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Realization of a magneto-optical trap in microgravity

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We report on the first realization of magneto-optically cooled atoms in microgravity as a first result of the collaboration project ATKAT (atom catapult). We present the compact and robust setup for cooling and trapping neutral ^{87}Rb atoms in microgravity conditions in the drop tower in Bremen⊥ and discuss the specific requirements the setup has to meet. In particular we present a small size and mechanically stable laser system and discuss the specifics of the ultra high vacuum chamber. A free falling magneto-optical trap (MOT) as realized in this project provides a basis for further experiments which aim at investigating cold quantum matter in microgravity.

1. Introduction

Trapping and cooling of neutral atoms has become an important tool for a very active field in modern physics in the last decades as documented by the Nobel prizes in 1997 and 2001 and several thousand publications per year. Owing to unique control and precise measurement possibilities of intrinsic and extrinsic parameters, ultracold atomic gases open new frontiers and relate to many different fields of physics. An outstanding example is the use of cold atoms in atom interferometers for high precision atom clocks, gravitational or rotational sensors. One limit of

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these devices in earth-bound laboratories is the gravitational acceleration, which restricts the maximum unperturbed time of flight in free fall to typically a few 100 ms. In this respect cold atoms in microgravity promise even higher precision as the time of unperturbed evolution between measurements on the system can be arbitrarily extended. Furthermore, the realization of a magneto-optical trap in microgravity is a first step on the way to quantum degenerate gases in microgravity, which would open perspectives to significantly shift boundaries in physics, e.g. realize unprecedented low temperatures by adiabatic expansion to extremely weak traps. Motivated by these prospects several initiatives around the world (e.g. PHARAO, ACES, RACE and initiatives at JPL and Stanford) have been started pursuing mobile and ruggedized cold atom experiments, which might be used in space applications. The first optical molasses experiments under weightlessness conditions during parabolic flights have been recently reported by the PHARAO/ACES project as a precursor to an atomic clock setup on the space station. In this article we present the first magneto-optical trap in microgravity based on a small, light, rigid and portable setup optimized for drop tower operation. This project is performed within the ATKAT collaboration as part of the QUANTUS project pursuing BEC in weightlessness at the drop tower.

We chose the drop tower in Bremen (ZARM, Center of Applied Space Technology and Microgravity) to start experiments in weightlessness as it offers outstanding residual accelerations of only $10^{-5}\,\mathrm{ms}^{-2}$ (in the frequency band below 100 Hz) during free fall. This promises smallest perturbations on our system. In the future we plan to double the microgravity time by running the experiment in catapult instead of drop mode. In this case the experiment not only has to withstand the capsule release with the transition from 1g to μg, but also the acceleration of about 200–$300\,\mathrm{ms}^{-2}$ during launch of the experiment as well as the deceleration of 400 to $500\,\mathrm{ms}^{-2}$ at the impact.

To maintain functionality of our assembly during the acceleration phase, we have designed very rigid components. The vacuum chamber is made of solid aluminium (section 2.1), pumped by a specially modified ion-getter pump (section 3.1). The lasers, including all mounts and housings are self-made and optimized for very high mechanical stability, small size and low power consumption. All components are fibre interlinked and remotely controlled.

In section 3 we will present the results of laser as well as vacuum chamber stability and present images of the first cold atoms in free fall.

2. Experimental setup

As mentioned above, the drop tower environment puts high demands on the specific design of any experimental setup. Obviously, all the components used have to be made rigid, robust and insensitive to the occurring deceleration forces. Another important limitation is the limited volume of the drop capsule (figure 1). It has an effective payload height of about 1.73 m, a diameter of 0.6 m and can carry up to a maximum payload of 243 kg. A common laboratory atom–optical experiment has

