CUORE DCS Operations and Software Guide

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1 Basic overview of the DCS

The Detector Calibration System (DCS) is how we calibrate the CUORE detectors. The calibration sources are small copper capsules containing a small amount of ^{232}Th. The capsules are crimped onto Kevlar strings (see Figure 1). These "source strings" live outside of the cryostat in large stainless steel "Motion Boxes", where they are wound onto spools. When it comes time to calibrate the detector, the motors turn the spools, lowering the source strings into the cryostat.

There are four Motion Boxes on the cryostat, each containing 3 source strings (see Figure 2), for a total of 12 source strings. Each Motion Boxes is separated from the cryostat with a gate valve. The strings are identified by a Motion Box number (1–4) and a letter representing their position inside the Motion Box (T for top, M for middle, and B for bottom). Each string follows its own path through the cryostat, passing through stainless steel and copper guide tubes (see Figure 3). When the strings reach their fully deployed position near the towers, 6 of them are among the detector towers ("inner strings") and 6 of them are outside the 50 mK shield ("outer strings"). The position of the strings with respect to the towers is in Figure 4.

There is one other key component of the DCS: the 4-K thermalizers. These are copper blocks that physically squeeze on the sources at 4 K in order to cool them down before the strings are lowered further. There are 4 thermalizers, one below each Motion Box. All 3 strings coming from a given Motion Box pass through the same thermalizer. Thus, it is very important that any strings passing through a given thermalizer are not moving while the thermalizer is closed. A model of the thermalizer system is shown in Figure 6.

Throughout the deployment, a variety of sensors monitor the source strings and other components of the DCS. These include:

- **Home switch**: One per string (12 total). On if string is at "home position", and off if string is not. The home position is when the string is fully extracted from the cryostat and wound up on its spool.
- **Global stop switch**: One per string (12 total). On if the string tension is very high, and off otherwise. This should never turn on in the course of normal operation.

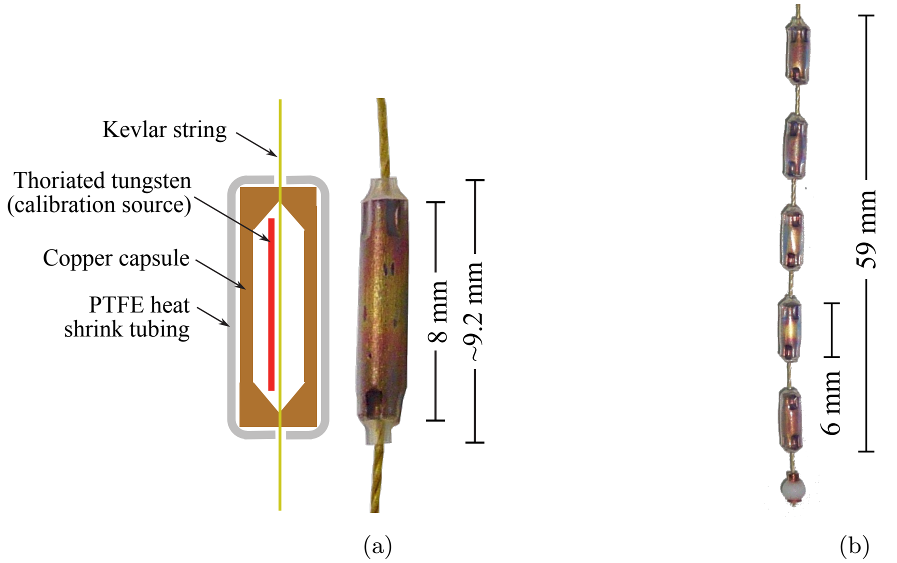


Figure 1: (a) Schematic and photograph of an assembled source capsule. (b) Photograph of five heavier bottom capsules and PTFE ball at the bottom of a source string.

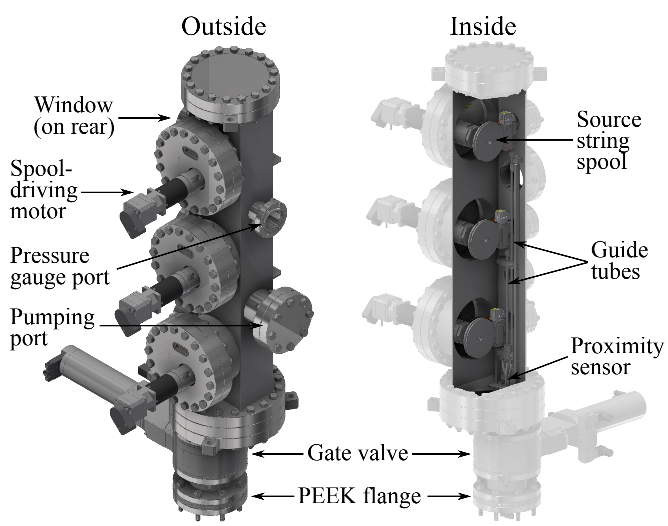
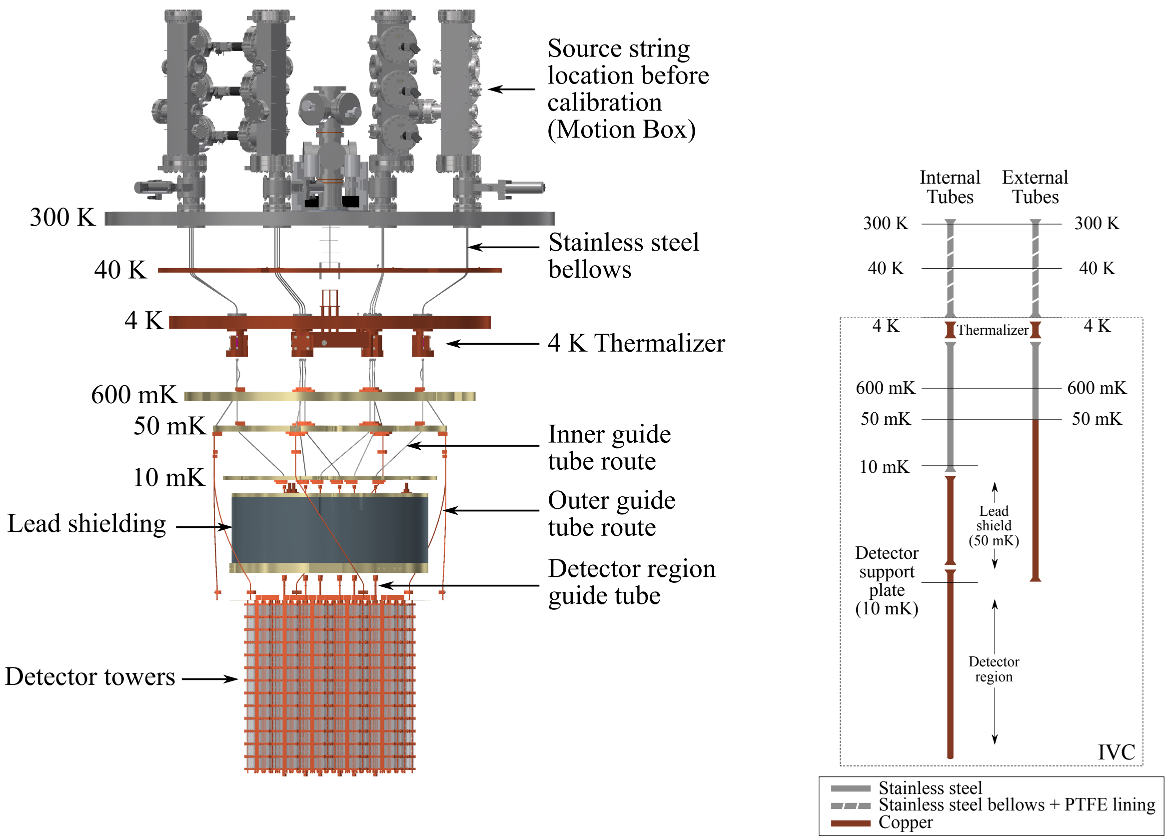


Figure 2: Rendering of a Motion Box that controls 3 strings. There are 4 Motion Boxes mounted above the cryostat.



(a) (b)

Figure 3: (a) Illustration of the DCS in the CUORE cryostat, showing the guide tube routes through the cryostat. See Figure 6 for a description of the thermalizers and linear actuators. (b) Schematic of the DCS guide tubes in the CUORE cryostat. All tubes are fully thermalized to the cryostat plates that they cross. The inner vacuum chamber is designated by the dotted line.

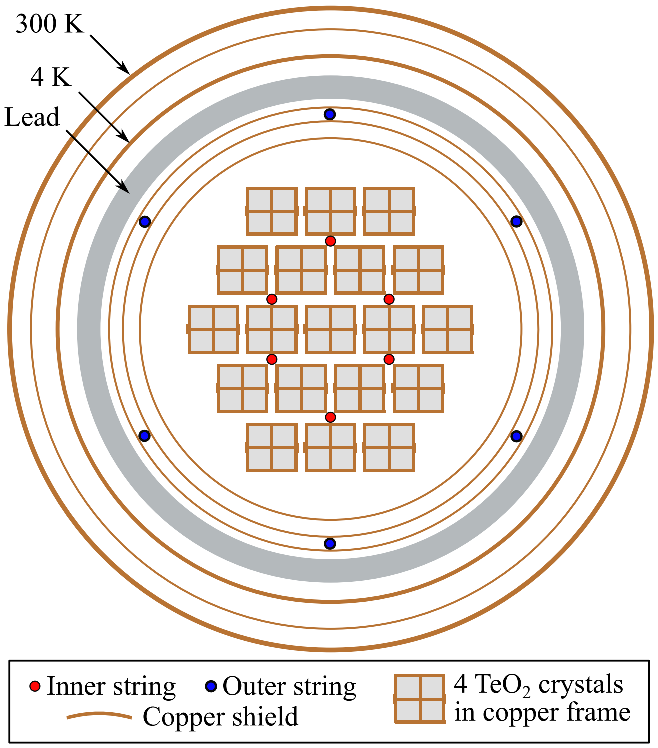


Figure 4: Top-down view of the 19 detector towers, showing the location of the source strings in their calibration position. Outer strings (19.4 Bq of ^{228}Th each) are shown in blue; inner strings (3.6 Bq each) are in red. The circles are the cryostat vessels, in order from outside: 300 K, 40 K, 4 K, side lead shielding, 600 mK, 50 mK, and 10 mK.

