# Chapter 1

# Polarized $^3$He Target [1]

## 1.1 General Description

### 1.1.1 Physics Principle

This target system provides a high-density ($\approx 2.5 \times 10^{20}$ nuclei/cm$^3$) polarized $^3$He gas target for spin physics experiments at JLab. The JLab polarized $^3$He target system was first constructed in 1998 and had been used for over a dozen experiments in Hall A during 6 GeV era. This Hall C polarized target is upgraded from the last version used in the transversity (E06-010) series of experiments in Hall A (2008).

The target employs the so-called spin-exchange technique. In the traditional spin–exchange technique $^3$He is polarized in a two-step process. First, rubidium vapor is polarized by optical pumping with circularly polarized 795 nm laser light. Second, the polarization of the Rb atoms is transferred to the $^3$He nucleus in spin-exchange collisions, in which $^3$He nuclei are polarized via the hyperfine interaction. Recently,a novel technique of hybrid pumping has been used. In addition to the direct spin exchange, it also happens indirectly for the hybrid Rb-K cells: spin-excahnge first happens between rubidium and potassium atoms (very fast) and then between potassium atoms and $^3$He nuclei, which is more efficient than the direct Rb-$^3$He spin exchange. The target cell contains high pressure $^3$He gas and a small amount of vapor of Rb-K mixture. In addition, it also contains a small amount of nitrogen to increase the pumping efficiency.

### 1.1.2 Apparatus

High power infrared (795 nm) diode lasers (up to 120 W) provide an intense monochromatic light beam for optical pumping. The lasers are housed in a laser room outside the hall next to the counting house. Laser light goes to the hall through an optical fiber

[1] Authors: Revised by T. Averett, J. H. Chen, J. P. Chen, M. Y. Chen, K. Jin, M. Rehfuss, B. Sawatzky, J. Segal, N. Ton and Z. Zhao, 2019/10/19. Base on Hall A Polarized He3 OSP.
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system. An overview of a typical arrangement of the target components in the Hall is shown in Fig. 1.1.

The polarized target comprises several components beyond its target cell (see Fig. 1.1) related to its operation, they are in subsection:

1. Two sets of orthogonal Helmholtz coils provide the target spins with a holding magnetic field of few tens of Gauss as well as define the orientation of the polarization in any required direction on the horizontal plane.

2. One pair of RF coils which allow for the measurement of the target polarization using the Adiabatic Fast Passage (AFP) technique, the pulsed NMR technique and the Electron Paramagnetic Resonance (EPR) technique.

3. A multi-purpose enclosure which is part of the laser light enclosure and provides a containment of the target cell in case of explosion. It also provides a containment volume for the nitrogen (or $^4$He) gas to cool the target windows with cooling jets to minimize the heating effect from electron beam hitting the galss windows.

4. An oven with all its related components for providing the necessary temperature to the pumping cell in order to bring Rb and K in their vapor phase and control their number densities.

5. A target ladder subassembly which supports a target cell, a reference cell, (which can be filled with Hydrogen, $^3$He or Nitrogen gas with pressure up to 10 atmospheres for calibration or to study dilution, density or background), a multi-foil $^{12}$C optics target, a single $^{12}$C foil and two $^{12}$C foils each with a hole(for beam centering), and an oven. It also includes a full mechanism for positioning the targets and the optical beam line mirrors.

6. A laser and optical fiber system in the laser room bring up to ten laser beams, each from a 30 Watt diode laser, to the hall. These laser beam lines are used for optical pumping of the rubidium-potassium alkali atoms in two different directions: along the electron beam (longitudinal), perpendicular to the electron beam line but on the horizontal plane (transverse). They can also be re-directed to any direction on the horizontal plane as needed.

### 1.1.3 Control System

The control (including monitoring and measurement) system for the target Helmholtz coil magnet power supplies, the NMR polarimetry, the pulzed NMR polarimetry and the EPR polarimetry are based on the LabView system on a PC. The control system for the target vertical motion, the lasers, the oven heater, and temperature and pressure monitoring runs under the EPICS environment utilizing an IOC in a VME crate. The LabView system records data on disk and communicates with the EPICS system through the network. Information from the EPICS IOC is logged on disk and selected information passed on to the event data stream.

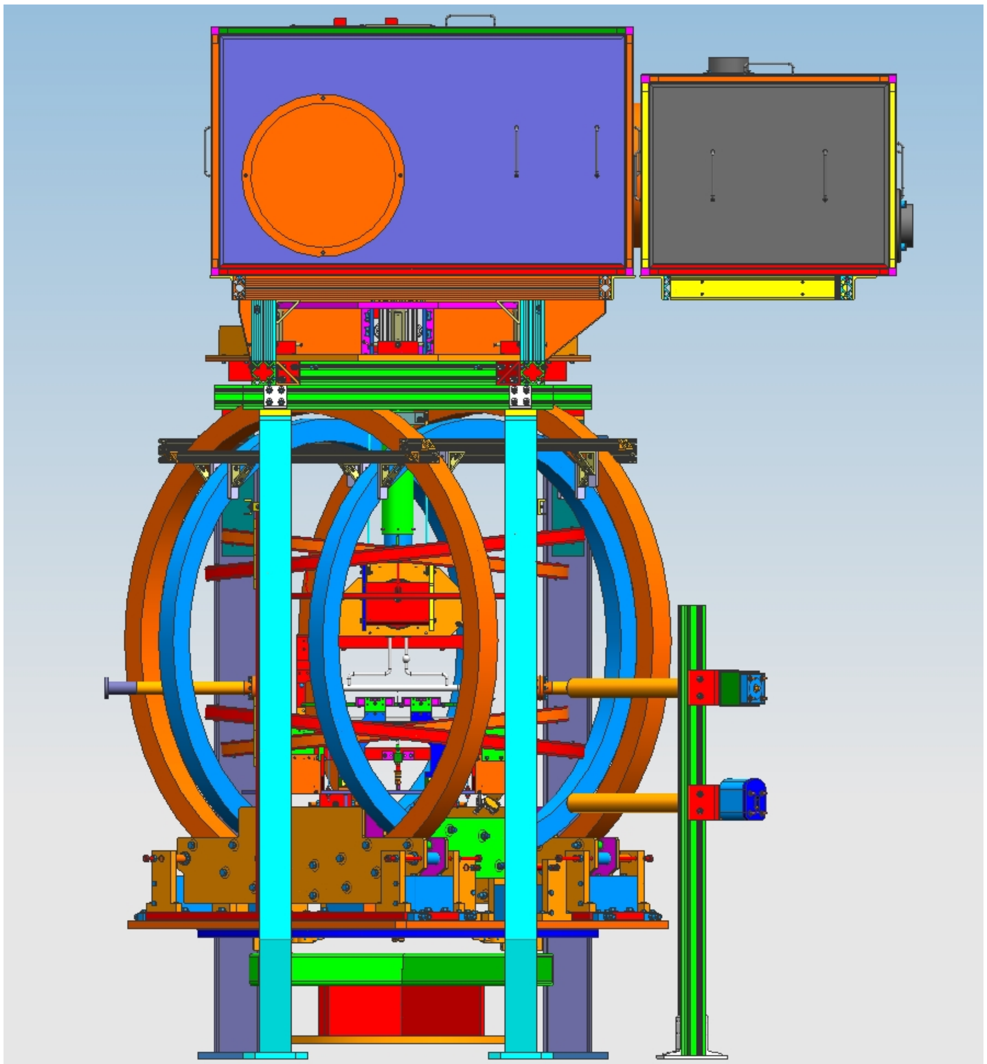

Figure 1.1: Overview of the target setup. Shown are the laser beam enclosure covering the laser beam line on top of the target area, and the two sets of Helmholtz coils with the support sub-assembly.

## 1.2 Operation Overview

In normal operation the target will be under one of the following situations described below.

1. The target is in "beam position", the fast raster set to a nominal 5 mm diameter circular area coverage and the experiment is running to collect physics data. In this configuration the monitoring of the target consists of reading a set of temperatures of the pumping cell, target cell and reference cell. The temperature in the pumping cell provides feedback for the temperature controller. A spectral-analyzer is monitoring the laser wavelength and the relative intensity. All interlocks of electron beam and laser beam shall be on.

2. The beam is turned off and the target is moved to "Pickup Coil Position" (polarized $^3$He target in a position between the NMR pickup coils) and a polarization measurement is performed using the NMR (AFP) method. The laser beam will be stopped first. If the polarization is in the transverse mode, a rotation of the polarization to the longitudinal direction is performed (procedure described in Section 1.9). Once the measurement is completed the target cell will be moved back to the "beam position". If the next running is in transverse mode, a rotation of the polarization to the transverse direction is performed. The laser beam will be turned on. The beam interlock is reset and the fast raster enabled before turning the beam back on target. The physics data taking can resume.

3. The "Polarized $^3$He Target" is either in "beam position" or in "pick-up coil position". The data taking is stopped and the beam is turned off. An EPR (or pulsed NMR) measurement is performed (procedure described in Section 1.11). After the measurement is completed and the fast raster enabled, the beam is put back on and data taking resumes.

4. The multi-foil or single $^{12}$C "Optics Target" is in "beam position". Data on the optics target are taken for spectrometer optics study or detector calibration.

5. The "hole" target is in "beam position". The "hole" target is two $^{12}$C foils each with a 2mm diamtere hole at the center. It is used for center the beam with respect to the target ladder.

6. The target ladder "Empty Target" frame is moved to "beam position" whenever beam tuning is performed, and when checking for possible beam halo background.

7. The "Reference Cell Target" is in "beam position" with the beam fast raster on and data on the reference cell are taken for calibration.

## 1.3 Laser System

The laser system provides 795 nm circularly polarized light for optical pumping of the target. The light is generated by several solid-state diode lasers, which are located in a laser room outside the hall. Each laser emits 30 W of power and is transported into the hall with an 110 meter long optical fiber (which causes about 10% loss in power). Up to four laser beams are combined to one through a 4-to-1 optical fiber combiner. It is then polarized by passing through a polarizer (beam splitter) followed by standard $\lambda/4$ waveplates. Because of the invisibility and high intensity of the laser beam, the lasers present a significant safety hazard. The system generates two independent laser beams for optical pumping of two different target spin directions: parallel, perpendicular, or vertical to the electron beam. In the standard configuration, up to five lasers are used for each direction. Further, the laser polarization direction can be reversed by rotating the $\lambda/4$ waveplates by 90 degrees.

### 1.3.1 Laser Room & Beam Path

To protect the lasers from radiation damage due to the electron beam and shield personnel from accidental exposure to hazardous laser light, all laser systems are located in a laser room outside the hall.

Up to 10 infrared diode lasers (five for each pumping direction) and the related interlock control box are located on two 19" racks in the laser room. Light is guided out of each laser and goes into the hall via an optical fiber. Four beams combined to one with a 4-to-1 combiner. The combined beam is focused by two 2" diameter convex lens then divided by a polarizing beam splitter cube into two linearly polarized rays. Because the laser light is initially unpolarized, both the direct and the split beam carry approximately half the power. To utilize the full laser power it is necessary to combine both beams and focus them onto the optical pumping cell. This is accomplished as follows:

The direct beam is reflected by a 3" diameter dielectric mirror which can be adjusted to steer it towards the pumping cell. The split beam passes through a $\lambda/4$ waveplate, is reflected by a 2" diameter dielectric mirror, and passes through the $\lambda/4$ waveplate again. The fast and slow axes of this $\lambda/4$ waveplate should be oriented at an angle of 45° to the horizontal or vertical direction. The linear polarization of this beam is thus rotated by 90°, and is able to pass through the beamsplitter, essentially without reflection. The second passing through the splitter is necessary to achieve a very high degree of linear polarization for the split beam since the splitter only gives high polarization for direct beam ($T_P > 95\%$,$R_S > 99.8\%$).

Now both beams from each laser have identical linear polarizations. Each passes through a $\lambda/4$ waveplate that transforms its polarization from linear to circular. The orientation of each $\lambda/4$ waveplate is shown in Fig. 1.2, note that all $\lambda/4$ waveplates should have the same orientation.

The resulting beams are reflected twice by a pair of adjustable 6" diameter mirrors mounted on top or next to the target pumping chamber. These mirrors can be standard dielectric ones since they will be in a polarization-preserving compensating configuration (one mirror rotated by 90° with respect to the other). The laser beams are carefully aligned to coincide on the pumping chamber of the cell. They enter the target chamber via transparent windows on the oven wall.

Under normal conditions, laser light will be mostly absorbed by the rubidium in the pumping cell. There are additional windows on the oven to allow lights to be collected for the EPR measurement and for spectral-analyzer to monitor laser spectrum and intensity. For the ERP measurement, light is focused by two lenses (mounted on the oven) into an optical fiber to be transported to the EPR photodiode which is located behind a shielding wall. At the meantime some light will be viewed by the spectral-analyzer through an optical fiber.

The laser beam line is protected by beam pipes that extend from the laser room to the target area. A laser enclosure with interlock covers the laser optics system and the target. It is important to point out that the complete laser beam lines and optics system are fully enclosed with laser intrelock system from the rest of the hall.

The entire laser room is a laser controlled area that requires special safety precautions (see Section 13 and Appendix A: LSOP for the Polarized 3He Target in Hall C and Laser Room).

### 1.3.2 Diode Lasers & Controls

The laser light for experiments is provided by multi (up to 10) 30 Watt, 795 nm solid-state diode lasers. The primary lasers used during the experiment are made by Coherent Semiconductor Inc. The diode lasers consist of a main enclosure which contains the diode, power supplies, fans and control systems for the laser. The laser light from the diode is sent into a flexible optical fiber which extends out of the main enclosure and goes into Hall A. The fiber is 110 m long in a stainless steel jacket.

The lasers operate at diode temperature from 15° C to 26.5° C depending on the system. They are run at output power of up to 30 Watts which uses an operating current of 35-40 Amps. The output laser light has a central wavelength of 795 nm with a spectral width of less than 0.3 nm. The fiber diamter is 600 microns. The beam divergence is $< 0.20$ N.A.

