CHAPTER 3

PREPARATION OF COLD ATOMS

A usual pathway starts with preparing a sample of cold atoms. To do that, the apparatus for cooling and trapping ^{85}Rb atoms was constructed at the Quantum-Atom Optics (QAO) Laboratory. The main parts of the apparatus and their construction are described in Section 3.1 of this chapter. The standard technique, magneto-optical trap (MOT), was used for preparing the cold ^{85}Rb atoms. Fluorescent imaging system provided the capability to detect the cold MOT atoms as detailed in Section 3.2.

3.1 Apparatus setup for preparing cold ^{85}Rb atoms

For getting the cold ^{85}Rb atoms with the long trapping lifetime, we need to minimize an external disturbance by keeping them in a high vacuum chamber (Section 3.1.1). Inside the chamber, the pre-cool released Rb atoms from Rb dispensers were slowed down and confined by MOT (Section 3.1.2) of which the configuration consists of laser systems and a pair of magnetic anti-Helmholtz coils.

3.1.1 Vacuum system

The MOT cloud was generated inside a high vacuum chamber called "science chamber." The chamber was connected to a set of vacuum pumps as shown in Figure

3.1. The science chamber made from the Synchrotron Light Research Institute (Part No.: SLRI-SW-CMU-540089) had a diameter of 280mm and a height of 190mm. It had two large ports of an 8-inch ConFlat (CF) flange and eight small ports of a 2¾-inch CF flange. One of the small ports was fitted with the Rb dispensers for ejecting Rb atoms into the chamber; another small port was connected with the series of the vacuum pumps; and the rest was fitted with the MDC zero profile viewports (Part No.: 450008 and 450002) for optical accessibility. The viewports have the flat optical windows that allow us to apply the cooling beam into the chamber. When the beams were incident, the cold ^{85}Rb atoms were accumulated inside the chamber where the two magnetic coils were mounted outside on the two big ports (not shown in the figure).

For the atomic source, the dispensers made from SAES (Part No.: RB/NF/3.4/12 FT10+10) were used to provide natural Rb atoms, which consisted of approximately 77.2% ^{85}Rb and 27.8% ^{87}Rb. As seen in Figure 3.2, the three dispensers were mounted with a MDC electrical feedthrough (Part No.: 9452014). The electric current of 6 Amps was applied to the dispensers for about 30s. Due to heating of the current applying, the dispensers released Rb atoms into the science chamber that made the pressure increased from the order of 10^{-9} to 10^{-5} Torr. Then the current was reduced to 3 Amps and kept at this value along the time of loading MOT. At this stage, the pressure was in the order of 10^{-8} Torr.

As mentioned before, the science chamber was connected to a high vacuum system. The two pumps, an Edwards Dry Scroll Pump (Part No.: A72401903) and an Edwards EXT Turbomolecular Pump (Part No.: B72242000), were used for pumping all of the volume starting from the atmospheric pressure. To connect this low vacuum part to the high vacuum one, the turbo pump was attached to the manual valve. An Edwards Pirani Gauge (Part No.: D02601000) was mounted at the other

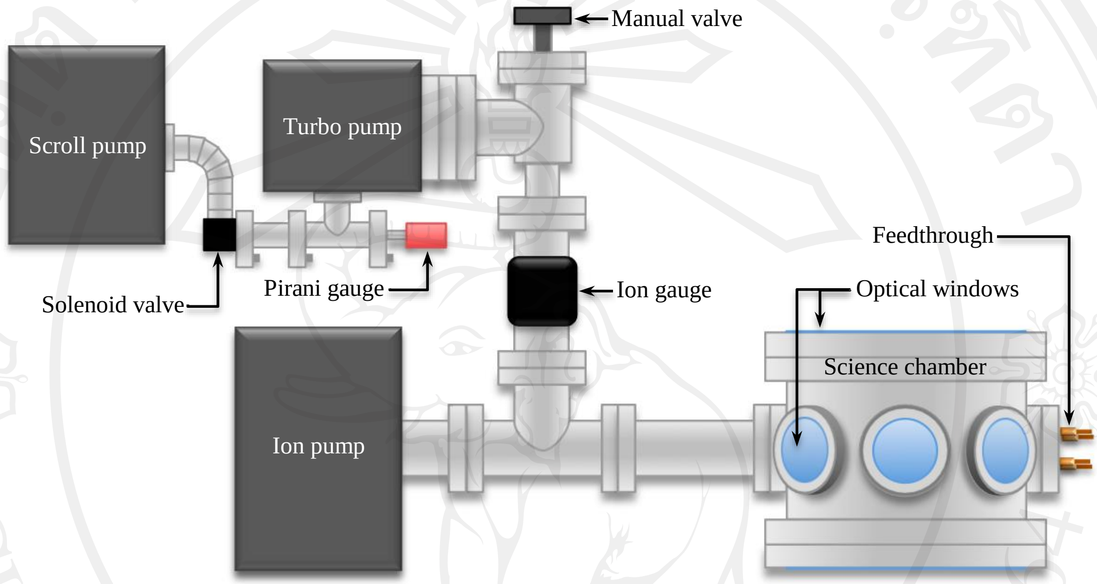

Figure 3.1. Top-view schematic of the vacuum system shows the science chamber connected with pumps, gauges, valves, and electrical feedthrough.

