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Magneto-optical trap for rubidium atoms

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A magneto-optical trap recently built in our laboratory is described. The principles of operation and construction details are given together with the description of the lasers used in the set-up.

1. Introduction

A rapid development has recently been observed in atomic physics concerning research on different methods of cooling and trapping of atoms with use of optical forces (light pressure). The effect of this research is a much better understanding of behaviour of an atom in the situation when internal degrees of freedom (which are normally studied in spectroscopy) are strongly coupled to external degrees of freedom – the movement of an atom as a whole [1]. This activity culminated in achievement of the Bose–Einstein condensation in a gas of non-interacting alkali atoms [2].

Magneto-optical trap (MOT) [3] is one of the tools most extensively used in the experiments performed with cold atoms. It can collect a could of some $10^6 - 10^8$ atoms cooled to the temperature of the order of a fraction of a millikelvin and is a kind of a starting platform for a variety of further experiments with cold atoms. In this article, we describe the magneto-optical trap, built in our laboratory for the studies of collective and non-linear effects in dense and cold clouds of rubidium atoms.

As a MOT has already become a standard experimental apparatus in the field of cold atoms and its principle of operation is well known, we will remind it briefly and concentrate on the description of details of the present realisation with particular emphasis on the lasers used in this set-up.

2. Principle of operation

Atoms are illuminated by three pairs of counter-propagating laser beams directed along three orthogonal axes (Fig. 1). The frequency of the laser light is set slightly below the frequency of the atomic transition, so that atoms must use some of their kinetic energy of the linear movement to compensate for the deficit of the excitation energy due to laser light. The spontaneous reemission of light that follows after excitation carries away energy equal to the total excitation energy and thus a complete cycle of absorption and emision reduces the kinetic energy of atoms or,

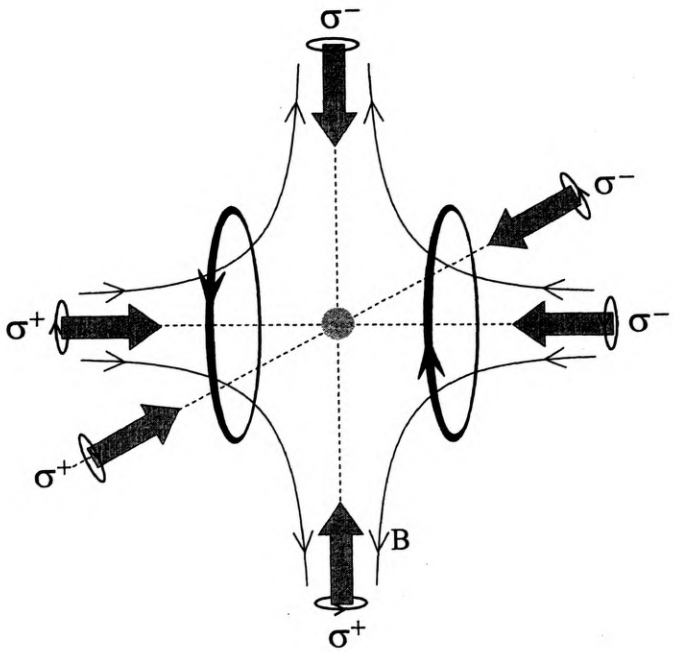

Fig. 1. Scheme of the magneto-optical trap: gray arrows – laser beams with marked polarisations, narrow solid lines – magnetic field

in other words, cools them by the momentum transfer between photons and atoms, *i.e.*, by radiation pressure. To accomplish also the spatial localisation of atoms, they are placed in an inhomogeneous magnetic field, which causes the splitting of atom magnetic sublevels, and laser beams are properly polarised. In such a situation, a displacement of an atom in any direction from the trap centre causes that one of the magnetic sublevels comes closer to resonance with laser radiation. Moreover, polarisations of laser beams are chosen in such a way that absorbed light pushes the atom towards the trap centre and thus produces the restoring force.

It should be mentioned that the trapping forces are due to radiation pressure and are not of magnetic origin; magnetic interaction is used only to control the absorption probability, which becomes spatially dependent.

