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A system for magnetooptical cooling and trapping of Rb atoms

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A system for magnetooptical cooling and trapping of Rb atoms built in our laboratory (at Institute of Physics, Polish Academy of Sciences) is briefly discussed. Emphasis is put on some parts of the apparatus designed and constructed in our lab. An arrangement for experiment control (*e.g.*, data acquisition sequence combined with digital laser frequency tuning) is presented.

Keywords: magnetooptical trap, cold Rb atoms, instrumentation.

1. Introduction

Systems for producing cold neutral atomic samples provide great opportunities for studying the behaviour of atoms in unusual experimental conditions [1, 2]. Due to the slow velocity, low kinetic energy, low rate of collisions, and storage of a large number of atoms at sufficiently high density, clouds of cold atoms establish fascinating environment for novel experiments. Taking advantage of the unique properties of cold atoms, and the development of cooling and trapping techniques, a vast progress has recently been observed in many fields of modern atomic and quantum physics, such as *e.g.*: quantum degenerate systems (with spectacular production of Bose–Einstein condensates (BEC)), atomic optics, cold collisions [3], atomic clocks, high resolution spectroscopy, quantum interference effects [4, 5] and others (see also recent monographs [6, 7]).

The backbone system, widely used for cooling and trapping neutral atoms is the one employing both optical and magnetic fields, to make a magnetooptical trap (MOT)

[8, 9]. In Poland, first MOT has been built in the group of W. Gawlik at the Jagiellonian University, Cracow, Poland [10] and applied in several studies [11].

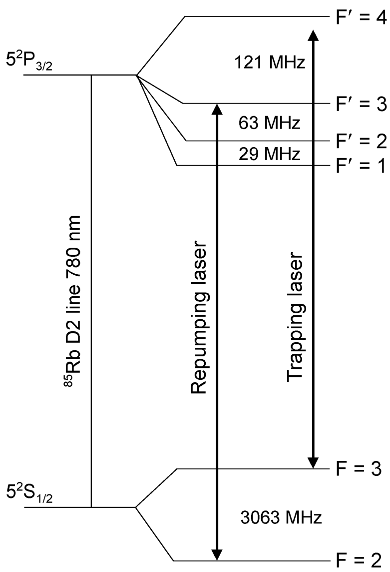


Fig. 1. Energy level diagram of the ^{85}Rb atom. The hf structure of the *D*2 line used in the cooling of ^{85}Rb atoms is shown. Red detuned trapping laser and resonant repumping laser are marked by arrows.