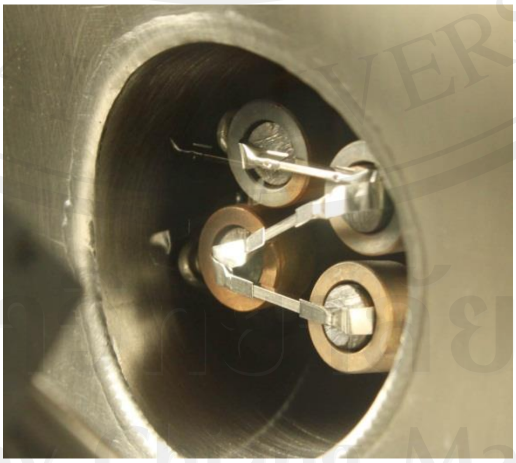

Figure 3.2. Three dispensers mounted with the electrical feedthrough inside the science chamber. This figure is reproduced from [45].

end of the turbo pump for measuring the low vacuum pressure. Edwards Solenoid Valve (Part No.: C41752000) was then connected to the gauge following with the scroll pump as shown in the figure.

The vacuum relied on a Varian Valcon Plus 40 Diode Ion Pump (Part No.: MC-INV-10-11-0118) where the pressure was directly read out from a Provac Ion Gauge (Part No.: MC-INV-10-11-0118). The ion pump was operated continuously for keeping the pressure of the system at high vacuum, which was around 6×10^{-9} Torr. However, the ion pump could be employed only when the pressure was below the limit of 7.5×10^{-3} torr. Thus the other two pumps were needed for operating at the low vacuum pressure. A Kurt J. Lesker Manual Valve (Part No.: SA0150MV CF) was used for isolating these two pumps from the high vacuum part.

When all parts of the vacuum chamber were assembled, the scroll pump of which an ultimate vacuum is 5.3×10^{-2} torr was firstly turned on. After the vacuum pressure reached the limit of the scroll pump, the turbomolecular pump was turned on for further pumping. The stainless parts of the chamber were baked to 170 ºC for 3 days while both pumps were operating for eliminating the contaminants inside the entire system. When the pressure of the chamber was reached the order of 10^{-6} torr, the ion pump was turned on, the manual vale was closed, and the turbomolecular pump and the dry scroll pump were turned off. With the ion pump alone, the pressure was reduced to 6×10^{-9} Torr with out any vibration.

3.1.2 Loading atoms into MOT

As introduced in Chapter 2, the MOT is used as a standard technique for cooling down atoms from the room temperature. This technique relies on the cooperation of the red-detuned laser light and the quadrupole magnetic field that provides the spatial confining force for trapping the atoms. In this section, two laser systems and a magnetic system used for experimentally realizing MOT are detailed.

The frequency of lasers employed in MOT scheme has to be locked near selected transitions of ^{85}Rb atoms. The hyperfine energy levels corresponding to the D2-line transitions are as illustrated in Figure 3.3. In MOT operation, there are two necessary lasers of which the frequencies with relevant atomic transitions are also shown in the figure. The first one is a MOT cooling laser locked to the $F = 3 \rightarrow$

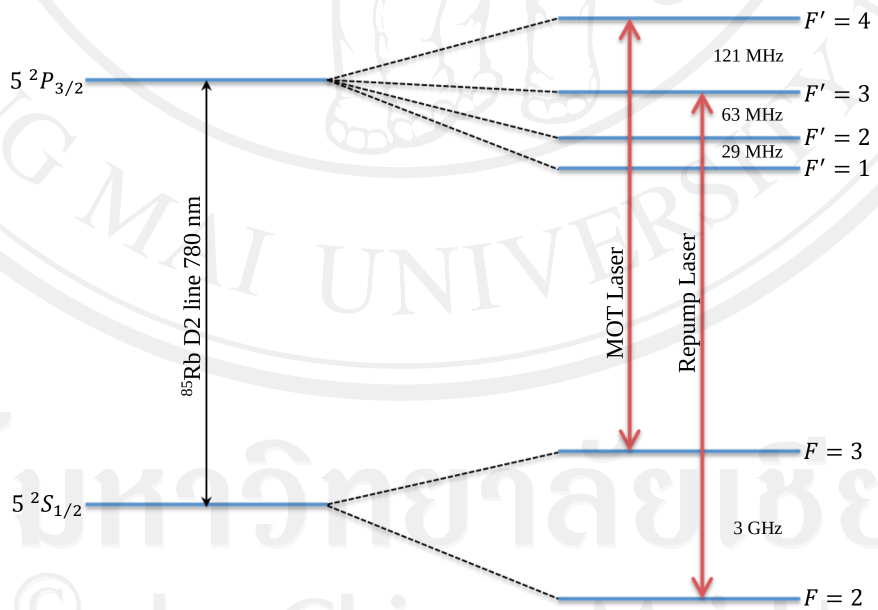

Figure 3.3. The relevant levels of ^{85}Rb for the D2 line transitions in the MOT operation.

$F' = 4$ transition. The second one is a hyperfine repump laser locked to the $F = 2 \rightarrow F' = 3$ transition.

The cooperation between the MOT laser and the repump laser provides the efficient cooling mechanism because the atoms are driven in the cooling cycle all the time of operating MOT. The atoms in the $F = 3$ ground state are excited into the $F' = 4$ state by absorbing photons in the MOT laser beams. In this excited state, the atoms can decay back to the $F = 3$ state only to interact with the cooling beam again. This mechanism is repeated many times that make the photons transfer the net of total momentum to the atoms in the direction of the laser beam as described in section 2.1.1. However, there is still a chance for an off-resonant excitation of another transition to the $F' = 3$ state as well. In this case, the atoms have a potential to decay to either the $F = 2$ or $F = 3$ ground state. If the atoms decay to $F = 2$, the atoms are not circulating in the cooling loop and get loss. The repump laser was used to correct this problem by exciting the atoms from the $F = 2$ state to the $F' = 3$ state. The atoms in this excited state may decay back to the $F = 3$ ground state where they are in resonance with the MOT laser again.