MOT can be loaded with atoms from a laser decelerated atomic beam, as in [3], or directly with low velocity atoms contained in a closed cell filled with atomic vapour at low pressure [4]. The second solution is much simpler, yet has a drawback of simultaneous presence of hot atoms in the cell, which can collide with trapped atoms and knock them out of the trap.

3. Trap construction

Our experiment is designed to trap atoms of ^{85}Rb, which constitute 80% of natural abundance. The atoms are trapped directly from the vapour phase as described in

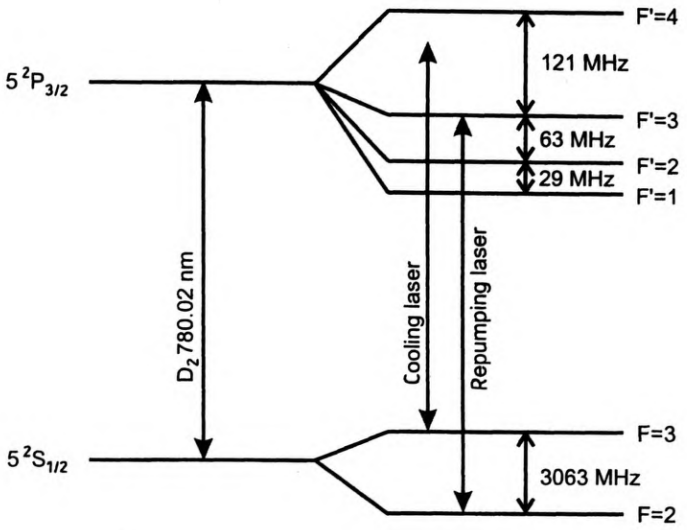

Fig. 2. Hyperfine structure of the D_2 line of ^{85}Rb

[4]. We might also trap the other stable isotope, ^{87}Rb (20% of natural abundance). We use the $5\,^2S_{1/2} \rightarrow 5\,^2P_{3/2}$ resonance transition (D_2 line, $\lambda = 780.02$ nm) for cooling atoms. Among many hyperfine structure components of the D_2 Rb line (Fig. 2), only one line can be used for efficient optical cooling of atoms. This is the transition $F = 3 \rightarrow F' = 4$, which forms a closed two-level system, because the only allowed transition from the $F' = 4$ state is back to the $F = 3$ ground state.

In reality, this system is not completely closed, as the far off-resonant excitation of the $F' = 3$ state is also possible and causes a spontaneous escape of atoms to the $F = 2$ ground state (optical pumping). Because the hyperfine splitting of the ground state of rubidium atom is much larger than that of the excited state, atoms in state $F = 2$ cannot absorb light and such pumping quickly decreases the number of atoms that can be cooled on the $F = 3 \rightarrow F' = 4$ transition. To avoid such a situation, a second laser is used, which is tuned to the $F = 2 \rightarrow F' = 3$ or $F = 2 \rightarrow F' = 2$ transition and produces an inverse optical pumping (repumping).

3.1. Laser system

The scheme of the whole optical set-up of our trap is presented in Fig. 3. Diode lasers are used for cooling and trapping. As the output power of a single diode laser is rather limited, especially after dividing the beam into three arms (see Fig. 1), our cooling laser is a tandem of a spectrally narrow laser oscillator, which is precisely tuned and stabilised to the atomic frequency, and a laser amplifier, which is injection locked to the oscillator. One more laser needed in the set-up is the repumper mentioned in the previous Section.

Cooling-laser oscillator and the repumping laser are diode lasers with external optical cavities in the Littman–Metcalf arrangement. The cavity is composed of a diffraction grating under a grazing (close to 90°) incidence angle and a tuning