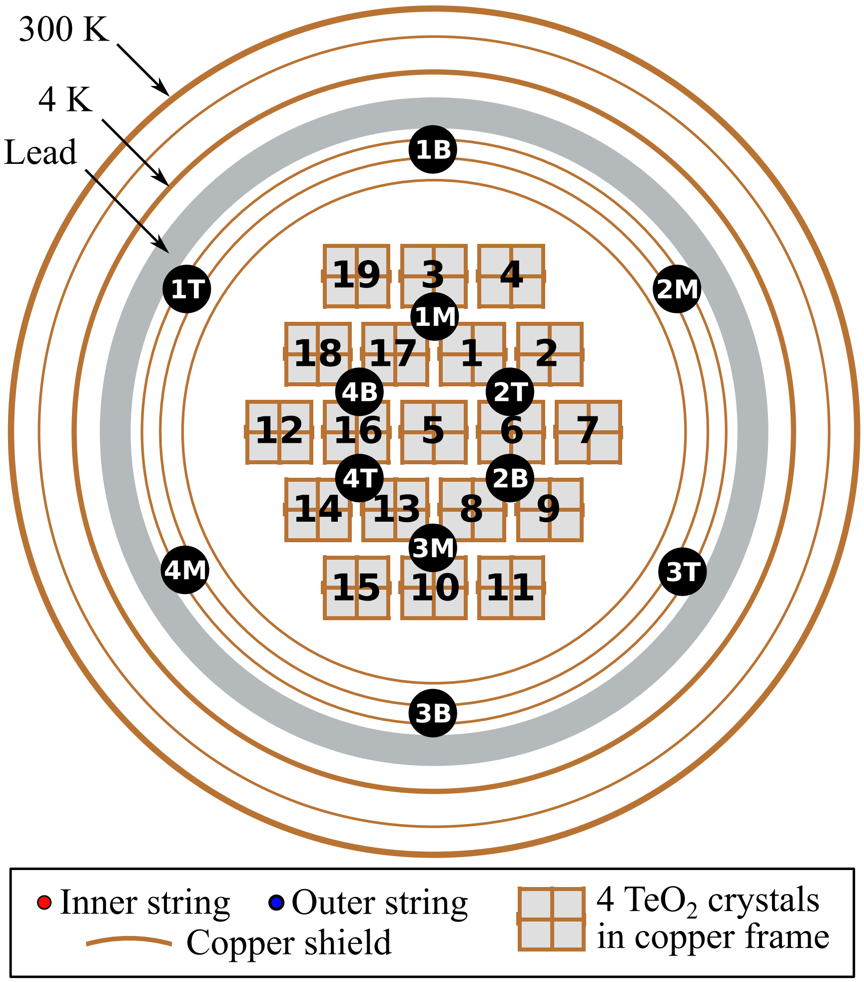


Figure 5: Similar to Figure 4, but showing the locations of the DCS strings in relation to the cryostat towers (DAQ numbering).

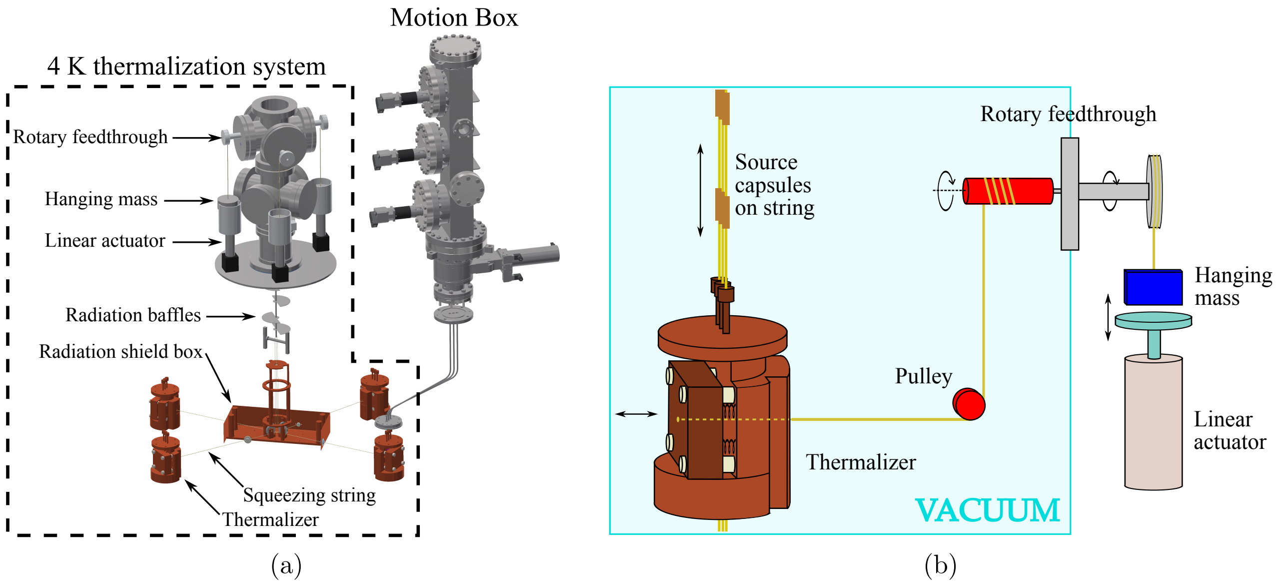


Figure 6: (a) Rendering of the 4-K thermalization hardware (boxed), with a Motion Box and S tube containing source strings is above one of the four Thermalizers. (b) A schematic of the thermalization system for one Thermalizer.

- **Load cell**: One per string (12 total). Reads the string tension in volts (uncalibrated).
- **Encoder**: One per string (12 total). Reads out the motor position as a number of rotations, but converted to millimeters in the software.
- **Thermalizer (TM) contact signal**: One per 4-K Thermalizer (4 total). Off if the thermalizer is fully open or closed. On when the thermalizer is neither fully closed nor open, such as when the thermalizer is closed on a capsule.
- **Thermalizer thermometer**: One per 4-K Thermalizer (4 total). Reads out the temperature of the sliding block of the 4-K Thermalizer.
- **Chicane thermometer**: One per 600-mK guide tube (12 total). Reads out the temperature of the guide tube a few centimeters below the 4-K Thermalizer.
- **Gate valve indicator**: One per Motion Box (4 total). Reads the state of the gate valve below the Motion Box (open, closed, or moving).
- **Proximity sensor**: One per Motion Box (4 total). Detects when capsules are entering or leaving the motion box.

Every component of the DCS is controlled by a computer running in a rack by the cryostat, on the second floor of the CUORE hut. Specifically, custom-written LabVIEW software is used to control the system, and the software can be operated either at the rack or remotely with TeamViewer. The layout of the rack is shown in Figure 7.

1.1 DCS Vacuum

NOTE: THIS SUBSECTION NEEDS EDITING FOR THE NEW CONFIGURATION OF THE VACUUM LINES AND PUMP.

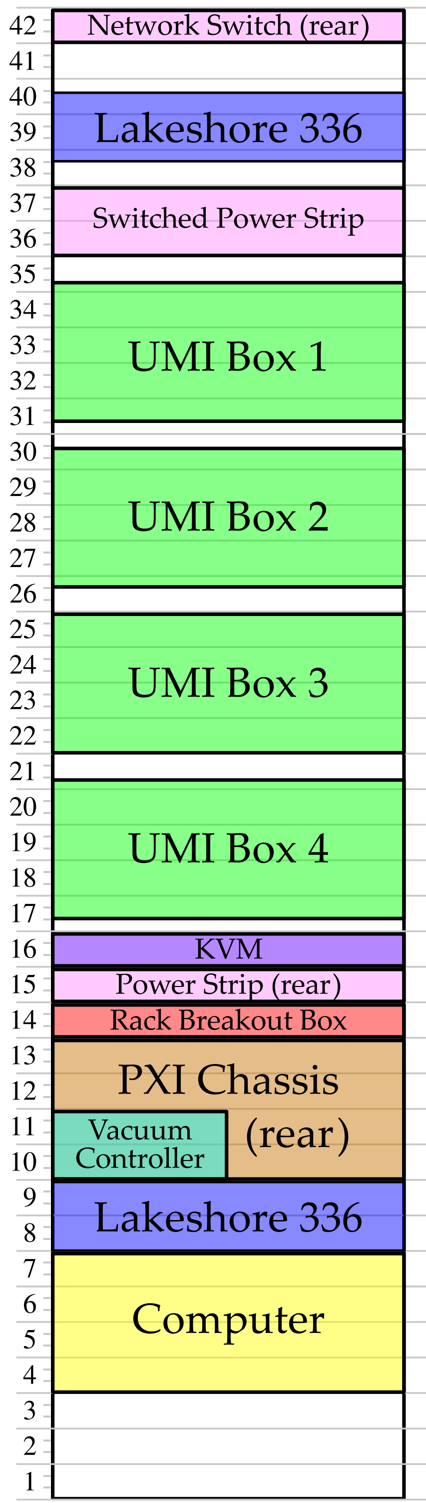


Figure 7: Diagram of the DCS rack as it is set up in the CUORE hut.