In the experiment, two external cavity diode lasers (ECDLs), which are the commercial MOT/cooling laser made from MOGlabs and the home-made repump laser were used. The details of the lasers and their frequency control are explained below.

Trap laser

The MOGlabs ECDL (model: ECD-003) with a MOGlabs laser controller and stabilizer (model: DLC-202) provided the cooling beam with an output power of 79.16 mW measured with an applied current of 118 mA at the wavelength of 780 nm. The ECDL was built in the Littrow configuration with a diffraction grating placed in front of a laser diode (Part No.: DL-780AP150). The angle of the grating was aligned in such a way that the first-order diffracted beam was fed back into the diode and the zero-order diffracted beam became the laser output beam. As consequence, adjusting an angle of the grating and an external cavity length could vary the dominant stimulated mode of the laser. The sketch of the MOGLabs laser is shown in Figure 3.4. The coarse adjustment of the wavelength was done by manually tuning a knob of the grating mount that has an adjustment screw with a displacement of 12 nm per full turn. For an electrical control of the wavelength, a piezo actuator mounted at the back of the grating was used to translate the grating for changing the external cavity length.

To lock the MOT laser frequency to the $F = 3 \rightarrow F' = 4$ transition, Doppler-free saturated absorption spectroscopy (DSAS) of the ^{85}Rb atoms was produced. Thorlabs optical isolator (Part No.: IO-3-780-HP) was placed just in front of the laser to protect its from optical back reflections into the laser cavity as illustrated in Figure 3.5. About 3 mW of the MOT beam was split into the spectroscopy part by propagating through a half wave plate and a polarizing cube beam splitter (PBS). The split beam was passed though an acrylic beam splitter and then divided into a bright beam and a pair of dimmer beams. The dimmer beams were equal in intensity called probe beams. The one that was more intense called a pump beam. The probe beams were delivered through the Rb vapor cell and were received by a MOGLabs photo detector.

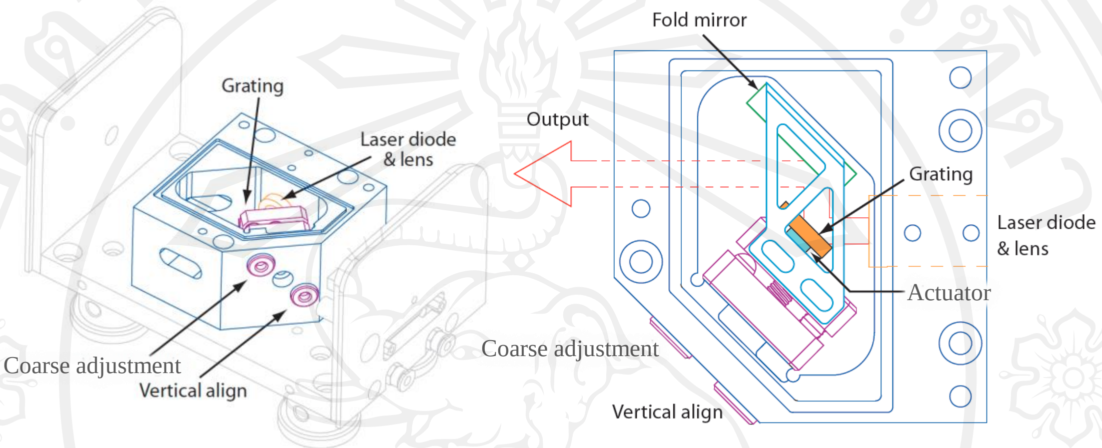

Figure 3.4. Sketch of the MOGLabs ECDL shows the essential components that are the laser diode and lens, the feedback grating mounted on a fine adjustable mount. This figure is reproduced from [46].

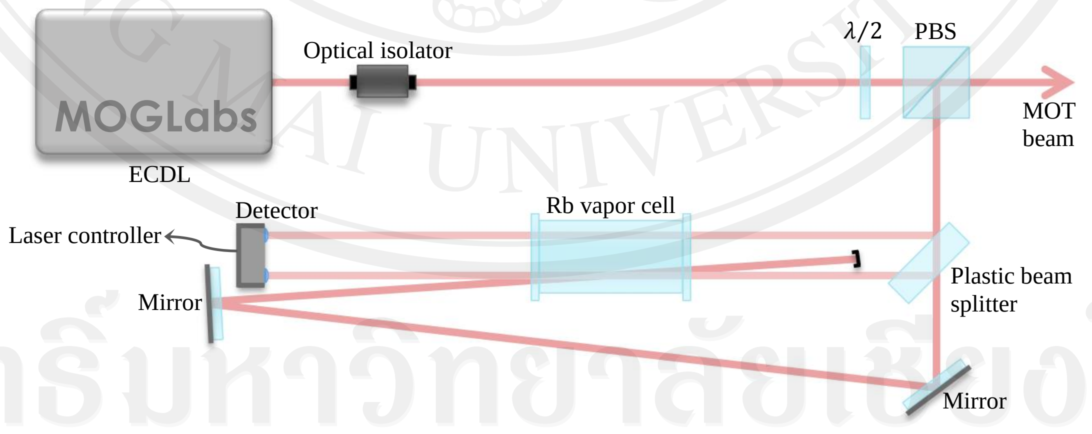

Figure 3.5. Optical alignment for locking the laser frequency to an atomic transition by using the saturated absorption spectroscopy technique.