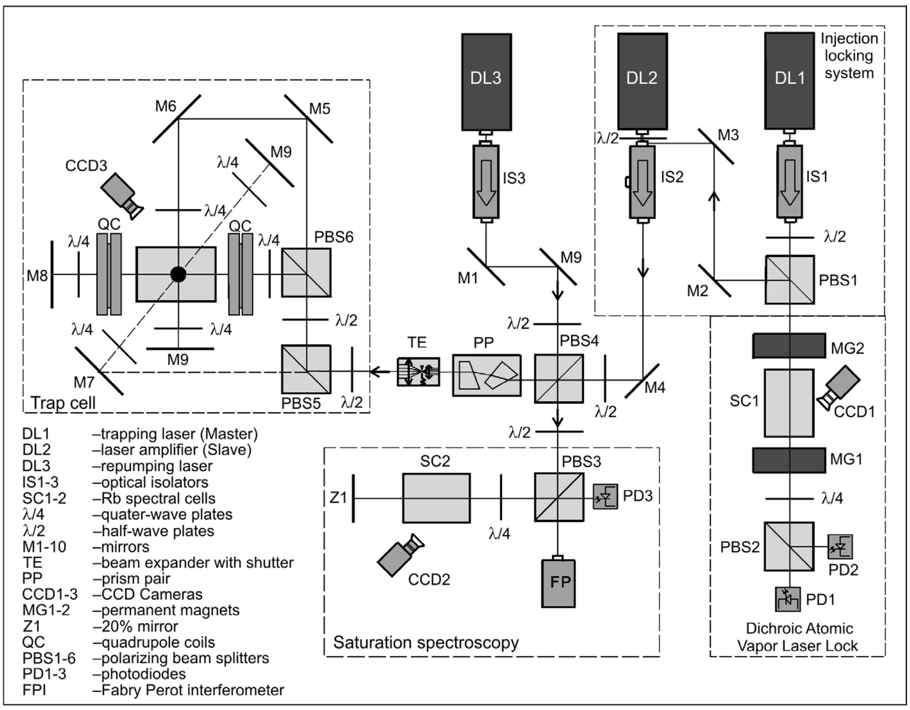


Fig. 2. General scheme of the magnetooptical trap. Essential blocks are marked with a dashed line.

In this report, we present a magnetooptical system for the cooling and trapping of neutral Rb atoms built in our laboratory at the IP PAS. In particular, the components developed or constructed for this purpose are described in some detail. Emphasis is also placed on the description of the system for data acquisition and control of the experiment.

2. System description

The use of momentum transfer between the atoms and radiation field resonant with an atomic transition constitute a basis of cooling process. With additionally applied quadrupole magnetic field, the action of both the velocity-dependent and spatially dependent forces induce cooling and confinement of atoms in the trap. An energy level diagram showing the hf structure of the *D*2 line used in the cooling of ^{85}Rb atoms is given in Fig. 1. A general scheme of the arrangement presented is depicted in Fig. 2. Since the system can be used for both ^{85}Rb and ^{87}Rb isotopes, for simplification purposes we will limit our presentation to the more abundant ^{85}Rb isotope.

2.1. Vacuum chamber

The cooling of the atoms is performed in a quartz cell. It consists of three perpendicularly intersecting tube sections (50, 30 and 30 mm in diameter, respectively, wall 2.5 mm in thickness) with 6 windows (3 mm in thickness) welded at the ends. The small glass vessel equipped with electrical feedthroughs and three Rb dispensers (FT-type, SAES Getters, natural abundance of isotopes) is attached to the cell and serves as a source of Rb atoms. A resistively heated (usually with a 3.5 A current) dispenser releases atoms at a rate enabling stable operation of the trap. The cell is connected with a 0.6 m long Pyrex glass tube of 50 mm in diameter to the vacuum system with ion pump (ZPK-20, Unitra). Since ultra-high vacuum is needed for proper functioning of the trap, before its first use the entire system was thoroughly outgassed at a high temperature by prolonged (*ca* 3 weeks long) pumping with turbomolecular, and later with sorption and ion pumps. The vacuum, as determined from the current of continuously working ion pump, is better than 10^{-8} torr.

The cell is situated in the center of magnetic coil system. Three pairs (the biggest one of 1 m in diameter) in Helmholtz configuration compensate the Earth and stray magnetic fields. Large coils are used to assure easy access to the cell. One pair (of 8 cm in diameter) in anti-Helmholtz configuration produces a quadrupolar field distribution, necessary for the confinement of atoms, with gradient up to 40 Gs/cm. All coils are fed from a single, steered by a microprocessor, high-stability current supply built in our lab. The controller allows the field to be rapidly switch off.