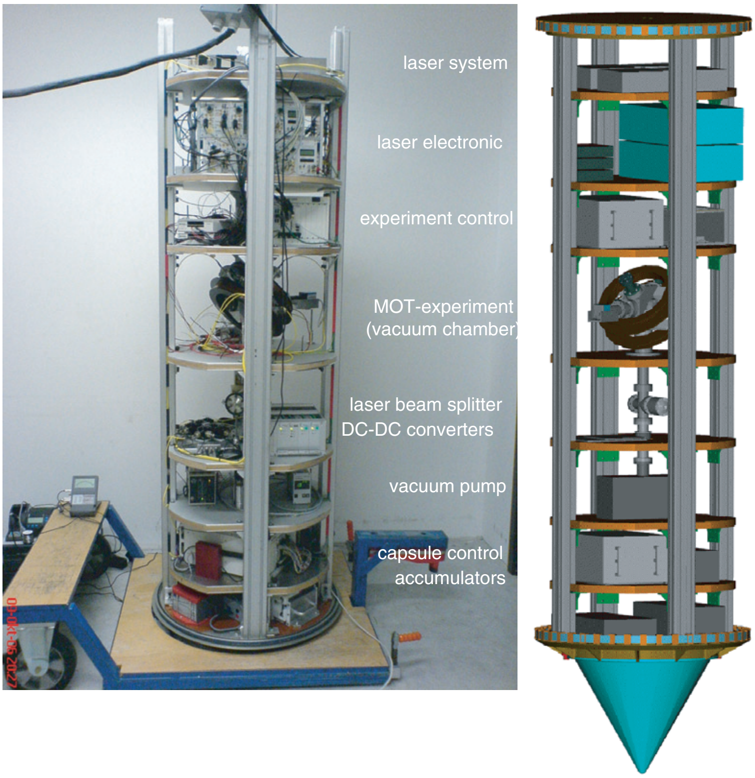

Figure 1. Drop capsule with magneto-optical trap. (The colour version of this figure is included in the online version of the journal.)

a typical size of one or two optical tables. Thus, a special challenge in constructing the setup was its miniaturization. In the following subsections we describe the individual components in detail.

2.1 *Free falling magneto-optical trap setup*

Our magneto-optical trap setup shown in figure 2 is based on a vacuum chamber, made of a solid aluminium block and is kept at ultra low pressure of less than 10^{-9} mbar by an ion-getter pump (for details of drop tower specific vacuum techniques see section 3.1). A mirror-MOT utilizing four laser beams and a mirror that reflects two of them is used for trapping the atoms. The laser light is transmitted to the vacuum chamber via polarization-maintaining optical fibres and the beams are expanded to a diameter of 20 mm. All telescope lenses as well as waveplates are rigidly attached to the body of the vacuum chamber, giving maximum stability and minimizing the need of realignment after the drop. A pair of anti-Helmholtz coils produce the magnetic field gradient of about $9\,\mathrm{G\,cm^{-1}}$ along the coil axis in the

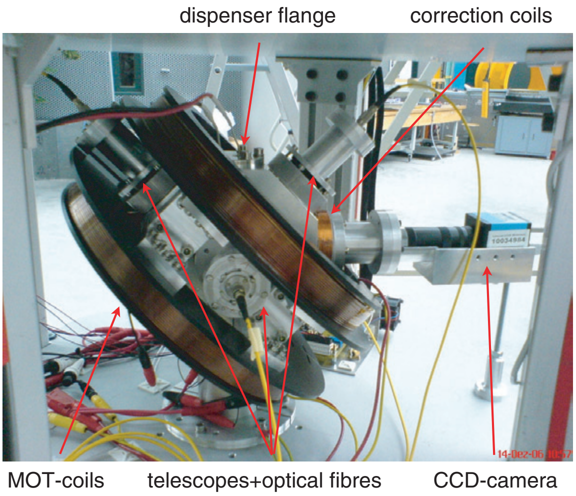

Figure 2. Experimental setup of the magnetic coils around the vacuum chamber. (The colour version of this figure is included in the online version of the journal.)

middle of the chamber. The Rb atoms are released to the chamber from a commercially available current controlled dispenser (SAES getters) and the MOT is directly loaded from the rubidium background gas. We are able to capture approximately 10^7 atoms at a temperature of $200\,\mu$K, which is similar to the values achieved in comparable earth-bound atom–chip setups with background gas loading [1]. The fluorescence light from the trapped atoms is recorded by a CCD camera.

2.2 *Laser system and laser electronics*

Stable frequency and intensity of light are crucial for the optimal performance of a MOT [2]. Thus, constructing a reliable and robust laser system, capable of operating at the drop tower, was a special challenge. In particular, critical vibrations of the platforms in the drop capsule at the moment of release must not be coupled to the light frequency and intensity.