The intensities of the probe beams were measured as voltage signals, which were monitored by using an oscilloscope. The pump beam was aligned in direction that it overlapped one of the probe beams as much as possible inside the cell. If the laser frequency is scanned about 10 GHz, the spectrum signal of the overlapping probe beam will be as shown in Figure 3.6. The spectrum represents an entire 780 nm Rb hyperfine structure, which consists of the ^{87}Rb transitions from the ground states with $F = 1$ and 2 to F', the ^{85}Rb $F = 2 \rightarrow F'$transitions (containing the transition for locking the repump laser), and the ^{85}Rb $F = 3 \rightarrow F'$ transitions (containing the transition for locking the MOT laser). For the other probe beam, the detector detects only a Doppler-broadened spectral line profile (linewidth ~500 MHz) due to a nonzero velocity of the Rb atoms in the cell.

The measured absorption spectra can be understood as the following. The pump beam with high intensity saturates the atomic population in the excited state when the beam frequency is resonant with the atomic transition. As a consequence, the probe breaches through the vapor cell with minimal absorption resulting in a voltage peak in the middle of the Doppler profile. The peak signal also corresponds to the group of atoms, which has zero velocity along the probe beam. The observed hyperfine structure peaks/lines of the $F = 3 \rightarrow F'$ transitions are shown in Figure 3.7.

As mentioned before, the frequency of the MOT laser need to be detuned by about 15 MHz below the $F = 3 \rightarrow F' = 4$ transition. The peak was used to give an error signal for locking and stabilizing the laser frequency. From the error signal, the controller generated a feed back signal to the laser through either the piezo actuator

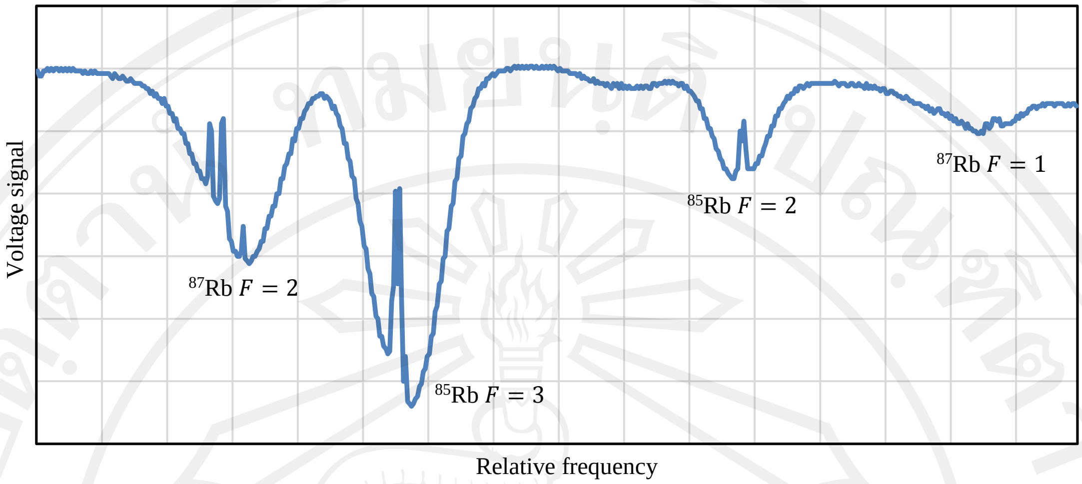

Figure 3.6. The voltage signal measured from the photodiode was plotted as a function of the relative frequency of the laser. The entire 780 nm Rb hyperfine structure was shown for both two natural isotopes when the laser frequency was scanned about 10 GHz.

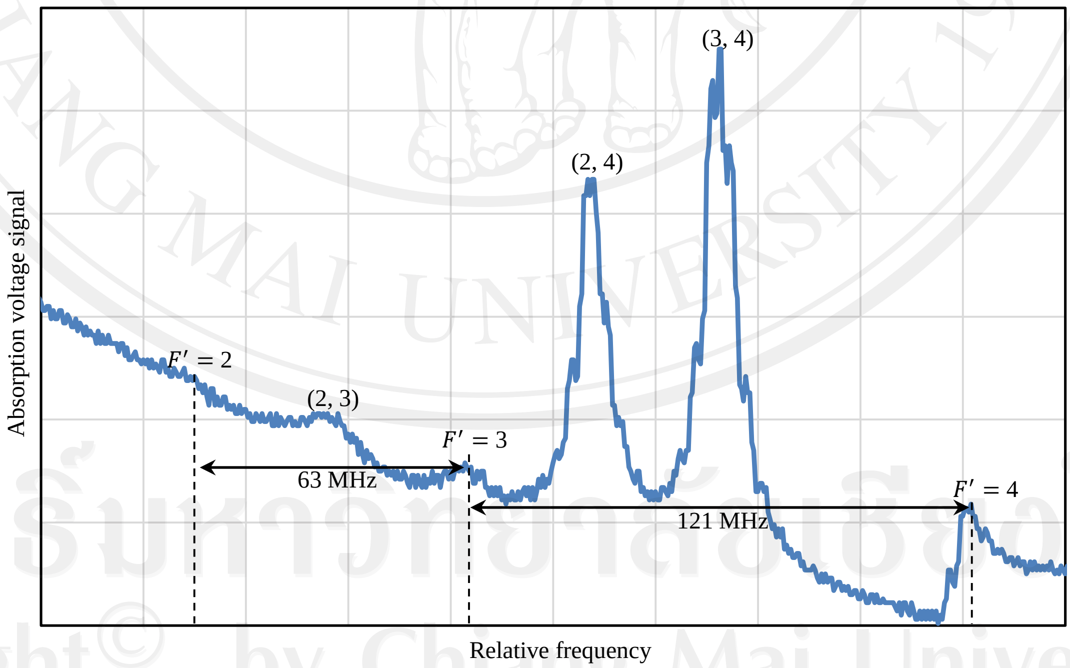

Figure 3.7. The voltage signal is plotted versus the relative frequency of the laser. A narrow scanning that covers the spectrum of the ^{85}Rb $\boldsymbol{F = 2 \rightarrow F'}$ hyperfine structure.