The lasers have a computer (PC) control system. The control allows adjustments in operating current (and therefore the laser power), diode temperature and the wavelength within a small range.

During the experiment the lasers will be controlled remotely through EPICS. There is an MEDM GUI interface for each of the lasers, which allows remote control, monitoring of current, temperature and wavelength as well as being able to turn each laser on and off.

### 1.3.3 Alignment

#### Basic procedure for laser alignment

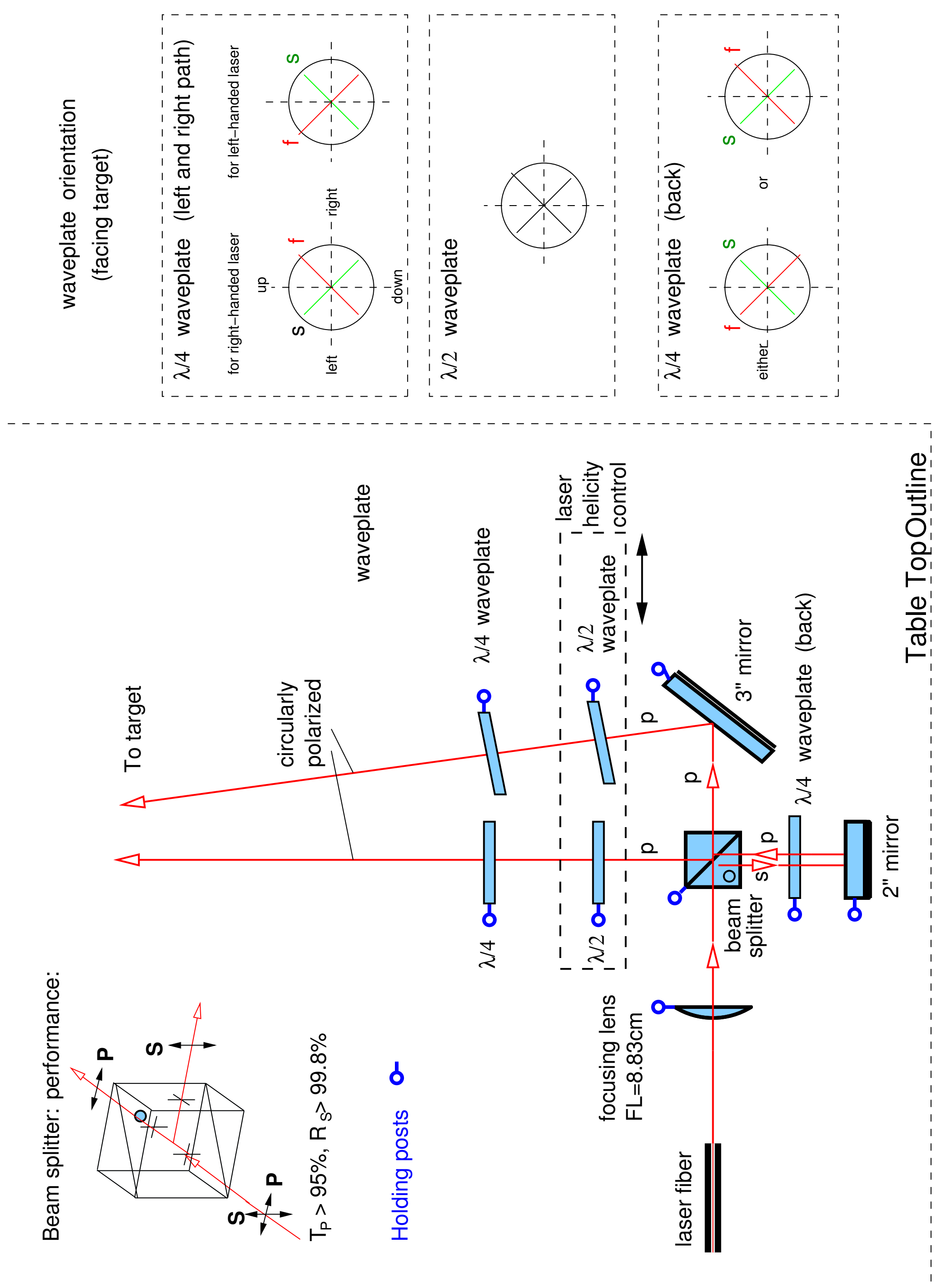


Figure 1.2: Top view of the optics setup.

Before turing on any class 4 laser for alignment, the procedure as outlines in the LOSP must be followed to secure the hall to be laser controlled environment. Use a class 3R alignement laser (laser pointer or HeNe laser) to do initial alignment, then diode laser at low power for final alignment. The Following procedure refers to diode laser at low power. Initial alignment following the same procedure, but with a class 3R laser.

1. Set the height of the single end of the 4-to-1 optical fiber combiner, the center of the polarizing cube (beam splitter), the two-inch mirror, the quarter wave plates, the lens, and the three-inch mirror to be at the same height.
2. Viewing along the direction of the cube, the mirror and the wave plates, you should be able to see the target. Here target refers to the 6" mirror on top of the oven.
3. Place an alignment laser (laser pointer or HeNe laser for initial alignment and low power diode laser for final alignment) such that it passes through the center of the polarizing cube and the center of the target.
4. Rotate the cube and change the angle such that the back reflection hits the alignment laser and such that the reflection hits the diode laser simultaneously.
5. Place the two focusing lens in its mount with the flat side away from the diode laser. Adjust them so that the back reflection goes back on itself.
6. Turn the diode laser on at LOW POWER.
7. Adjust the head of the diode laser such that the light goes through the center of the lens.
8. Rotate the cube mount such that the light passes through the center. Be sure that the cube is mounted so that the light enters the marked side and is reflected towards the two-inch mirror.
9. Turn off the laser.
10. Place the two-inch mirror into its mount and move such that the alignment laser hits the center.
11. Place a quarter wave plate between the cube and the two-inch mirror.
12. Turn the diode laser on at LOW POWER).
13. Adjust the position of quarter wave plate so that the laser passes through the center.
14. Adjust the two-inch mirror so that the reflected light hits the target.
15. If you know the axes of quarter wave plate, rotate it according to Fig. 1.2. If not,
    - Rotate the quarter wave plate so that the light which passes through the cube from the two-inch mirror is a minimum.
    - Rotate the quarter wave plate forty-five degrees.
16. Adjust the two-inch mirror so that the light hits the target.

17. Check to see where the back reflection of the diode is hitting. It shall be near the head of the diode laser but not directly on top of it. If it is then rotate the cube slightly and realign the two-inch mirror. Repeat if necessary. It is important to keep the back reflection away from the fiber since a small amount of back reflected laser could reach the diode through fiber and will damage the laser.
18. Place the three-inch mirror in its mount.
19. Check to see that the diode light is hitting the mirror.
20. Adjust the three-inch mirror so that the light is hitting the target.
21. Center a quarter wave plate in the path of each beam.
22. If you know the axes of quarter wave plate, rotate it according to Fig. 1.2. If not, you need to do bench test first to find the axes of each quarter wave plate.
23. Repeat for all beams heading towards the target.
24. Be sure that the helicity of each beam line is the same.

**Testing quarter wave plates**

- Find the direction of the axes:
  1. Use the laser beam which passes through the polarizing cube (beam splitter).
  2. Place the unknown wave plate in the beam.
  3. Place a polarizing cube after the unknown wave plate.
  4. Place a power meter perpendicular to the polarizing cube such that it measures the power of reflected light.
  5. Rotate the unknown wave plate such that the reflected light coming from the second cube is at a minimum.
  6. Now one of the axes is in horizontal direction and the other is in vertical direction.
- Make sure the axes of all quarter wave plates are identical (either fast or slow):
  1. Use the laser beam which passes through the polarizing cube (beam splitter).
  2. Measure the laser beam power P.
  3. Place the 1st quarter wave plate in the beam, rotate it such that one of the axes (marked axis) is in vertical direction.
  4. Rotate the 1st quarter wave plate by 45° clockwise.
  5. Place a 2nd quarter wave plate after the 1st one, rotate it such that one of the axes (marked axis) is in vertical direction.
  6. Rotate the 2nd quarter wave plate by 45° clockwise.

7. Place a polarizing cube after the 2nd quarter wave plate.
8. If the reflected light coming from the cube is at a minimum, then the marked axes of these two quarter wave plates are opposite (one is fast and the other is slow);
9. If the reflected light coming from the cube is at a maximum and equals roughtly the full power P, then the marked axes of these two quarter wave plates are identical (both are fast or both are slow);
10. If the reflected light coming from the cube is at a maximum and equals roughtly the half power P/2, one of the two wave plates is a half wave plate.

**Some technical details**

- One needs to be careful about backscattering light since it may damage the laser diode if it is right on top of the fiber. However, if the backscattering light is far away from the fiber, it indicates that the system is not optimized and will affect the quality (intensity and polarization) of laser light to the target. The major part of backscattering light comes from the P light reflected from the 2" mirror and the beam-splitter. To check the position of backscattering light, one shall use a backscattering test plate. Never use paper or any flammable material around the fiber. Always turn off the laser when putting on or taking off the test plate.

- Adjust position of back-scattering spot vertically: Probably the reflecting surface of the beam-splitter is not exactly perpendicular to the laser beam. Make sure the fiber, focuing lens and cube(beam-splitter) are at the same level, then rotate cube, at the same time adjust the 2" mirror if necessary.

- Adjust position of back-scattering spot horizontally:

    1. Moving the spot to the left (viewing towards fiber): Rotate cube holder clockwise (viewing from the top), then rotate cube (relative to its holder) anticlockwise. Keep the spot at the center of 2" mirror. See Fig. 1.3
    2. Moving spot to the right (viewing towards fiber): Rotate cube holder anticlockwise, then rotate cube anticlockwise. Keep the spot at the center of 2" mirror.

### 1.3.4 Operation I: Local Mode

To turn a laser on:

1. Be sure to connect the laser control box to the interlock and to the correct laser.
2. Turn on the switch on the back panel of the laser.
3. Turn the key on the front panel to turn on the power.

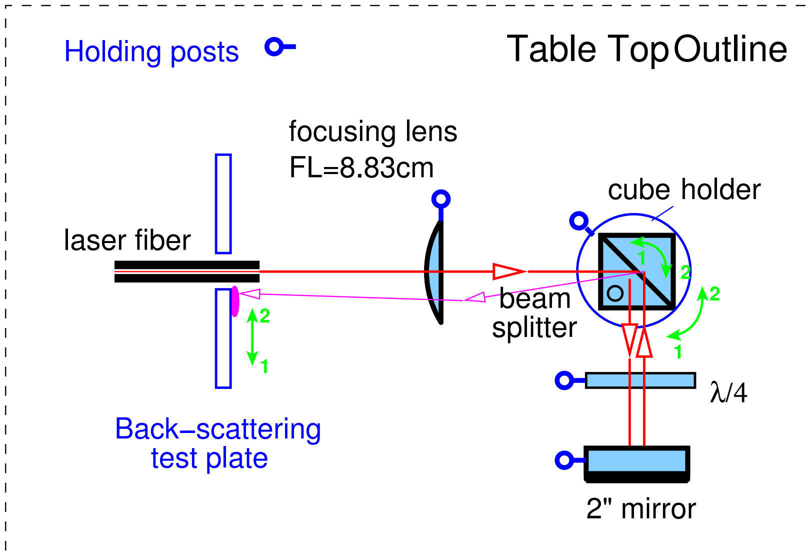


Figure 1.3: Adjusting back-scattering light

4. Set the current through the computer.
5. Press the On/Off button. The screen should show 'laser enabled'.
6. Press the On/Off button again. The screen should show 'laser on'. The laser should be on now.

To turn a laser off:

- Press the On/Off button. The screen should show 'laser disabled'.

### 1.3.5 Operation II: Remote Mode

For the remote mode to work, the lasers must be connected to the interlock box, the interlock system must be engaged and the laser key turned on as described above. The lasers can then be controlled through the MEDM GUIs:

To turn a laser on:

1. Set the desired temperature and current in the "Set Temp" and "Set Current" enter boxes.
2. Press the "Enable" button. If you have a camera pointing at the laser box in the Hall then you should see 'laser enabled'.
3. Press the "Start" button. If you have a camera pointing at the laser box in the Hall then you should see 'laser on'. The laser should now be on.

To turn a laser off:

- Press the "Stop" button.

To monitor lasers on or off, there is a spectral-analyzer which monitors both the relative power and the waveform of the lasers. The spectral-analyzer has remote readback. Alarm will be set when the readback deviate from the regular running condition by more than 10%. This will enable us to know when one laser goes off or when the cell ruptured.

## 1.4 Target Cell

### 1.4.1 Description

The target cell is usually a 40 cm long aluminosilicate glass (GE180) high pressure (about 10 atm) double chamber cell. Typical dimensions for a 40 cm cell are shown in Fig. 1.4. It is a closed system filled with a gas mixture which consists of $^3$He, rubidium and nitrogen.

The cell volume is about 3 l for a 40 cm cell with 3.5 inch diameter sphere pumping chamber.. The interior pressure of the cell at room temperature is between 7 and 10 times atmospheric pressure. The cells contain approximately 70 torr of nitrogen to help with the spin-exchange process. There is usually 0.1-0.3 g of Rb-K mixture with a mixing ratio of 1:5 in the pumping chamber. The tritium contamination of the $^3$He gas used to fill the cell is less than $10^{-11}$% according to the specifications from the manufacturer, Spectra Gases.

The glass walls of the cell vary in thickness from cell to cell and from chamber to chamber. The end windows of the target chamber are 120-150 microns thick and are therefore the thinnest part of the cell. The walls of the target chamber and transfer tube are over a millimeter thick and the pumping chamber walls are up to 2 mm thick.