2.2. Laser system

In Figure 2 a scheme of the optical part of the trap is shown. Two commercial extended cavity diode lasers (ECDLs) (type DL100, TuiOptics-Toptica) in Littrow mount with 1800 mm^{-1} diffraction gratings (DL1, DL3), and a home made one (DL2) comprise a laser system. Sanyo laser diodes (model DL-7140-201, power 70 mW) are used. The lasers DL1 and DL2 work in a master-slave injection locking configuration [12, 13]. The radiation of DL1 (oscillator or master), spectrally narrowed (linewidth below 1MHz) by the feedback from a diffraction grating and stabilised into desired frequency, is injected into the cavity of DL2 (amplifier or slave). Providing proper tuning of the slave, it assumes the spectral properties of the radiation originating in the master, delivering a meaningly amplified output. The injection is performed with a polarising beam splitter cube and a half-wave plate. The amount of light injected into the slave, as well as the final amplified output power can be varied by rotating the half-wave plate ($\lambda/2$). A compromise between both values is necessary for optimal performance. The method, although not very efficient (loss of power), proved to be useful and satisfactory. Light from this laser-tandem, red detuned by 1–2 Γ below the $5^2S_{1/2}(F = 3) \rightarrow 5^2P_{3/2}(F' = 4)$ resonance ($\Gamma = 6$ MHz is the natural linewidth of transition), is used for cooling and trapping (compare Fig. 1). The third laser (DL3), free running at this stage, serves as a repumper. Its radiation resonant with the $5^2S_{1/2}(F = 2) \rightarrow 5^2P_{3/2}(F' = 3)$ transition counteracts the loss of atoms from the cooling cycle towards the non-detectable lower $5^2S_{1/2}(F = 2)$ hyperfine state. All lasers are protected from return signals by double (60 dB) optical isolators (Gsänger). Both trapping (40 mW) and repumping (15 mW) beams are combined to co-propagate on the polarising beam splitter, spatially reshaped with anamorphic prism pair, and expanded with a telescope to a diameter of 17 mm. Subsequently, the beam is split into three mutually perpendicular, retro-reflected beams, of the same intensities and proper circular polarizations intersecting in the center of the cell.

2.3. Frequency stabilization and control

A system for the laser frequency control consists of parts shown schematically in Fig. 3: i) frequency stabilization and tuning unit based on the dichroic atomic vapor laser lock (DAVLL) scheme [14], ii) frequency control unit based on the Doppler-free saturated absorption spectrometer, and iii) relevant electronic functional systems.

Re i): The method makes use of induced circular dichroism (different absorption for different circular polarisations). Linearly polarised laser beam passes through Rb vapor cell placed in an axial magnetic field (*ca* 50 G) produced by toroidal permanent magnets. After passing the cell, two circular components σ_+ and σ_- are converted into two orthogonal linear polarizations, and separated on the polarizing cube beam splitter. Respective signals from photodiodes are subtracted. The difference signal from the DAVLL is compared to the adjustable reference in the servo lock circuits (consisting of operational amplifiers and PID controller), resulting signal is applied to the piezoelectric transducer of the ECDL grating, the grating is tilted and tuning frequency of the master. By varying an external reference voltage the frequency is tunable within ±100 MHz limits from the center of gravity of the Doppler broadened $5^2S_{1/2}(F = 3) \rightarrow 5^2P_{3/2}(F' = 2, 3, 4)$ resonances. With laser lock off, an adjustable offset voltage is used for coarse frequency setting. DAVLL method provides a high frequency stability (not dependent on laser intensity fluctuations and with very broad

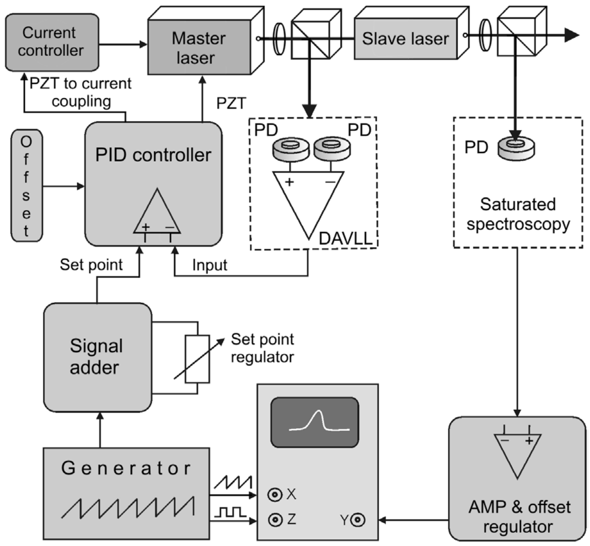


Fig. 3. Scheme of the system for laser frequency stabilization and control. For explanation see the text.

locking range), and does not require laser frequency modulation. Relying on the Doppler broadened transitions, however, the DAVLL scheme does not allow us to observe (and halt at) any characteristic spectral features. Therefore, an accompanying method is necessary to determine the right frequency.