voltage or the laser diode current. The temperature of the laser was stabilized at 21 ºC along the operating time.

Repump laser

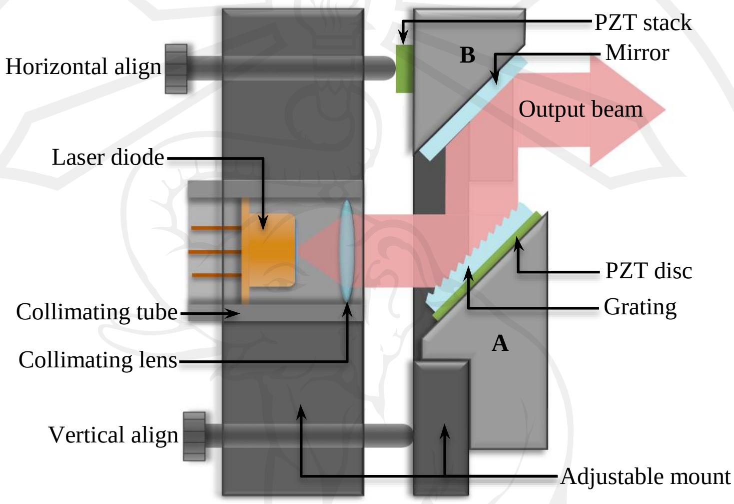

Figure 3.8. Sketch of the home-built external cavity diode laser shows the essential components that are the laser diode and the collimating lens, the diffraction grating mounted on the adjustable mount.

The Repump laser was built by using the Littrow configuration [48] as illustrated in Figure 3.8. A Thorlabs laser diode (Part No.: L785P100) was used for providing a 780 nm beam with an output power of 90 mW. An electrical current was applied to the diode by using a home-built driver and stabilizer [49]. The laser diode and a lens were mounted inside a collimating tube (Thorlabs, Part No.: LT110P-B) for getting the collimated output beam.

For frequency control, the other parts of the laser were assembled as following. A Newport grating (Part No.: 33001FL02-330H) with the size of 15×15×3.2 mm and

1800 Grooves/mm attached on the stack of three piezoelectric transducer (PZT) discs was mounted on an aluminum piece A as seen in Figure 3.8. The collimating tube and the piece A were installed on a Newport adjustable mount (Part No.: U100-P) with two knobs (Part No.: AJS100-0.5K). A PZT stack was installed at the end of the horizontal knob for finely tuning the wavelength. Finally, a mirror attached on aluminum piece B was installed in front of the grating for fixing the direction of the output beam during changing the grating angle.

As mentioned before in the subtitle of trapping laser, the laser frequency was calibrated against the ^{85}Rb hyperfine structure lines obtained from DSAS. The DSAS alignment of the repump laser is shown in Figure 3.9. The photograph shows the home-built laser providing repump beams with the power of about 64 mW. The beam was steering by two mirrors to propagate through a Thorlabs optical isolator (Part No.: IO-D3-780-VLP). Then about 2 mW of the MOT beam was split into the DSAS part by using a half-wave plate and a PBS as shown. The spectroscopy signals were detected by two photo diodes. The obtained signals was sent to a home-built laser stabilizer for locking the frequency at the $F = 2 \rightarrow F' = 3$ D2-line transition.

An oscilloscope was used to monitor the signals. As the result, the hyperfine structure lines of the ^{85}Rb $F = 2 \rightarrow F'$ transitions are shown in Figure 3.10. The $F = 2 \rightarrow F' = 3$ transition is indicated by the last small peak.