The cell is installed on a target ladder and then this ladder is mounted to the bottom of the oven. The cell is attached to the target ladder with a high-temperature elastomer, GE RTV106. The ladder is then bolted onto the oven.

### 1.4.2 Installation & Replacement

The target installation is a delicate procedure and shall be performed only by qualified personnel. A minimum requirement is Radiation Worker II training. Only the first time installation does not require the monitoring of radiation around the pivot area. After the cell has been exposed to the electron beam, any replacement of the cell must be done under strict observation of possible radiation and contamination hazards.

The cells are fragile and under high pressure so they can cause damage not only to exposed skin and eyes, but also hearing. It is therefore important to wear hearing protection in the vicinity of an exposed cell and also to wear a face shield and a safety glasses when handling or in the vicinity of someone handling a cell.

In the following we describe the procedure for cell replacement. The procedure applies both to a routine replacement and a replacement after a cell explosion.

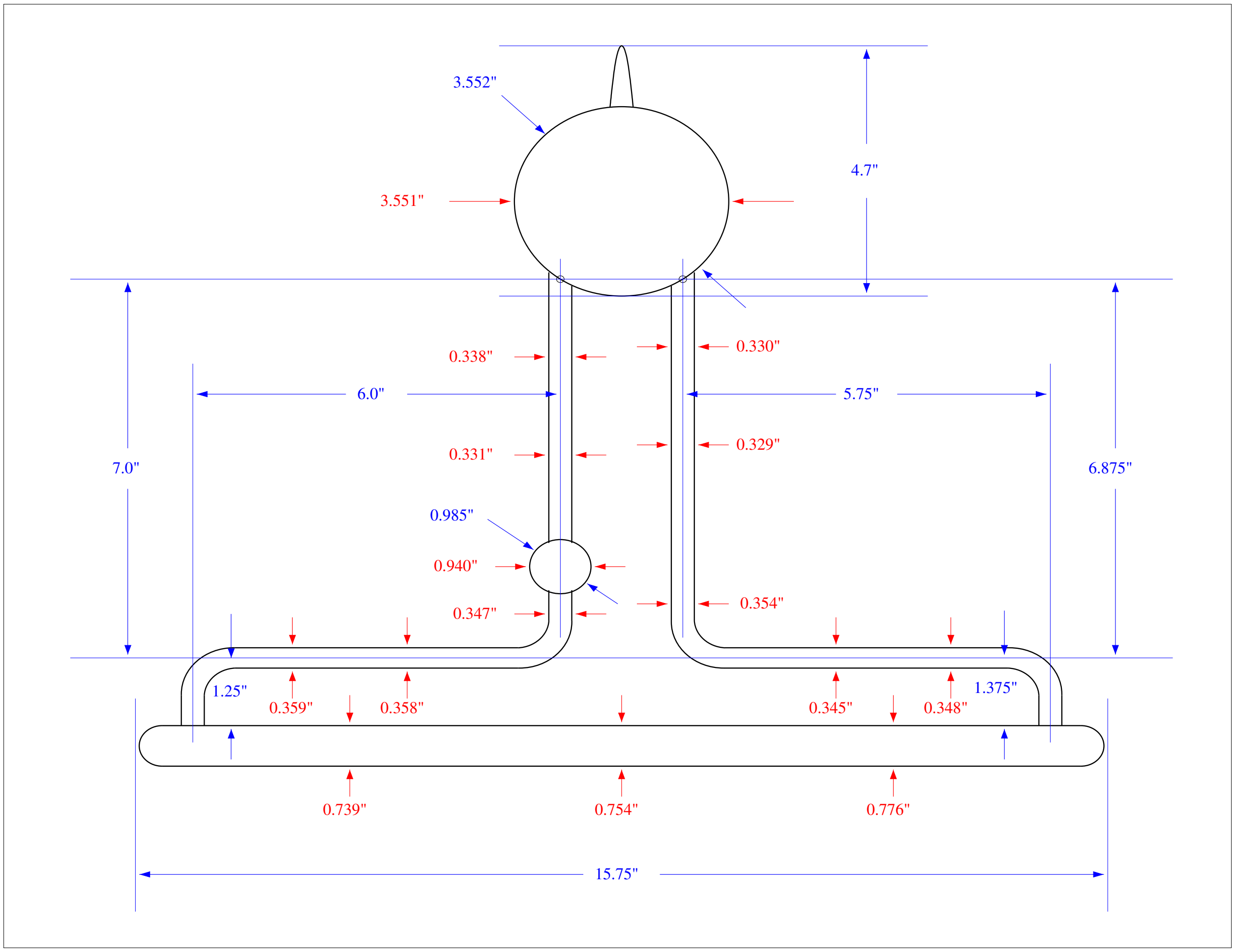


Figure 1.4: Typical 40 cm polarized $^3$He target cell used in this experiment.

- If the replacement of the cell follows the rupture of a previous target, a new $Q$ curve of the pickup coils shall be measured. If the pickup coils have deteriorated, they shall be replaced as well.
- Lasers must be turned off. Laser fibers be disconnected from the lasers and be lock-away following the lockout-and-tagout procedure.
- Prepare the replacement target and, if necessary, a new set of pickup coils. Request Hall access from MCC, and wait for a member from the RADCON team to accompany the group of qualified people authorized to change a target cell.
- The member of the RADCON group will evaluate the radiation level around the target area. If safe levels of radiations are observed, the work can proceed. Otherwise a Radiation Work Permit will have to be written. The member of the RADCON

group will either clean up the glass pieces or, after determining that there is no contamination, informs us that we can proceed to clean up the glass pieces.

- All personnel within the target area platform must wear hearing protection, a face shield, a pair of safety glasses and buttonned cotton jacket during any access to the inside of the target enclosure when the pressurized glass cell is or will be exposed.
- Remove the side enclosure to provide sufficient access to the target. Monitor the radiation level close to the target ladder and oven. Determine what conditions are required to comply with a radiation safe work condition.
- Qualified personnel shall proceed to replace the target and align it according to well defined reference lines of the target ladder. The motion of the target and the clearance between the pickup coils shall be tested. When finished, the enclosure shall be put back in place.
- If an intact target cell was removed, it shall be stored in a wooden or plastic box with a lid or a metal box specially designed for store target cell. It must be left in the hall with "Pressurized Glass Cell, Open By Authorized Personnel Only" warning sign on the box. It can only be removed from the hall after approval from RADCON.

## 1.5 Target Ladder & Motion System

### 1.5.1 Description

The polarized $^3$He target system has six target positions: the actual polarized target cell, which can be replaced by a water cell for NMR calibration (see Section 1.9), a seven-foil Carbon target and a single carbon target for optics calibration, a "hole" target for alignment, an empty target position that contains no target and allows the beam to pass undisturbed through the apparatus, and a reference cell position (see Section 1.12). These targets are mounted on a target ladder as shown in Fig. 1.5.

The target ladder can be positioned vertically using a stepper-motor-driven motion control system. The controller can drive the ladder to seven different fixed positions, five of which correspond to the five targets, the sixth to the empty (no target) configuration, and the seventh to the position used for NMR measurements where the target cell is surrounded by the pick-up coils.

The motion controller employed was developed at JLab and has been used for previous experiments. Vertical target motion is provided by a leadscrew-driven linear slide system with a 5/8"x8mm leadscrew (8mm advance per revolution) (Bishop-Wisecarver Corporation Lo-PRO LP3). The system incorporates a 200 step/rev stepper motor resulting in positioning accuracy of about $\pm 40\,\mu$m (not using micro-stepping) at a maximum load of 225 lbs (102 kg). The maximum range of motion is 45.7 cm. Mechanical position switches are mounted on the target support frame to indicate motion limits. These

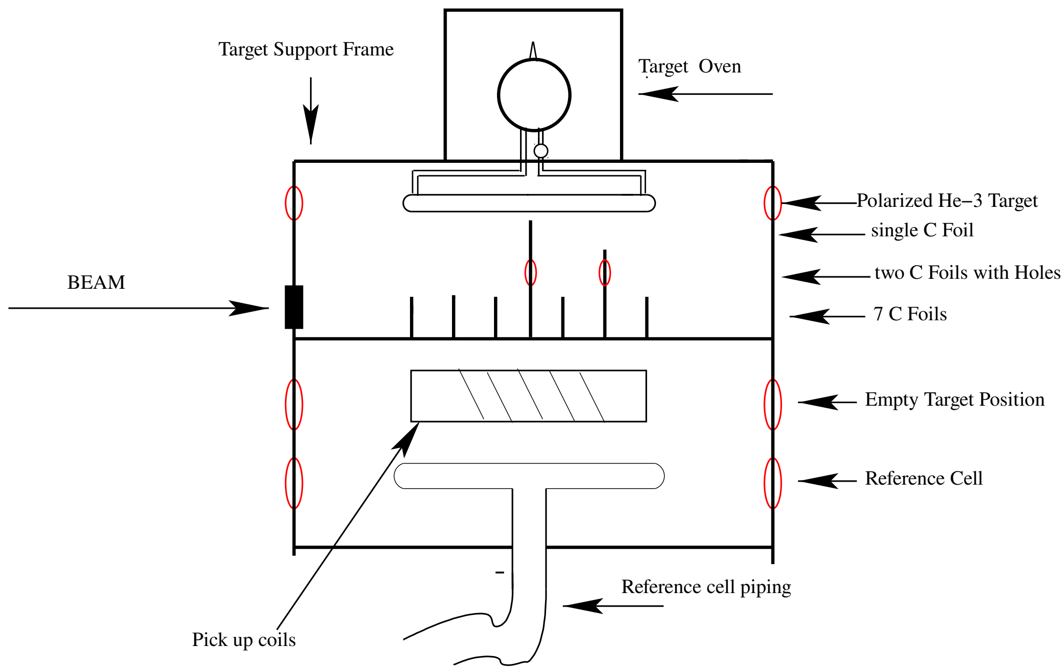


Figure 1.5: Schematic diagram of the target ladder and target positions.

switches are wired normally closed and fail open. Mechanical switches are mounted to serve as position indicators for home and the various targets mounted on the ladder. Additionally, a linear potentiometer provides independent readback of the slide position.

### 1.5.2 Operation

The motor can be controlled locally and remotely. Local control is provided through the SmartStep 23 keypad controller. The keypad allows the target to be jogged into position. It also allows for small codes to be saved which will move the target ladder into preset target positions. Remote control is provided through the EPICS environment. During norml operation, target motion is controlled through the lifter MEDM GUI running on one of the computers in the Hall C counting house. The GUI has buttons for preset target positions, as well as lights indicating the status of the controller (i.e. any faults, at a limit, etc.). The velocity, acceleration time, deceleration time and position can also be manually set from the GUI, but the defaults should be correct for all but special situations. The position of the motor is readback on the GUI. This position is displayed in revolutions from the home position and can be compared with preset target positions.

The electronics provide a Fast Shutdown (FSD) interlock signal to the accelerator that is triggered whenever the target is moved with the beam on. This prevents damage to the target cell and ladder due to the electron beam. The FSD signal is generated by the SmartStep controller and sent to an FSD node in the Hall. Target changes require

Hall personnel to telephone MCC and request temporary masking of this FSD channel.

## 1.6 Target Enclosure & Windows

The target is surrounded by an enclosure. The enclosure serves three purposes: First, it is part of the laser light enclosure. Second, it provides a containment volume in case of explosion of the target cell and so limits the potential hazard working area. Third, it allows the region around the target to be filled with helium gas, minimizing ionization and energy loss of the electron beam crossing the target area.

The enclosure is made fiber glass material and part of the middle section is removable for access to work in the target area. The material at the forward part where the scattered particles passing through is 0.762 mm thick. The other parts are thicker.

If the middle section is open, people working anywhere on the *target platform* must wear double ear protection and a face shield. Lasers should have been turned off and optics fiber ends be locked away following the lock-and-tag procedure. This region is designated as the “target area”. Signs will be posted indicating that the enclosure is open and that work is in progress. If the enclosure is closed the target area is no longer restricted except for possible reasons of radiation safety.

The electron beam line is under vacuum and separate from the target enclosure for both upstream and down-stream of the target enclosure with the enclosure windows. The beam inlet and outlet windows of the target enclosure are made of 0.254 mm and 0.508 mm thick Be and are strong enough to stop any flying glass shards in case of a target cell explosion. Each Be window has an additional 0.076 mm thick aluminum foil cover to protect it from exposing to air.

## 1.7 Target Cell Heater

The target pumping cell must be kept at a temperature of about 230°C for optical pumping of Rb-K to be effective. This is accomplished by flowing hot air through a special temperature-resistant enclosure (“oven”) around the pumping cell and regulating the temperature of the air using a process controller. The system is described in detail in the following.

