MUSE Liquid Hydrogen Target

Operating Procedures Manual

November 16, 2018

(Version 1.1)

Table of Contents

A. The Gas System

A schematic of the gas system is shown in Fig. 1. Pictures of the gas panel are shown in Fig. 2.

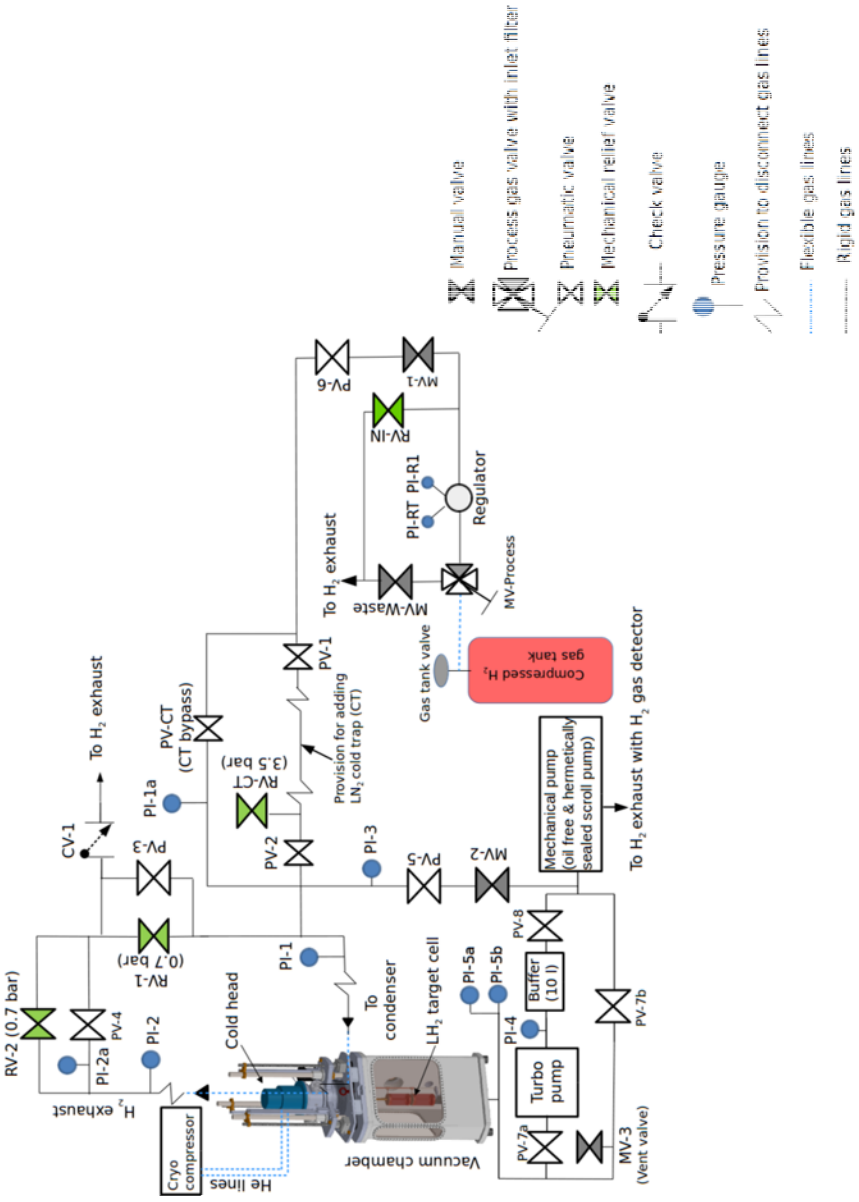

Figure 1: A schematic layout of the gas flow control system. Flexible lines are required to allow vertical movement of the ladder. The set pressures (relative to atmospheric pressure of 1 bar) of the relief valves RV-1 and RV-2, that serve as passive safety valves for the gas system, are indicated in the diagram.

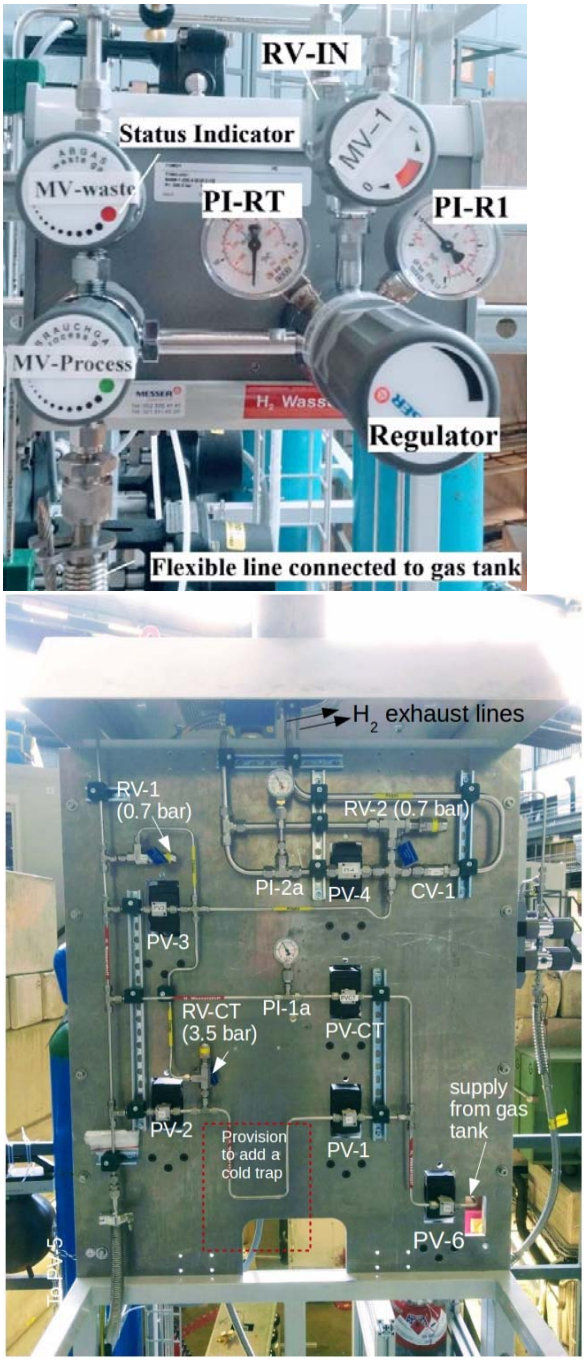

Figure 2: (Left) a side view of the gas panel showing a control panel which is connected to the gas tank via a flexible supply line. The control panel consists of manual valves (MV-Process, MV-waste, MV-1), a regulator, a relief valve (RV-IN) and analog pressure gauges (PI-RT, PI-R1). The status indicators on the MV-valves are not reliable, so be sure to open/close these fully. (Right) a front view of the gas panel showing the pneumatically controlled valves (labeled as PV), over-pressure mechanical relief valves (labeled as RV) and analog pressure gauges (labeled as PI). The relief valves RV-1 and RV-2 serve as passive

safety valves for the gas system.

NOTE: In the rest of the document, the pressures are specified either as absolute values or relative to atmospheric pressure of 1 bar, depending on what the corresponding pressure gauge measures. The details of which pressure gauges measure absolute pressures, and which measure relative pressures (relative to 1 bar) are given in **Section B (List of Valves and Pressure Gauges)**.

B. List of Valves and Pressure Gauges

Vacuum system's pressure indicators

1. PI-4: CMR 363 Pfeiffer activeline gauge to measure the pressure of the buffer volume. Pressure range: $1x10^{-3}$ to 11 mbar (absolute). Output: 1 to 9.8 V.

2. PI-5a: CMR 361 Pfeiffer activeline gauge to measure the vacuum chamber's pressure. Pressure range: $1x10^{-1}$ to 1,100 mbar (absolute). Output: 1 to 9.8 V.

3. PI-5b: CMR 365 Pfeiffer activeline gauge to measure the vacuum chamber's pressure. Pressure range: $1x10^{-5}$ to $1x10^{-1}$ mbar (absolute). Output: 1 to 9.8 V.