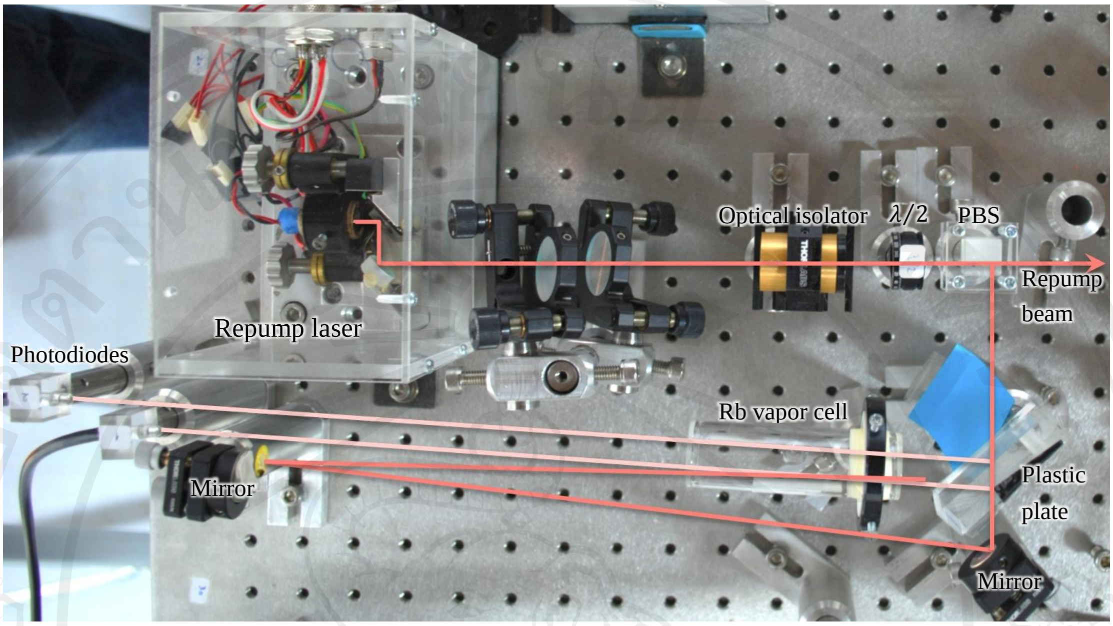

Figure 3.9. Repump laser and optical alignment for Doppler-free saturated absorption spectroscopy.

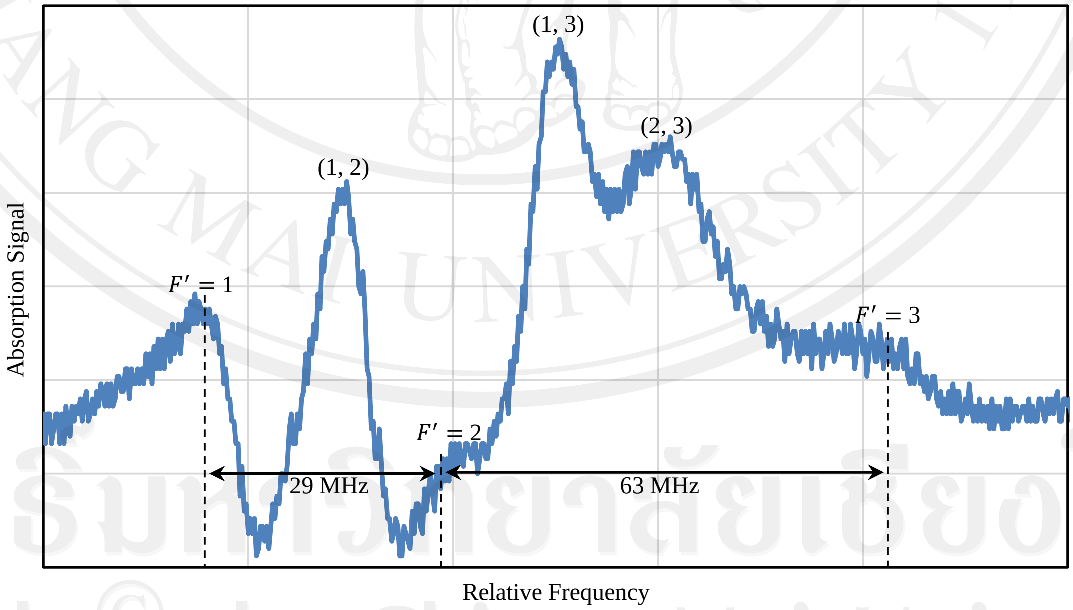

Figure 3.10. The voltage signal is plotted versus the relative frequency of the laser. A narrow scanning that covers the spectrum of the ^{85}Rb $\boldsymbol{F = 2 \rightarrow F'}$ hyperfine structure.

Magnetic coils

Two coils of copper wire were employed to produce the quadrupole magnetic field necessary for the atomic confinement in the MOT configuration. Each coil consisted of 102 turns of a SWG#14 wire with an inner diameter of 210 mm. The coils were placed on two main ports of the vacuum chamber and separated by 70 mm from each other as seen in Figure 3.11. A current of 9 A was applied to the coils that provided the field gradient of 8 Gcm^{-1} in the axial axis of the coils while the MOT operation.

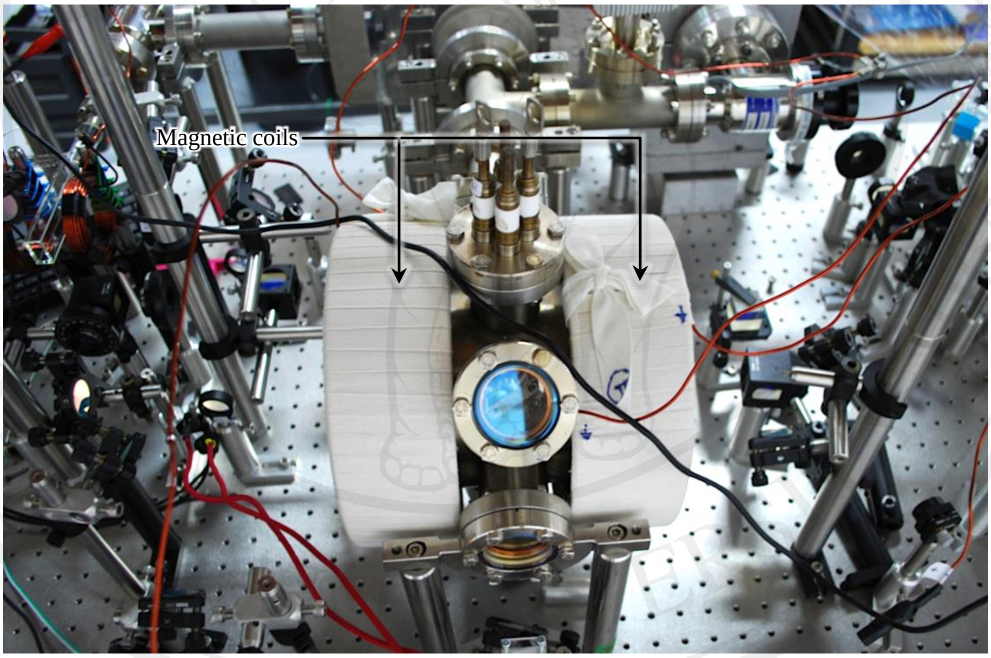

Figure 3.11. The magnetic coils attached on 8-inch ports of the vacuum chamber. The coils were wrapped by using white cloth tape.