### 1.7.1 Description

Fig. 1.6 shows a schematic diagram of the heater system and the associated controls. Pressurized dry and filtered air at room temperature is provided by a dedicated compressor in the Hall. The air enters the system through a shut-off valve and a pressure regulator, which is typically set to an output pressure of 15 psi. The flow rate is measured with a gas velocity sensor (Omega model FMA-905) connected to a display unit (Omega DP41-E-S2R) that provides an alarm to indicate insufficient flow. The air then passes through two resistive heaters (120 VAC, 1200 W) and continues through insulated

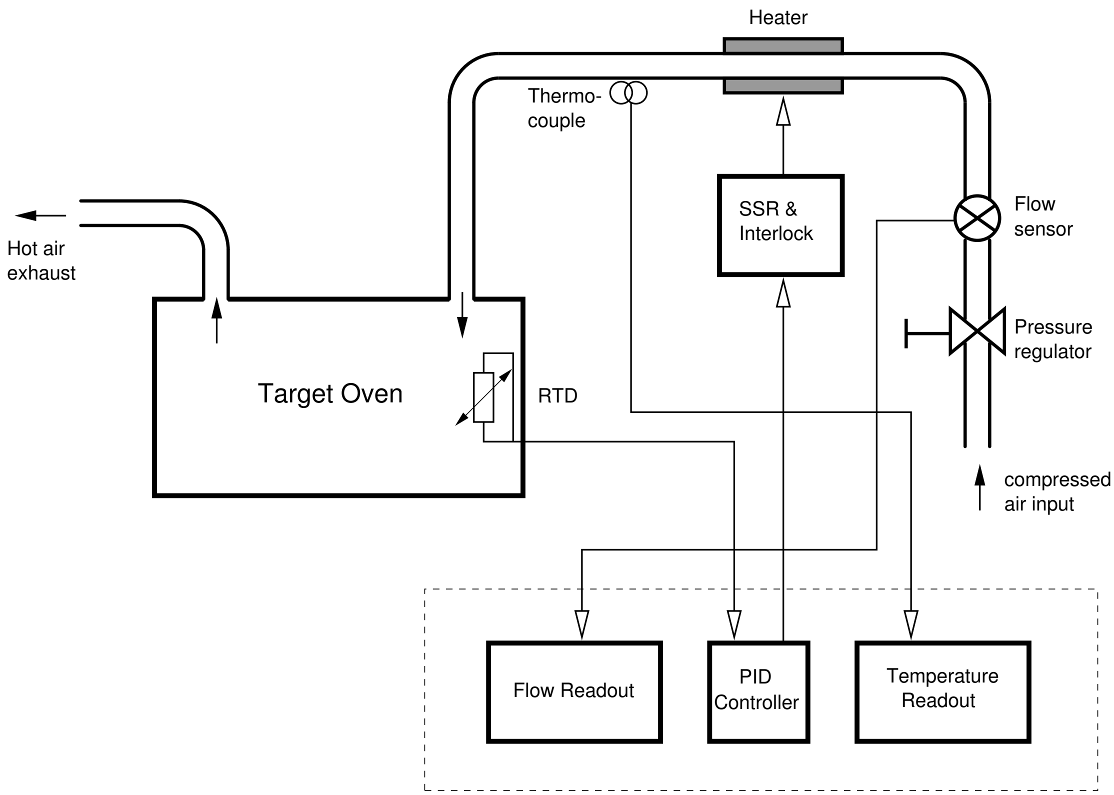


Figure 1.6: Schematic diagram of the target cell oven control system. The instruments in the dashed box are located upstairs, while the remaining components are located in the Hall in the vicinity of the target. For clarity, the interlock circuitry is not shown (see Fig. 1.7).

copper tubing into the target oven. The oven material is ceramic which can withstand a temperature of at least 300°C continuously. The air finally exits the system through an exhaust pipe where it can cool down. Both inlet and exhaust pipes are inside the oven supporting tube filled with insulation material.

A 100Ω Pt RTD (Omega model F3105) measures the temperature inside the oven. A process controller (Omega CN77540-C2) operating in PID mode drives the heater via a solid-state relay (SSR) regulating the heater power dependent on the temperature detected by the RTD. The SSR (Omega model SSR240DC10) accepts a low-voltage (3 − 32 VDC) control signal of about 30 mA. A mechanical relay between the SSR and the heater allows interruption of the 120 VAC heater power in case of a malfunction (see subsection 1.7.2).

A thermocouple (Omega 5SC-GG-K-30-36) is mounted on the tubing right after the heater to allow monitoring of the temperature of the air exiting the heater. Another display unit (Omega DP41-TC-S2R) reads the thermocouple and generates an alarm if the temperature exceeds a preset threshold.

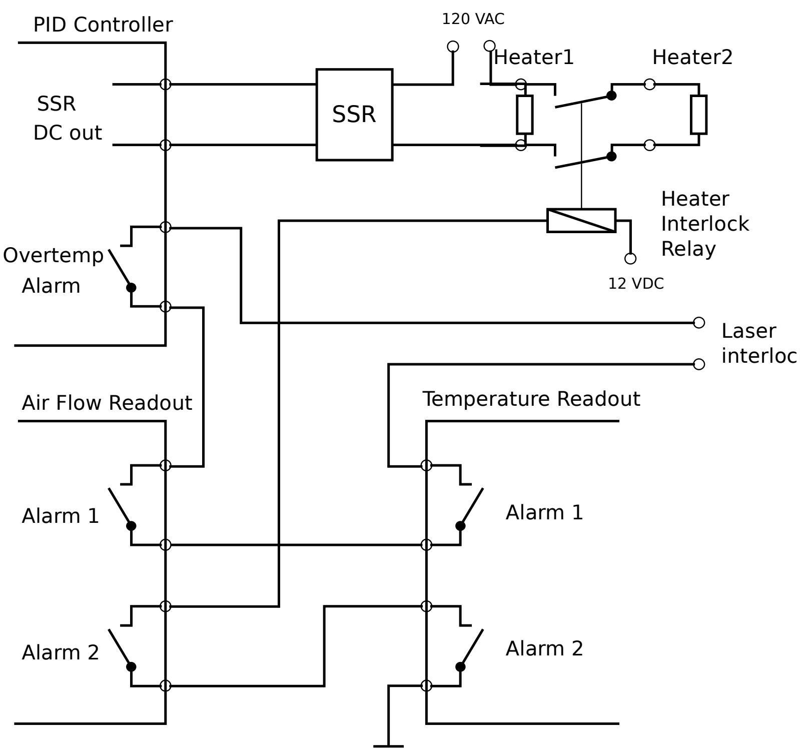


Figure 1.7: Schematic diagram of the oven heater interlock system. The switches represent relays. In normal operation, the relays are energized (contacts closed). An alarm condition (or instrument power failure) will de-energize (open) the corresponding relays, interrupting the interlock circuit. The instruments are programmed such that their dual alarm outputs operate simultaneously.

The PID controller as well as the two display units are installed in a 19" chassis in the electronics racks on the second floor of the counting house where they can be manually operated if necessary. All other components are located in the Hall in the vicinity of the target. The instruments can be monitored and programmed remotely via serial RS-232 communications, which allows convenient control via an EPICS/MEDM graphical user interface (GUI) in the counting house.

### 1.7.2 Safety Considerations

The heater system represents a significant fire hazard and therefore requires good failsafe protection. Possible failure modes include:

1. Insufficient air flow. Possible causes: Compressor failure; obstruction in filter; operator error. Possible harzards: Overheating of heater element, resulting in equipment damage and/or fire. Protection: Air flow is monitored; insufficient flow disables heater (and laser) via hardware interlock.

2. Heater overtemperature. Possible causes: Insufficient airflow; temperature controller failure; RTD failure; operator error. Possible hazards: Damage to heater element and/or tubing; fire. Protection: Heater temperature is monitored; excessive temperature disables heater (and laser) via hardware interlock.

3. Oven overtemperature. Possible causes: Temperature controller failure; RTD failure; insufficient air flow; excessive laser power; operator error. Possible hazards: Explosion of target cell; damage to oven enclosure and/or optical elements; fire. Protection: Temperature controller will generate alarm if RTD indicates excessive temperature, disabling heater via internal logic and and laser via hardware interlock.

A schematic diagram of the interlock system is shown in Fig. 1.7. The instruments are programmed such that their dual alarm relays operate simultaneously if a value is out of range. An interlock condition disables the heater as well as puts the lasers in standby mode. Interlocking the lasers is important as the laser light contributes significantly to the heating of the target oven.

### 1.7.3 Operation

The oven can be controlled from a GUI running on one of the Hall A counting house computers, or manually using the front panel controls.

#### 1.7.3.1 Local Operation

A brief description of the manual operating procedure is given here:

1. The oven controller and temperature and flow displays are located in a 19" chassis in one of the racks upstairs. Make sure power to this chassis is on. The green light on the front panel should be lit.

2. Verify the alarm set points for the flow meter and temperature indicator. Press the `SETPTS` button until the display shows `SP3`. After about 1 second, the setpoint value appears. It should be 250 for the air flow display and 220 for the temperature display. Press `SETPTS` again and check setpoint `SP4`. It should be identical to `SP3`.

   To change any of the values use the `MIN` and `MAX` buttons. The `MIN` button selects the digit to be changed whereas the `MAX` button changes the value of the currently selected digit. Press `SETPTS` again to store the new value. When finished, press `SETPTS` until `RUN` appears in the display.

3. Verify the current temperature of the oven. It is shown in the upper (red) display of the temperature controller and is labeled `PV` for "Process Value". The units are °C. The value should be reasonable, *e.g.* around room temperature if the oven has been off for several hours or more. If the value does not make sense, either the controller is misconfigured (see below) or the RTD in the oven is broken or incorrectly connected. Do not proceed before you have a sensible reading.

4. (Optional) Verify the correct configuration of the controller. Use the `MENU` button on the controller to scroll through the various configuration menus. To inspect parameters within a menu, press `ENTER` followed by `MENU` again. The suggested default parameters are listed in Tables 1.1 and 1.2. This step is time-consuming and can be skipped if you are relatively certain that the configuration is ok. A detailed description of the controller parameters is given in the controller manual.

5. Verify that air is flowing. The air flow readout should indicate a value of 350–450. These are arbitrary units. As long as the heater is off, the reading should not fluctuate by more than about ±10 units.

6. Verify the current temperature of the heater. It should be close to room temperature. If the value is unreasonable, either the readout is misconfigured or the thermocouple is broken. Do not proceed before the problem is corrected.

7. Verify that alarms are reset. Underneath the main display there are four LEDs, one for each alarm 1–4. If either LED `3` or `4` is on on either instrument, it indicates that an alarm has been triggered and that the system is interlocked. You must reset the alarms before you can continue. To do so, first correct the problem (*e.g.* turn the air flow on) then press `RESET` once on the affected instrument(s). If the LEDs stay on despite correct setpoints and readings, the instrument is probably misconfigured.

8. Begin heating. To avoid damage to the oven, the temperature must be increased to the final value slowly. A good final operating temperature is 170°C, and a good

ramping rate is 60°C/h, *i.e.* heating of the oven will take about three hours to complete.

In manual mode, you must enter a new temperature setpoint by hand at fixed time intervals. ("Ramp and Soak" does not seem to work reliably with this controller.) You should increase the value by 10°C every 10 minutes. For example, if the current oven temperature is 35°C, start with a setpoint of 45°C and increase this value by 10°C in approximately 10 minute intervals.

To enter a new setpoint, do the following

(a) Press `MENU` on the temperature controller. A little green light marked `SP1` in the upper left corner of the display will start to blink. Also, the first digit of the green numerical display, labeled `SV` for "Setpoint Value", will blink.

(b) Use `MIN` to select the digit you wish to change and `MAX` to modify the value.

(c) When done, press `ENTER`. The display will briefly show `run` when the controller enters normal operating mode. This starts the heating process.

9. Check correct operation of the controller. A little green light marked `SP1` in the upper left corner of the temperature controller display indicates that the heater is active. This light should blink slowly, being mostly on while the oven is heating up and being mostly off (or even completely off for periods of up to a few minutes) when the oven temperature has reached the setpoint.

   The heater temperature should increase proportionally to the fraction of time that the `SP1` indicator is on. Note that the temperature reading is *not* directly related to the oven temperature. In particular, the heater may become significantly hotter than the oven, and its temperature might fluctuate from almost room temperature to high values over short periods of time as the heater power is automatically cycled on and off by the controller. As long as the temperature stays below the alarm threshold (220°C) there is no reason for concern.

10. Check stability of the final temperature. The temperature might overshoot slightly. If the overshoot is less than about 5°C then this is normal. If the stability is poor it is probably due to incorrectly set PID parameters in the controller. Changing these parameters is best done by an expert since this requires in-depth understanding of the system.

    The laser contributes significantly to the heating of the oven. Therefore, you will notice sudden temperature instabilities when the laser is turned off or on. It will take several minutes for the controller to compensate for such changes.

11. The air flow rate is slightly dependent on the heater power applied (conductance varies with temperature). Therefore, the flow rate will fluctuate by some 10-20%. This is normal.

12. At any time you can place the controller in standby mode by pressing `ENTER` twice. The display will show a blinking text `STBY`. This will turn the heater off completely and can be used when the system appears to malfunction. However, exercise some caution if the oven is at an elevated temperature since it will quickly cool down if heater power is disabled and you will lose time bringing it back up to operating temperature.

13. In an emergency, simply turn the power to the chassis off completely. This will open the interlock loops, thereby cutting power to the heater and placing the laser in standby mode.

#### 1.7.3.2 Remote Operation

1. Make sure the power is on to the Oven Heater Controller Chassis as described above. Also verify the alarm set points for the oven air flow and heater temperature as above.

2. Verify the current temperature of the oven. It is shown on the GUI on the blue HacOMEGA_RTD readback. It's shown on the meter and also in the readback box. Also, a plot of oven temperature vs time is shown on the stripchart in the bottom-left of the GUI (labelled oven temperature). The units are °C. The value should be reasonable, *e.g.* around room temperature if the oven has been off for several hours or more. If the value does not make sense, either the controller is misconfigured (see directions for manual control above) or the RTD in the oven is broken or incorrectly connected. Do not proceed before you have a sensible reading.

3. Verify that air is flowing. The air flow readout should indicate a value of 350–450. These are arbitrary units. As long as the heater is off, the reading should not fluctuate by more than about $\pm 10$ units.

4. Verify the current temperature of the heater. It should be close to room temperature. If the value is unreasonable, either the readout is misconfigured or the thermocouple is broken. Do not proceed before the problem is corrected.

5. Verify that alarms are reset. The alarms are reset by pressing the "Reset" button in the upper-left of the GUI.

6. Begin heating. To avoid damage to the oven, the temperature must be increased to the final value slowly. A good final operating temperature is 230°C, and a good ramping rate is 60°C/h, *i.e.* heating of the oven will take about four hours to complete.