Vacuum system's valves

1. PV-5: Gas panel and target cell outlet valve (pneumatic) to mechanical pump for purging prior to starting the target. Normally closed-type valve. It will be operated using the LabView program for target slow control. Upon opening this valve, the mechanical pump will turn on automatically to pump out the supply line and the target cell. To protect the turbo pump, the vacuum control system will not allow opening this valve if the foreline valve (PV-8) is open to pump on the buffer. In such cases, the vacuum control system will first close PV-8 after the buffer pressure reaches 0.3 mbar, then open PV-5 if 'PV-5 open' is enabled on the LabView program.

2. MV-2 (with DN16 ISO-KF port): backup valve (manual) in case PV-5 does not close. The physical location of MV-2 is shown in Fig. 10 of section **G.1 (Target Start Procedure)**.

3. MV-3: Vacuum chamber vent valve (manual). The physical location of MV-3 is shown in Fig. 5 of section **E. (Target Installation Checklist)**.

4. PV-7b (with DN25 ISO-KF port): Roughing valve or bypass valve (pneumatic). Normally-closed type. It will be operated automatically by the PSI-built vacuum control system. It will be opened to pump out the vacuum chamber to 0.1 mbar (measured by PI-5a) using the mechanical pump. It will be closed after the chamber reaches 0.1 mbar absolute pressure. In case the vacuum chamber's pressure rises beyond 2 mbar, the high vacuum valve (PV-7a) will be closed, the mechanical pump will be turned on and then this valve will be opened. The vacuum chamber will be pumped by the mechanical pump until the pressure reaches 0.1 mbar.

5. PV-7a (with DN63 ISO-KF port): High vacuum valve (gate valve with pneumatic actuator). Normally closed-type. It will be operated automatically by the vacuum control system. It will be opened if PI-5a measures 0.1 mbar absolute pressure, the speed of the turbo pump is at 97% and the buffer pressure (measured by PI-4) is below 10 mbar. PV-7b will be closed before PV-7a is opened. If the vacuum chamber's pressure (measured by PI-5a) is above 2 mbar, or if the speed of the turbo pump is below 83% or if the buffer

pressure (measured by PI-4) is above 10 mbar, then PV-7a will be closed.

6. PV-8 (with DN25 ISO-KF port): Foreline valve (pneumatic). Normally closed-type. Another purpose of this valve is to isolate the buffer from the mechanical pump when the mechanical pump is turned off. It will be operated automatically by the vacuum control system. The vacuum control system will close PV-8 and turn off the mechanical pump when the buffer pressure, measured by PI-4, goes below 0.3 mbar. On the other hand, the vacuum control system will turn on the mechanical pump and open PV-8 when PI-4 goes above 4.0 mbar.

Gas system's pressure indicators

1. PI-RT: Analog pressure gauge to measure the inlet pressure from the gas tank. Pressure range 0 to 400 bar (relative to atmospheric pressure of 1 bar).

2. PI-R1: Analog pressure gauge to measure the outlet pressure of the regulator. Pressure range: -1.0 to 1.5 bar (relative to atmospheric pressure of 1 bar).

3. PI-1: PR-33XEd pressure gauge to measure pressure in the hydrogen supply flexline. Pressure range: -0.45 to 2.5 bar (relative to atmospheric pressure of 1 bar).

4. PI-1a: Analog pressure gauge to measure pressure in hydrogen supply line. Pressure range: -1.0 to 1.5 bar (relative to atmospheric pressure of 1 bar). Serves as a backup to PI-1 pressure transmitter.

5. PI-2: PR-33XEd pressure gauge to measure target exhaust pressure at the hydrogen return flexline. Pressure range: -0.45 to 2.5 bar (relative to atmospheric pressure of 1 bar).

6. PI-2a: Analog pressure gauge to measure target exhaust pressure at the hydrogen return line. Pressure range: -1.0 to 1.5 bar (relative to atmospheric pressure of 1 bar). Serves as a backup to PI-2 pressure transmitter.

7. PI-3: CMR 363 Pfeiffer activeline gauge to measure the pressure in the hydrogen supply line during purging prior to starting the target. Pressure range: $1x10^{-3}$ to 11 mbar (absolute). Output: 1 to 9.8 V.

Gas system's valves

1. Gas tank valve: valve on gas tank (manual).

2. MV-Process: Process gas valve (manual). This valve separates the control panel (Fig. 2 (left)) of the gas panel from the gas tank. Before replacing a gas tank connected to the gas panel, this valve will be closed to prevent exposure of the entire gas system to ambient air.

3. MV-waste: Waste gas valve or purge valve (manual). Before replacing a gas tank connected to the gas panel, this valve will be opened to relieve the pressure in the gas line from the gas tank to MV-Process while keeping MV-Process closed. After replacing the gas tank, this valve will be opened to purge the gas line from the compressed gas tank to MV-Process while keeping MV-Process closed.

4. Regulator: Regulates the inlet pressure from the gas tank to achieve a set outlet pressure level. The hand wheel of the regulator will be rotated clockwise to set a desired outlet pressure. To stop regulating, the hand wheel will be backed off by rotating it anticlockwise.

5. RV-IN: Mechanical over-pressure relief valve to protect the control panel (Fig. 2 (left)) of the gas panel from impermissibly high outlet pressure. It does not function as a safety valve for the entire gas system.

6. MV-1: Hydrogen supply valve (manual). This will be opened to supply a regulated pressure of hydrogen gas from a compressed hydrogen gas tank.

7. PV-6: Hydrogen supply valve (pneumatic), added for safety purpose. Normally closed-type valve. It will be interlocked to hydrogen gas detectors. If any hydrogen gas detector detects a leak, this pneumatic valve will close immediately.

8. PV-1: Cold trap inlet valve (pneumatic). Normally closed-type valve. Currently it is not used because there is no cold trap at the gas panel.

9. PV-2: Cold trap outlet valve (pneumatic). Normally closed-type valve. Currently it is not used because there is no cold trap at the gas panel.

10. PV-CT: Cold trap bypass valve (pneumatic). Normally closed-type. Currently it is not used because there is no cold trap at the gas panel. However, if we add a cold trap at the location shown in Fig. 1 in the future, this valve will allow bypassing the cold trap in case it gets blocked due to possibly frozen contaminants.

11. RV-CT: This mechanical over-pressure relief valve will open if the pipe pressure of the cold trap reaches 3.5 bar relative to atmospheric pressure of 1 bar upon warming up the cold trap. Currently it is not used because there is no cold trap at the gas panel.

12. PV-3: Safety valve (pneumatic) for hydrogen supply line. Normally open-type valve. The slow control system will open it if the target inlet pressure, measured by PI-1, goes beyond 0.5 bar relative to atmospheric pressure. This limit is lower than the limit at which RV-1 opens (which is 0.7 bar relative to atmospheric pressure).

13. RV-1: Mechanical over-pressure relief valve as an emergency backup if the target inlet pressure, measured by PI-1, reaches 0.7 bar relative to atmospheric pressure and PV-3 fails to open. RV-1 will close automatically once the pressure drops below 0.5 bar.

14. PV-4: Safety valve (pneumatic) for exhaust line. Normally open-type valve. The slow control system will open it if the target exhaust pressure, measured by PI-2, goes beyond

0.5 bar relative to atmospheric pressure. This limit is lower than the limit at which RV-2 opens (which is 0.7 bar relative to atmospheric pressure).

15. RV-2: Mechanical over-pressure relief valve as an emergency backup if the target exhaust pressure, measured by PI-2, reaches 0.7 bar relative to atmospheric pressure and PV-4 fails to open. RV-2 will close automatically once the pressure drops below 0.5 bar.

16. CV-1: Check valve or one-way valve. It will allow gas flow to hydrogen exhaust pipe (which is open to air) if the pressure difference across the two ends of the valve is above 0.07 bar. But it will prevent air from being cryo-pumped into the target from outside through the hydrogen exhaust pipe.

C. Target Management

There are three categories of personnel managing the target:

C.1. Target experts

1. The target experts have the permission to start, run and shut down the target. Additionally, they have the permission to perform maintenance on the target components, make operational or system-level changes, if necessary.
2. The target experts will be on call at PSI during the operation of the liquid hydrogen target.
3. The U-M cryotarget group are the designated target experts. Members are:

   Priyashree Roy
   Noah Wuerfel
   Noah Steinberg
   Richard Raymond
   Wolfgang Lorenzon

   If need arises, the U-M group will train additional members of the MUSE collaboration to become target experts.