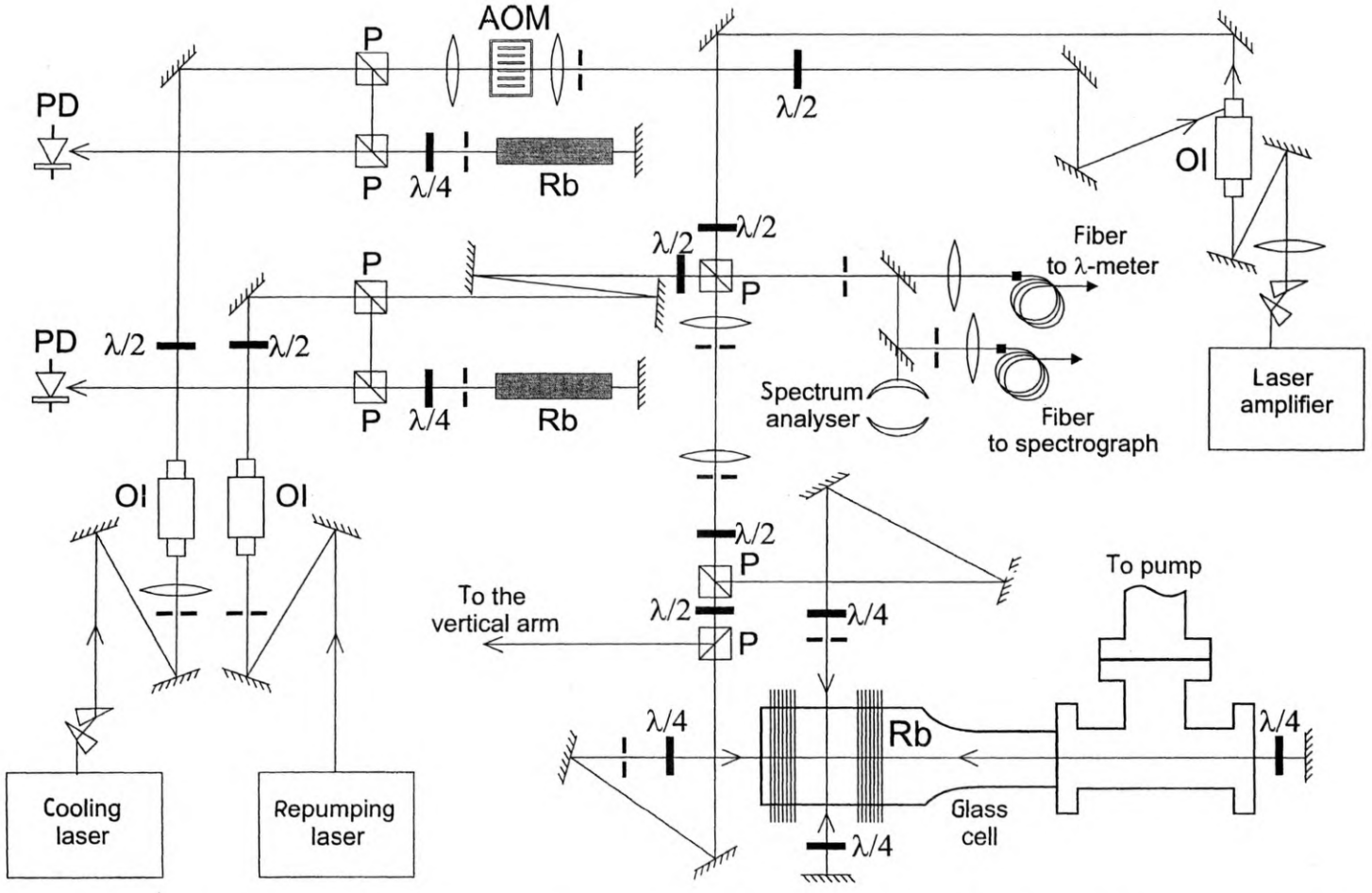

Fig. 3. Scheme of optical set-up of the magneto-optical trap. OI – optical isolator, PD – photodiode, AOM – acousto-optical modulator, P – polarisation beam splitter, $\lambda/2$ and $\lambda/4$ – phase plates, gray rectangles – cells with Rb vapours