The DCS needs to be under vacuum while in operation as the motion boxes become part of the IVC when the gate valves are opened. To this end, we have vacuum lines that extends from each box to the OVC pump. These lines can be valved off at the front of each motion box. They are also connected above the OVC gatevalve so that the motion boxes can be pumped while remaining independent of the rest of the cryostat.

Two of the motion boxes have vacuum gauges on them (MB1 and MB3), while the other two are uninstrumented (MB2 and MB4). Because of this, if the motion boxes are all valved off, we are blind to the state of the vacuum in the uninstrumented boxes.

If the gate valves are CLOSED and the motion boxes are isolated from the cryostat: first, pump out the vacuum lines to the boxes with a scroll pump, then slowly open the valve for each box in sequence starting from an instrumented box, being careful to watch the pressure. After all the hand valves are open and the pressure has dropped down below 1 mbar, then start the OVC turbo pump. DO NOT OPEN THE VALVES TO THE MOTION BOXES WHILE THE TURBO IS RUNNING. Once all the pressures have dropped below 10^{-5} mbar and are beginning to stabilize, then it is safe to open the gate valves.

If the gate valves are OPEN and the motion boxes are not isolated from the cryostat: first, pump out the vacuum lines to the boxes with a scroll pump and then turn on the OVC turbo pump once the pressure has dropped down below 1 mbar. Then, after the vacuum lines have been pumped out by the turbo, slowly open the hand valves on each box, being careful to watch the pressure.

The system has also been checked for leaks in the past and we are confident that there are no outside leaks in the motion boxes, however, there is outgassing in the boxes and possible virtual leaks. We observe a leak rate of [$\sim 10^{-9}$ mbar $\cdot\, l \cdot s^{-1}$] on the motion boxes to the outside world. The outgassing rate depends greatly on how much water there is in the system. To remove the water from the system (for example, if the motion boxes are vented to atmosphere), it needs to be pumped on for a considerable amount of time (~week or more).

The gate valves can be opened by the software or manually (see Section 7 as only an expert should manually open a gate valve). For the software to open the gate valve, the operator needs to simultaneously press the appropriate button on the front of the breakout box on the rack while running the procedure (see Section 3.2) to open the gate valve. This operation, done either manually or in the software, requires pressurized air to be flowing to each of the gate valves.

1.2 DCS Thermometers

The DCS has thermometry on both the 4-K and 600-mK stages. At the 4-K stages, there is a LakeShore Cernox thermometer on each of the 4-K thermalizers, and, at the 600-mK stage, there is a Cernox thermometer on each of the guide tubes below each thermalizer.

The purpose of the thermalizer thermometers is to observe the cooling of the copper capsules as the strings are deployed. A proper cooling of the capsule looks like the one shown in Figure 8 and Figure 9. If a string has not been properly cooled by the thermalizer, we can see that the temperature on the 600-mK guide tubes will increase considerably more than shown in Figure 9.

2 Performing a Calibration

This section describes the procedure for operating the DCS. Please make sure you have read and understand Section 1 before reading this section, and ask an expert if have any questions.

2.1 DCS Personnel Requirements

During a calibration, the DCS requires an expert operator on-site to deal with any issues as they come up and as a liaison with the other on-site personnel. The on-site DCS expert is further supported by two off-site shifters who will assist in the operation via Teamviewer and Skype.

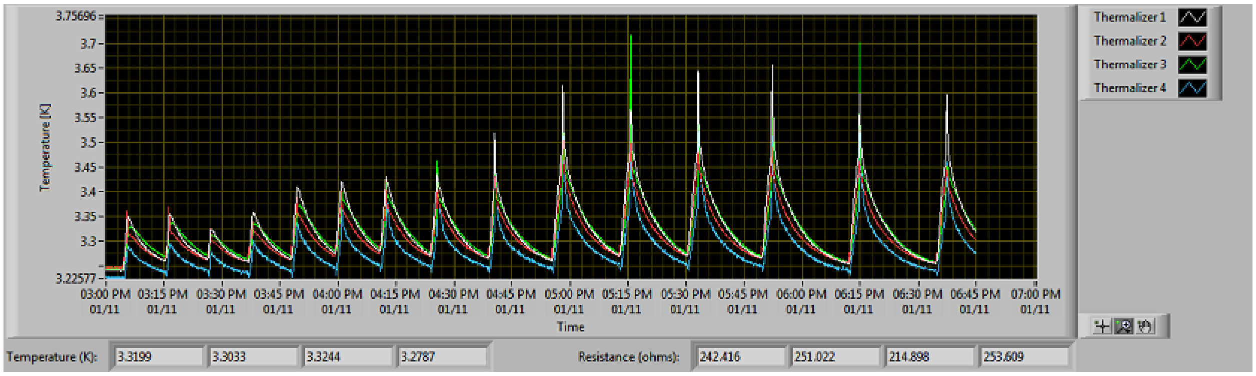


Figure 8: The temperature on the thermalizers during squeezes. The string was moved downwards between squeezes according to our calculated squeezing positions. A string was in each thermalizer during each squeeze.

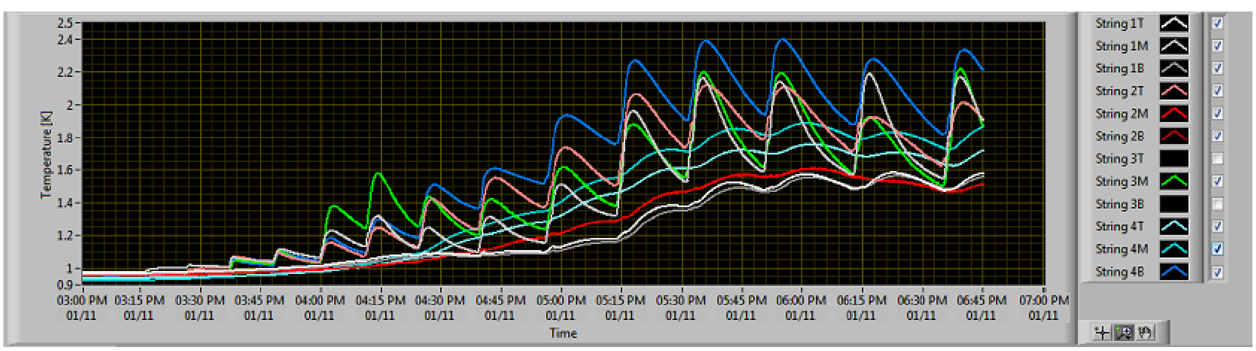


Figure 9: The temperature on the 600-mK thermometers as 1T, 2T, 3T, and 4T were moving through the thermalizers. The higher parts of the strings come in hotter to the guidetubes than the colder, lower parts of the strings. There is a small thermal coupling to the other thermometers on neighboring guide tubes, so they also experience a temperature rise.

For the deployment, operation takes ~3 hours to deploy for overnight (~12 hours) precooling at the 4-K stage with the DCS expert shifter and one off-site shifter. The detector region deployment takes ~24 hours to complete, during which the off-site shifters and the DCS expert will rotate monitoring the deployment. As this is the riskiest part of the deployment, constant monitoring with 2 persons is necessary.

For the extraction, operation takes ~12 hours to remove all the strings from the cryostat. For this, the on-site expert will operate with assistance from the off-site shifter.

2.2 Calibration Set-up

Follow the following steps, **in order**, to get set up for a calibration.

1. READ EVERYTHING IN THIS MANUAL. ASK QUESTIONS TO THE PREVIOUS EXPERT SHIFTERS IF YOU HAVE ANY! CATASTROPHIC ISSUES CAN OCCUR BY MAKING INCORRECT DECISIONS.

2. If any maintenance has been performed that has required disconnecting cables between the DCS rack and the cryostat, we need to reconnect the cables. **Please consult a DCS expert prior to doing so. This may damage parts.** Before connecting or disconnecting any cables (and this is extremely important), ensure that every single thing in the rack is turned off, except for the computer. Follow the *DCS Wiring Document* to reconnect the cables as necessary. Note that any work that disturbs the MSP will affect the pulse tube scan.

3. Plug the DCS rack into the wall outlets.

4. Turn on the PXI chassis on the rear of the rack. Turning on the PXI chassis should also turn on the computer in the front of the rack. If both are on, but the PXI chassis was not turned on before the computer, the computer will need to be restarted.

5. Switch on Lakeshores from the rear of the rack. Check that Lakeshores are reading correct values.

6. Switch on the Vacuum Controller.

7. Open the pull-out KVM monitor for the computer in the front of the rack. Log in as the cuore user with the standard P****** password.

8. Make sure that Teamviewer is running on the computer. Check that the off-site shifters can connect to the machine.

9. Open the MAX software menu and initialize the PXI cards for each motion controller.

10. Open the DCS Software (Section 3).

11. Start the labview VI.

12. Load the previous string positions from the DB. All strings should be in the home positions.

13. Load the proper load cell profile for each string (Table 1).

14. Disable any strings that are unusable (Section 6.5).

15. Turn on the motion controller boxes via the back of the rack. Turn the boxes on by plugging the power cords in.

16. Remove the separation between the batteries on the front of the rack.

17. Connect the wire to cryostat ground at the batteries.

18. Perform the following checks (All should be ‘yes’ in standard operation):

(a) Are the home switches engaged?
(b) Is the cryostat ground wire connected to the cryostat?
(c) Are the TM contact signals off?
(d) Are the thermalizers closed?
(e) Are the gate valves reading open?
(f) Are the motion boxes under vacuum?
(g) Is the noise in each load cell at the level of the ADC?