C.2. 2nd level experts

1. The 2nd level experts have the permission to start, run and shut down the target. They have the permission to perform operation level changes, such as changing the target heater current during the shut down mode.
2. The U-M cryotarget group has trained the following local MUSE members to be the 2nd level experts:

   Alexander Golossanov
   Konrad Deiters
   Tigran Rostomyan

   The main criteria for selecting candidates to become 2nd level experts is that they are present at PSI for extended periods to be available during target operation. If need arises, the U-M group will train additional members of the MUSE collaboration to become 2nd level experts.

C.3. Shift takers

1. The shift takers have the permission to monitor the target system and to change the target positions. They do not have the permission to make operational changes to the system.
2. If operational changes are necessary, then the shift taker must notify the 2nd level expert on call. The 2nd level expert will evaluate the situation, take immediate action if necessary or notify the target expert on call.
3. All MUSE members are eligible to be shift takers.

Password-based restricted access

The different levels of permissions for target experts, 2nd level experts and shift takers are implemented in the slow-control system using password-based restricted access. The target experts are responsible for training, certification and distribution of appropriate passwords. There are two passwords, an 'expert' password and a 'shifter' password. The expert password is provided only to the target experts and the 2nd level experts. The shifter password is provided to the shift takers, the 2nd level experts and the target experts. If expert password is used to login to the target slow control system, all four target operation modes (see **Section D (Target Operation Modes)**) can be used. On the other hand, if the shifter password is used to login, then only the 'target running mode' can be used whereby the target status can be monitored, and the target's position can be changed. If no password is used to login, then the FPGA, stepper motor and Lakeshore parameters cannot be changed, the alarms cannot be enabled/disabled, and the target position cannot be changed.

D. Target Operation Modes

There are four main modes of operation of the target. All four modes are password protected as explained in the previous section.

1. **Target start mode**: for cooling down and filling the target with LH_2. This mode can be used only by the 2nd level experts and the target experts.

2. **Target running mode**: for normal running conditions of the filled target. This mode can be used by the shift taker, the 2nd level experts and the target experts to monitor the target and to change target position. He/she cannot make any operation or system-level changes, such as operating the pneumatic valves of the gas and pump system, changing the compressor status, changing the FPGA parameters etc.

3. **Target shut down mode**: for warming up and emptying the target. This mode can be used only by the 2nd level experts and the target experts.

4. **Target standby mode**: for purging the target. It is also the default mode when the FPGA starts/restarts. Upon starting/restarting, the PV valves go to their default state. This mode can be used only by the 2nd level experts and the target experts.

Mode	Features	Who has access
Target start mode	Target cool down procedure can be enacted.	Target experts and 2nd level experts
Target running mode	Target status can be observed, target position can be changed.	Target experts, 2nd level experts and shift takers
Target shut down mode	Target warm up procedure can be enacted.	Target experts and 2nd level experts
Target standby mode	Target can be purged. Default mode upon rebooting FPGA.	Target experts, 2nd level experts

Table 1: Summary table of the operation modes and who can access these modes.

E. Target Installation Checklist

(only for target experts and 2nd level experts)

Note: This checklist will be used when the MUSE frame is moved back to the PiM1 area, or after performing target maintenance that involved disconnecting the hydrogen gas connection between the chamber and the gas panel.

Name _____
Date _____

1. ☐ No physical damage to chamber, gas lines or cables.
2. ☐ Target windows are intact. Window covers are placed on chamber windows.
3. ☐ Supply power to vacuum control system.
4. ☐ Connect compressed air supply to pneumatic actuator of gate valve of vacuum system.
5. ☐ Connect helium lines to cold head following instructions in Sumitomo manual.
6. ☐ Connect hydrogen supply and return lines to chamber. Use new VCR gaskets.
7. ☐ Connect receptacle cable from compressor to cold head.
8. ☐ Connect feedthrough cable from slow control system to electrical feedthrough on chamber.
9. ☐ <u>Check resistances on electrical feedthrough cable near Lakeshore temperature controller:</u>
   a) the two condenser heaters, labeled ‘heat 1’ and ‘heat 2’, have about 28 Ω resistance. One of them is connected to ‘Output 1’ at back panel of Lakeshore,
   b) the target heater, labeled ‘HEATER TARGET’, has about 28 Ω resistance.

Figure 3: A picture of the ‘Expert’ tab of RTMain.vi.

10. ☐ Check RTMain.vi is running on slow control's display panel. If not running, click on arrow displayed on top-left to start the vi. Go to 'Expert' tab of RTMain.vi (Fig. 3). Use expert password to login.
11. ☐ Select 'Start Mode' and check on 'Operation LH2' tab of RTMain.vi that the level sensor resistance is about 111 Ω (Fig. 4). Change back to 'Standby Mode'.
    Note that the level resistor will read 0 in standby mode.
12. ☐ Check 'StepperCamera' program is running on mpc2001 (i.e. 'position' LED is green).

13. ☐ <u>Leak check RV valves, gas lines and target ladder using neon/argon/nitrogen gas:</u>

    a) ☐ <u>Replace hydrogen gas tank with neon/argon/nitrogen gas tank:</u>
       i. check MV-Process and MV-waste on control panel of gas panel are closed,
       ii. check hydrogen gas tank valve is closed,
       iii. open MV-waste to relieve pressure in supply line from hydrogen gas tank to MV-Process,
       iv. close MV-waste,
       v. disconnect supply line from hydrogen gas tank. Securely fasten and place this tank in designated area,
       vi. connect special gas fitting for non-flammable gases to supply line. Then connect supply line to neon or argon or nitrogen gas tank.

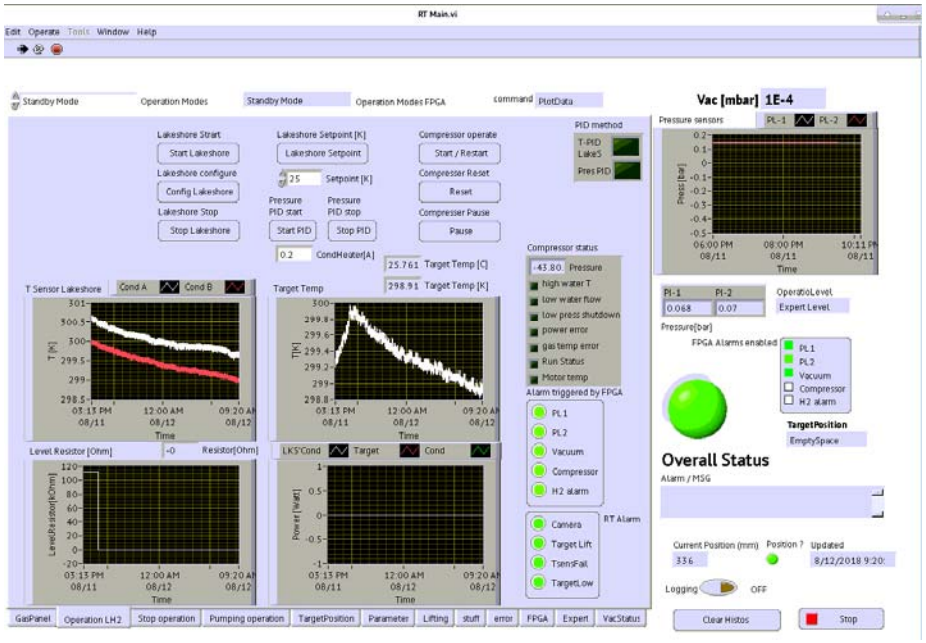

Figure 4: A picture of the 'Operation LH2' tab of RTMain.vi.

    b) ☐ <u>Establish vacuum in the target chamber:</u>
       i. check power switch on Lakeshore temperature controller is in OFF position,
       ii. check no voltage is applied to the beam focusing detector,

iii. select ‘standby mode’ on RTMain.vi (use drop-down menu at the top) to stop current supply to level sensor,
iv. close manual vent valve MV-3 of vacuum system (see Fig. 5),
v. press 'pump' button on vacuum control panel. Wait 8-10 hours until pressure reaches $1x10^{-4}$ mbar (check ‘Vac [mbar]’ on top-right of any tab of RTMain.vi).
Note: the pressure reading on the vacuum control box on the MUSE frame will show $3x10^{-4}$ mbar but occasionally it may drop to $1x10^{-4}$ mbar.