Re ii): Fraction of the (amplified) laser power is sent into a saturated absorption spectrometer arrangement. The detected signal containing both the true Doppler-free and cross-over resonances is visualised on the oscilloscope working in XY(Z) mode. While the output of the (multichannel, with independently adjustable amplitudes) sawtooth generator is fed to X channel, the saturated absorption signal is fed to the Y channel. Simultaneously, another generator output summed up with offset voltage makes up reference for the DAVLL unit. Channel Z is used to switch off the oscilloscope spot, when in return trace. By manipulating (proper tuning) the offset voltage and reducing the sawtooth amplitude to zero, the desired frequency of the laser can be precisely selected and stabilised.

Re iii): Most of the electronic circuitry used in the frequency control arrangement were built in our lab. Besides the above mentioned components, they include precision analog signal adders and offset regulators, signal amplifiers and precision voltmeter.

2.4. A system for digital frequency tuning and data acquisition

The actual measurements in the cloud of cold atoms can be performed in the steady state of the trap (fields on) or in the transient state (after switching off the trapping optical and/or magnetic fields). To facilitate acquisition of experimental (analog) signals, a multipurpose, multichannel, versatile system DMS200 was built (Fig. 4). It allows digital tuning of the laser frequency and acquisition of the measurement

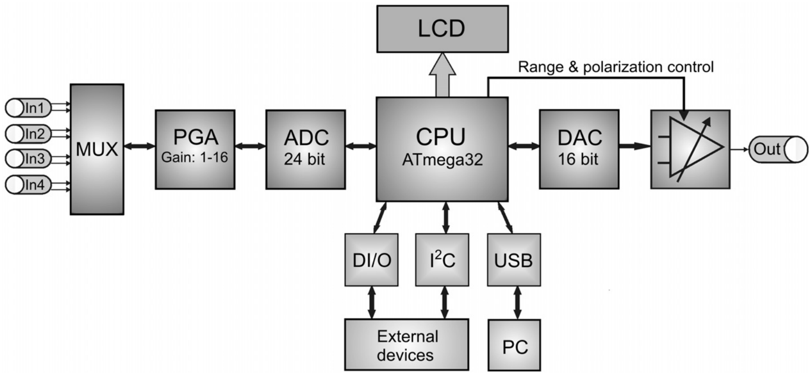


Fig. 4. Functional diagram of the DMS200 system for data acquisition, digital laser frequency tuning and control of the experiment: MUX – 4 channel analog multiplexer, PGA – programmable gain amplifier, ADC – 24 bit analog to digital converter, CPU – ATmega32 microcontroller, DAC – 16 bit digital to analog converter, DI/O – 4 digital output lines and 2 digital input lines, I^2C – two wire bus, USB – universal serial bus, LCD – 4 line LCD display.

data. The system consists of two converters: i) A/D of a very high 24 bit resolution, with 4 channel multiplexer, and the PGA (Programmable Gain Amplifier) unit in the input (type ADS1211, Burr–Brown), and ii) D/A of 16 bit resolution (type DAC8571, Burr-Brown). Both converters are steered by a micro-controller (type ATmega32, Atmel) connected via USB port to a PC. Applying the micro-controller increases enormously the potential for operating the experiment. By preparing the software code adapted to particular experimental needs, the timing sequence can be precisely established (with μs accuracy). Such accuracy is usually not available in most of measuring systems based on the Windows platform. For experiments with cold atoms requiring the absence of trapping fields, this problem can be of special importance since, after the fields are switched off (in a shortest time possible, which in the case of magnetic coils requires great care in electronic circuitry) the sample remains "frozen" (*i.e.*, without significant cloud expansion) only for *ca* 10 ms interval. In this transient period the actual measurement has to be performed, lasers switched on and frequency advanced.