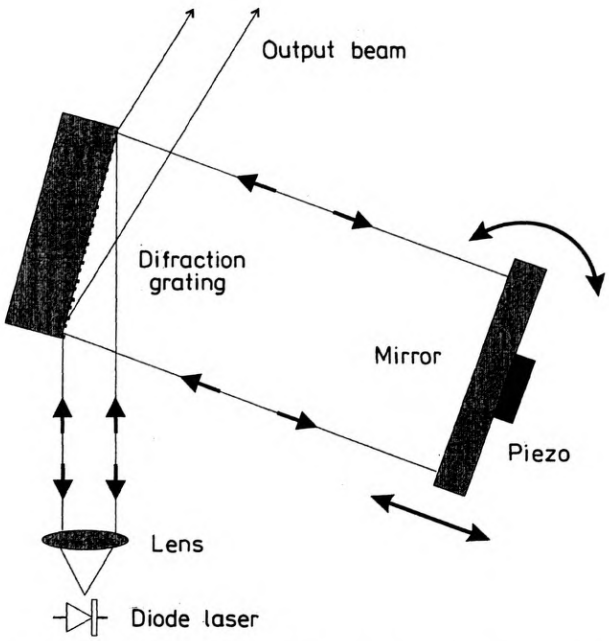

Fig. 4. Diode laser with external optical resonator in Littman–Metcalf scheme

mirror fixed to a piezoceramic element (Fig. 4). The emission frequency of the diode is controlled by the current flowing through the junction and by its temperature. External resonator narrows the emission line (the estimated spectral width of the laser is below 1 MHz) and allows for a broad tuning of the laser: the coarse tuning is done by turning the mirror and fine tuning results from a precision change of the resonator length.

Laser beam has an elliptic cross-section, it is, therefore, corrected by two anamorphic prisms, which circularise the beam shape. The beam is formed by a long focal-length lens and passes an optical isolator (Isowave, I-80-T5H) to avoid any influence of reflections on the laser frequency. The beam is then split and a very low intensity part is directed into the frequency stabilisation system (Fig. 5).