Figure 5: A picture of the vent valve, MV-3, of vacuum pump system under the chamber.

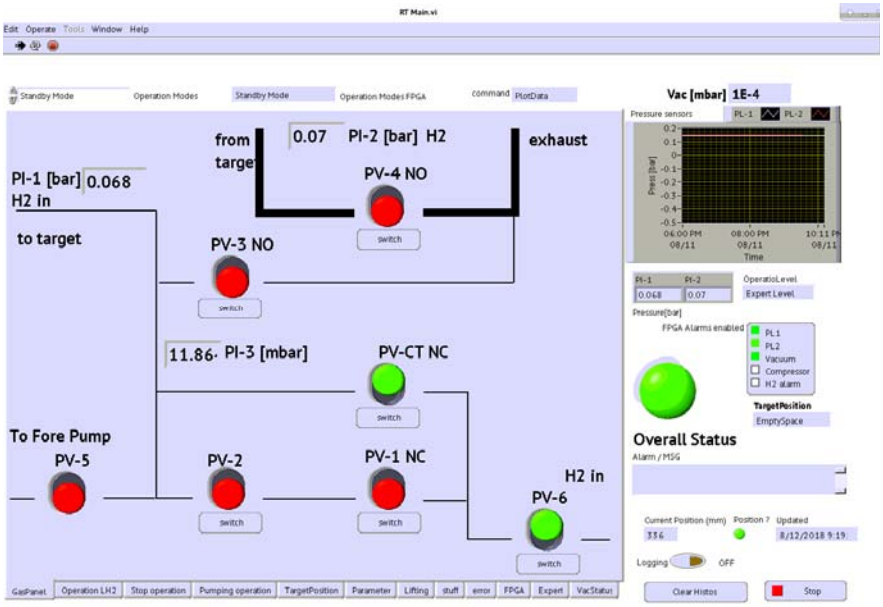

Figure 6: The 'GasPanel' tab of RTMain.vi. If the status indicator is red (green), it indicates that the corresponding PV valve is closed (open).

c) ☐ Leak-check RV valves and gas lines (under-pressure test):

i. Check that MV-2, between the gas panel and PV-5, is open (Fig. 10 of **Section G.1(Target Start Procedure)**).
ii. Open 'GasPanel' tab of RTMain.vi (Fig. 6),
iii. stay in 'standby mode' on RTMain.vi to operate PV-5. Close PV-3 and PV-4,
iv. check gas tank valve is closed,
v. confirm chamber pressure is below 1 mbar. Otherwise the target cell will implode,
vi. check MV-waste and MV-Process on gas panel are closed,
vii. check PV-6 is closed on 'GasPanel' tab of RTMain.vi so that PV-5 can be opened (interlock prevents both to be open at same time),
viii. using 'GasPanel' tab of RTMain.vi open PV-1, PV-2, PV-CT,
ix. using 'Pumping operation' tab of RTMain.vi open PV-5 (Fig. 7). Mechanical pump will turn on automatically. Pump out gas lines and target cell. Wait until the supply pressure, PI-1, shows -0.45 bar,
x. close PV-5 using 'Pumping operation' tab of RTMain.vi,
xi. wait for 1-2 hours. Check PI-1 and PI-2 pressures on 'GasPanel' tab of RTMain.vi. If they remain steady, this indicates no leak. If the pressures increase, helium leak check the RV valves and the gas lines. Repair the leak.

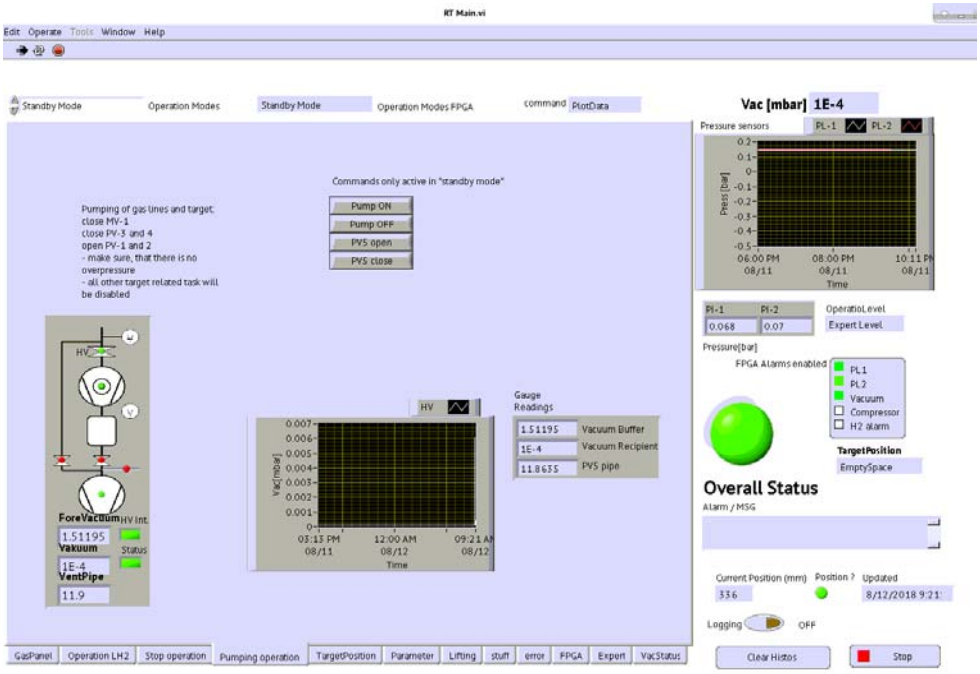

Figure 7: The 'Pumping operation' tab of RTMain.vi. This is used to operate PV-5 for purging the target, and to monitor vacuum system's pressures.

d) ☐ Leak-check target ladder (over-pressure test):
   i. with target cell pumped out, wait for chamber to reach lowest pressure (about $1x10^{-4}$ mbar on the slow control system),
   ii. check MV-waste on gas panel is closed,
   iii. check regulator is backed off,
   iv. using 'GasPanel' tab of RTMain.vi check PV-3, PV-4 and PV-5 are closed. Open PV-6 using this tab,
   v. open gas tank valve,
   vi. open MV-Process and MV-1 on gas panel,
   vii. use regulator on gas panel to backfill target until PI-1 reads 0.1 bar on RTMain.vi. Back off regulator,
   viii. close gas tank valve,
   ix. leave target cell pressurized for about 5 hours. Check time evolution over those 5 hours of PI-1 (target pressure) and 'HV' (vacuum chamber pressure) using real-time graphs on 'Pumping operation' tab of RTMain.vi (Fig. 7).

   If 'HV' increases and PI-1 drops, this may indicate a leak in target cell. In case of a leak, replace target ladder with a leak-free ladder. If PI-1 drops but 'HV' remains constant, this indicates leak in gas lines outside of target chamber. Helium leak check the gas lines and repair the leak.

   x. stay in 'standby mode'. Open PV-3 and PV-4. This will depressurize target.

14. ☐ Reconnect hydrogen gas tank to gas panel:
   a) check MV-Process and MV-waste on control panel of gas panel are closed,
   b) check neon/argon/nitrogen gas tank valve is closed,
   c) open MV-waste to relieve pressure in supply line from gas tank to MV-Process,
   d) close MV-waste,
   e) disconnect supply line from gas tank. Securely fasten and place this tank in designated area,
   f) disconnect special gas fitting for non-hydrogen gases from supply line. Then connect supply line to hydrogen gas tank.
   g) with MV-Process and MV-waste closed, open hydrogen gas tank valve to pressurize supply line. Leak-check connection to hydrogen gas tank with snoop/soapy water. Wipe off soap water from connection at end of test,
   h) with MV-Process closed, open MV-waste to purge supply line from hydrogen gas tank to MV-Process. Repeat two times.

15. ☐ Check connections to the Lakeshore temperature controller:
   a) temperature sensors (labeled D1 and D2) of condenser are connected to Lakeshore's inputs A and B, respectively,
   b) target temperature sensor (labeled as D3) is connected to Lakeshore's input C,
   c) check at back panel of Lakeshore that one of the two condenser heaters, labeled 'heat 1' and 'heat 2', is connected to Lakeshore's Output 1 (which can provide 100 W max power).