2.3 Starting a Calibration Deployment

Once all the steps in the Section 2.2 have been completed, the calibration is ready to begin. Note that the procedures to run and which procedure slot to load them in are described in Section 3.2. The steps of a calibration are as follows:

1. Work with a cryostat shifter to begin these steps:
    (a) Connect the scroll pump to the OVC turbo.
    (b) Turn on the scroll pump
    (c) Turn on the OVC pump
    (d) Once the pressures are below $O(10^{-5}$ mbar$)$ open the handvalves on the motion boxes, one at a time.
2. Open the thermalizers
3. Run the procedures to deploy the strings to their precooling positions.
4. Watch the load cell readings on the moving strings for issues (See Section 4).
    - Watch the load cells for drift outside the load cell range.
    - Watch the load cells for the strings becoming obstructed.
5. Close the thermalizers on the strings that are in the precooling positions and wait overnight for the strings to cool (≈ 12 hours). When you leave the tunnel, ensure that:
    - The thermalizers are in the state you expect them to be in (for precooling, they should be closed).
    - The hand valves are closed.
    - The DCS software is still running to record the temperatures and pressures in the system.
    - No procedures are still running in the software.
    - The cryostat base temperature, 600 mK thermometer temperatures, and 4K thermometer temperatures are all stable or decreasing.
    - The motion box pressures stabilize or appear to be stabilizing around or below 10^{-4} mbar after the hand valves are closed.
6. The next day, come back and double check the system to see that things are as you left them. Reopen the hand valves if the pumping has continued overnight as it should.
7. Open the thermalizers and continue the deployment from precooling.
8. Run procedures to deploy the strings according to the deployment plan. See Section 2.4.
    - Continue to watch the load cells.

- Watch the temperatures of the thermalizers to make sure they are opening, closing, and cooling properly.
- Watch the temperatures of the 600 mK thermometers to make sure the capsules have been cooled enough.
- Watch the base temperature to make sure the heating is within acceptable bounds.

2.4 Deployment Strategy

> No plan of operations extends with any certainty beyond the first contact with the main hostile force –Helmuth von Moltke the Elder

The deployment strategy is designed to minimize the temperature effects on the towers while also deploying as quickly as possible. The heating effects are localized to the very end of the deployments as the strings reach the detector region (inner strings have a much larger effect than outer). Thus, we only move one inner string at a time in the detector region while the other strings are either being squeezed, cooling below 4 K, or, for outer strings, deploying. This is shown in Figure 10.

This strategy does not always perfectly survive the realities of a deployment. If a string encounters an obstruction, the shifter will need to stop the other strings until the obstruction is either cleared or if it will be left in place while other strings are deployed. However, decisions as to which string should be deployed next should be made with a goal in mind of minimizing the total time needed for a deployment. This is usually accomplished by prioritizing 4 K thermalization and detector region deployment of the inner strings, particularly on motion boxes with two inner strings (MB2 and MB4).

2.5 Finishing a Calibration Deployment

Once the strings have all reached their deployment positions, the deployment is completed. Once this is done, the DCS needs to be turned off to remove any possible sources of noise during the calibration (such as any current to the motors). To do so, perform the following steps, **in order**:

1. Double check that all strings have correctly been deployed to their calibration positions.
2. Take a screenshot and record the final locations on the elog.
3. Replace the separator between the batteries.
4. Turn off the control boxes.
5. Turn off the Lakeshores.
6. Turn off the vacuum gauge.
7. Turn off the DCS computer and the PXI chassis.
8. Unplug the DCS rack from the wall.
9. Close the hand valves separating the motion boxes from the turbo pump, and then work with the cryogenics expert to turn off and disconnect the vacuum pumps.

2.6 Starting a Calibration Extraction

After the calibration period has ended, the strings need to be returned to their home positions back in the motion boxes. To do so, perform the following steps, **in order**:

1. Plug the DCS rack back into the wall.

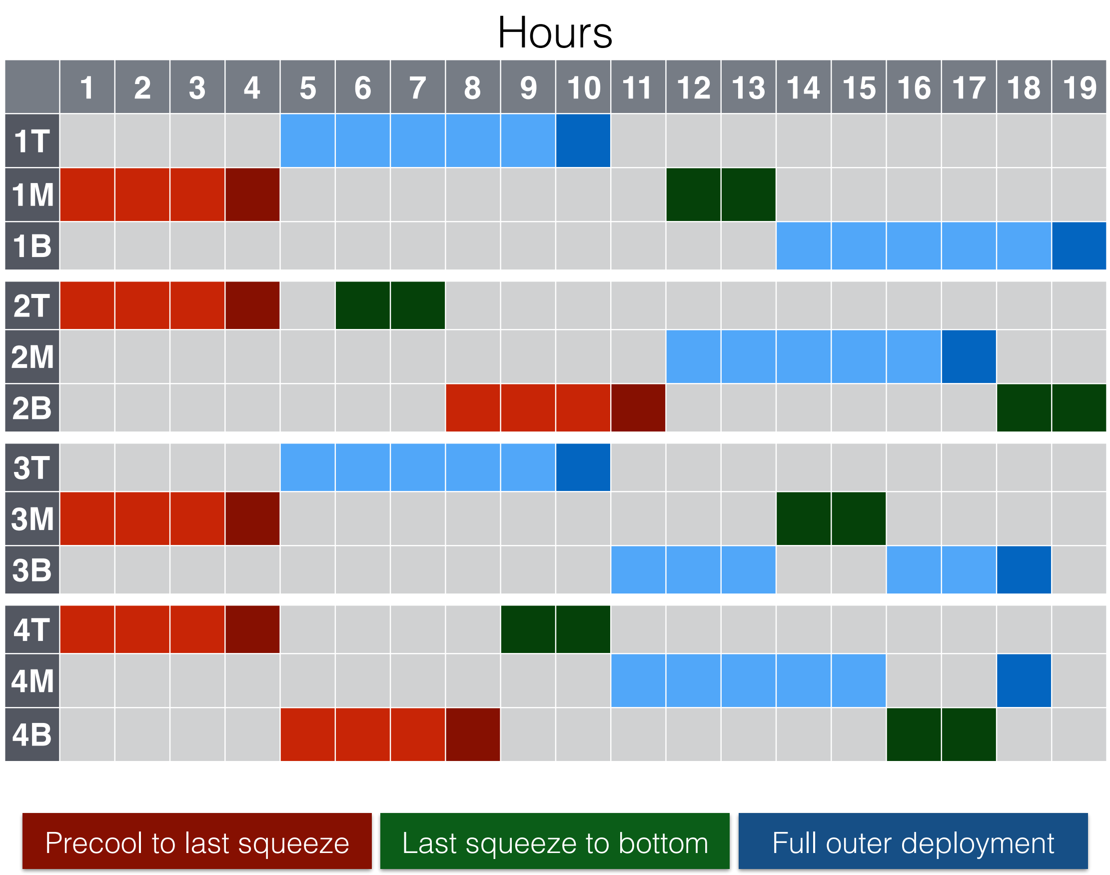


Figure 10: Schematic of the procedure to deploy strings. The darker regions are the times with higher heat load on the cryostat. In particular, deploying inner strings from the last thermalizer squeeze down to the bottom is a high heat load (and can only be done in series).

2. Turn on the PXI chassis. This will turn on the DCS computer.
3. Turn on the vacuum gauge.
4. Turn on the Lakeshores.
5. Turn on the motion controller boxes.
6. Remove the separator between the batteries.
7. Double check that the DCS software has continued running.
    - If not, reload the software and load the previous string locations from the database.

2.7 Extraction Strategy

Similar to the deployment strategy described in Section 2.4, the extraction strategy is also designed to minimize the temperature effects on the towers while also extracting as quickly as possible. The extraction procedure is much simpler, as the strings do not need to be cooled as they are raised throughout the cryostat. The only heat load during this time is then only due to the friction of moving the strings up in the cryostat. This is mostly felt on the cryostat when the strings are in the detector region, so we raise one internal DCS string at a time. At that same time, we also raise an external string as they do not cause much of a temperature rise on the cryostat. Once the heat load from the internal string begins to decrease, the extraction continues with the next string.

2.8 Finishing a Calibration Extraction

Once all the strings have returned home, the DCS needs to be turned off to remove any possible sources of noise during the upcoming background data runs. To do this, perform the following steps, **in order**.

1. Double check that all the strings are in the "home" position. Close the gate valves.
2. Disconnect the wire to cryostat ground at the batteries.
3. Reinsert the separator for the batteries on the front of the rack. Check that this correctly changes the TM contact signal.
4. Close the DCS motion box hand valves.
5. Close the VI by pressing the 'exit' button.
6. Turn off the motion controller boxes.
7. Turn off the vacuum controller.
8. Turn off the Lakeshores.
9. Turn off the DCS computer.
10. Turn off the PXI controller.
11. Unplug the DCS rack from the wall.
12. Work with the cryostat shifter to turn off and disconnect the pumps.
13. If you have set up the wireless router, disconnect it and return it to the Wireless Router Drawer in the onsite shifter desk.