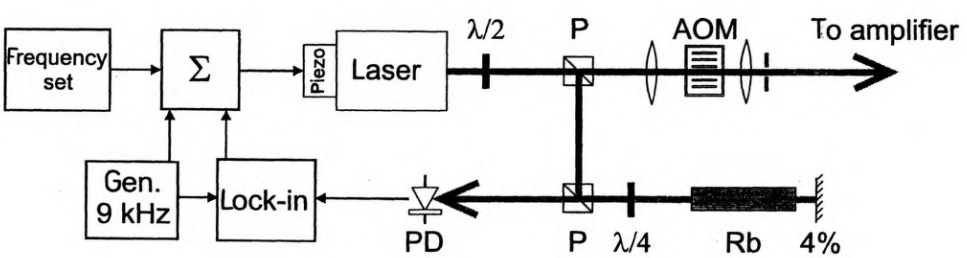

Fig. 5. Scheme of the laser frequency stabilisation system

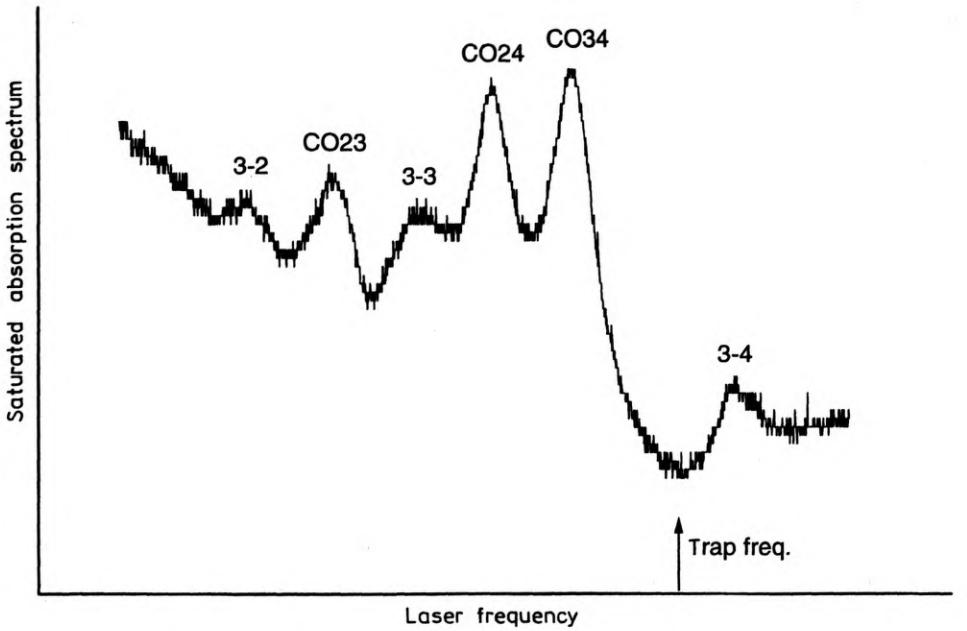

Fig. 6. Central part of the saturated absorption spectrum of the $5^2S_{1/2}\,F = 3 \rightarrow 5^2P_{3/2} = F' = 2, 3, 4$ transition

This stabilisation system forms a standard saturated spectroscopy set-up [5], which produces a Doppler-free spectrum of the atomic line, with the resolution given by the natural width of the atomic transition, which for Rb is 5.9 MHz (Fig. 6). Low amplitude modulation at 9 kHz frequency is applied to the piezo transducer, which produces a slight modulation of the laser frequency. The saturated absorption signal is fed to the lock-in amplifier and we thus get a signal, which is a derivative of the absorption versus frequency function. This signal may be used as an error signal in the feedback system. After amplification this signal is fed to the piezoceramic. For a proper cooling and trapping the laser should be red detuned (*i.e.*, shifted towards lower frequencies) from the exact resonance by a few natural widths. Unfortunately, this part of the spectrum has no feature which we could lock to. Therefore, the cooling laser is stabilised to the so-called cross-over resonance between transitions $F = 3 \rightarrow F' = 4$ and $F = 3 \rightarrow F' = 2$ in the saturated absorption spectrum (CO24 in Fig. 6), *i.e.*, 92 MHz below the frequency of the cooling transition $F = 3 \rightarrow F' = 4$ and an acousto-optical modulator is used. The acousto-optical modulator (Isomet, 1205C-2) deflects the laser beam on an acoustic wave in a crystal and causes a frequency shift equal to the modulation frequency. In our experiment the modulation frequency is set to 74 MHz, so that the final detuning of the cooling laser from the atomic transition frequency is 18 MHz which corresponds to about 3Γ.

The laser diode of the oscillator (Sharp, LT024MDO) can deliver up to 20 mW of power, but all the elements in the set-up: external resonator, prism extender, stabilisation system, modulator cause that the useful output power does not exceede

5 mW. Because higher power is required for a trouble-free operation of the trap, the output beam must be amplified. We use another diode laser (Hitachi, HL7851G) as an amplifier; it works without cavity and can deliver up to 50 mW of power with the spectral width of the laser line (free running) of about 10 MHz. This diode is first tuned by a proper choice of temperature and current to the close vicinity of the cooling laser frequency and then is locked to it by injection of the cooling laser beam into the amplifier. When amplifier is injection locked, its spectral width becomes as narrow as the oscillator's width, while the useful power of the amplifier (after expansion and optical amplification) is at least 40 mW.

The repumping laser does not require much power, its construction is analogous to the cooling oscillator, it is stabilised to the cross-over resonance between the $F = 2 \rightarrow F' = 3$ and $F = 2 \rightarrow F' = 2$ transitions.

We have a triple system to monitor the laser frequency and spectral purity with different resolutions. The first one is a 2 m grating spectrograph (Zeiss Jena, PGS2); laser light is coupled to the spectrograph via a plastic optical fibre, and the spectrum is registered by a miniature TV camera with a CCD matrix. With this spectrum in sight we perform the coarse tuning of the laser to the desired transition (accuracy ± 0.04 nm) and check whether the laser emission is really monomode. On the second level of accuracy is a commercial lambdameter (Burleigh, WA4500) with ± 0.0001 nm resolution and direct wavelength display, but not working properly when laser radiation is not single mode. Light is coupled to the lambdameter also via a fibre, this time a standard quartz one. Finally, a spectrum analyser – scanning confocal Fabry–Perot interferometer – is used to give information on the spectral width of laser radiation (COBRABiD, KB6316, 1.5 GHz free spectral range, finesse of about 100). Final tuning to the chosen hyperfine component of the line is accomplished while observing a Doppler-free spectrum like the one in Fig. 6.