Figure 8: A picture of the front panel of the Lakeshore temperature controller.

16. ☐ Check settings on Lakeshore temperature controller using front panel (Fig. 8):
    a) PID settings P=150.5, I=76.0, D=0 on front display panel,
    b) check heat range set to 'High'. To check this, press 'Heater Range' key. Press 'ESCAPE' key to exit.
    c) check resistance, current setting is 25 Ω, 2A. To check resistance (current) setting, press '4' key -> check 'Output 1' is selected -> select 'Heater Resistance' ('Max Current') using 'up/down arrow' key -> press 'Enter' key -> check '25 Ω' ('2 A') is selected -> press 'Escape' to exit.
    d) calibration curves for the three temperature sensors: user 22 for input A, user 21 for input B, user 25 for input C. To check this, press '7' key -> select Input A (or B or C) -> Select 'Curve' and check. Press 'Escape' key to exit.

17. ☐ Do general housekeeping around the area.

F. Target Start Checklist

(only for target experts and 2nd level experts)

Name _____
Date _____

These checks are to be performed by an expert a day in advance of cooldown.

1. ☐ No physical damage to chamber, gas lines or cables.
2. ☐ Target windows are intact. Window covers are placed on chamber windows.
3. ☐ Record hydrogen gas tank pressure. For a 10 l gas tank, 45 bar tank pressure is minimum requirement to completely fill target cell with liquid hydrogen.

_____ Hydrogen Gas Tank Pressure

4. ☐ Check RTMain.vi is running on slow control's display panel. Go to 'Expert' tab of RTMain.vi (Fig. 3). Use expert password to login.

5. ☐ Check supply pressure, PI-1, and target exhaust pressure, PI-2, read less than 0.01 bar on 'Operation LH2' tab of RTMain.vi (Fig. 4).

6. ☐ Check FPGA parameters settings:
   a) go to 'Parameter' tab of RTMain.vi (see Fig. 9),
   b) under 'Interlock FPGA' column, ensure FPGA is set to open PV-3 and PV-4 at 0.5 bar. If the set pressures are different, alert target expert,
   c) under 'FPGA alarms' box, check PI-1, PI-2, H_2 and Vacuum alarms are enabled.

7. ☐ Establish vacuum in target chamber:
   a) turn off power button of Lakeshore temperature controller,
   b) select 'standby mode' on RTMain.vi to stop current supply to level sensor,
   c) check no voltage is applied to the beam focusing detector,
   d) close manual vent valve MV-3 of vacuum system (see Fig. 5),
   e) press 'pump' button on vacuum control panel. Wait 8-10 hours until pressure reaches $1x10^{-4}$ mbar (check 'Vac [mbar]' on top-right of any tab of RTMain.vi). Note: the pressure reading on the vacuum control box on the MUSE frame will display $3x10^{-4}$ mbar but occasionally it may also display to $1x10^{-4}$ mbar. (This appears to be a feature of the readout box).

8. ☐ Post 'Target Chamber Under Vacuum' warning signs in PiM1 area.
9. ☐ Turn on Lakeshore temperature controller.

10. ☐ Confirm gas lines and target ladder have no leak:
    a) check MV-waste on gas panel is closed,

b) regulator is backed off,
c) go to ‘GasPanel’ tab of RTMain.vi (Fig. 6), check PV-3 and PV-4 are closed (corresponding status indicators on ‘GasPanel’ are red),
d) open gas tank valve,
e) open MV-Process and MV-1 on gas panel,
f) use regulator on gas panel to pressurize target until PI-1 reads 0.1 bar on RTMain.vi. Back off regulator,
g) close gas tank valve,
h) leave target cell pressurized for 10 minutes. PI-1 should remain steady. If not, notify target expert on call.

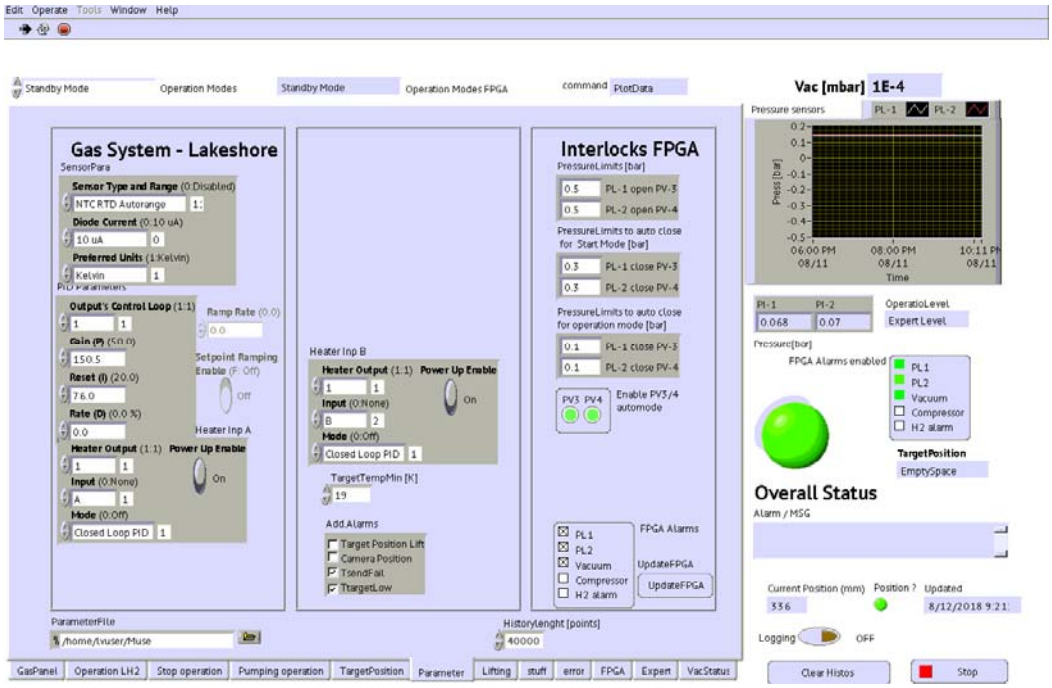

Figure 9: A picture of the 'Parameter' tab of RTMain.vi.

11. ☐ Stay in ‘standby mode’ to open PV-3 and PV-4 to depressurize target cell.

12. ☐ <u>Check Lakeshore PID controller is regulating on a condenser heater:</u>
    a) go to ‘Operation LH2’ tab of RTMain.vi (see Fig. 4),
    b) check condenser and target temperatures, displayed on real-time graphs, show room temperature (about 298 K). The three readings should agree within 1.0 K,
    c) go to ‘Parameter’ tab of RTMain.vi (see Fig. 9). Check PID is on input A or B. Check front display of Lakeshore shows ‘L1 A’ or ‘L1 B’ depending on input choice,
    d) check ‘Heater Output’ on ‘Parameter’ tab is set to 1. Check ‘Power Up Enable’ is ON,
    e) to confirm PID is working, go to ‘Operation LH2’ tab of RTMain.vi, increase set point by 1 K above measured condenser temperature. Press ‘Start Lakeshore’. Lakeshore heater power should rise to 100% on real-time graph,

f) press ‘Stop Lakeshore’. Heater power should fall to 0%.

13. ☐ Compressor is off. Cold head cable is connected to compressor and chamber.
14. ☐ Helium lines are connected to cold head and compressor.
15. ☐ Water cooling lines are connected to compressor.
16. ☐ Water supply and return lines on compressor closed.
17. ☐ No voltage is applied to the beam focusing detector.

G. Operating Procedures

Procedures to safely start, operate and shut down the target are described here.

G.1. Target start procedure
(only for target experts and 2nd level experts)

1. ☐ Record hydrogen gas tank pressure. For a 10 l gas tank, 45 bar tank pressure is minimum requirement to completely fill target cell with liquid hydrogen.

   _____ Hydrogen Gas Tank Pressure
2. ☐ Remove window covers only if Scattered Particle Spectrometer (SPS) is in running position or if no one is accessing MUSE platform.
3. ☐ Check MV-2 (Fig. 10), between PV-5 and target, is open or it will not be possible to purge the target cell.

