reminiscent of the one used in atomic fountain clocks to launch the atoms through the cavity [4].

3.2. How does one load atoms in the injector?

To load the injector magneto-optical trap we have investigated two methods.

First, we have loaded the atoms from a low-pressure background gas. By controlling the temperature of the rubidium reservoir and the size of its aperture, we could vary the ^{87}Rb pressure from 10^{-9} to a few 10^{-8} mbar. This method suffers from the following drawback. In order to increase the flux, one would like to increase the vapor pressure. However, this also increases the losses due to collisions between atoms coming out of the injector MOT with thermal background atoms. The best results we obtained, subject to this trade-off, were a flux of 10^9 atoms/s at 2 m/s for a ^{87}Rb vapor pressure of $P_{87} = 10^{-8}$ mbar [3].

In order to avoid the losses from the background pressure, we have implemented a new setup relying on two magneto-optical traps in two different vacuum chambers connected by a differential vacuum tube. In the first chamber, we used a two-dimensional trap in the presence of a relatively high rubidium pressure (10^{-7} mbar) [5,6]. It generated a beam of pre-cooled atoms with a flux of typically 10^{10} atoms/s with an average velocity of 40 m/s [7]. This beam was captured by the injector located in the second chamber with background pressure of the order of 10^{-9} mbar. At this level the residual pressure did not affect any more the output flux. For technical reasons, the pre-cooled beam was along the axis of the injector magneto-optical trap for which no gradient of magnetic field existed. Actually, this geometry was not very efficient for good capturing of the incoming atoms. Indeed, atoms are decelerated more efficiently in the presence of a magnetic gradient, since the latter enables full on-resonant deceleration while the atoms are being captured. As a result the loading efficiency of the injector is very anisotropic. For an incoming flux of 10^{10} atoms/s (along the trap axis), we estimate to recapture a few 10^8 atoms/s despite the large intensity used for the laser beams.

In order to deal with this anisotropic loading rate, we are currently implementing a Zeeman slower with a recirculating oven. This should provide a high flux ($> 10^{10}$ atoms/s) which arrives perpendicular to the longitudinal axis of the injector to take advantage of the transverse gradient of the trap in order to more efficiently capture atoms.

3.3. Continuous injection of atoms into the magnetic guide

Different magnetic guides have already been investigated experimentally for guiding ultracold atoms [8–15]. Since our application requires a long guiding time, we developed a 2.3 meter long magnetic guide. It consisted of four copper tubes ($\O_{\mathrm{ext}} = 6$ mm and $\O_{\mathrm{int}} = 4$ mm) in quadrupolar configuration joined at the beginning of the guide by a hollow metal cylinder (see Fig. 1*b*) which allowed for the circulation of high current and cooling water from tube to tube. The distance between the tubes at the entrance was 14 mm. For this separation between the tubes, we obtained a gradient of 300 G/cm with a current of 400 A. The magnetic field produced by the guide fell off sufficiently fast and did not affect the injector performance. However, there existed an intermediate region from the output of the injector to the entrance of the magnetic guide where no significant confinement was provided. In this free flight region, the jet of atoms expanded outwards in space and became dilute. As a consequence, the collision rate decreased dramatically. To circumvent this problem, we investigated two different strategies to confine the atoms in this region.

3.3.1. Far-detuned magneto-optical trap

In the first set of experiments, the magnetic guide was 0.6 meters long [3] and the injector was vapor-loaded. To confine the atoms in the intermediate region we superimposed a far-detuned ($\delta \sim -7\Gamma$) two-dimensional magneto-optical trap (see Fig. 2*a*). We operated the injector in the continuous mode and achieved the continuous feeding of the magnetic guide with a flux of 3×10^8 atoms/s at 2 m/s. We evaluated the total number of collisions N_c undergone by an atom reaching the end of the magnetic guide to be 0.3. This first experiment demonstrated the feasibility of the continuous loading with high flux. However, it remained very far from the requirement (1) to start an efficient evaporative cooling of the guided beam.

3.3.2. Miniature guide

In a second set of experiments we used a 2.3 meter long guide and the injector was loaded from a two-dimensional magneto-optical trap in a different vacuum chamber, as described above. The far-detuned two-dimensional magneto-optical trap did not provide an efficient coupling of atoms into the guide at low velocity due to strong recoil heating in the longitudinal direction. For this reason, we developed a miniature magnetic guide on a conical supporting structure. The shape was chosen in order to maintain a good optical access for the beams of the injecting magneto-optical trap. This miniature guide [7] was

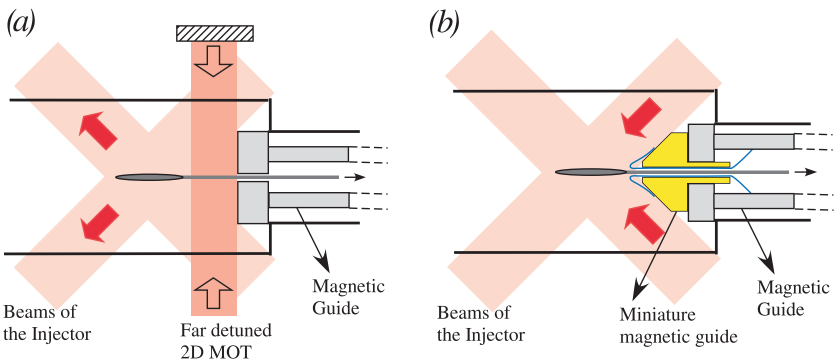

Figure 2. (*a*) Use of a two-dimensional far-detuned magneto-optical trap to transfer the atoms from the injector to the magnetic guide. Alternatively, we use a miniature magnetic guide (*b*) placed at the entrance of the magnetic guide to facilitate the transfer.

added at the entrance of the magnetic guide as depicted in Fig. 2*b*. With this improved setup, we were able to couple a flux of 1.5×10^8 atoms/s at a very low velocity of the order of 60 cm/s, thereby reaching a total number of collisions per atom in the guide of $N_c = 3$.