3.2. Vacuum cell

Trapping of rubidium atoms is performed in a rectangular glass cell ($30 \times 30 \times 50$ mm) attached to a metal vacuum apparatus. The apparatus is first evacuated to high vacuum (10^{-9} mbar) with a turbomolecular pump, then the pump is detached from the apparatus, and the system is further pumped by a small ion pump (Physical Electronics, 11 l/s). A valve connects the system to a container with metallic Rb; by opening or closing this valve rubidium vapour pressure in the cell is controlled. The saturated vapour pressure of Rb in room temperature is more than enough to allow the filling of the trap by capturing the slowest atoms from the thermal velocity distribution.

We first allowed for a higher Rb pressure in the cell (determined by the saturated vapour pressure at room temperature) which was convenient for the adjustment of trap beams, because the rubidium fluorescence along the beams could then be observed by the infrared viewer or a CCD camera. For the efficient trap operation, this pressure is too high, we therefore opened the pump valve and decreased the Rb pressure in the cell.

3.3. Magnetic field and trapping beams

The trap magnetic field has a quadrupole configuration and is produced by two coils of 60 mm diameter at 38 mm distance from each other, where currents flow in opposing directions. This set-up produces a gradient of the field, which at 2 A of current amounts to 6 G/cm along the coils axis and a half of that in two orthogonal directions.

The laser beam from the laser amplifier and the beam from the repumping laser are superimposed with good accuracy, expanded in a telescopic system to some 10 mm diameter, and then divided by the polarising beam splitters into three beams propagating in three orthogonal directions. The balance of power in all three arms is controlled by the half-wave plates placed in front of the beam splitters. Each beam is circularly polarised by the quarter-wave plates. The beams propagate through the cell and are retroreflected, additional quarter-wave plates inserted in the beams provide the proper polarisation of the return beams. As our cell is not antireflection coated, the inevitable losses of power are compensated by a slight convergence of the beams, so that the power density of the forward and backward propagating beams are equal and amount to 200 $\mu W/mm^2$, which corresponds to the saturation parameter of about 12.

3.4. Observation of trapped atoms

Trapped atoms are constantly excited by light beams and reemit resonance fluorescence light. They can be thus observed (the D_2 line of Rb has a wavelength of 780 nm and detectors for close infrared are required). A spectacular effect is the appearance of a cloud of cold atoms a fraction of a second after the switch-on of the inhomogeneous magnetic field of the trap. Without this field, atoms in the intersection of the beams are cooled only but not trapped and form the so-called optical molasses. At our initial density of atoms the fluorescence of the molasses region is too low to be recorded and the cell centre remains dark. After the field is switched on, the concentration of atoms increases and a bright, well localised point appears in the trap centre (Fig. 7). One can study the temporal behaviour of the cloud fluorescence at switching on and off of the trap and deduce from this the trap parameters (see our web page: silly.if.uj.edu.pl/mot for a display of the trap filling dynamics).

4. Trap parameters

Some 10^6 to 10^8 atoms can be trapped in the magneto-optical trap in the cloud of a size of a fraction of millimetre (the actual size depends on the magnetic field gradient, on intensities of laser beams, and on the number of trapped atoms). The atomic density in the trap is limited to some 10^{11} cm^{-3}; this limit is due to the nature of the trapping forces and not due to interatomic interactions of the type encountered in condensed phase. At such high density the atomic cloud ceases to be an optically thin medium, the cooling beams are strongly absorbed in the cloud. An