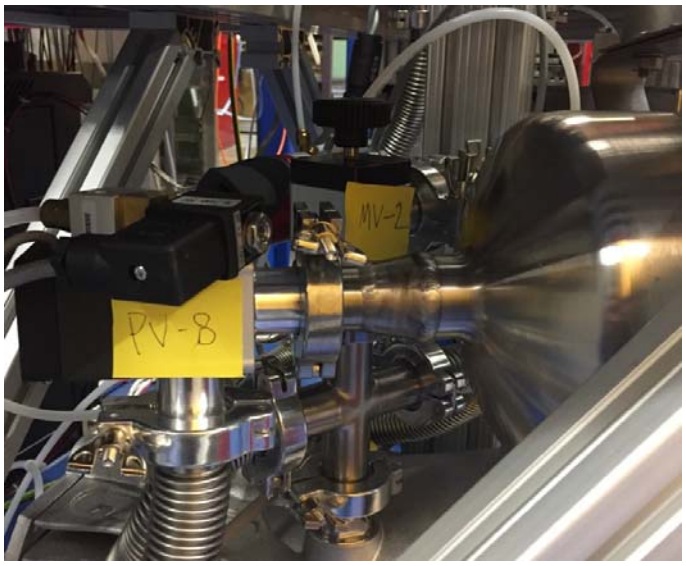

Figure 10: A picture of MV-2 between PV-5 (not pictured) and the target cell.

4. ☐ Open compressor supply and return water lines on wall.
5. ☐ Place warning signs, 'Liquid Hydrogen Target Mode', at designated locations.
6. ☐ Check for alarms/messages on RTMain.vi. If no alarms, or if issues are resolved, press 'clear Histo' button.
7. ☐ Open water return valve on compressor.
8. ☐ Open water supply valve on compressor.
9. ☐ Check compressor pressure reads about 250 psi.
10. ☐ Record vacuum chamber pressure:

    _____ Vacuum Chamber Pressure

11. ☐ Go to ‘Expert’ tab of RTMain.vi (Fig. 3). Use expert password to login.
12. ☐ Purge target:
    a) ☐ confirm chamber pressure is below 1 mbar. Otherwise the target cell will implode,
    b) ☐ select ‘standby mode’ on RTMain.vi to operate PV-5,
    c) ☐ hydrogen gas tank valve is closed,
    d) ☐ MV-Process on gas panel is closed,
    e) ☐ check regulator is backed off,
    f) ☐ check PV-3, PV-4, PV-5 are closed using ‘GasPanel’ tab of RTMain.vi (Fig. 6) (corresponding status indicators will show red),
    g) ☐ check PV-6 is closed on 'GasPanel' tab of RTMain.vi so that PV-5 can be opened,
    h) ☐ open PV-1, PV-2, PV-CT using ‘GasPanel’ tab of RTMain.vi (corresponding status indicators will show green),
    i) ☐ open PV-5 using ‘Pump operation’ tab of RTMain.vi (Fig. 7). Mechanical pump will turn on automatically,
        Note: The same pump is used to purge the cell and to pump the buffer. Priority is given to pumping out the buffer. If PV-5 does not immediately open or purging is interrupted, this is likely the cause. The purging operation will automatically resume after the buffer is pumped out.
    j) ☐ wait until target supply pressure, PI-1, reads -0.45 bar on RTMain.vi,
    k) ☐ close PV-5 using ‘Pump operation’ tab of RTMain.vi,
    l) ☐ check MV-waste on gas panel is closed,
    m) ☐ check regulator is backed off,
    n) ☐ open hydrogen gas tank valve,
    o) ☐ open MV-process and MV-1 on gas panel,
    p) ☐ Backfill target until PI-1 reads 0.1 bar:
        i. open PV-6 using ‘GasPanel’ tab of RTMain.vi,
        ii. use regulator on gas panel to pressurize target until PI-1 reads 0.1 bar on RTMain.vi, DO NOT back off regulator.
        iii. close PV-6 using ‘GasPanel’ tab to allow opening PV-5 again,
    q) ☐ open PV-5 using ‘Pump operation’ tab,
    r) ☐ close PV-5 when PI-1 reads -0.45 bar on RTMain.vi,
    s) ☐ repeat steps (p-r) to purge target two more time, for a total of three purges,
        Note: because the regulator has not been backed off, it is sufficient to open PV-6 to fill the target cell,
    t) ☐ check PV-5 is closed using ‘Pump operation’ tab.
13. ☐ Select ‘start mode’ on RTMain.vi.
14. ☐ Set supply pressure, PI-1, to 0.2 bar:

a) keep gas tank valve open,
b) check MV-process and MV-1 are open on gas panel,
c) check PV-CT is open, PV-3, PV-4 are closed using 'GasPanel' tab of RTMain.vi,
d) close PV-1, PV-2 using 'GasPanel' tab of RTMain.vi,
e) open PV-6 using 'GasPanel' tab of RTMain.vi,
f) use regulator on gas panel to pressurize target until PI-1 reads 0.2 bar on RTMain.vi. DO NOT back off regulator.

15. ☐ On 'Operation LH2' tab of RTMain.vi, set Lakeshore set point to 19.5 K.
16. ☐ Click on 'Lakeshore Setpoint' on 'Operation LH2' tab,
Note: while the lakeshore is running, this can also be used to change the temperature set point, without having to restart the device.
17. ☐ Click on 'Start Lakeshore' on 'Operation LH2' tab,
18. ☐ Turn logging ON in 'Operation LH2' tab.
Note: the current file location is /home/lvuser/MUSE and is named by date.
19. ☐ Turn compressor ON:
    a) ☐ turn ON main power switch on front panel of compressor (Fig. 12),
    b) ☐ click on 'START/Reset' button under 'Compressor Operate' on 'Operation LH2' tab. Compressor's pressure will read between 370-380 psi on analog gauge on its front panel. Record start time.
    Cool-down Start Time: _____
    Compressor will start cooling down hydrogen gas, supply lines, condenser and target ladder. Lakeshore PID heat output will read 0% on real-time graph on 'Operation LH2' tab until condenser temperature goes below set point.
20. ☐ Occasionally check supply pressure, PI-1, and target exhaust pressure, PI-2 on RTMain.vi. They should read the same.
21. ☐ When condenser temperature gets close to 20.3 K, hydrogen will start to condense and drip into target cell.
22. ☐ When target temperature on real-time graph of 'Operation LH2' tab reads about 20 K, target cell will start filling with liquid hydrogen. Using regulator on gas panel, keep PI-1 about 0.15 bar. PI-2 will be much lower than PI-1 while target is being filled. Keep PI-2 slightly above 0.0 bar by adjusting regulator on gas panel. Record fill start time.

    Fill Start Time: _____
23. ☐ In about 40 min from fill start time, change set point to 20.7 K. Click on 'Lakeshore Setpoint' on 'Operation LH2' tab.
24. ☐ Stop filling once target cell is full:
    Close to one hour from fill start time, you will see steep jump in resistance of level sensor on real-time graph of 'Operation LH2'. This will indicate target cell is full.
    a) close PV-6, PV-CT using 'GasPanel' tab of RTMain.vi. Check PV-1, PV-2, PV-3 and PV-4 are closed,
    b) close MV-1 on gas panel,
    c) close gas tank valve,
    d) back off regulator,
    e) PI-1 and PI-2 should read same pressure, otherwise it will indicate a blockage in

gas lines. Record fill end time.

Fill End Time: _____

25. ☐ Check temperature PID is keeping target exhaust pressure (PI-2) at about 0.1 bar, using real-time graph on ‘Operation LH2’ tab of RTMain.vi (Fig. 4). If not, change Lakeshore set point a little bit, until target exhaust pressure is stable at 0.1 bar.
26. ☐ Select ‘running mode’ on RTMain vi.
27. ☐ On ‘Expert’ tab of RTMain.vi, log off as expert and login using shifter password to monitor target status.

G.2. Target running procedure
(for shift takers, 2nd level experts and target experts)

1. ☐ Check Scattered Particle Scintillator (SPS) is in running position. Remove window covers if they were not removed at beginning of starting target.
2. ☐ Check all target-related warning signs (‘Target Chamber Under Vacuum’, ‘Liquid Hydrogen Target Mode’) are posted in designated locations before beam is turned ON.
3. ☐ Place signs in PiM1 indicating window covers should be placed if anyone wants to access MUSE platform but SPS is not in running position.
4. ☐ Check no voltage is applied to beam focusing detector.
5. ☐ On ‘Expert’ tab of RTMain.vi (Fig. 3), login using shifter password.