Congratulations! Now the entire DCS calibration has been completed. Finish writing up notes for elog/evernote, take a break, go outside, and get ready for the next one! ☺

3 DCS Software Overview

The DCS Software is written as a LabVIEW VI http://www.ni.com/labview/. This VI is used to program, monitor, and operate the DCS. The user will be able to fully control nearly everything in the DCS from this display. The only parts that will need external input to control are the gate valves which need both a manual and computer signal to operate.

3.1 DCS VI Panels

Visual Overview Visual overview of the DCS strings. The strings are displayed as yellow bars coming down from the "home" position and deploy down through the stages of the cryostat. The thermalizers at the 4K stage are also shown on this panel when they are in the closed position.

Procedures A list of the procedures to be run by the system. At most, 4 procedures can be run concurrently. Displayed are the completed procedures, the current procedure, and the queued procedures. Procedures can be added via a text file or manually. During standard operation, it is best to run procedures by loading the relevant text files.

Log A log of the actions in the software. Includes all errors and all steps in the procedures.

Details A detailed panel for the DCS. Shows the status of each string, the thermalizers, proximity sensor, gate valve, and the load cell for a particular string.

Load Cells A panel showing all the load cells for the DCS strings simultaneously. Non-moving strings are greyed out. This is the tab to watch the most while deploying and extracting, as all moving channels need to be observed closely in case issues occur. The only part of this tab that can be changed manually, and in real time, is the load cell history control that sets the length of the x-axis for all of the plots.

Load Cell Derivatives Same as the *Load Cells* panel, but instead shows the derivative of each of the load cells. This panel is not as useful for general running, but it is useful for investigating noise levels.

Temperature Panel detailing the temperature and resistance of the thermometry of the DCS. The thermometers are located at the thermalizers on the 4K plate, and on the 600 mK tubes below the thermalizers. These plots can be edited in real time as the system is running using the lab view plot controls next to each plot.

Pressure Panel detailing the pressure in the motion boxes. These plots can be edited in real time as the system is running.

Settings The strings in each motion box can be enabled/disabled here, and their load cell profiles can be set here. The database run can be reset on this page, and the positions and capsule counts can be manually set or set from the most recent record in the database. Finally, the list of emails for notifications can be edited on this page.

Help Lists how to operate the software and the syntax for many commands used.

3.2 Procedures

The software is run by writing procedure steps that the software will run sequentially. Up to 4 independent sets of procedure steps can be run simultaneously. The procedures are written to the system inside the "procedures" tab. Procedures can be added in manually or via pre-written text files. There are text files written for both testing and deploying the strings. Non-expert DCS shifters should only use these pre-written text files to run the DCS and not write in procedure steps manually.

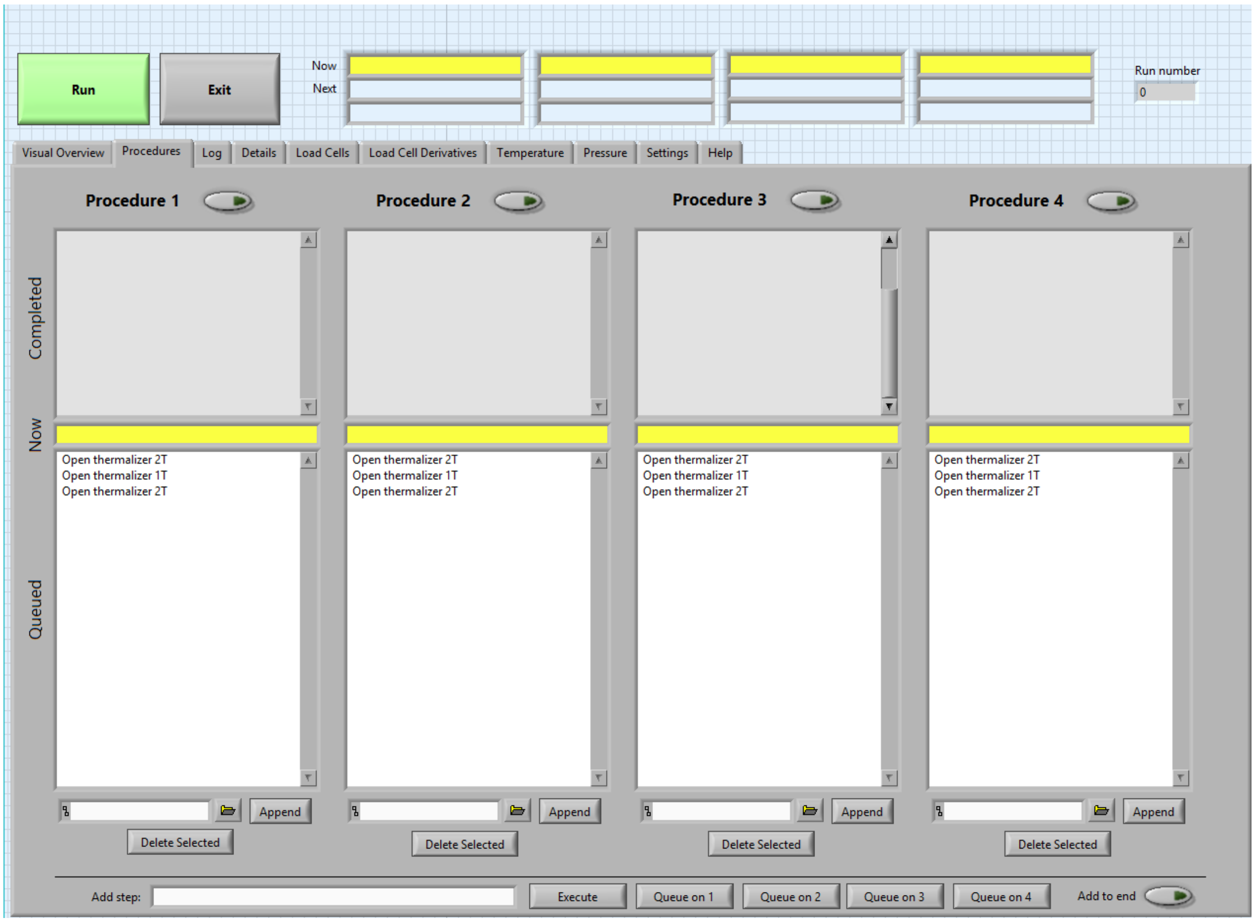


Figure 11: A screenshot of the procedures tab. Procedures can be enabled or disabled as needed, and each procedure will run sequentially through its queued steps.

3.2.1 List of Procedure Text Files

The procedure text files can be found on the DCS machine in the DCS Control Software directory and also on the MIT Github at `https://github.mit.edu/CUORE/cuore-dcs`. These text files contain scripts to run the DCS and can be uploaded on the procedures page. These procedures are located in the directory labeled 'procedures' in case this wasn't obvious enough.

SingleDeployments/Home To Precool/XX home to precool.txt Contains the steps for lowering a string from the home switch down to the precooling stage at the thermalizers.

SingleDeployments/Post Precool/XX raise out of thermalzier.txt Contains the steps to raise a string from the precool position up out of the thermalizers so that other strings can be thermalized.

SingleDeployments/Thermalizer Squeezes/String XX push.txt Contains the steps for lowering a string from the precooling stage through the thermalizer squeezes. Includes a short raise after each squeeze to check for any issues. Also moves the string down further after the last squeeze so that the next string can be lowered.

SingleDeployments/Down to Detectors/XX_down_to_bottom.txt Lowers strings down to their final deployment position. Once the strings reach a certain point, they are raised every 5 cm until they are completely deployed, and then have a single, final raise/lower in place.

PreOperationChecks/Thermalizer Test Open and Close.txt Contains a quick test of the thermalizer motion moving from open to closed. Use this if the current state of the thermalizers is open.

PreOperationChecks/Thermalizer Test Close and Open.txt Contains a quick test of the thermalizer motion moving from closed to open. Use this if the current state of all the thermalizers is closed.

SimpleCommands/Open Thermalizer X.txt Opens thermalizer X.

SimpleCommands/Close Thermalizer X.txt Closes thermalizer X.

SimpleCommands/FixDrift/Fix drift XX up (down) Y.txt This script fixes the drift on string X while it is moving up or down. The script will move the opposite direction first and then back to the original position to fix the drift. This script is meant to be used at whichever speed the string was deploying at. Be careful to watch the voltage closely when this is done.

SingleExtractions/XX Extraction.txt This script extracts a string from its deployment position back to home, with increasing speed as it reaches certain locations in the cryostat. Note that in running this script, the drift may need to be fixed.

3.3 Settings

3.3.1 Load Cell Profiles

The proper load cell profile for each string is listed in Table 1. Make sure that each string has the correct profile before starting motion. To create a new load cell profile to use for a particular string, follow the instructions listed in Section 7.

3.4 Global Constants

Some DCS hardware and software parameters are stored in the globals.ini file that is read by the LabVIEW software. While most of the file is system-specific and should not be altered, an expert shifter may see a need to alter some of these values. See Section 7 for more details.

Table 1: The current load cell profile to be used for each string. This list may change as more run data is taken.

String	Profile Name
1T	Run 3 Start Aug 2015: 1T
1M	Sept_2016_Inner_1M
1B	Run 3 Start Aug 2015: 1B
2T	Sept_2016_Inner_2T
2M	Run 3 Start Aug 2015: 2M
2B	Sept_2016_Inner_2B
3T	Sept2016_3T_Fixed_Version2
3M	Sept_2016_Inner_3M
3B	Run 3 Start Aug 2015: 3B
4T	Sept_2016_Inner_4T
4M	Run 3 Start Aug 2015: 4M
4B	Sept_2016_Inner_4B

4 Detecting and Recovering From Errors

Careful user operation and monitoring of the system is required at all times!