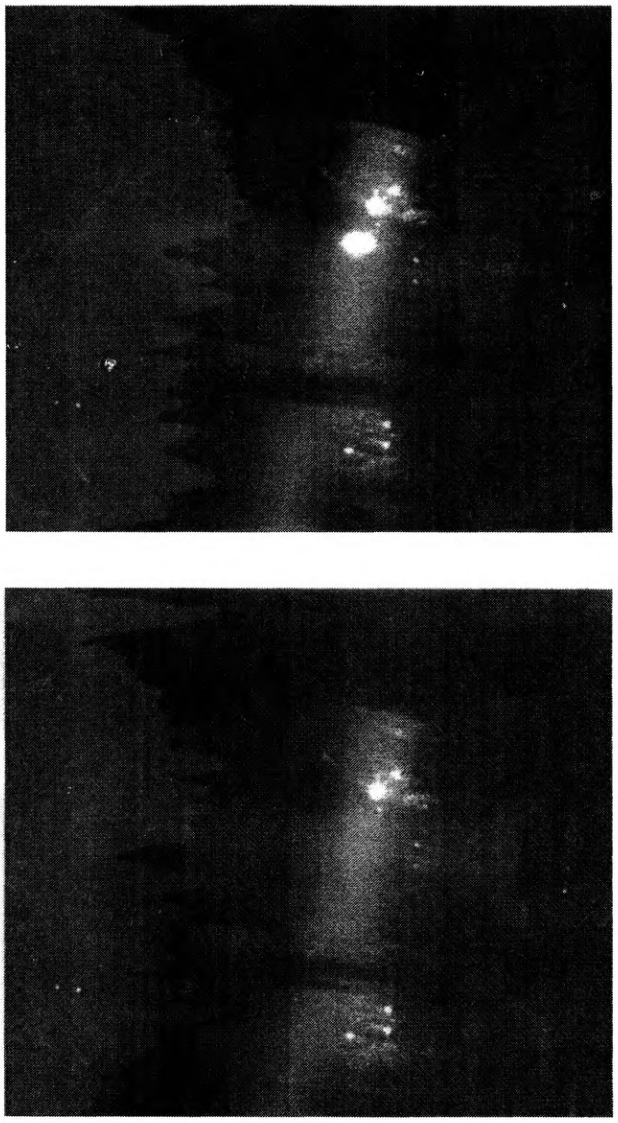

Fig. 7. Camera view of the trap with the magnetic field on and off. In the upper picture a bright cloud of trapped atoms can be seen, in the lower one only the reflections in the cell are visible. The parameters are such as to see the fluorescence of the beams in the cell

important role is played by the light scattered by trapped atoms, which can be reabsorbed inside the cloud. Thus, apart from the compressing mechanism, one has an interatomic repulsion and the balance of these two sets the limiting density.

A typical temperature for the atoms in a trap is in sub-millikelvin range. The limit is given by a statistic character of the cooling process, where the mean atomic velocity tends to zero, but the dispersion of the velocity distribution increases.

Measurements of the temperature in our trap have not been performed yet, but the early estimates give the value close to the so-called Doppler-limit temperature which for Rb is 140 μK.

5. Conclusions and outlook

The construction of a trap is a difficult task, no matter how well it is described in literature. A serious constraint is a high cost of all the required equipment. Three or four lasers (including also an independent laser for detection) are needed, together with very stable current sources and thermostatic systems capable of keeping the 0.01 K temperature stability. A high mechanical stability is required in resonator construction, which must be tunable yet stable. To lock the laser frequency to the atomic transition, techniques of high resolution laser spectroscopy are required and an electronic system must be constructed with low noise and drifts. For the efficient use of acousto-optical modulators in precise tuning of the laser frequency the electronic radio-frequency techniques (100 MHz, up to 1 W) must be mastered. The whole optical set-up (see the scheme in Fig. 3) must be constructed with elements of very good quality, low losses, and high polarisation qualities. Without that it would be impossible to obtain beams of well controlled intensity, polarisation, ans spatial purity. Finally, we must mention ultrahigh vacuum apparatus and computers to control some of the parameters of the experiment.

The first plans of further work with our trap are connected with precise measurements of the trap parameters including the temperature, density and number of trapped atoms. Further experiments aim at non-linear optical effects for cold atoms. Since trapped atoms have low velocities and negligible Doppler broadening of spectral lines, we believe that we will be able to observe some subtle effects in interaction of atoms with light. Another field of interest are collective effects in the cloud of cold atoms. We intend to study the possibility of obtaining higher densities of atoms in the trap, without the limits imposed by radiation trapping and study behaviour of the cloud upon periodical modulation of trap parameters.

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