   In controlling the Oven Temperature from the GUI, you must enter a new temperature setpoint by hand at fixed time intervals. Enter the desired setpoint in the "SP1" enter box in the lower right of the GUI. You should increase the value by

| Menu | Submenu | Setting |
|---|---|---|
| Output Redirection | | S1.o1 |
| Input Type | | RTD |
| | RTD Type | 385.3 |
| | RTD Value | 100_ |
| RDG Configuration | Decimal Point | FFF.F |
| | Temperature Units | °C |
| | Filter Constant | 0004 |
| Alarm 1 | | Enabled |
| | Type | Absolute |
| | Latched | Latched |
| | Contact | n.c. |
| | Setup | Above |
| | Power On | Enabled |
| | Low Value | (anything) |
| | Hi Value | 210.0 |
| Alarm 2 | | Not Installed |
| Loop Break | | Disabled |
| Output 1 | Self | Disabled |
| | % Low | 0000 |
| | % High | 0095 |
| | Control Type | PID |
| | Action Type | Reverse |
| | Auto PID | Disabled |
| | Adaptive Control | Disabled |
| | Anti Integral | Enabled |
| | Start PID | Disabled |
| | Proportional Band | 0038 |
| | Reset Setup | 0050 |
| | Rate Setup | 0000 |
| | Cycle Time | 0001 |
| | Damping Factor | 0001 |
| Output 2 | (any) | (anything) |

Table 1.1: Suggested default parameters for the temperature controller.

| Menu | Submenu | Setting |
|---|---|---|
| Ramp & Soak | Ramp | Disabled |
| | Soak | Disabled |
| Analog Output | | Not installed |
| Communication Option | Baud | 9600 |
| | Parity | Odd |
| | Data Bits | 7bit |
| | Stop Bits | 1bit |
| Bus Format | Checksum | no |
| | Line Feed | no |
| | Echo | no |
| | Standard | 232C |
| | Mode | Command |
| | Separator | Space |
| Data Format | Status | yes |
| | Reading | yes |
| | Peak | no |
| | Valley | no |
| | Unit | yes |
| | ID | no |
| Address Setup | (any) | (anything) |
| Transmit Time | (any) | (anything) |
| Remote Setpoint | | Not installed |

Table 1.2: Suggested default parameters for the temperature controller (continued).

10°C every 10 minutes. For example, if the current oven temperature is 35°C, start with a setpoint of 45°C and increase this value by 10°C in approximately 10 minute intervals. The heater is controlled in PID (proportional, integral, derivative) mode. It approaches the setpoint according to the PID parameters defined in the "Prop. Band", "Reset" and "Rate" boxes in the lower-right of the GUI. These values can be changed, but the defaults should be fine except for special circumstances.

7. Check stability of the final temperature. The temperature might overshoot slightly. If the overshoot is less than about 5°C then this is normal. If the stability is poor it is probably due to incorrectly set PID parameters on the GUI. Changing these parameters is best done by an expert since this requires in-depth understanding of the system.

   The laser contributes significantly to the heating of the oven. Therefore, you will notice sudden temperature instabilities when the laser is turned off or on. It will take several minutes for the controller to compensate for such changes.

8. The air flow rate is slightly dependent on the heater power applied (conductance varies with temperature). Therefore, the flow rate will fluctuate by some 10-20%. This is normal.

9. At any time you can place the controller in standby mode by pressing the "Standby" button in the upper-left of the GUI. This will turn the heater off completely and can be used when the system appears to malfunction. However, exercise some caution if the oven is at an elevated temperature since it will quickly cool down if heater power is disabled and you will lose time bringing it back up to operating temperature.

10. In an emergency, simply turn the power to the chassis off completely. This will open the interlock loops, thereby cutting power to the heater and placing the laser in standby mode.

## 1.8 Helmholtz Coils

The Helmholtz coils are four large rings of coils that provide a large constant magnetic field. Two sets are necessary so that the magnetic field can point in any direction in the horizontal plane. The larger pair horizontal coils each has an inner diameter of 1.45 m and consists of 272 turns of coil. The smaller set of coils each has an inner diameter of 1.27 m and is made of 256 turns of coil. Each pair of the horizontal coils has a resistance of 3 Ohms.

The normal holding field for the target is 25 Gauss which corresponds to approximately 7.2 Amps of current and 25 Volts in the horizontal coils. However, when doing an NMR measurement the field gets as high as 32 Gauss, which corresponds to 9.2 Amps and 32 Volts. The maximum field will not exceed 35 Gauss, which corresponds to 10.0 Amps and 35 Volts.

Table 1.3: Polarized $^3$He target: personnel authorized to operate the power supply and the target magnets

| | | | |
|---|---|---|---|
| Jian-ping Chen | JLab | 7413 | System Supervisor |
| Junhao Chen | W&M | | |
| Mingyu Chen | UVa | | |
| Murchhana Roy | UKy | | |
| Arun Tadepalli | JLab | | |

The coils are powered by two Agilent 6675A power supplies. The maximum range of power supply is 18A and 120 V. The operation condition for the magnet is typically 25-32 Gauss. The maximum field will not exceed 35 Gauss, which corresponds to 10 A and max 35 V. The power supplies are controlled by a LabView Vi running on a PC.

Hazards associated with the operation of the target magnet include exposure to voltage and exposure to magnetic field. All Hazards are mitigated by the use of the engineering and administrative controls detailed below.

The power supplies are located in an electronics rack. Two insulated cables connect each power supply to the magnet. The voltage hazards are electrical shock or burns.The hazards are mitigated by:

- Engineering control:
  - Connectors are covered with insulated material.
  - Magnet support is grounded.
  - Electronic rack is grounded.
- Administrative controls:
  - Warning signs in front of the power supply and on the magnet wall.
  - Voltage to be used is not to exceed 35 V for the Agilent power supply.

In addition, there is a hazard associated with magnetic field. The maximum magnetic field is 35 Gauss inside the magnet. A warning sign will be posted around the target area. No person with a pace maker will be allowed around the target area.

The following personnel have received the proper training. They are the only ones authorized to operate the power supplies and the magnets. Names may be added with authorization from the supervisor of the system (Jian-ping Chen, x7413).

Attached to the horizontal Helmholtz coils are two smaller sets of coils. These consist of 100 loops of 12 AWG wire attached to smaller DC power supplies. In addition there are two pairs of correction coils in the vertical direction. The inner set has 80 loops of 12 AWG wires and the outer set has 70 loops of 12 AWG wires. They are connected to two smaller DC power supplies.

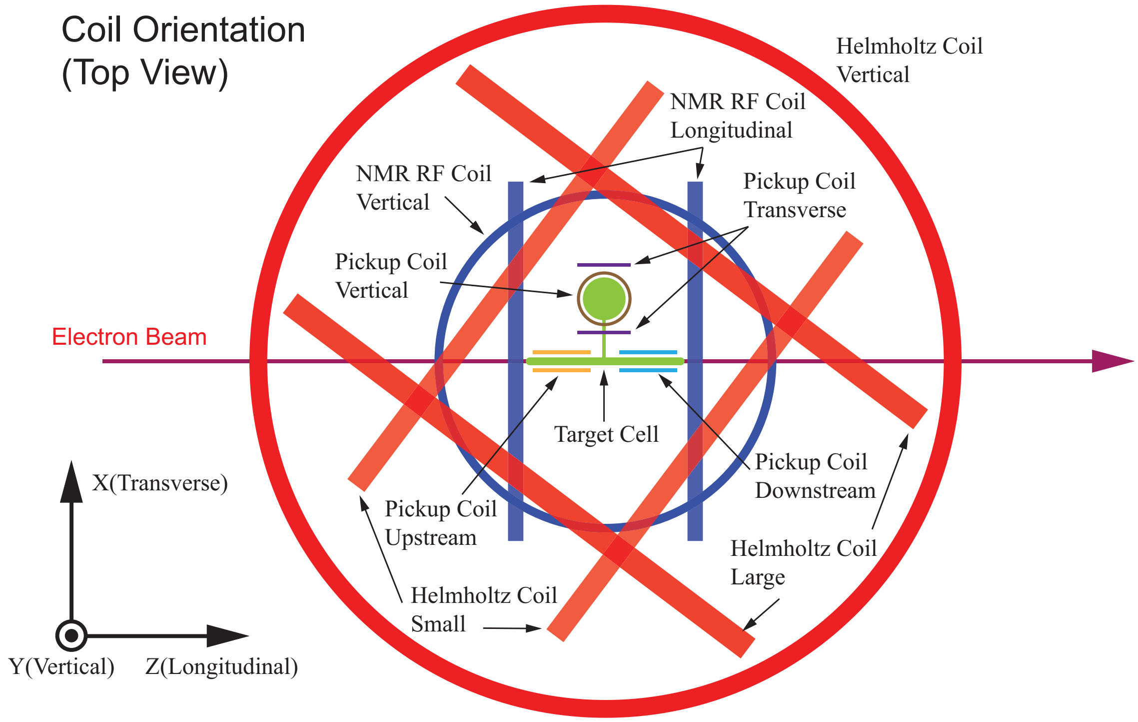


Figure 1.8: Top view of the coils used in the $^3$He target setup. The combination of the 2 pairs of Helmholtz coils power the main holding field to either longitudinal or transverse directions while 2 lines of lasers are available as well in these two directions to polarize the target. One set of RF coils are used for NMR-AFP and EPR measurements. Four pairs of NMR pick up coils are used during the measurement to read out the polarization strength. Two of the pairs are located below the beam line to measure the NMR signal from upstream and downstream part of the target chamber. The other two of the pairs are fixed in the target oven to measure the NMR signal from the pumping chamber.

These coils can be used to compensate for field gradient to minimize AFP polarization loss. These coils can also be used to introduce a field gradient to reduce masing effect.

## 1.9 NMR Polarimetry

This guide explains briefly how to perform safely an NMR AFP sweep on the polarized $^3$He target. Figure. 1.8 shows the target setup and explaining the angle conventions of the polarized target system.

### 1.9.1 NMR polarization measurement

An NMR-AFP measurement has the following steps:

- Turn OFF the lasers (optional).
- Turn ON the NMR RF amplifier.
- Make sure the coil current and oven temperature readings are normal.
- Call MCC to mask the beam motion FSD and make sure the target motion FSD is masked before doing the actual movement. Move the target down to the "pick-up coils" position.
- Run the NMR Measurement VI.
- Load appropriate parameters by clicking "Load Default" button.
- Start NMR Measurement.
- Check result and submit log entry by inputing required info.
- Exit the NMR VI.
- Move the target back to the beam position the experiment needs.
- Call MCC, tell them you have measured the polarization and that the target is back to its beam position. Be sure to follow the beam back procedure before sending the beam back to the target (beam position, raster ON and beam current.)

### 1.9.2 Warnings

- Never stop a running LabVIEW VI (Normally you can't but don't try to hack it);
- Never put CW beam ON the target without raster;
- Every target operator must read and sign the Target Operation and Safety Procedure;
- If the target ruptures, turn OFF the lasers immediately, and then turn off the heaters;
- The lasers must be OFF before rotating the holding field;
- Do not manually change the voltage of the HP6675A;
- We indicate on Table 1.4 the voltage and current information for each power supply.

| Coil | Radius (m) | Turns | Power Supply | $I_{Max}$ (A) | $V_{Max}$ (V) |
|---|---|---|---|---|---|
| Small | 0.667 | 256 | HP6675A | 10 | 35 |
| Large | 0.758 | 272 | HP6675A | 10 | 35 |

Table 1.4: Maximum condition of the power supplies during $^3$He target system operation (35 Gauss).

### 1.9.3 NMR AFP Safety

The NMR AFP system provides the DC current in the holding coils (up to 15 A) and the AC current in the RF coils (usually 1 A rms) of the target setup. Any human contact with the wires shall be avoided. The electronic devices and the PC used to sweep are located in the Counting House and Hall C. Refer to Fig. 1.9 and Fig. 1.10 for a description of the electronics.

#### 1.9.3.1 The DC current

The DC currents are produced by two Agilent power supplies located in a rack behind the shielding wall in Hall C. One power supply drives the large horizontal coils, and the other drives the small ones, as labeled on their front panel. The output of each power supply consists of two wires. The output plugs are located on the back panel of each power supply which can only be reached through the back panel of the rack. All connections are protected either by plastic strips or covers and can not be touched directly by hands. At the coil end, simple metal screws are used to connect those wires to the coils. They shall never be touched while power is ON. All power supply chassis are grounded to the ground of the hall.

#### 1.9.3.2 How to turn the Power Supplies OFF in an emergency?

1. Turn the Function Generators SRS DS345 OFF (one for each coil) by pressing the ON/OFF switch.

2. Turn the Agilent ON/OFF switches to OFF.

#### 1.9.3.3 The AC current

It is produced by the AG Series Power Amplifier located at the bottom of the right rack in counting house. When it is running, the power switch is set to the ON position, the yellow LED is steady and the display shows loaded power above zero. The AC current comes out from the BNC OUTPUT plug, goes through a current monitor (looks like a small toroid) and finally goes to the RF coils. In the hall, the cable is connected to the RF coils along the RF mounting using simple connectors with screws. Those are protected by electrical black tape. They shall never be touched when the RF Power Amplifier is running. The grounding of the system is provided by the RF Power Amplifier.