The DCS is also designed to assist the user with monitoring and detect any possible errors with both hardware and software interlocks. However, the system is not perfect and can miss errors and will stop motion on false positives.

4.1 DCS Interlocks

The DCS has multiple ways that it looks into determining if there are errors while deploying and stops the current procedure. **These checks are not 100% foolproof, as a careless operator could create a catastrophic situation**. These checks will help the operator in catching possible errors and will prevent dangerous steps that a careless operator could write.

Below is a list of the interlocks employed by the DCS:

Global Stop switch This is a mechanical stop that activates if too much pressure is applied at this switch. When the switch activates, a kill signal is sent to the system which will stop all motion (independent of the VI).

Load Cell Profile The averaged load cell values from previous deployments. As the DCS strings are deployed, the current load cell voltage is compared with this value to see if there are significant deviations

Error Count If the load cell value is outside of the load cell profile by larger than a preset margin, the error count will increase. If the error count fills the meter, the software will stop motion. However, if the load cell returns to within the acceptable bounds, the error count will decrease. This decrease is not immediate and requires multiple readings inside the load cell profile bounds to return to zero. This check is meant to catch errors such as load cell drift. (see Section 4.2)

Multi-factor Gate Valve operation The gate valve requires both a software step and a manual button press on the DCS rack for any change in state to occur. The pressure in the motion boxes should always be checked with the pressure in the cryostat before opening.

Load Cell Replateau If the load cell drops quickly and reaches a new plateau, the software will stop the motion as this can be indicative of a dangerous situation. (see Figure 12)

Load Cell Range If the load cell reaches a voltage that is substantially large or small, the motors will stop. This software feature should trigger before the global stop switch becomes engaged if the string is moving slowly enough.

4.2 Possible Errors/Issues

There are several issues that may occur during running of the DCS:

4.2.1 Both Deployment and Extraction

Load Cell Drift The load cells in the DCS are used to measure the tension in the strings by outputting a voltage (higher voltage $\implies$ higher tension). However, these load cells are very sensitive to temperature and other effects and can slowly drift by a few tenths of a volt over a few hours.

Cryostat Heating The cryostat can heat up as the strings are deployed and extracted. Different sections of the deployment and extraction plans will have higher or lower heat loads, so the PID will need to react accordingly. If the PID is not able to keep up with these changes, we will see heating on the towers.

4.2.2 During Deployment

String Spooling This issue can occur when the string does not correctly deploy down inside a tube and instead the teflon ball and weight capsules begin resting on a cryostat component or tube obstruction and the string begins to spool. This issue can look like a downward drift in the load cell, but is generally characterized by a drop with a sudden plateau in the voltage. *This can be a particularly dangerous situation!* The software is equipped with multiple ways to find these situations, but cannot always find them. The shifter needs to be looking for these situations during the deployment. If this issue is not caught, the DCS strings can become knotted and stuck in the cryostat. These issues look similar to Figure 12 and can elude the software if the load cell starts higher in the load cell profile range.

See Section 6.6 for a description of different situations that can cause string spooling and how to look out for them.

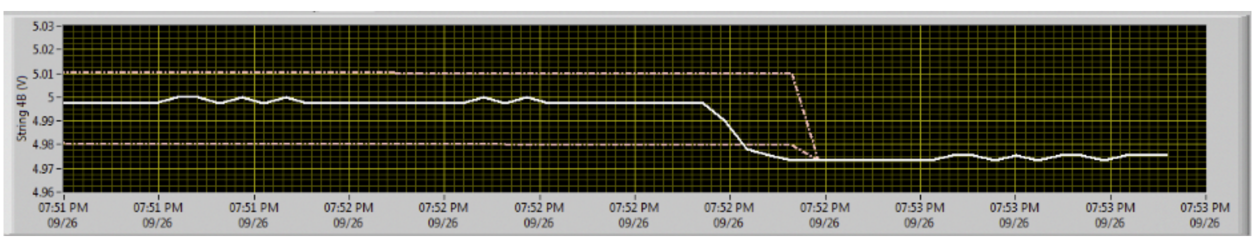


Figure 12: The load cell reading as a string becomes blocked by an obstruction. The software interlocks caught this issue and correctly stopped the motion.

4.2.3 During Extraction

String Catches This issue can occur as the string is moving up and does not correctly progress back up as a capsule can become caught on a funnel or obstruction. This issue will be quickly caught by the software/hardware and rarely requires a direct shifter intervention (as opposed to the harder-to-detect string spooling).

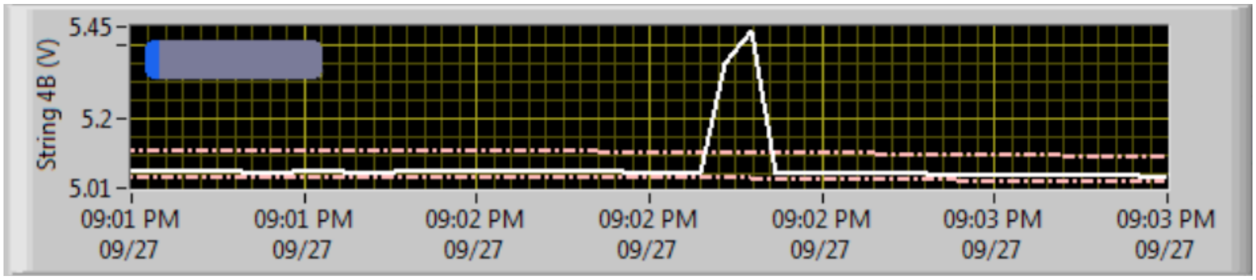


Figure 13: The load cell reading as a string catches on an obstruction going upwards. The software did not stop the motion as this rise was not large enough and the string fixed itself quickly before the error count filled. If the string does not correctly and quickly fix itself, the interlocks will catch this and stop motion.

5 Troubleshooting

5.1 Thermalizer Contact Only Reading Ungrounded

If the thermalizer contact signal is not reading at all when you start the system after following the steps listed in Section 2.6, then it is possible that the grounding cable has become unstuck from the cryostat. Check and make sure that it is connected both at the cryostat and with the alligator clip to the batteries. If these are all connected and the contacts still read ungrounded, then the batteries may need to be replaced. Spare batteries can be found in the DCS cabinet.

5.2 VI Not Loading

If the VI does not load (Error: -70072: End Program Storage.flx), that may be due to the PXI cards not having been initialized. This needs to be done every time the PXI chassis or computer have been restarted. To do so, open NI MAX (Measurement and Automation Explorer) and initialize the PXI cards for each motion box. The interface to do so is shown in Figure 14.

5.3 Thermometers Not Reading

If the thermometers are not reading on the VI, check to see that the LakeShores have been turned on at the back of the rack (see Figure 7). These also need to be on before the VI is started, so the VI may need to be restarted.

If thermometers are still not reading, check the readout on the LakeShores themselves. If none of the thermometers are reading, then it's likely that the cables have been disconnected either on the cryostat at the fischer box, or at the LakeShore and need to be reconnected. Some thermometers are intentionally disconnected as they have broken connections. Occasionally, some interferences may kill/resurrect a thermometer (warm-ups and cool-downs in particular). As long as there is at least one thermometer on a particular motion box, then we are able to detect the temperature change well.

A table showing the placement and connection of the 600 mK thermometers is shown in Table 2.

The thermometers on the thermalizers are mapped with channel A for thermalizer on motion box 1, B for 2, etc.

5.4 Noisy Load Cell

A requirement of smooth DCS operation is that the level of noise on the motion boxes needs to be less than the ADC resolution. If the noise is larger than this value (0.002441 V), then the software's ability to identify problems is greatly reduced. In the past, these situations have been caused by two separate issues. Firstly,