MOT alignment

As mentioned before in Section 2.1.2, the MOT system consisted of the quadrupole magnetic field, the MOT beams and the repump beam for trapping and cooling Rb atoms in three orthogonal dimensions. The magnetic field was created from the quadrupole coils detailed above. The MOT laser and the repump laser were operated to generate the six cooling beams. The top view of the schematic of our MOT alignment and the necessary apparatus is illustrated in Figure 3.12 where the magnetic coils and the half-wave plates for the $\sigma_{-,x}$ and $\sigma_{-,y}$ cooling beams are not shown.

The MOT alignment began with combining the MOT beam and the repump beam by sending the beams pass through two half-wave plates and a PBS as shown in Figure 3.12. The orientations of the linear polarizations of the beams were chosen by tuning the half-wave plates in such the way that both beams propagate in the same direction after they pass through the PBS. This combined MOT/repump beam was expanded into one-inch diameter beams by using a pair of lens with $f = 25$ and 250 mm respectively. The MOT/repump beam was split into three beams equally by using two pairs of half-wave plates and PBSs. Each beam originally linearly polarized was passed through a quarter-wave plate and turned into circularly polarized beam. Five mirrors were used for steering all three beams to be mutually perpendicular and across each other inside the vacuum chamber as labeled with $\sigma_{-,x}$, $\sigma_{-,y}$ and $\sigma_{+,z}$ in the figure, where the subscripts of x, y and z represent the axis in three dimensions. After each beam left from the chamber, it propagated through another quarter-wave plate, retro reflected off a mirror, and propagated through the quarter-wave plate for the second time. Due to double passing the quarter wave plate, the reflected beam turned into a left-handed circularly polarized beam. These six crossing MOT/repump beams with proper circular polarization were intersected in the center of the science chamber where the magnetic trap potential is minimum.

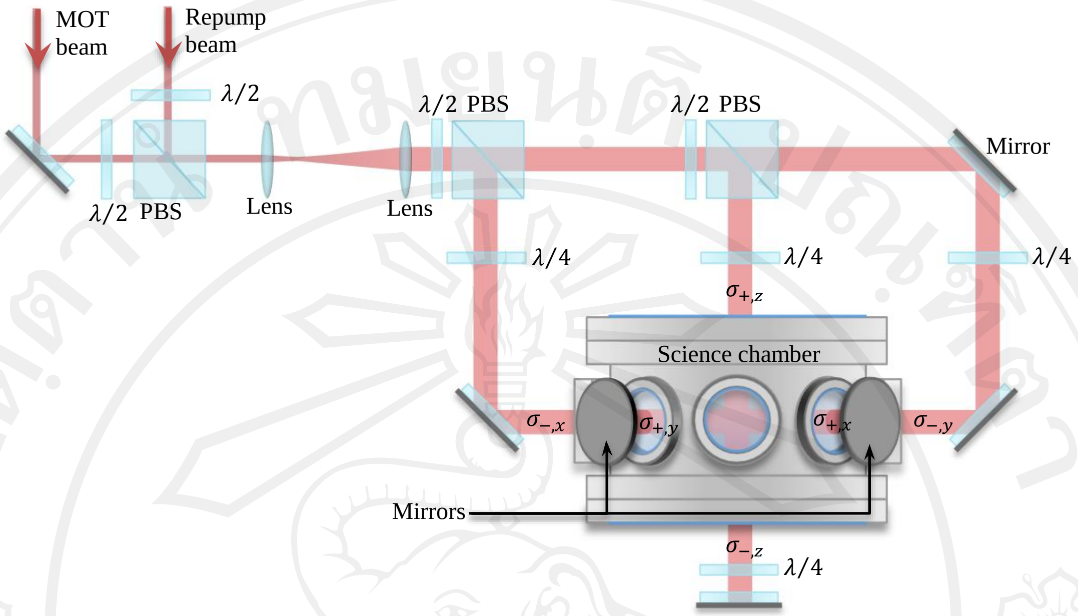

Figure 3.12. Schematic of our MOT apparatus (top view). The quadrupole magnetic coils and some wave plates of the cooling beams are not shown.