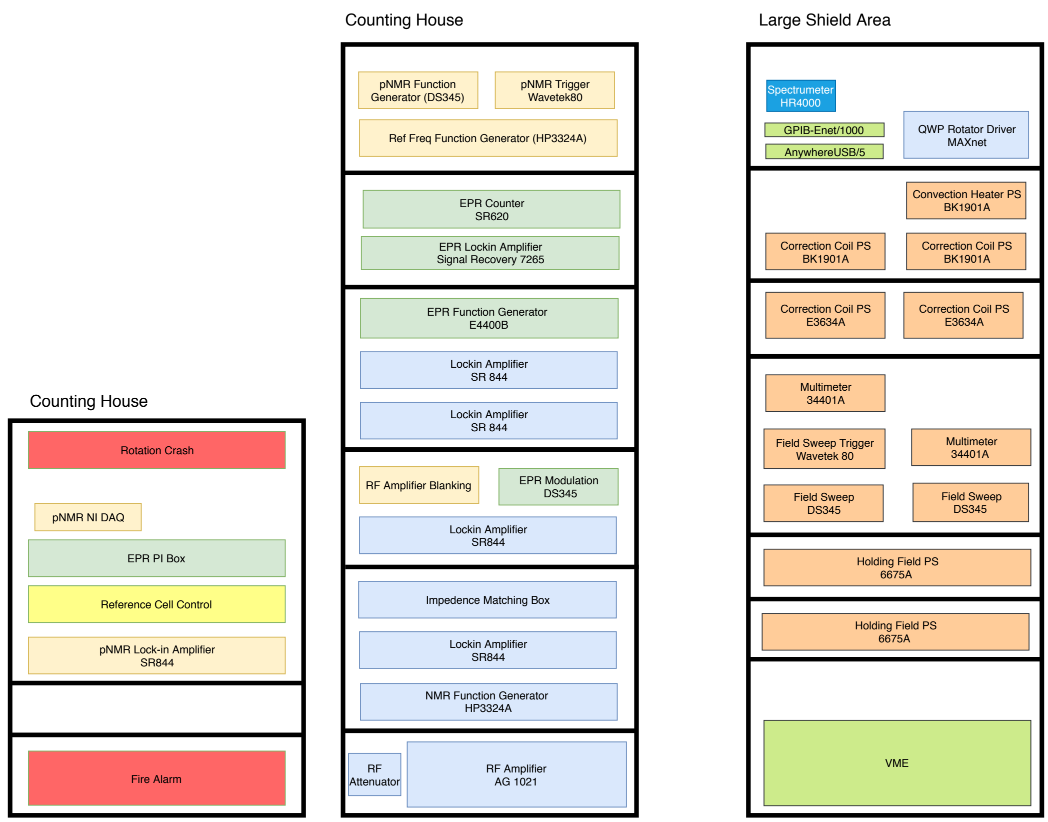


Figure 1.9: The electronics located in the Hall C Counting House.

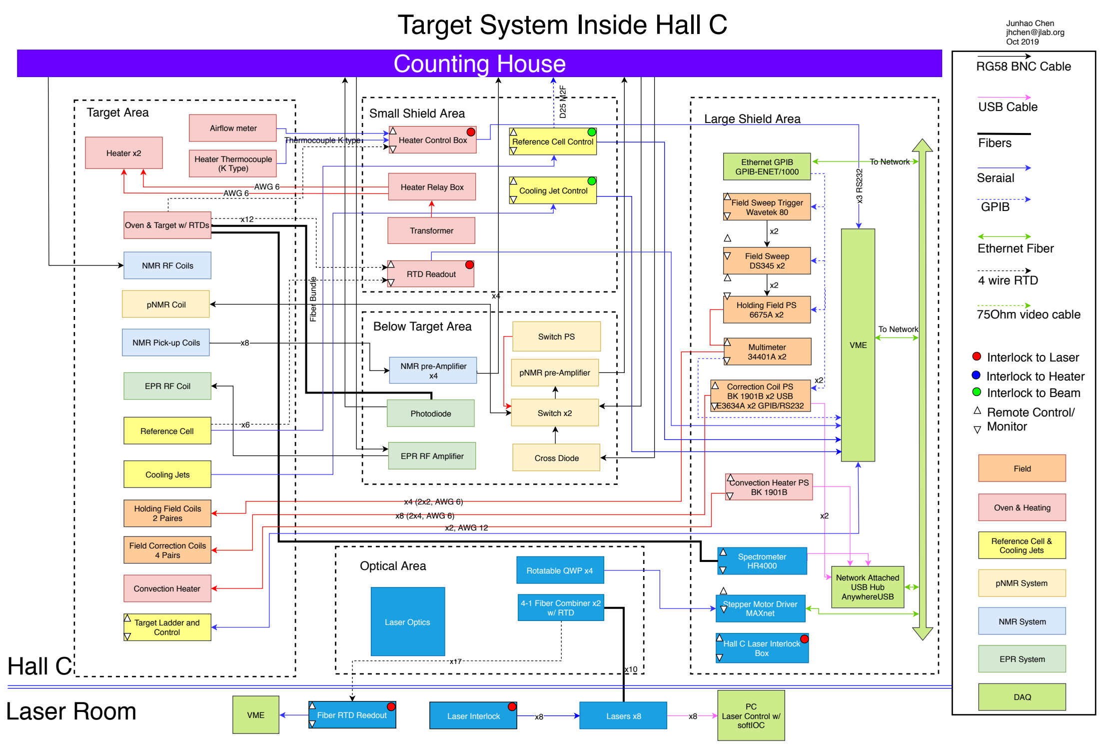


Figure 1.10: Instrumentation diagram of Hall C $^3$He target system.

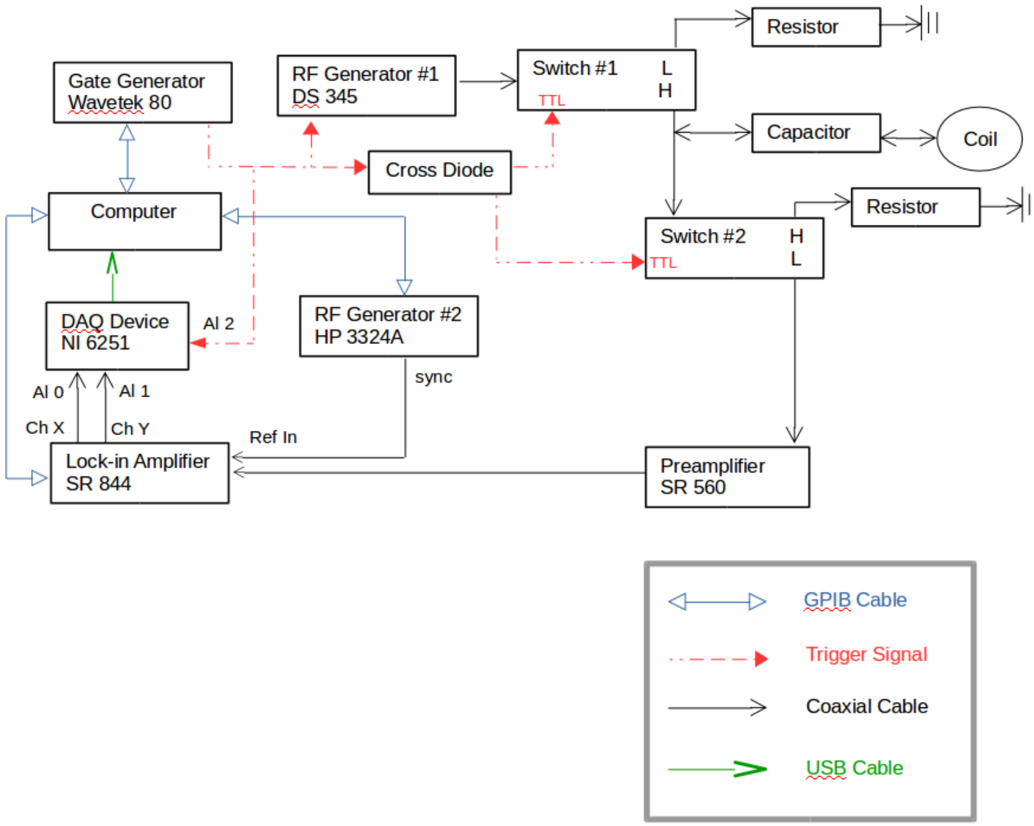


Figure 1.11: Circuit for PNMR FID signal measurement.

#### 1.9.3.4 How to turn the RF Power Amplifier OFF in an emergency?

1. Turn the Function Generator HP 3324A connected to the RF Power Amplifier OFF.
2. Turn the RF Power Amplifier OFF by setting the power ON/OFF switch to the OFF position. All LEDs should turn OFF.

Detailed description of the NMR system is contained in the Hall A wiki page: http://hallaweb.jlab.org/wiki

## 1.10 Pulse NMR Polarimetry

This guide explains briefly how to perform safely a PNMR sweep on the polarized 3He target. The PNMR circuit is shown in Fig. 1.11

### 1.10.1 PNMR polarization measurement

For PNMR measurement, it has the following steps:

1. Make sure the coil current in Helmholtz coils and correction coils are normal.
2. Make sure oven temperature readings are normal.
3. Run the PNMR Measurement VI.
4. ON Labview VI front panel, make sure that the slide button choose the "Helium".
5. Load appropriate parameters by clicking "Load Default" button.
6. Start PNMR Measurement.
7. On plot shows the trigger signal sent by the gate generator, make sure the trigger signal is normal.
8. On plot shows the PNMR free induction decay (FID) signal, make sure the FID signal starts right after the end of trigger signal (to ensure both RF switches worked properly).
9. Check the result and submit log entry by inputting required info.
10. Exit the PNMR VI.

A sample PNMR Labview VI front panel with test free induction decay (FID) signal is shown in Fig. 1.12. The FID signal shape might have different shape depends on the experimental conditions (ex. signal to noise level, magnetic field gradient at measurement location).

### 1.10.2 Warnings

1. Never stop a running LabVIEW VI (Normally you can't but don't try to hack it);
2. Never put CW beam ON the target without raster;
3. Every target operator must read and sign the Target Operation and Safety Procedure;
4. If the target ruptures, turn OFF the lasers immediately, and then turn off the oven heaters;
5. The lasers must be OFF before rotating the holding field;
6. Do not manually change the voltage of the HP6675A;
7. We indicate on Table 1.5 the voltage and current values for each coils power supply.

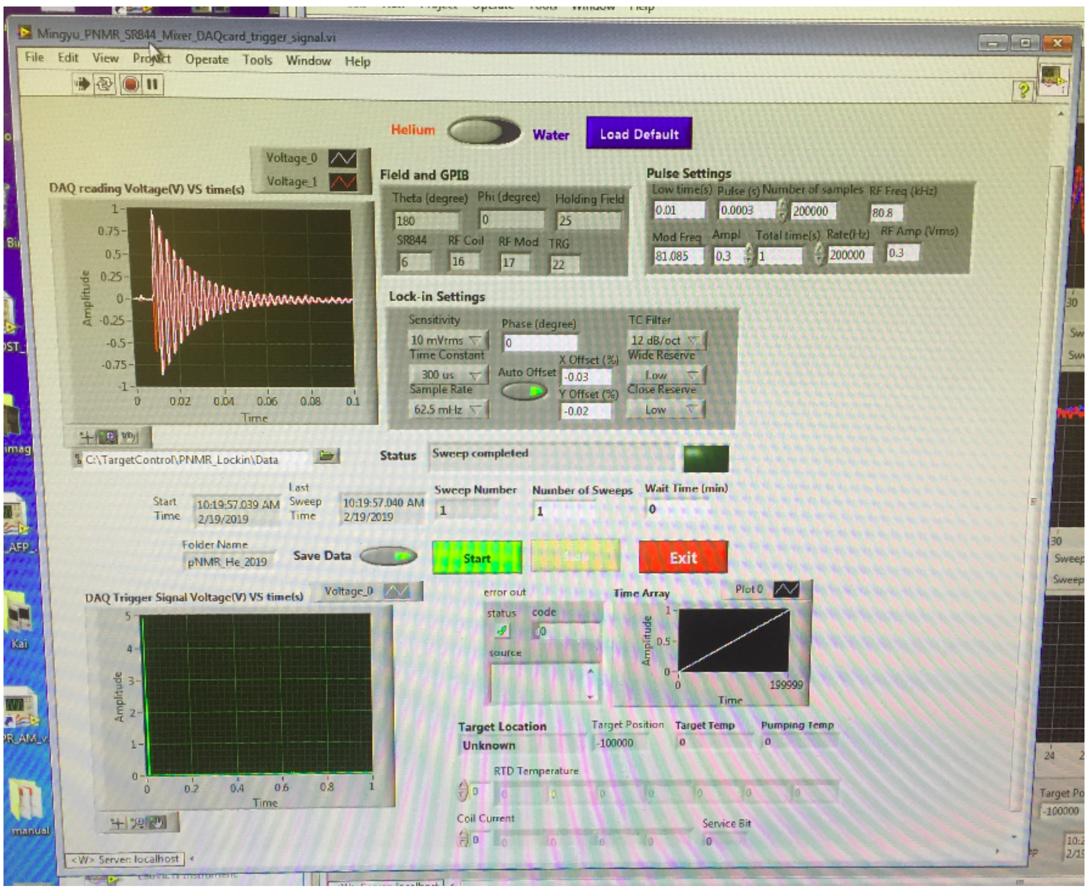


Figure 1.12: A sample PNMR Labview VI front panel with test free induction decay (FID) signal.

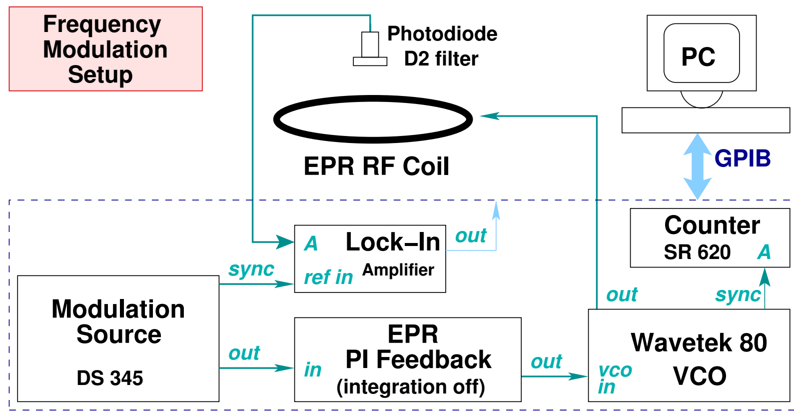


Figure 1.13: Circuit for EPR lineshape measurement

### 1.10.3 PNMR Safety

The electronic devices and the PC used to sweep are located in the Counting House and Hall C. Refer to Fig. 1.9 and Fig. 1.10 for a description of the electronics.