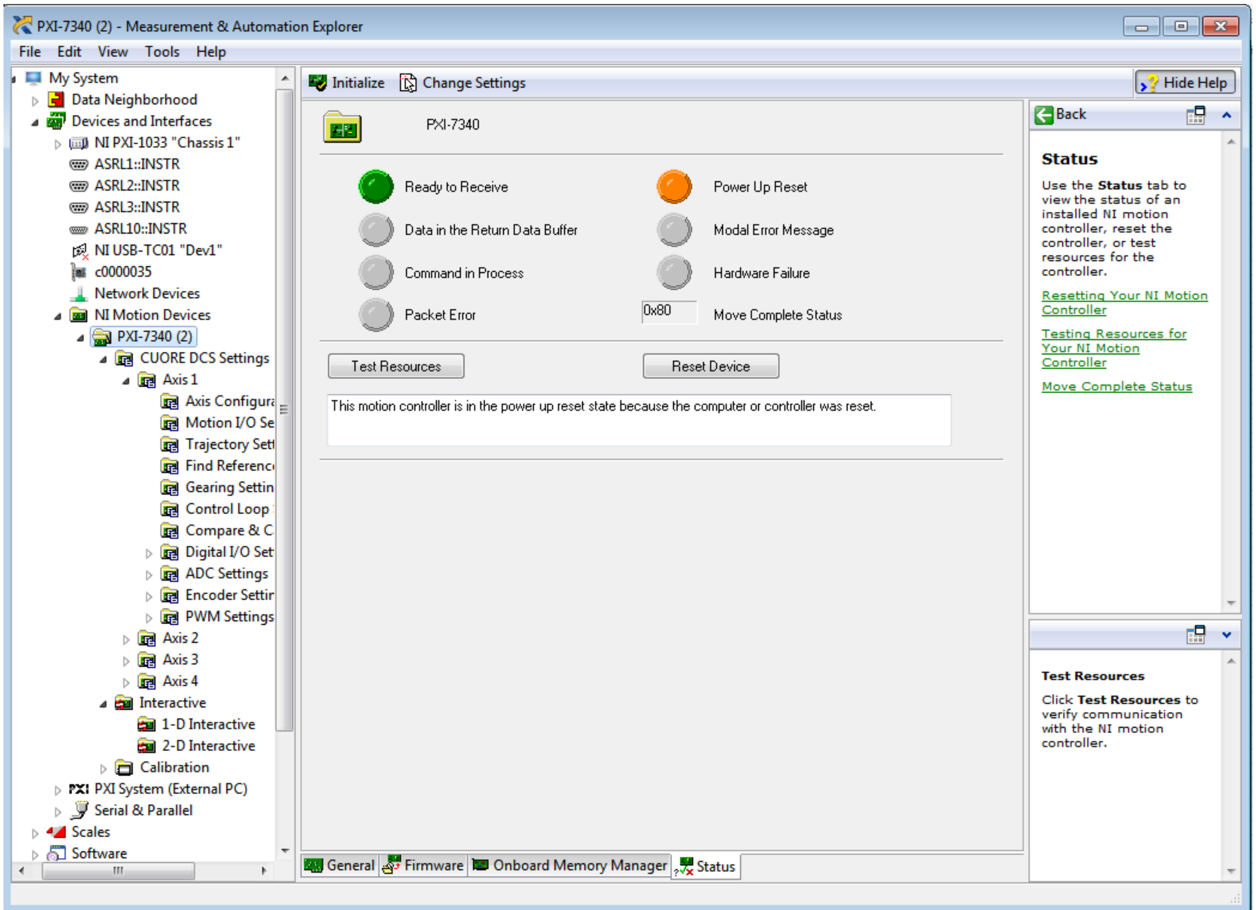


Figure 14: The MAX software showing the PXI chassis and a single card. To initialize, press the "Initialize" button.

Table 2: Location and channel numbers for the cernox thermometers on the LakeShore thermometer controller. Some channels are intentionally disconnected.

Motion Box axis	Guide tube path	Cernox wiring path	Cernox channel	Connected
4B (inner)	S4, left	12	C5 (6)	Y
4T (inner)	S4, right	9	C2 (3)	Y
4M (outer)	S4, center	10	C3 (4)	Y
1T (outer)	S1, right	11	C4 (5)	Y
1B (outer)	S1, left	8	D1 (7)	Y
1M (inner)	S1, center	7	C1 (2)	Y
2M (outer)	S2, center	3	D4 (10)	Y
2B (inner)	S2, left	6	B (1)	N
2T (inner)	S2, right	4	D5 (11)	Y
3B (outer)	S3, left	5	A (0)	N
3T (outer)	S3, right	1	D2 (8)	N
3M (inner)	S3, center	2	D3 (9)	Y

the cables in the preamp may be slightly touching, or the capacitor may be shorted. The capacitor in the ADC acts as a low-pass filter to reduce the effect of external noise sources such as the motors. Secondly, the issue may be due to cables in the D-shells on the top of the Motion Box or out of the flange having a stray connection to the backing of the D-shell. Due to the nature of these issues, these fixes should only be attempted by an expert shifter looking at the DCS wiring document, see Section 7.

5.5 Load Cell Drift

When the load cell drifts, this can occasionally cause the load cell to rise or fall out of profile band. When this occurs for too long, the error count can fill and stop the motion of the string. When extracting a string, this is generally just due to the load cell drift; however, for deploying strings, string spooling can, in some cases, look similar to the load cell drifting down. In this cases, it is important to be careful to check the load cell profile to see that it is, in fact, load cell drift. A general test is to see the timescale with which the load cell decreased outside the profile. Load cell drift is generally a long, slow process, whereas string spooling is generally a quicker process (as can be seen in Figure 12). However, even a case that may seem like load cell drift may mask the string spooling.

With that in mind, the procedure for fixing drift involves moving the string first back to a previous position (higher in the cryostat for deployment and lower for extraction) and then forward (lower and higher, respectively) to the position in which the string motion stopped. To resolve this issue, follow the flowchart in Figure 15.

5.6 Global Stop Engaged

If the string tension reaches a certain limit (well below the tension at which Kevlar will snap), the global stop switch will become engaged. When this occurs, the hardware will stop the motors, regardless of the state of the LabVIEW software. The mechanism is shown in Figure 16.

5.7 String Stuck (Down)

If a string appears to be stuck, stop the motion of the string (if the software hasn't already) and do the following

1. Log the position that this step has happened.
2. Check Section 6.6 to see if this problem is listed.
3. If problem is listed there, follow instructions listed for solving the issue.
4. Wait a few minutes to see if the obstruction clears and tension returns.
5. Raise the string slightly, watching for the tension in the string to rise.
6. Lower the string, watching for the tension to return to a proper value.
7. If the tension does not return to a proper value, log the new position, then repeat the above steps.

5.8 String Stuck (Up)

When a string encounters an obstruction on the way back out of the cryostat, there will be a large and sudden increase in tension outside of the load cell profile, which will be caught by the software (which will stop the motion immediately). The motion should stop before the global stop switch is engaged if the speed is slow enough as shown in Figure 17. If the global stop becomes engaged, see Section 7.

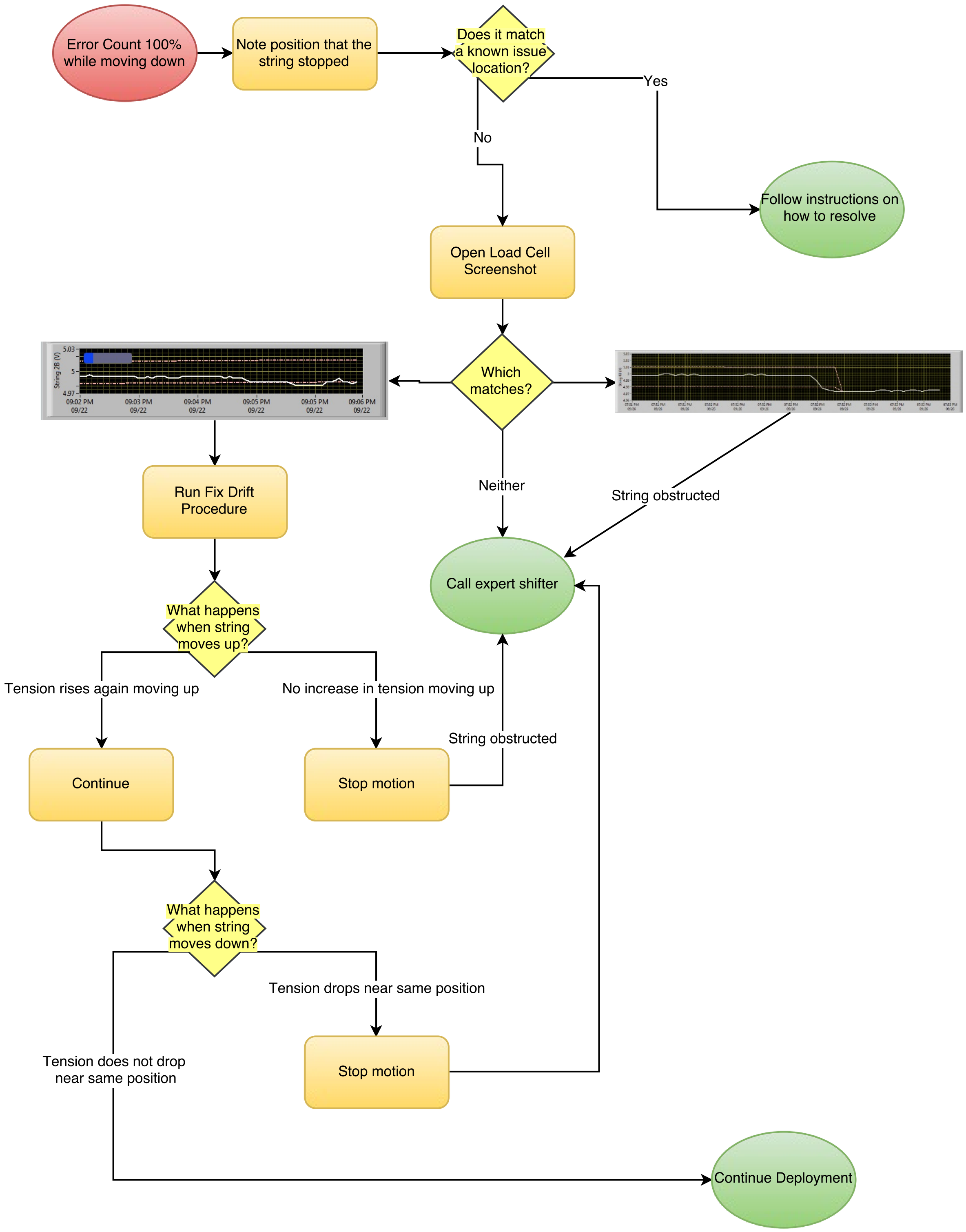


Figure 15: If a string motion stops due to the error count reaching 100%, follow the steps shown here.