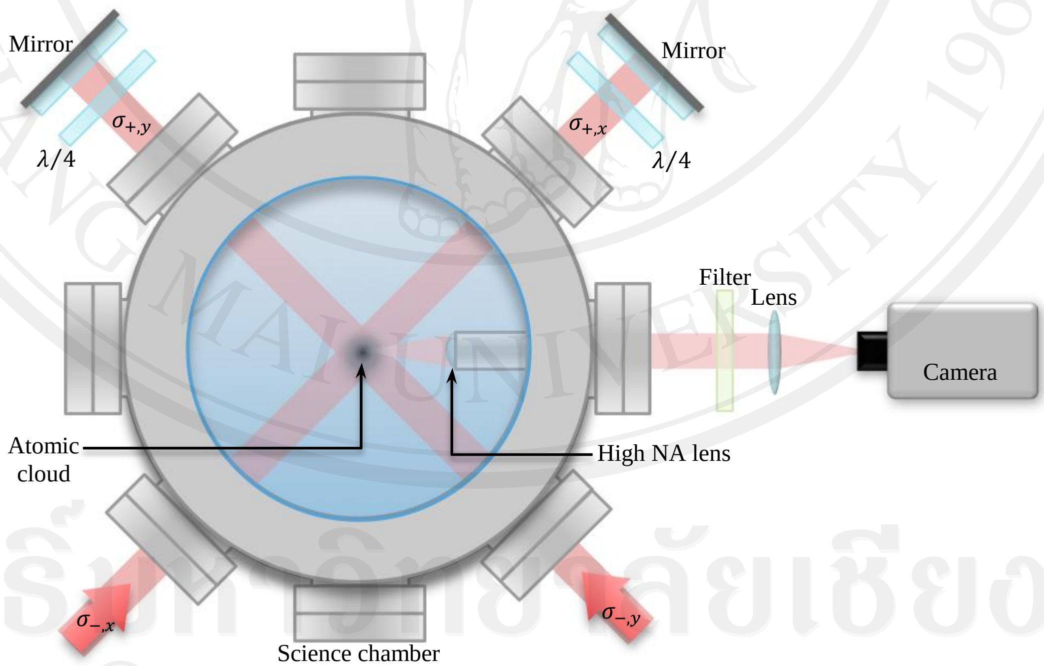

Figure 3.13. Side view of the optical layout shows an alignment of the fluorescence imaging system (the $\boldsymbol{\sigma}_{-,z}$ and $\boldsymbol{\sigma}_{+,z}$ beams are not shown). The imaging system consists of a pair of lens, a filter and a high sensitivity CCD camera.

3.2 Magneto-optical trap detection

The cooperation between the laser system and the magnetic system supplied cold atoms inside the vacuum chamber. The fluorescence imaging was chosen because this technique could be conveniently setup and give us the sufficient information for detecting the atoms. An optical layout for the imaging system is shown in Figure 3.13. While the MOT was operating, the confined atoms absorbed photons from the six MOT beams and then emitted photons spontaneously in a random direction. A high numerical aperture (NA) lens from Thorlabs (Part No.: C240TME-B) was mounted on an aluminium tube inside the chamber to collect the photons. The collected photon beam passed through a 780 nm bandpass filter for reducing the unwanted light, and then focused to a pco. CCD camera (Type: sensicam qe, Part No.: 672 LS 4912) for recording the photons in real time.

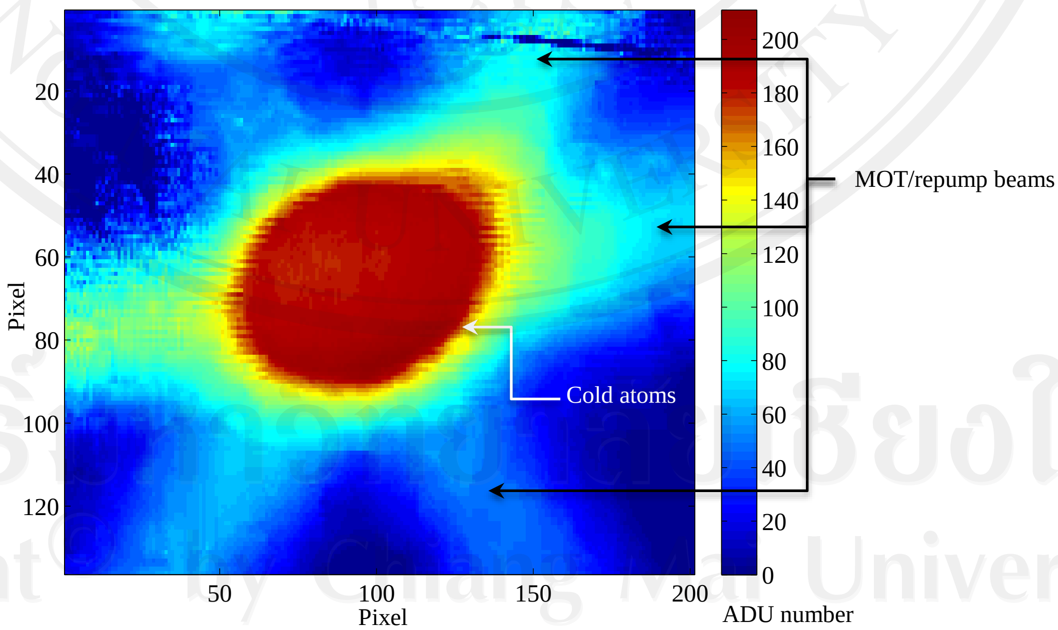

Figure 3.14. Image of the cold atomic cloud inside the vacuum chamber.

The video signal from the CCD camera was sent into the control computer to display and record the fluorescence of the atoms. As the result, the captured frame of the cold atoms trapped in MOT is shown in the Figure 3.14. The image of background light is subtracted from the original image of the MOT cloud that left only the emitted photons to be displayed. The color of each pixel indicates the collected light intensity of the atomic fluorescence in an analog-to-digital unit (ADU), which is shown in the color bar. The red cloud at the center of figure represents the dense cold atoms trapped at the crossed section of the MOT/repump beams.