#### 1.10.3.1 The AC current

It is produced by the function generator (DS345) located at a rack in counting house. When it is running, the power switch is set to the ON position. The AC current comes out from the BNC OUTPUT plug and then goes to the RF coils. The current is very small ( 20 mA).

## 1.11 EPR Polarimetry

In what follows we describe two methods to setup and perform an EPR measurement of the target polarization.

### 1.11.1 EPR Lineshape Measurement – Frequency Modulation Sweep:

Use this configuration when you wish only to find the Electron Paramagnetic Resonance (EPR) frequency, not actually track its position. This method allows the user to observe the lineshape of the EPR transition (Rb D2 line or K lines) light emitted from the cell as a function of applied frequency to the EPR coil.

First, construct the circuit described in Fig. 1.11.1 by following these steps:

1. Position the EPR optical fiber mount so that the front opening is flush against the hole of the oven above the ledge. Insert the fiber into the mount as far as possible, until you feel resistance. Tighten all three set screws into place.

2. Turn the dial on the Avalanche Photodiode (APD) to set the “M Factor” to 50, and switch the APD ON. Make sure the flip is switched ON on the power adapter too.

3. Locate the RF Amplifier, and push the “RF Output” button to “ON” and the “Source” button to “EXT”. Only the very left and very right buttons should be lit up. Rotate the “EDITOR” knob to set the gain to 30

4. Manually set the Lock-in amplifier parameters:

   Sensitivity: 1 mV;
   Time Constant: 200 ms;
   Osc: 0.000 Hz;

   * The sensitivity may need to be changed according to the FM signal strength observed. *

5. Connect the output of the Avalanche Photodiode (APD) to input A of the Lock-in amplifier.

6. Set Modulation source DS345 parameters:
   Function: sine wave;
   Sweep/modulate: LIN SWP.

7. Connect DS345 'output' to PI circuit 'mod in', DS345 'sync output' to Lock-in Amplifier 'ref in'.

8. Set PI circuit Integration off, make sure the input is disconnected.

9. Manually set the parameters for the function generator E4400B:
   FM: ON,
   RF: ON,
   Source: External DC,
   Dev: 100 KHz/V,
   Gain: $-5$dB (range is from 5 to $-12$ dB depending on the signal strength)
   Frequency: 10 MHz to 24 MHz (you need to set the frequency limit according to Rb or K resonance. At this moment this is controlled by the Labview program. So you don't have to worry about it).

10. Connect the RF output of E4400B to the RF amplifier and also to the A input of the counter SR620.

11. Do not connect the lock-in back output to the INPUT of the PI box. Leave that INPUT OPEN.
12. Connect the OUTPUT of the PI box to the INPUT of the E4400.
13. Turn INT GAIN OFF.
14. Make sure you have exactly the same circuit as in the figure.

Now that the circuit is in place, open the LabView program "EPR_FM_PI_Box_0.VI".

1. Click the arrow at the top left to initialize the program.
2. Set the "Start Frequency" to 15.6 MHz (19.6 MHz) and "Stop Frequency" to 16 MHz (20 MHz) if the pumping lasers are right (left) circularly-polarized. The range might need to be extended depending on the signal, and if a masing gradient coil is being used (this increases the EPR frequency because of the additional magnetic field it's generating).
3. Set the step size to 0.01 MHz for a quick scan. Or 0.005 MHz for a nominal scan.
4. Set the lockin time constant to 200 ms. Set the Modulation Frequency to 100 Hz and the Modulation Amplitude to 0.75 V (which is 1.5 Vpp)
5. Set the lockin sensitivity to 1 mV, 5 mV, or 10 mV nominal.
6. Set the FM Deviation to 100 kHz/V and ignore the lock-in phase for now.
7. Set the RF amplitude to $-5$ dBm. This value may vary between -12 dBm to 5 dBm, depending on the signal strength.
8. Set the modulator frequency to 100 Hz and the amplitude to 1.5 Vpp.
9. Click "Start FM Sweep."
10. Once you have the lineshape signal, PLOT it. Choose /select the linear regions of both channels (X and Y). FIT with order 3 unless it is really linear. Once you fit, take a look at the calculated PHASE (Just take a look, nothing needs to be done).
11. SET PARAMETER and click on I KNOW I KNOW.
12. START SWEEP again. This time you should see all the signal is in one channel (X usually unless the program is broken) and you have the correct phase.
13. Repeat steps 9 to 11 again. In step 10, this time you probably can use FIT ORDER 1. When you are done with the SET PARAMETER and I KNOW I KNOW, record the number of turns for the gain in the PI box. Make sure that the overall gain we are shooting for is $-0.5$. It is the default value in the VI . But if you find its different, SET IT TO $-0.5$ and RECALCULATE the number of turns again. This NUMBER OF TURNS in the PI gain is the heart of our measurement.

14. If the FM scan looks good (the slope across zero is linear and well-defined, with minimal background from the blue y-channel), save the data file.

### 1.11.2 Common Problems

1. The plot shows no peak/dip.
   - Try adjusting the lock-in phase to get most of the signal contained in the red x-channel.
   - Try lowering the Start Frequency and increasing the Stop Frequency to extend the range. (Is the correct range used for the given laser helicity? Does the range extend far enough to compensate for a gradient coil?)
   - Make sure the pumping lasers are ON
   - Last resort: make sure the EPR RF coil is connected to the RF Amplifier cable down in the hall. **This would require Hall Access**
2. The plot shows multiple peaks. It might be the signal is mixed with background (cable resonance, noise etc.). The solution might be complicated and will not be discussed here. Contact target experts on call.
3. How do I use the output data? The data is saved in a text file consisting of two columns. The first column contains the frequency of the EPR coil, while the second column holds the corresponding signal from the Lock-in Amplifier. Its format can be read by programs such as SigmaPlot, Excel, and Paw.

### 1.11.3 EPR Polarization Measurement – AFP Sweep

This configuration uses the lock-in amplifier with a PI feedback box to lock into the EPR resonance frequency and then track its behavior. With AFP spin-flip, a shift in EPR resonance frequency will be measured, which is proportional to the pumping cell polarization.

Once you are done with the FM sweep and have the number for the turns for the GAIN for the PI box, follow the procedure below to get the AFP sweep done.

1. Refer to the circuit diagram. Start from the configuration as you were doing FM sweep.
2. Connect the lockin output from the back of the lockin to the INPUT of the PI box.
3. Rotate the Absolute Gain (proportional gain) to the number you got from the FM Sweep program.
4. Open EPR_AFP.VI

5. Click the arrow in the top left corner to run the program. Click “Default” to set the default parameters. Make sure the Amplitude (Vrms) is 1.5 V, the Low Frequency is 77 kHz and the High Frequency is 85 kHz.

6. Set the Control Mode to Manual or Auto. If Auto, set the Wait Time to 15 seconds. Make sure the Number of Cycles is set to 2.

7. POWER ON. You will see the frequency (GREEN) in the first plot, frequency fluctuation in the second plot and lockin signal in the third plot. Just dont worry about those at this moment.

8. Rotate the Relative Gain (integral gain) to 0.5. The value that will allow us to lock onto the EPR frequency will range between 0.5 to 2.5. Typically, it’s around 1.0.

9. TURN the INT GAIN ON in the PI box. You should see in the third plot the lockin signal approaching $0 \pm 5$ mV is okay. If not, try to increase the INT GAIN slowly till you feel comfortable.

10. WAIT for a couple of seconds.

11. START SWEEP. You should hear a “click” and see a drop or rise in the frequency (“well” or “hat” shape) in the first plot.

12. If you are doing it MANUALLY, wait for 10 to 15 sec in that flipped state and hit “START SWEEP” again to get back to the original state. If you feel you need more data in that flipped state, wait for another 10 sec.

13. Repeat the above two steps one more time or two.

14. Make sure you end up in the original state. Then POWER OFF. SAVE the data.

15. *Never stop the program during sweeping, this could cause the $^3$He to stay at the wrong state and hence a big loss in target polarization.*

### 1.11.4 Common Problems

1. The lock-in does not remain stable. Or the lock-in but does not seem to track the resonance.

   You may see a big fluctuation in either lock-in signal or resonance frequency. This effect can be caused by several things.

   First, it is possible that the frequency to which you are locked is not the true resonance, or you are completely out of resonance region. The solution is again to find manually the resonance, looking for the most pronounced signal.

   The problem could also be caused by a wrong lock-in amplifier phase. Please refer to Section 1.11.1.

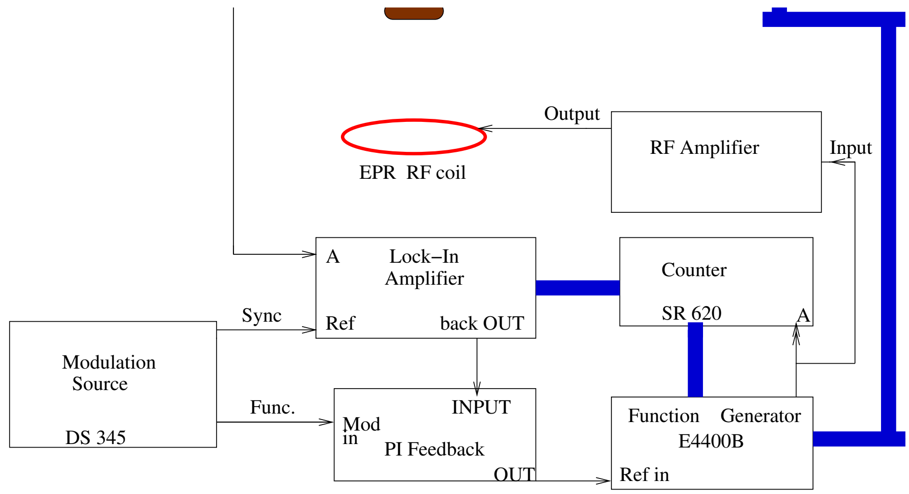


Figure 1.14: Circuit for EPR measurement with AFP spin flip

Finally, it could be that the PI Feedback box is improperly set. Adjust the gains until the lock-in becomes more stable. Admittedly this method is not very quantitative. Based on experience, at high polarization (>40%), both gains should be adjusted anti-clockwisely nearly to the end. At lower polarization (∼20%), both gains should be adjusted by about 4∼5 turns clockwisely. These numbers may also vary at a higher or lower EPR D2 signal amplitude.

You may also optimize the PI circuit gains by observing how fast the circuit follows the resonance. When counter reading is stablized, change Wavetek frequency manually by 0.04 MHz (which is close to the real jump during sweeping, at a target polarization ∼ 40%). If the counter goes back to resonance in roughly 3 5 seconds, then the circuit is working well. If less than 2 seconds and counter reading is not stable, decrease both the relative and absolute gain. If longer than 6 seconds or lose the signal, increase both the relative and absolute gain.

2. The lock-in does not track the resonance when doing AFP flips. This is common, since the frequency shift during the spin flip can be quite large, on the order of 20-40kHz.

   First, it's possible that the PI feedback is not strong enough for the circuit to follow the resonance shift. Try increasing the absolute gain of the PI circuit if possible. Second, it could be that the modulation DS 345 amplitude is too small. The size of this amplitude determines how far from the central frequency the circuit looks for the resonance. Try increasing the modulation amplitude (but do not increase too much, usually it is less than 1.5 Vrms). This will cause the counter reading to be less stable and you need to compromise between stablizing the circuit and following the frequency shift.

## 1.12 Reference Cell

### 1.12.1 Description of the Reference Cell System

The reference cell system is comprised of three subsystems—the reference target cell, the gas handling system, and the control electronics. The reference target cell is mounted inside the target enclosure, which is located in the beam path immediately upstream of the spectrometers. The gas handling system consists of a gas manifold, which is located in an electronics rack in the bunker under the target platform, and a series of gas lines that connect the manifold to the reference cell. A control box consisting of electronics that control the solenoid valves of the gas system is also located in the electronics rack. A remote control box, identical to the one in the hall, is located in the counting house. A schematic of the entire system is shown in Fig. 1.15. Fig. 1.16 shows a simplified schematic of the system indicating the valves relevant for filling and evacuating the reference cell.

Under normal operating conditions, the manifold, the reference cell, and the intervening gas lines will be filled with either $H_2$, $^3$He, or $N_2$ gas at high pressure (typically $\approx$ 10 atm). The system may be operated either locally (at the panel) or remotely (via switches mounted in the counting house). A switch on the remote gas panel itself allows one to toggle between local and remote control. All switches, local and remote, are equipped with LED displays so that one can readily determine the status of any switch.

The reference cell consists of a very thin-walled glass flask. An outlet at the opening is joined to a Copper tube by means of a glass-to-metal seal. This Copper tube is connected to a 1/8" dia. Copper tube with quick-plug-on gas fittings. High pressure $^3$He gas bottle is mounted near the target chamber and is connected to the other end of the 1/8" Copper tube through solenoid valve **V3**. The rest of the gas system is connected to the 1/8" copper tube by a long 1/2" Copper tube. The reference cell is mounted at the gas fitting. A special coupling tool has been designed to facilitate the coupling/decoupling of the reference cell at the quick-plug-on gas joint.

The gas handling system consists of 7 solenoid-controlled, air-actuated valves, one hand-set needle valve, two Baratron pressure gauges (0–1000 Torr and 0–1000 psia), two pressure relief valves, a bottle of high-pressure $^3$He gas, a bottle of high pressure $N_2$ gas, a bottle of high pressure $H_2$ gas, an oil-free MD pump backed up by a backing pump, and sufficient tubing and pipe fittings to connect them all together. There are 5 basic actions that the gas handling system must accomplish; pump-out, vent, fill with $H_2$, $N_2$, or fill with $^3$He.