For magneto-optical cooling of rubidium one needs a few tens of mW of 780 nm laser radiation with a linewidth not greater than the natural width of the ^{87}Rb-D2 transition, $\Gamma \approx 6$ MHz. For the sake of mechanical stability we have intentionally refrained from using extended cavity diode lasers (ECDL), which are the most common choice for laser cooling. Instead, we utilize distributed feedback (DFB) laser diodes with an intrinsic grating in the active semiconductor area [3]. In contrast to an ECDL, a DFB diode has a very high intrinsic stability. Furthermore, it has an extremely wide mode-hop-free operation range of more than 100 GHz, which greatly facilitates its use. Though its emission linewidth (typically 4 MHz) is wider than that of an ECDL, it is still comparable with the natural linewidth, which assures effective cooling.

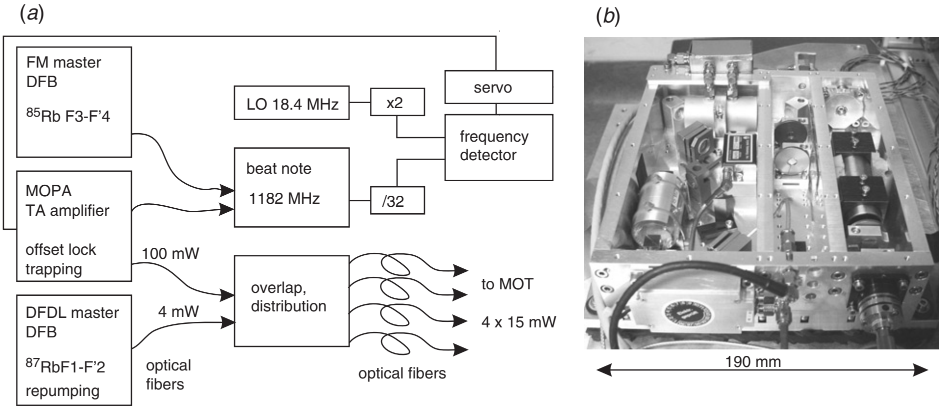

Figure 3. (*a*) Schema of the compact laser system. (*b*) MTS master laser in robust stress-free aluminium chassis. (The colour version of this figure is included in the online version of the journal.)

Our laser system is schematically shown in figure 3(*a*). It consists of two DFB master lasers stabilized to atomic transitions, a master oscillator power amplifier (MOPA), beat module, and a power distribution module. The first master laser is based on a Doppler-free dichroic atomic vapour laser lock (DFDL) technique [4] and provides about 4 mW of light for the repumping transition in the cooling cycle. The second one utilizes modulation transfer spectroscopy (MTS) lock [5, 6] and serves as a reliable frequency reference for the cooling transition. The MOPA is offset-locked to the MTS-master laser and its tapered amplifier supplies the required 100 mW of trapping light after coupling into the fibre guiding the light from the MOPA module to the power splitting module. Subsequently, the trapping and repumping beams are superimposed, split into four beams of equal power (approx. 15 mW) and coupled into four fibres in the distribution module. All mounts for optics with a beam height of 20 mm are self-designed with a special emphasis on mechanical stability. The lasers and optics (including stabilization with Rb spectroscopy cell) are placed in robust housings which are made of stress-free aluminium (wall thickness 10 mm) and are only $210 \times 190 \times 60\,\mathrm{mm}^3$ small (figure 3(*b*)). The whole system with attendant electronics fits the area of two platforms in the drop capsule. Note also, that all modules are interlinked with optical fibres, which enhances flexibility of use.

As already mentioned, we split the MOPA laser power into four beams of equal intensity and superimpose it with the repumping beam. For this purpose we use a commercially available module (Schafter + Kirchhoff GmbH). Additionally, the power of two input beams is monitored with a pair of photodiodes.

2.3 *Power supply and capsule control*

The experiment is powered from a series of lead accumulators which are placed at the very bottom platform in the drop capsule. They provide a nominal 28 V DC voltage into six current channels, each of which is protected with a slow 40 A fuse. The available energy amount is limited to about 0.7 kW h. However, the batteries can be buffered by an external power supply, which can be disconnected a few minutes before the drop. The run of an experiment is controlled by an integrated, compact PXI computer with a real-time operation system (www.ni.com).