We emphasize that the low mean velocity v_b requirement implies the need for a fine control of the height of the guide. For instance, a 2 mm vertical displacement of the guide would be sufficient to stop atoms moving at 20 cm/s.

4. PULSED MODE

4.1. Motivation

In a regular Bose-Einstein condensation experiment, atoms are first captured by a magneto-optical trap, are cooled further by means of a molasses and are polarized before being trapped magnetically. The shape of the magnetic trap is adjusted to the size and temperature of the cloud to achieve good mode matching. This method allows one to obtain the highest possible initial phase space density and collision rate.

Strictly speaking, this mode-matching procedure cannot be applied to a continuous beam. Indeed, the jet of atoms produced by the injector cannot be cooled efficiently by a molasses since the gradient of the magnetic field and the small detuning should remain to capture atoms continuously, and furthermore atoms are not transferred instantaneously into the magnetic guide. Another significant problem encountered, especially at low velocities, was the unavoidable presence of repumping light at the entrance of the magnetic guide, which could kick atoms out of the trapped spin-state. Repumping light rescattered by atoms did not appear to be a significant contribution, and, if necessary, could be reduced by providing off-resonant repumping light at higher intensities. These problems, which arise for a continuous mode, made it difficult to achieve a high number of collisions N_c [3].

4.2. Pulsed injection

To optimize the transfer of the atoms from the injector into the magnetic guide, we are currently investigating the possibility to operate in pulsed mode. The atoms are first captured in the injector set to zero launch velocity. During this stage the detuning and transverse magnetic field gradient are optimized for efficient capturing. Then the detuning of the injector is adjusted to a larger value and its intensity is turned down so that the temperature of the atoms is decreased by the molasses effect. Also, during this stage the injector is ramped to a finite velocity (between 0.5 m/s and 1 m/s) to launch the atoms. Subsequently the atoms are optically pumped to the proper Zeeman sublevel. Next, they are magnetically trapped by a two-dimensional quadrupole field strong enough ($\sim$ 60 G/cm) to uphold them from falling due to gravity. A longitudinal bias field (a few gauss) is temporarily provided to ensure mode matching during this catching stage and is then removed adiabatically, which causes a first compression. As soon as this packet has left the capture region of the injector and enters the long magnetic guide, another packet is prepared, and so on. In this way we can still capture a large fraction of the atoms, while optimally treating the packet for injection into the waveguide. These packets eventually overlap after a propagation into the magnetic guide of the order of 50 cm for realistic experimental conditions, leading to a truly continuous beam afterwards.

5. HOW DOES ONE INCREASE THE COLLISION RATE OF THE GUIDED BEAM?

The collision rate of the beam can be modified by changing the external potential experienced by the atoms. In our experiment, the compression is twofold. First, it is provided by the removal of the longitudinal bias field used for mode matching. At this stage the confinement is changed from initially harmonic to linear. Second, the atoms are compressed by entering and propagating in a tapered magnetic guide in which the transverse confinement increases as the atoms progress into the guide. In practice, the latter compression is achieved by decreasing the distance between the guide tubes.

The increase of the strength of the transverse confinement would ideally be slow enough to ensure the validity of thermodynamical adiabatic conditions. In this case, the phase space density and the enthalpy remain constant through the constriction, and the collision rate γ as well as N_c increase significantly. Upon compression, the temperature T and the thermal velocity $v_{\mathrm{th}} = (k_B T/m)^{1/2}$ increase, while the velocity of the beam decreases by up to a factor $2\sqrt{2}$ [16].

The initial injection velocity should be chosen such that the thermal velocity remains lower than the mean velocity during the compression: $M \equiv v_{\mathrm{b}}/v_{\mathrm{th}} > 1$. In the hydrodynamic regime, M would be the Mach number within a numerical factor of order unity. Actually, if the compression is too strong, with M reaching unity, atoms are reflected. As a consequence, a stronger compression requires a larger initial ratio M, but nevertheless a net gain in N_c is achieved. The initial temperature is a crucial factor, since it determines the initial density of the cloud, as well as how slow we can inject the atoms into the guide: if the injection velocity is kept as low as possible, *i.e.*, with M fixed, N_c scales as $\sim \phi T^{-5/2}$, where ϕ is the initial incoming flux. We stress that evaporation during compression could be beneficial, since it enhances the ratio M, allowing for an even lower injection velocity. However, if the optimal injection ratio M is higher due to experimental limitations in the injection region, we still have the possibility to locally tilt the guide in order to increase N_c [16].

We recently realized the first part of the pulsed injection procedure and were able to obtain an initial collision rate of 4 s^{-1} in packets magnetically trapped in the injection region at a transverse gradient of 60 G/cm. With this performance, N_c could exceed 100 in the 2.3 m long guide, by taking advantage of the compression, which is encouraging.

6. CONCLUSION

We have summarized our experimental results concerning the continuous loading of a high flux of atoms into a long magnetic guide. We have briefly discussed a new strategy based on a pulsed feeding of the guide. To implement an efficient evaporative cooling we need a high number of collisions per atom through their propagation into the guide. In this paper we have considered the possibility of increasing the collision rate by adiabatically modifying the external potential experienced by the atoms. We have emphasized that adiabatic modifications require the velocity of the beam to be significantly larger than the thermal velocity.

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