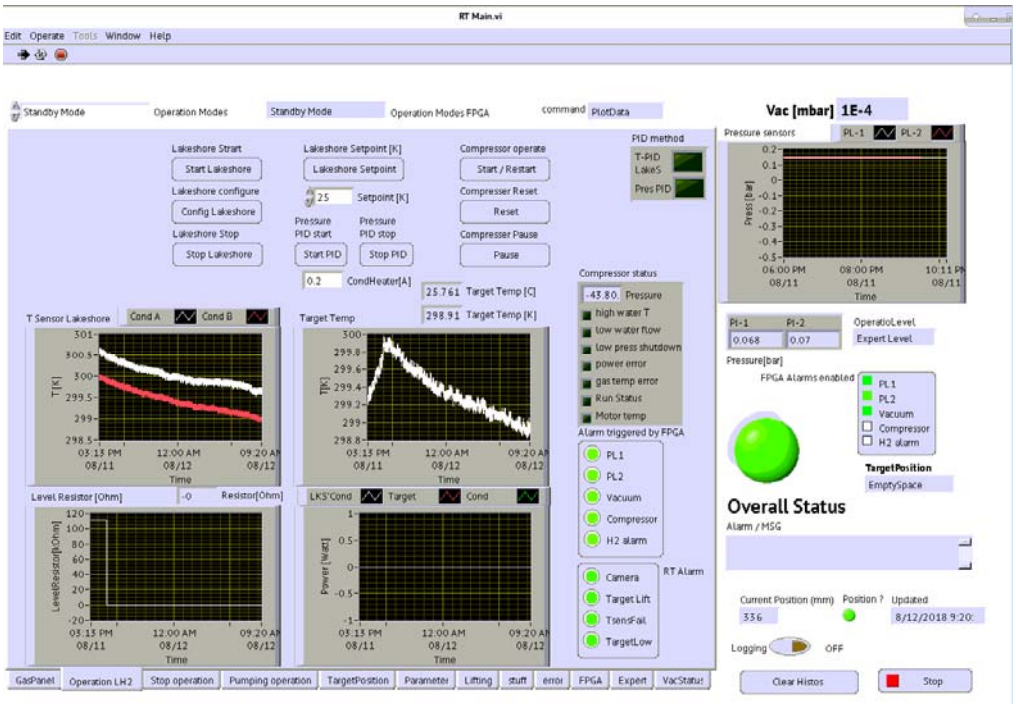

Figure 11: A picture of the ‘Operation LH2’ tab of RTMain.vi.

6. ☐ Monitor target status using 'Operation LH2' sub-panel of RTMain.vi (Fig. 11):
   a) target exhaust pressure, PI-2 = 0.1 bar,
   b) the supply line pressure, PI-1, is same as PI-2. If not, notify the 2nd level expert.
   c) condenser temperature, 'Cond A' and 'Cond B' = 20.7 K,
   d) target temperature = 21.5 K,
   e) vacuum chamber pressure 'Vac [mbar]' is $1x10^{-4}$ mbar (note: it will read about $3x10^{-4}$ mbar on the vacuum control box on the MUSE frame),
   f) level resistor is steady and reads about 150-180 Ω depending on how much the target was filled,
   g) time stamp is current (check under 'Updated' on 'OperationLH2' tab). If it is old, it will indicate that slow control system has frozen (in which case, notify the 2nd level expert),
   h) system is in running mode (check drop-down menu next to 'Operation Modes' on 'OperationLH2' tab).

   Important: if slow-control system switches to 'shut down mode' for safety reasons, physically check that compressor is turned OFF by the slow control system to prevent freezing. This can be checked by touching the compressor and confirming it has stopped vibrating. If it is still ON, manually set the main power switch of the compressor to OFF. It is located on the front panel (see Fig. 12).

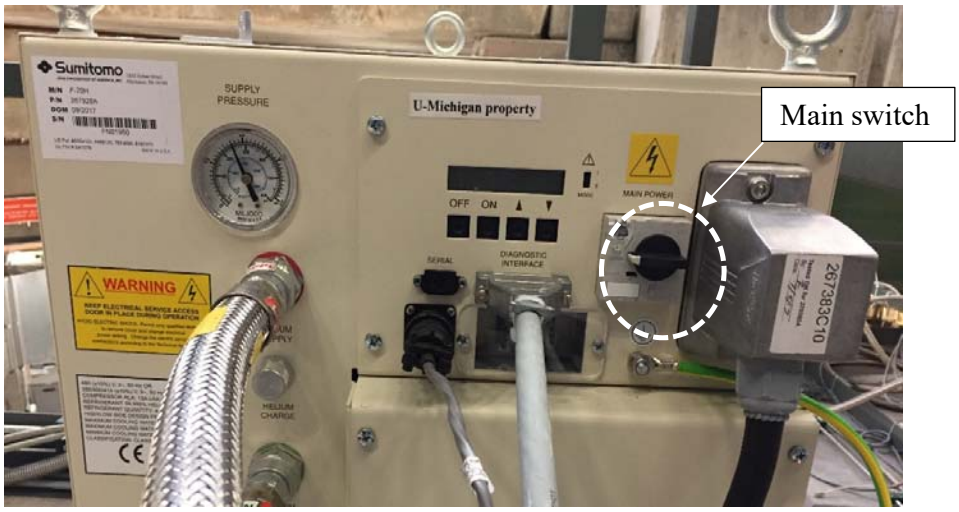

Figure 12: A picture of the front panel of the compressor showing the main power switch in OFF position

7. ☐ To change target position:
   a) Check 'StepperCamera' program is running on mpc2001 ('position' LED is green),
   b) turn off beam by closing beam plug,
   c) enable 'Lifting' on 'TargetPosition' tab of RTMain.vi (Fig. 13),
   d) Press 'move' button next to desired target position,
   e) wait until desired target position is attained (few minutes). Turn on beam by opening beam plug.

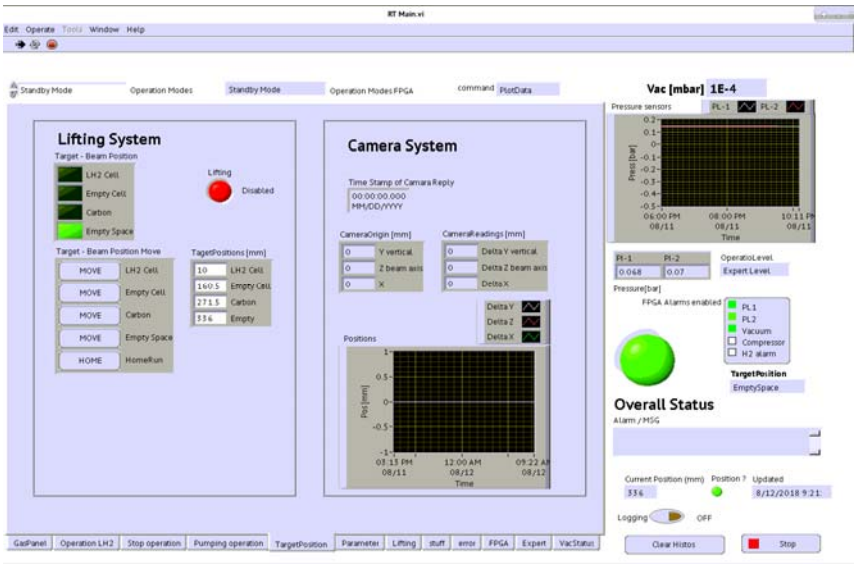

Figure 13: A picture of the 'TargetPosition' tab of RTMain.vi.