3. Results

3.1 *Vacuum stability test*

In order to minimize collisions between residual gas atoms it has been essential to achieve an ultra high vacuum (UHV) in an atom–optical experimental vacuum chamber. A UHV chamber has not been used at the drop tower so far and its vacuum stability in the deceleration phase of the drop is a critical aspect. We operate with standard and non-standard vacuum gasket techniques realizing an UHV inside our vacuum chamber. We use a 'Varian VacIon Plus 40 Diode' ion-getter pump which was specially modified to pass the drop tower requirements. A cold cathode gauge is used for pressure measurement. Our vacuum chamber is made of aluminium, which is too soft for standard CF vacuum connections. Instead we used lead and indium gaskets, the latter for the sensitive BK7 glass windows. One winding of lead resp. indium wire (0.5 mm resp. 2 mm diameter) is formed to a ring and squeezed between the vacuum components. Figure 4 shows the leak tightness of the vacuum chamber in a drop experiment. Besides the occurring acceleration during the drop, the high voltage at the ion-getter pump and the reading of the cold cathode gauge, corresponding to a vacuum pressure of 1.8×10^{-10} mbar is shown. The figure shows that the pressure in the chamber stays constant during the acceleration and deceleration phases of the drop capsule, although the high voltage at the ion-getter pump drops from 5 to 2.5 kV for about half a second.

3.2 *Laser stability test*

As already mentioned, stable laser frequency and power are important for efficient cooling. So far we have performed several dedicated drop tower tests of the laser system. Furthermore we recorded the frequency error signals and the light intensity during each flight of the MOT. Error signals of all three lasers during capsule release can be seen in figure 5(*a*). No significant frequency change has been observed, which indicates a good performance of the laser lock loops. Figure 5(*b*) shows the intensity of the trapping and repumping beams at the input ports 1 and 2 of the power splitting module during the whole flight. A little acceptable jitter of about 3% of the total intensity can be seen at the moment of capsule release. The intensity stays stable during the whole flight and varies by typically no more than 10% after the impact, so that fibre coupling has to be only slightly readjusted. Note that so far we have not used any active stabilization system for the light power and we rely only on the mechanical stability of our setup.

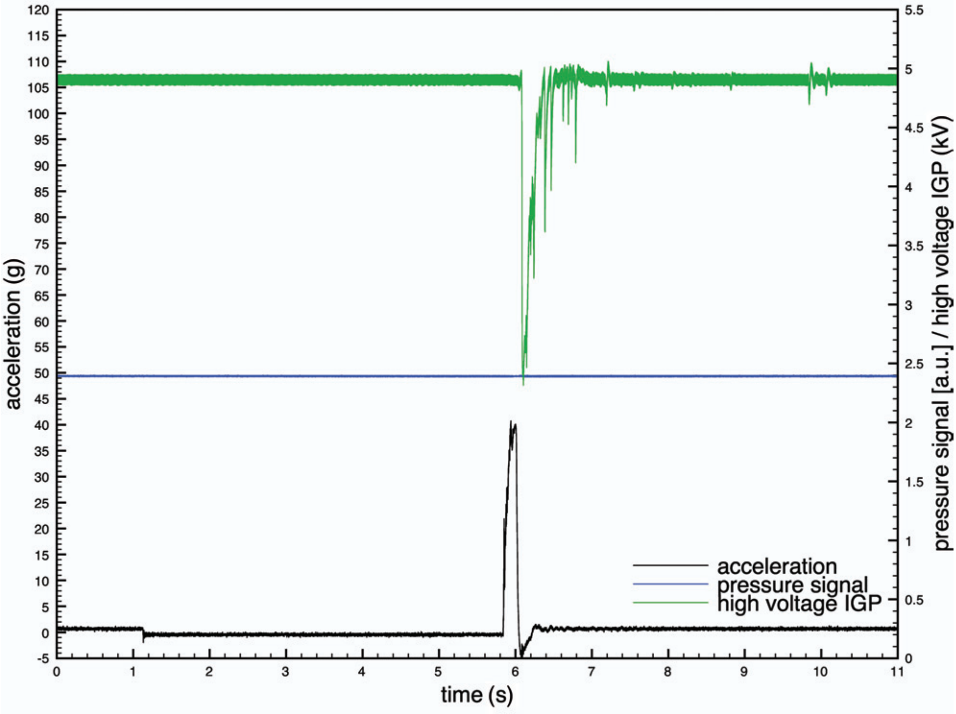

Figure 4. Vacuum stability test of one vacuum chamber drop at the drop tower Bremen. (The colour version of this figure is included in the online version of the journal.)