A simplified flowchart of the main program of the microcontroller is shown in Fig. 5. The DMS200 allows also for time resolved measurements. As an example, a dependence of the number of trapped atoms on the time after switching on the trap is shown in Fig. 6**a**. The number of atoms in a steady state (given by the balance between loading and loss rates) in this measurement amounted to 10^7. This number was recalculated from the measured (calibrated) fluorescence intensity [15]. In Fig. 6**b**, an image of the cloud of cold ^{85}Rb atoms (its actual size being close to 1 mm, the picture taken from the CRT monitor screen), as seen by CCD camera, is presented.

The voltage used for frequency tuning can be selected in the ±15 V range. It allows tuning both the ECDL and the VCO (voltage-controlled oscillator) used for driving the acoustooptical modulator (AOM). When tuning an ECDL, the increased

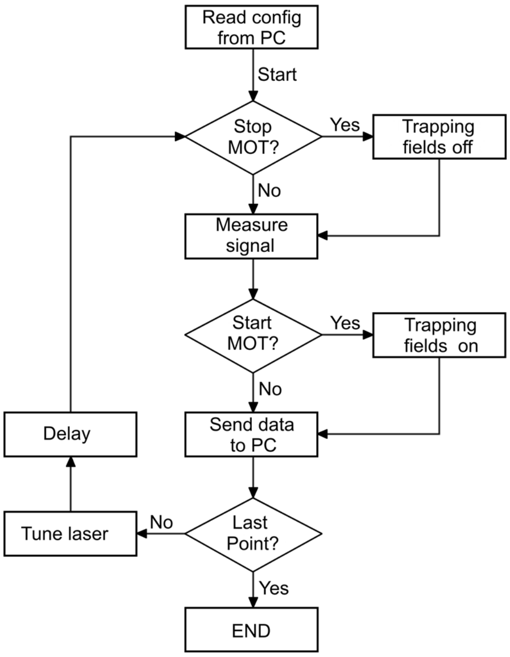
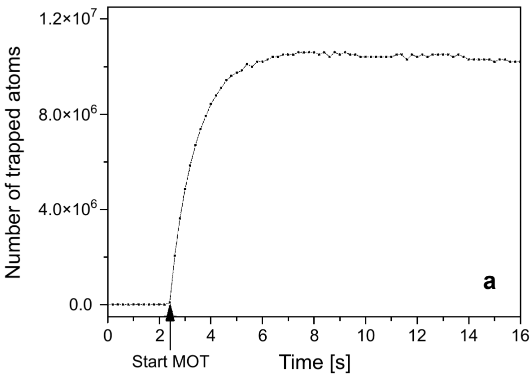


Fig. 5. The simplified flowchart of the main program of the microcontroller, steering the DMS200 system (a measurement on MOT with tuning laser wavelength).



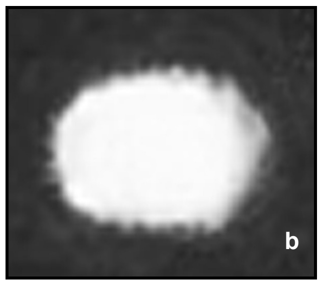


Fig. 6. Number of trapped atoms as a function of time elapsed from the switch on the trap – **a**. Image of the cloud of cold ^{85}Rb atoms), as seen by CCD camera (its actual size is close to 1 mm, the picture was taken from the TV screen) – **b**.

probability of mode-hopping at the beginning and at the end of frequency scan was noticed. We discovered, that it was due to rapid changes (jumps) of the tuning voltage when the start value differed from zero, and after the scan ended when voltage returned to its initial value. The problem was solved by supplying additional routine to the microcontroller code, which accomplishes a single voltage change as consecutive series of small steps. The DMS200 is additionally equipped with an I^2C output bus in order to enable future steering of the AOM by an PLL synthesizer module based on the TSA6057 integrated circuit.