G.3. Target shut down procedure
(only for target experts and 2nd level experts)

1. ☐ On ‘Expert’ tab of RTMain.vi (Fig. 3), login using expert password.
2. ☐ MV-1 on gas panel is closed, PV-6 & PV-CT on ‘GasPanel’ tab of RTMain.vi (Fig. 6) are closed.
3. ☐ Hydrogen gas tank valve is closed.
4. ☐ On RTMain.vi, check logging is ON.
5. ☐ Select ‘shut down mode’ on RTMain.vi. PV-3 and PV-4 will open automatically.
6. ☐ On ‘Operation LH2’ of RTMain.vi (Fig. 11), set Lakeshore set point to 23 K.
7. ☐ Click on ‘Lakeshore Setpoint’ on ‘Operation LH2’ tab of RTMain.vi.
8. ☐ Check PI-1 and PI-2 are slightly above 0 bar on RTMain.vi.
9. ☐ For a faster warm up, set target heater power to 3 W on ‘Stop operation’ tab on RTMain.vi (Fig. 14). Press ‘Start-Set’.

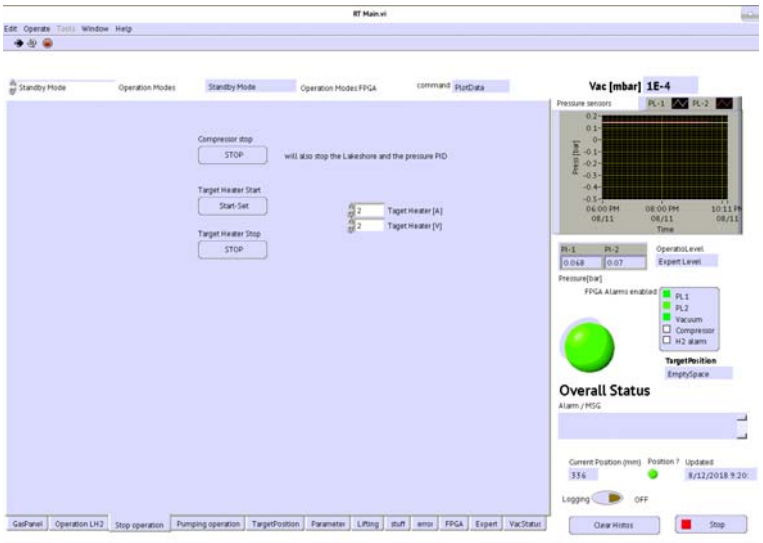

Figure 14: A picture of the 'Stop operation' tab of RTMain.vi.

10. ☐ When the liquid boils off completely, target temperature will rise quickly above 23 K. Press ‘STOP’ button under ‘Target Heater Stop’ on ‘Stop operation’ tab of RTMain.vi.
11. ☐ Turn off compressor and Lakeshore PID by pressing Compressor stop’s ‘STOP’ on the same tab.
12. ☐ turn OFF main power switch on front panel of compressor.
13. ☐ Close PV-3 and PV-4 to prevent cryopumping air into target from exhaust lines, FPGA will automatically open and close PV-3 and PV-4 to regulate pressure as needed.
14. ☐ Close water supply and return lines on compressor and then on wall.
15. ☐ Remove ‘Liquid Hydrogen Target Mode’ warning sign when target reaches room temperature.

G.4. Procedure for disconnecting the target from the gas panel (only for target experts)

1. ☐ Check chamber is under vacuum (about $1x10^{-4}$ mbar on the slow control system). If chamber is not under vacuum, follow instructions given in step 7 of **Section F (Target Start Checklist)** to establish 10^{-4} mbar pressure in chamber.
2. ☐ Go to 'Expert' tab of RTMain.vi (Fig. 3). Use expert password to login.
3. ☐ Select 'standby mode' on RTMain.vi.
4. ☐ Connect neon or argon gas tank to gas panel following instructions given in step 13 a) of **Section E (Target Installation Checklist)**.
5. ☐ Pump out target hydrogen circuit:
   a) ☐ Check MV-2 (Fig. 10) between PV-5 and target is open
   b) ☐ hydrogen gas tank valve is closed,
   c) ☐ MV-Process on gas panel is closed,
   d) ☐ check PV-3, PV-4, PV-5 are closed using 'GasPanel' tab (Fig. 6) of RTMain.vi (corresponding status indicators will show red),
   e) ☐ check PV-6 is closed on 'GasPanel' tab of RTMain.vi so that PV-5 can be opened,
   f) ☐ open PV-1, PV-2, PV-CT using 'GasPanel' tab of RTMain.vi,
   g) ☐ open PV-5 using 'Pump operation' tab of RTMain.vi (Fig. 7). Mechanical pump will turn on automatically,
      Note: see 12 i) of **Section G.1 (Target Start Procedure)** for further details.
   h) ☐ Wait until target exhaust pressure, PI-1, reads -0.45 bar on RTMain.vi,
   i) ☐ close PV-5 using 'Pump operation' tab of RTMain.vi.
6. ☐ Backfill circuit to prevent crushing target cell:
   a) check MV-waste is closed,
   b) check regulator is backed off,
   c) open gas tank valve,
   d) open MV-Process and MV-1 on gas panel,
   e) open PV-6 using 'GasPanel' tab of RTMain.vi,
   f) use regulator on gas panel to pressurize target until PI-1 reads 0.0 bar on RTMain.vi. Back off regulator,
   g) close gas tank valve.
7. ☐ Disconnect hydrogen supply and return lines to chamber. Plug open ends of gas lines.
8. ☐ To vent target chamber:
   a) turn off power button of Lakeshore temperature controller,
   b) check no voltage is applied to the beam focusing detector,
   c) select 'standby mode' on RTMain.vi to stop current supply to level sensor,
   d) press 'vent' button on vacuum control panel,
   e) when vacuum chamber pressure reaches 0.1 mbar, open vent valve MV-3 (Fig. 5) on vacuum pump system to vent chamber at 4 mbar/s rate.

Note: chamber should be vented slowly to prevent empty cell from imploding.

G.5. Target restart after power outage
(only for target experts)

1. ☐ Perform system analysis before restarting target.
2. ☐ Establish vacuum in chamber (see step 7 of **Section F (Target Start Checklist)**).
3. ☐ Go to 'Expert' tab of RTMain.vi (Fig. 3). Use expert password to login.
4. ☐ Select 'start mode' on RTMain.vi.
5. ☐ Turn compressor ON:
   a) turn ON main power switch on front panel of compressor (Fig. 12),
   b) click on 'START/Reset' under 'Compressor Operate' on 'Operation LH2' tab.

6. ☐ If PI-1, PI-2 exceed 0.5 bar on RTMain.vi before turning compressor ON, PV-3 and PV-4 will be opened automatically. Check using 'GasPanel' tab of RTMain.vi (Fig. 6) that PV-3 and PV-4 close when pressure drops below 0.3 bar.
7. ☐ Go to 'Operation LH2' tab of RTMain.vi. Check level sensor's resistance on real-time graph to decide whether some hydrogen may need to be added to target.

   If target cell is full:
   a) ☐ on 'Operation LH2' of RTMain.vi (Fig. 4), set Lakeshore set point to 20.7 K,
   b) ☐ press 'Lakeshore Setpoint'. Press 'Start Lakeshore' on 'Operation LH2' tab,
   c) ☐ select 'running mode' on RTMain.vi. On 'Expert' tab, log off as expert and login using shifter password.

   If the target cell is not full:
   a) ☐ on 'Operation LH2', set Lakeshore set point to 20.7 K,
   b) ☐ press 'Lakeshore Setpoint'. Press 'Start Lakeshore' on 'Operation LH2' tab,
   c) ☐ Check MV-waste on gas panel is closed,
   d) ☐ check PV-1, PV-2, PV-3, PV-4 are closed using 'GasPanel' tab of RTMain.vi,
   e) ☐ open PV-6, PV-CT using 'GasPanel' tab of RTMain.vi,
   f) ☐ open MV-Process and MV-1 on gas panel,
   g) ☐ check regulator is backed off, open hydrogen gas tank valve,
   h) ☐ use regulator on gas panel to pressurize target until PI-1 reads 0.2 bar on RTMain.vi. DO NOT back off regulator,
   i) ☐ when level sensor resistance shows steep jump on real-time graph on 'Operation LH2' tab, go to 'GasPanel' tab of RTMain.vi and close PV-6, PV-CT,
   j) ☐ check PV-1, PV-2, PV-3 and PV-4 are closed,
   k) ☐ close MV-1 on gas panel, close gas tank valve, back off regulator,
   l) ☐ select target running mode. On 'Expert' tab, log off as expert and login using shifter password.