3.3 *Cold atoms in weightlessness*

As a main result of this paper, we were able to maintain operation of the magneto-optical trap described in section 2.1 during free fall in the drop tower and thus to demonstrate for the first time magneto-optically trapped atoms in microgravity. After creation of the magneto-optical trap with the drop capsule located at the top of the drop tower it was successfully maintained running during release of the capsule and the subsequent period of $\approx$4.7 s of free fall (see figure 6). The atom number in the MOT on the order of 10^7 remains approximately constant during the period of free fall. Slight fluctuations arise due to the movement of the trapped atoms in the magnetic field environment of the drop tower as discussed in the following section.

3.3.1 The effect of residual magnetic field in the tower. Since the beginning of laser cooling in the early 1980s, magneto-optical traps for neutral atoms have been constructed in a multitude of laboratories worldwide. However, there exists only a tiny number of MOT setups that are portable. Besides the aspects of mechanical stability and small size, one reason for this is a high sensitivity of the position of an atomic cloud to residual magnetic fields. For a typical magnetic field gradient of

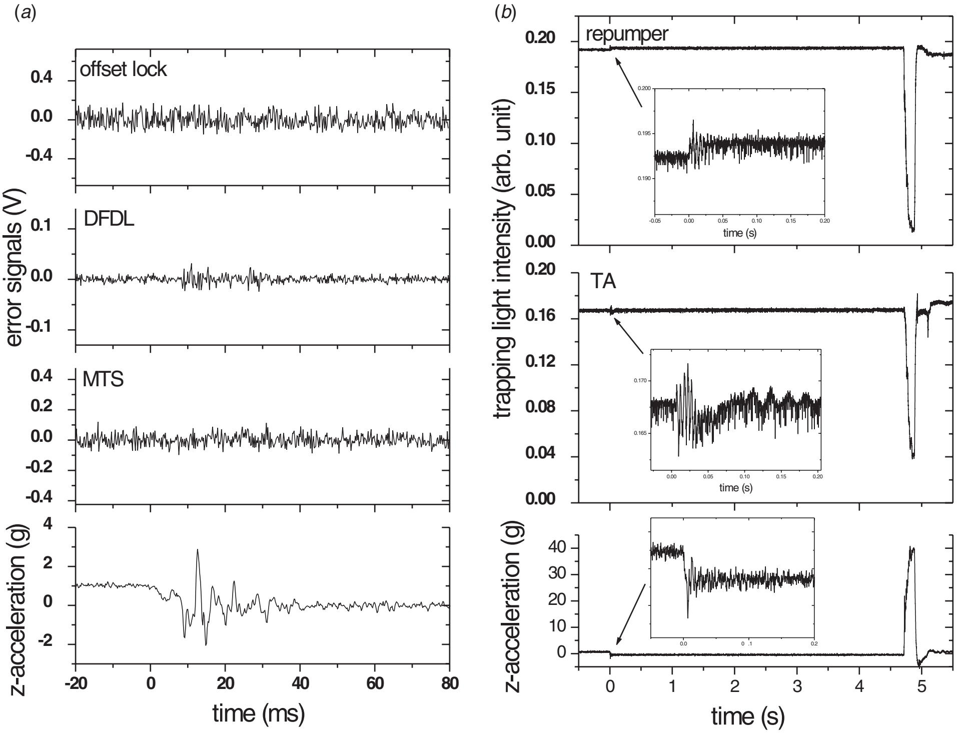

Figure 5. (*a*) Error signals of the three laser locks during the capsule release. No change of the laser frequency has been observed. (*b*) Intensity of the laser light at the input ports of the power splitting module during the flight. In the moment of capsule release. There is a little intensity jitter of about 3%. After the final impact the intensity changes no more than 10% of its beginning value. The latter indicates a need of just a slight readjustment of the fibre coupling after each drop.

several gauss cm^{-1} in a MOT, the position of the minimum (and that of the cloud) is shifted by the Earth magnetic field by about 1 mm.