The reference cell control panel (shown in Fig. 1.17 ) is comprised of 5 push button switches, which activate the 5 possible valve setting conditions, a Baratron high-pressure gauge which reads between 0-1000 psia, a Baratron low-pressure gauge which reads between 0-1000 Torr, two toggle switches to turn on and off the vacuum pump and a toggle switch to select local or remote operation. The valve configurations for the five actions are described in Table 1.5.

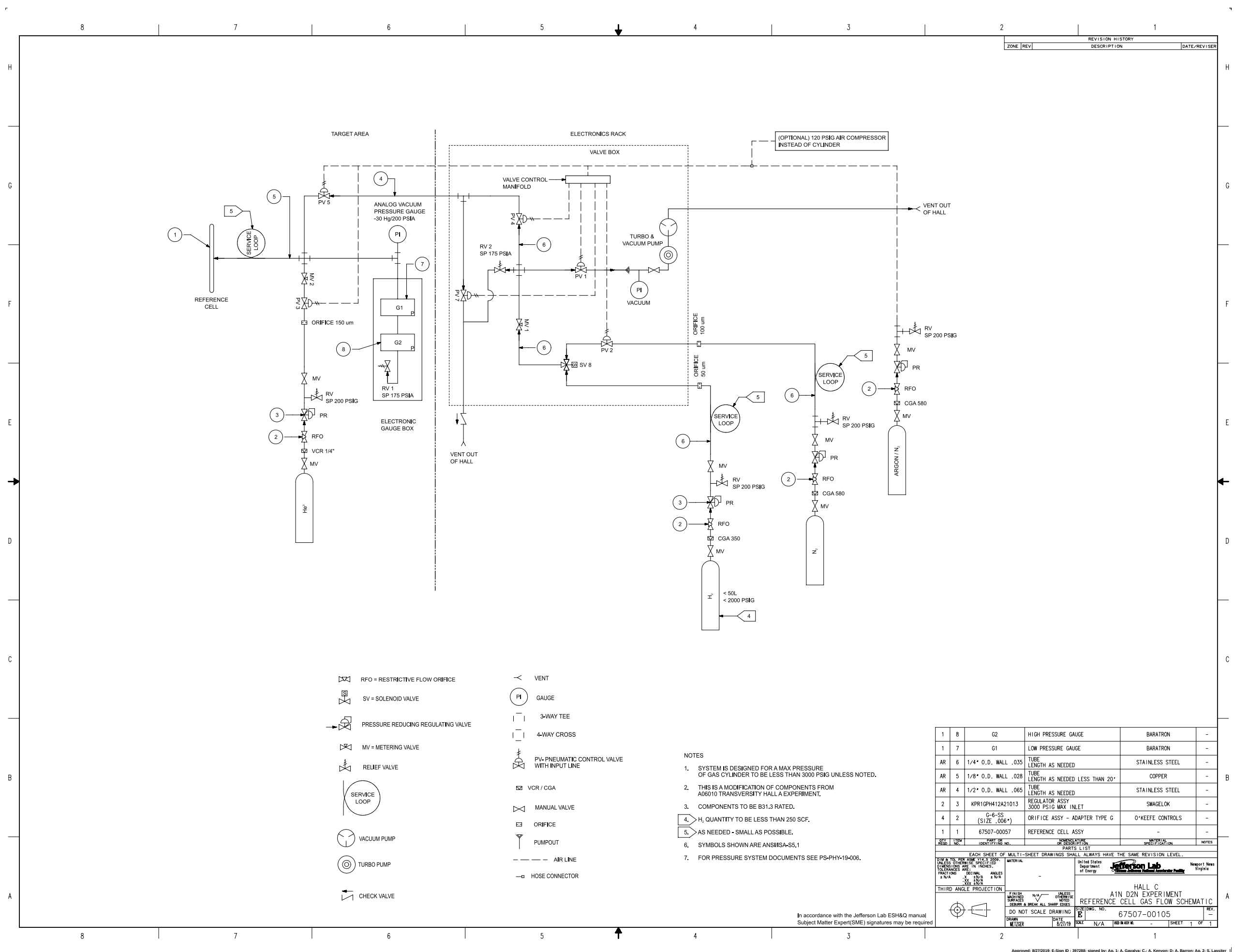


Figure 1.15: Schematic of reference cell system

| Condition | Action | Valves activated (open) |
|---|---|---|
| C1 | **Evacuate** | V1+V4+V5 |
| C2 | **Vent** | V4+V5+V7 |
| C3 | **$^3$He fill** | V3 |
| C4 | **$N_2$ fill** | V2+V4+V5+V8 |
| C5 | **$H_2$ fill** | V4+V5+V8 |

Table 1.5: Action of the remote-control switch panel

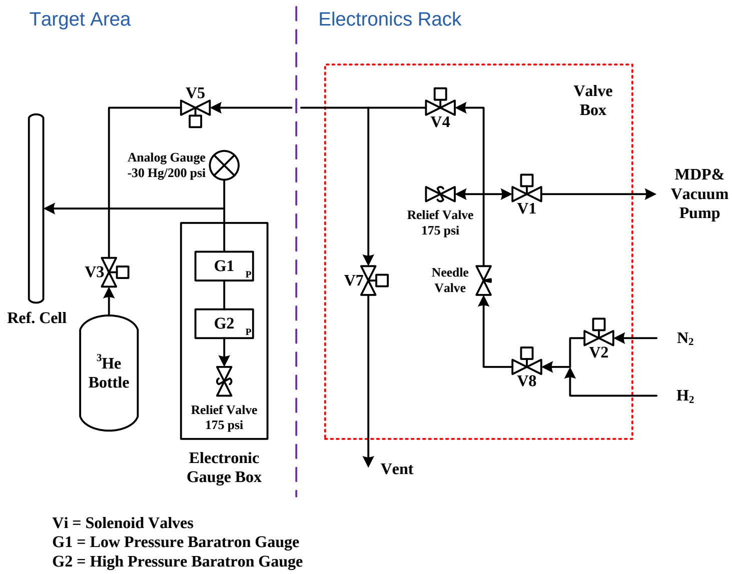


Figure 1.16: Valve configuration of the reference cell gas system.

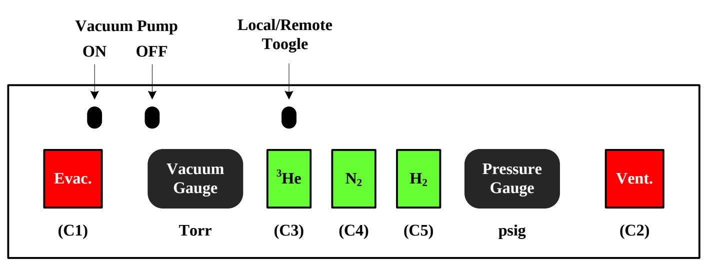


Figure 1.17: Control panel

### 1.12.2 Operation

The following operational sequences will allow the filling of the reference cell with the three gases:

- Fill with $N_2$
  - Step 1: Vent to 16 psia.
  - Step 2: Evacuate until vacuum reaches 1 mtorr.
  - Step 3: Hold the $N_2$ button down while checking the high-pressure gauge, until the desired pressure is established.
  - Repeat steps 2,and 3 three times.
- Fill with $H_2$
  - Step 1: Vent to 16 psia.
  - Step 2: Evacuate until vacuum reaches $< 10$ mtorr.
  - Step 4: Hold the $H_2$ button down while checking the high-pressure gauge, until the desired pressure is established.
  - Repeat steps 2, and 3 three times.
- Fill with $^3$He
  - Step 1: Vent to 16 psia.
  - Step 2: Evacuate until vacuum reaches $< 1$ mtorr.
  - Step 4: Hold the $^3$He button down while checking the high-pressure gauge, until the desired pressure is established.

The pressure at the location of the gas manifold is measured by a baratron gauge. The baratron pressure is read into the data stream and is also output to a remote sensing unit located in the counting house.

### 1.12.3 Cautions

1. Be careful with the $^3$He, we have a limited supply.
2. If the system is above atmospheric pressure, always vent it before pumping.
3. Always monitor the high-pressure gauge when filling. Do not exceed 150 psia.

### 1.12.4 Potential Hazards

The principal hazards associated with the reference cell are flying material and loud noise if the gas panel or reference cell fails catastrophically under high pressure. Of the two subsystems, the reference cell subsystem presents the greater hazard, both because it is more likely to fail, and because it is likely to be more dangerous if it does. The target enclosure is designed to contain all the debris in case of a cell explosion.

### 1.12.5 Hazard Mitigation

After testing the reference cell system to 200 psia and to protect the cell from rupturing during normal operation, the relief valves have been set to 175 psia.

All personnel shall wear double hearing protection when accessing the platform area while the cell is under high pressure and no windows are on the target enclosure.

Special care must be taken when accessing the region inside the target enclosure. Full face shielding, safety glasses and buttoned cotton jacket shall be worn under these conditions. Before working in the vicinity of any of the reference cell components, personnel shall check the pressure in the manifold from the baratron readout in the remote control area.

## 1.13 Hazards and Safety Issues

The main potential hazards encountered in the overall operation of the target are listed below. As we address the operation of each subsystem, a description on how to alleviate the potential hazards is reported.

- Personnel eye sight damage due to exposure to infrared laser light;
- Fire due to the operation of the high power lasers;
- Fire due to the operation of the target oven;
- Rupture of the high pressure target cell;
- Rupture of the reference cell;
- Activation of the target caused by the electron beam.

For personnel safety to be effective all personnel authorized to operate any subsystem of the target will be required be familiar with that specific subsystem as well as read this target OSP.

A target operator is on shift usually when the target laser system is on. A training session is required of any target operator.

## 1.14 Laser Safety

### 1.14.1 Laser Safety

Laser safety is fully addressed in the LOSP. Below are some good practices the laser workers should follow:

1. Always have your safety goggles on when the laser is on!
2. When the yellow beacon is flashing, have goggles on when you enter the hall.
3. Alignment should be done at low power.
4. Be sure that the beam is hitting the target.
5. Do not turn the beam up to full power unless the oven temperature is at least 150 degrees Celsius.
6. Do not look directly into the beam even with safety goggles on.
7. Do not stand in the way of a beam that is at full power.
8. Understand where the beam is and where the reflections are.

### 1.14.2 Fire Hazards and Safety

The fire and safety in the laser room is covered in the LOSP for the laser room, however, in the target area where the laser beam is directed, there is a case where a potential fire hazard exists. No flammable materials should be on or near the path of the laser beam. Temperature sensors are mounted on the optical connection points and inside the laser/optics box and are interlocked with lasers. Hall C VESDA system will be interlocked with lasers as well. Cameras in the hall will be used monitor during the normal operation.

In case the target cell ruptures during optical pumping, the temperature sensors mounted on the target and pumping cells will respond immediately and an alarm will be triggered. The alarm will be triggered whenever a temperature reading of any sensor is 10% out of its nominal range. The target operator shall shut off all the lasers immediately. The target oven will sustain with full laser power incident and no rubidium atoms. There is a plate behind serving as a beam dump.

### 1.14.3 Personnel Safety/ Working in the Hall

When the installation of the full target setup is finished, working in the hall shall be safe from laser light hazards or target explosion hazards, because laser light as well as the target cell will be safely enclosed. Therefore when considering the overall aspects of the safety of personnel working in the Hall two distinct periods are to be considered.

Table 1.6: Polarized $^3$He target: authorized personnel

| | | | |
|---|---|---|---|
| Jian-ping Chen | JLab | 218-0722 | System Supervisor |
| Junhao Chen | W&M | 749-9758 | |
| Mingyu Chen | UVa | 802-535-6612 | |
| Murchhana Roy | UKy | 890-3784 | |
| Arun Tadepalli | JLab | 646-703-3450 | |

1. One period is during the laser beam alignment because part of the laser enclosure on the laser box and around the target need to be removed. During this time period we will ensure that no other person except those people who are laser trained are in the hall. This will be arranged by using a controlled access to the Hall provided by the CANS system. This alignment will be performed usually during the evening, night time and (or) weekend. Clear warning signs will be posted at the entrances of the Hall when the alignment is in progress.

2. One period is during the setup of the high pressure target cell in its final position, or when replacing a target cell, or performing target related work requiring opening the enclosure. In this case the "target platform" which is a natural perimeter around the target area will be marked and signs posted requiring the wearing of ear protection and faceshield. Lasers shall be tuned off and fibers disconnected and locked away following the lock-and-tag procedure. Beyond that defined perimeter all personnel working in the hall will not be affected in case of explosion of the cell if they are not wearing a faceshield. Nevertheless, it is strongly recommended to have ear protection when working anywhere in the Hall.

## 1.15 Appendix: Laser Operation Standard Procedure

See the updated "LOSP for the Polarized 3He Target in Hall C and Laser Room".

## 1.16 List of authorized personnel

The personnel showed in Table 1.6 have completed the training requirements defined in the LOSP and this OSP are authorized to operate the diode lasers and the associated polarized $^3$He target facility.

Names can be added to this list by the Laser System Supervisor.

Other authorized personnel is shown in Tables 1.7 and 1.8.

Names can be added to the lists after proper training and authorized by Jian-Ping Chen, phone 7413 and jpchen@jlab.org.

Table 1.7: Polarized $^3$He target: authorized personnel to change cells

| | | | |
|---|---|---|---|
| Jian-ping Chen | JLab | 218-0722 | System Supervisor |
| Junhao Chen | W&M | 749-9758 | |
| Mingyu Chen | UVa | 802-535-6612 | |
| Murchhana Roy | UKy | 890-3784 | |
| Arun Tadepalli | JLab | 646-703-3450 | |

Table 1.8: Polarized $^3$He target: authorized personnel to perform laser alignment

| | | | |
|---|---|---|---|
| Jian-ping Chen | JLab | 218-0722 | System Supervisor |
| Junhao Chen | W&M | 749-9758 | |
| Mingyu Chen | UVa | 802-535-6612 | |
| Murchhana Roy | UKy | 890-3784 | |
| Arun Tadepalli | JLab | 646-703-3450 | |