3. Summary and plans

Many components of the MOT presented were designed and built entirely in our lab. We have tested the system and dependence of its performance on several parameters, such as beam intensity and diameter, field gradient, laser detuning. We also gained a working knowledge about the setup. Our trap proved to be reliable and efficient. Several improvements are underway, such as: adding a new home made ECDLs with current- and temperature-controllers, implementation of the AOMs for very precise frequency tuning, and the Pockels cell as a fast switch, improvement of the stabilisation system [16], development of the detection and diagnostic systems.

Our nearest goals include a study of electromagnetically induced transparency (EIT) in the low Rydberg states of cold Rb [4].

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References

[1] ADAMS C.S., RIIS E., *Laser cooling and trapping of neutral atoms*, Progress in Quantum Electronics **21**(1), 1997, pp. 1–79.

[2] BALYKIN V.I., MINOGIN V.G., LETOKHOV V.S., *Electromagnetic trapping of cold atoms*, Reports on Progress in Physics **63**(9), 2000, pp. 1429–510.

[3] WEINER J., BAGNATO V.S., ZILIO S., JULIENNE P.S., *Experiments and theory in cold and ultracold collisions*, Reviews of Modern Physics **71**(1), 1999, pp. 1–85.

[4] HOPKINS S.A., USADI E., CHEN H.X., DURRANT A.V., *Electromagnetically induced transparency of laser-cooled rubidium atoms in three-level Λ-type systems*, Optics Communications **138**(1–3), 1997, pp. 185–92.

[5] GU S., BEHR J.A, GROVES M.N., DHAT D., *Coherent population trapping states with cold atoms in a magnetic field*, Optics Communications **220**(4–6), 2003, pp. 365–70.

[6] METCALF H.J., VAN DER STRATEN P., *Laser Cooling and Trapping*, Springer, New York 1999.

[7] WEIDEMÜLLER M., ZIMMERMANN C. [Eds.], *Interactions in Ultracold Gases*, Wiley-VCH, Weinheim 2003.

[8] RAAB E., PRENTISS M., CABLE A., CHU S., PRITCHARD D., *Trapping of neutral sodium atoms with radiation pressure*, Physical Review Letters **59**(23), 1987, pp. 2631–4.

[9] MONROE C., SWANN W., ROBINSON H., WIEMAN C., *Very cold trapped atoms in a vapor cell*, Physical Review Letters **65**(13), 1990, pp. 1571–4.

[10] ZACHOROWSKI J., PAŁASZ T., GAWLIK W., *Magneto-optical trap for rubidium atoms*, Optica Applicata **28**(3), 1998, pp. 239–48.

[11] BRZOZOWSKI T.M., BRZOZOWSKA M., ZACHOROWSKI J., ZAWADA M., GAWLIK W., *Probe spectroscopy in an operating magnetooptical trap: The role of Raman transitions between discrete and continuum atomic states*, Physical Review A **71**, 2005, p. 013401.

[12] SNADDEN M., CLARKE R.B.M., RIIS E., *Injection-locking technique for heterodyne optical phase locking of a diode laser*, Optics Letters **22**(12), 1997, pp. 892–4.
[13] GOLDBERG L., TAYLOR H.F., WELLER J.F., BLOOM D.M., *Microwave signal generation with injection -locked laser diodes*, Electronics Letters **19**(13), 1983, pp. 491–3.
[14] CORVIN K.L., LU Z.-T., HAND C.F., EPSTEIN R.J., WIEMAN C.E., *Frequency-stabilized diode laser with the Zeeman shift in an atomic vapor*, Applied Optics **37**(15), 1998, pp. 3295–8.
[15] TOWNSEND C.G., EDWARDS H.T., COOPER C.J, ZETIE K.P., FOOT C.J., STEANE A. M., SZRIFTGISER P., PERRIN H., DALIBARD J., *Phase-space density in the magnetooptical trap*, Physical Review A **52**(2), 1995, pp. 1423–40.
[16] WĄSIK G., GAWLIK W., ZACHOROWSKI J., ZAWADZKI W., *Laser frequency stabilization by Doppler -free magnetic dichroism*, Applied Physics B: Lasers and Optics **75**(6–7), 2002, pp. 613–9.

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