During our drop campaigns we have also observed a fluctuation of the MOT position, which was strongly correlated to the measured residual magnetic field inside the tower tube. The movements of the MOT are shown in figure 6. In future experiments a μ-metal screening of the vacuum chamber will fully eliminate the effect. Proper compensation of the residual magnetic fields is very important for polarization-gradient cooling, which is planned to be implemented subsequently.

4. Conclusion

In summary, we presented the first MOT under microgravity conditions at the drop tower Bremen. We discussed our experimental setup, in particular the mechanically

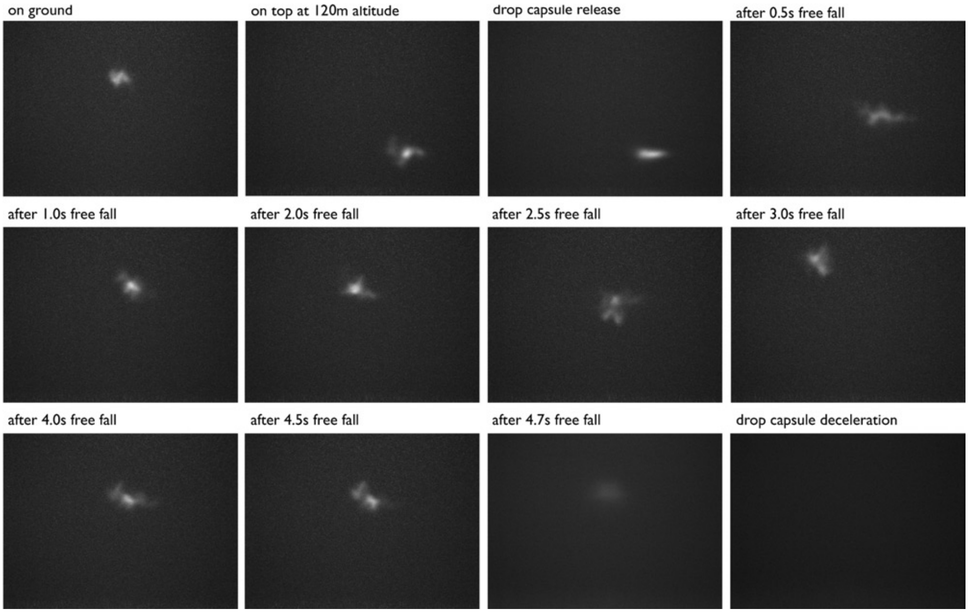

Figure 6. Chronological excerpt from the first free falling ^{87}Rb magneto-optical trap including the effect of residual magnetic fields at the drop tower Bremen.

stable laser system and vacuum chamber which revealed to be absolutely sufficient for the special requirements of the drop tower. These results have provided important information on the general feasibility of laser cooling and magnetic shielding requirements in the drop tower environment at ZARM. As a next step we will implement a μ-metal shielding to suppress the MOT movement due to residual magnetic fields and test our setup in the catapult for doubled measurement times. These experimental tests provide the basis for the installation of the BEC experiment [7] within our collaborative effort QUANTUS at the drop tower in the near future.

Acknowledgements

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References

[1] W. Hänsel, P. Hommelhoff, T.W. Hänsch and J. Reichel, Nature **413** 498 (2001).
[2] H.J. Metcalf and P. van der Straten, *Laser Cooling and Trapping* (Springer-Verlag, New York, 1999).

[3] J.E. Caroll, J.E.A. Whiteaway and R.G.S. Plumb, *Distributed Feedback Semiconductor Lasers* (IEEE, Redwood Books, Trowbridge, NJ, 1998).
[4] G. Wasik, W. Gawlik, J. Zachorowski and W. Zawadzki, Appl. Phys. B **75** 613 (2002).
[5] J.H. Shirley, Opt. Lett. **7** 537 (1982).
[6] J. Zhang, C. Xie and K. Peng, Opt. Express **11** 1338 (2003).
[7] A. Vogel, M. Schmidt and K. Sengstock, Appl. Phys. B **84** 664 (2006).