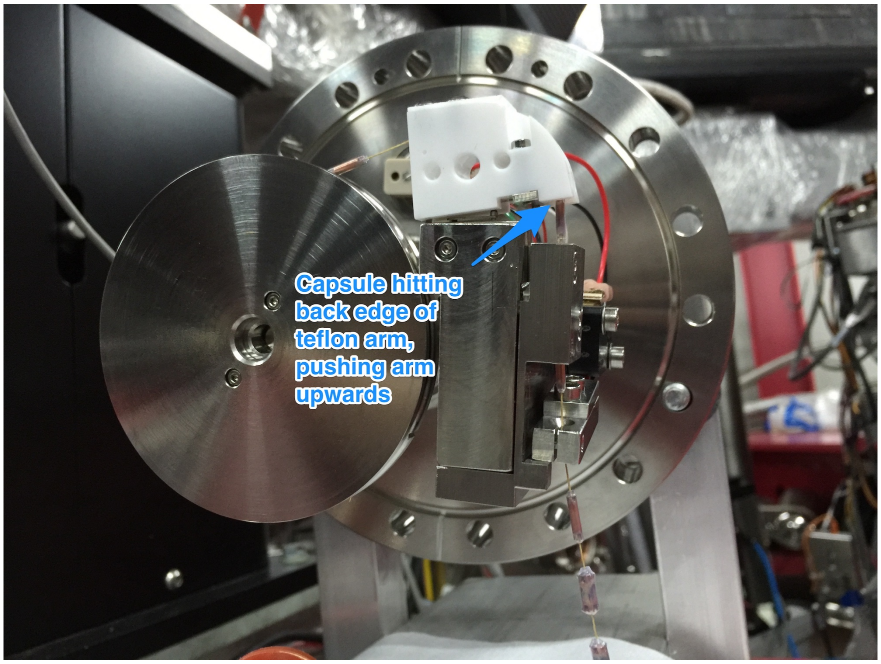


Figure 16: The engaged global stop switch is shown here. This capsule caused an interference going back into the spool, and caused the engagement of the switch. When this switch is engaged, the UMI board will not allow the strings to move at all.

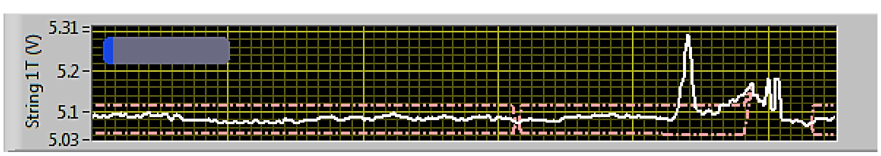


Figure 17: Load cell readings during an extraction. The spike in the load cell was due to obstructions that the string cleared. The error count responded to a slow increase in tension afterwards, and after fixing drift, the load cell responded normally.

5.9 Thermalizer not Closing/Opening

When the thermalizer opens/closes without a capsule in place, the thermalizer contact signal should change from grounded, to ungrounded, and then back to grounded. If there is significant ice buildup on the thermalizers, then the blockage may keep the thermalizers from fully opening or closing and the contact signal will not correctly reground. If this occurs, check the hanging weights shown in Figure 18. However, if a capsule is in the thermalizer, then that would keep the signal from regrounding and is the expected behavior.

5.10 Thermalizer not Cooling Enough

If the capsules are coming down to the 600 mK stage much hotter than shown in Figure 9, then the 4-K Thermalizers are not cooling them enough. This may occur if the precooling time was too short, or if the Thermalizers are not squeezing with enough force. The Thermalizers can be checked by seeing how the weights hang when Thermalizers are set to close. When the thermalizer is closed, the hanging weights should be as shown in Figure 18, and the mass should be free hanging (this can be tested by **lightly** pressing down on the hanging weight to see if there is any give or if it is resting).

5.11 Gate Valve not Opening/Closing

The gate valves under the motion boxes require both a software signal and a button press on the box for the signal to reach the gate valves. If these do not work, then there may not be compressed air reaching the gate valves. This can be checked by inspecting the compressed air line behind the DCS rack.

5.12 Cryostat Heating

When the strings deploy or extract, this will dump a heat load into the cryostat. This heat load comes from the friction from moving the strings, and, when deploying, the cooling of the strings at each stage. These effects are all velocity dependent, and stopping the motion of the strings will reduce the heat load on the cryostat. If the heat load on the cryostat is due to a hot capsule going too far down the cryostat, then the cryostat temperature may still increase. Inner strings have a larger heat footprint on the cryostat than outer strings (as inner strings are closer to the detectors at 10 mK); however, heating the 50 mK stage too much will cause the DU to be unable to cool the 10 mK stage properly.

6 Known Issues

6.1 Broken Power Switches

The power switches on Motion Control Boxes 2, 3, and 4 do not work, nor do the power switches on the power strips. To turn on/off these components, plug/unplug these devices.

6.2 Software

- Because the software saves a screenshot whenever an error message occurs, there is an associated slowdown, and the screen may hang momentarily.

6.3 TM contact signal heating

When the TM contact signal is off, i.e., when the TM contact circuit is complete, there is a heat load added to the cryostat at the 4-K stage that is seen by the thermometers on the 4-K thermalizers. This heat load does not appreciably affect the operation of the cryostat or the DCS.

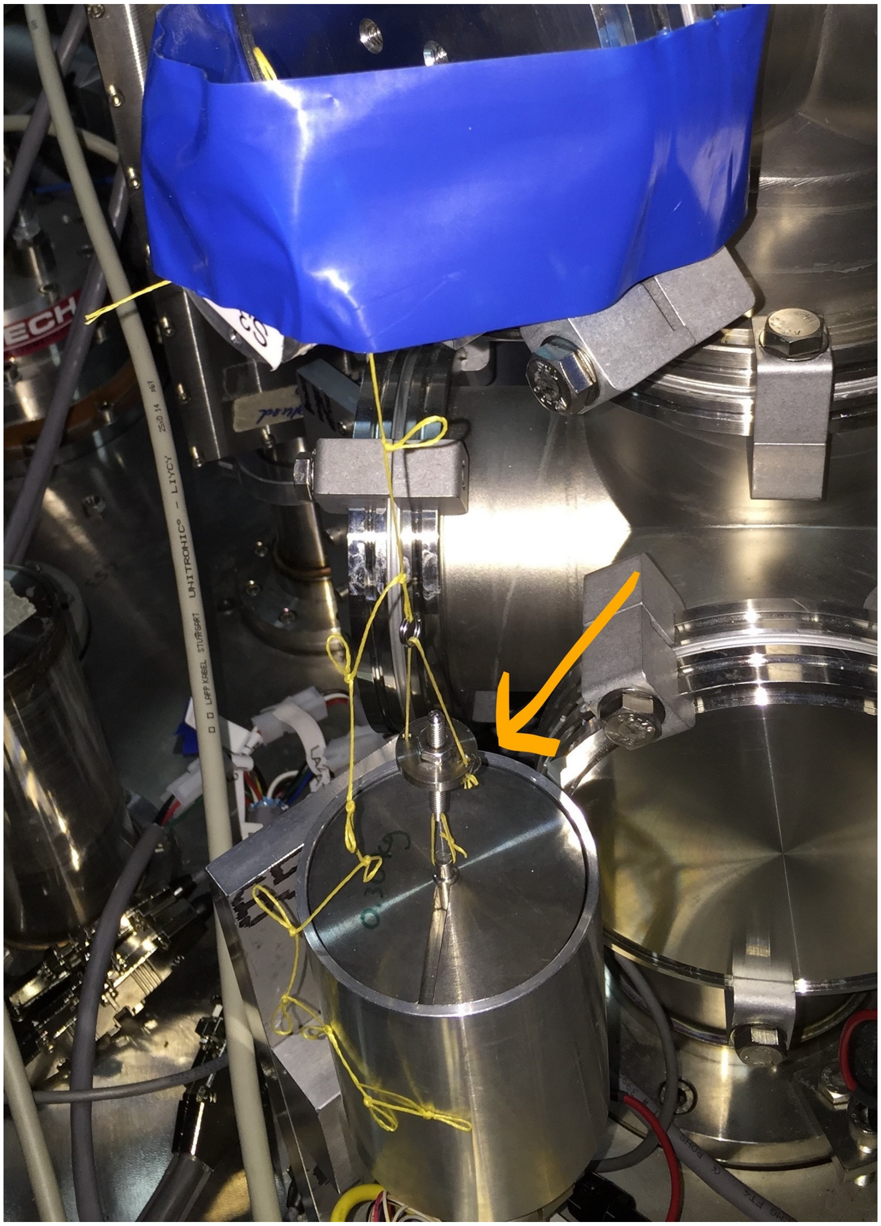


Figure 18: The weight hanging properly from the Thermalizer when the Thermalizer is in the closed state.

6.4 Grounding Issues

The DCS is intended to be electrically isolated from the rest of the cryostat and electronics, except the connection through the wall. If anything else connects the DCS ground to the cryostat, for example a grounding sheath on the electronics cables or even just a metal object, the detectors will need to be regrounded. The symptom here is that the cryostat will heat up uncontrollably to around 50 mK, and remain there with a constant heat load. When the detectors are regrounded, the cryostat temperature will recover immediately.

6.5 Unusable strings

6.5.1 String 1M – Resolved

String 1M formerly had an issue where it was incorrectly spooled around the axis of the drive shaft. This issue was resolved in early 2018 and can be deployed normally.

6.6 String Deployment Problem Areas

S-Tubes When the strings first enter into the S-tubes, i.e. while the capsules are still being counted by the proximity sensor, there is a risk that they will become obstructed. This obstruction is generally quickly caught by the software and a attentive monitor. When these obstructions occur, it is usually due to some ice interfering with the normal deployment of the string. Since the strings, when deploying, are much warmer than their environment, the ice can quickly melt within a few seconds, and tension will recover and deployment can continue. Otherwise, a few tries of moving up then back down should be sufficient to get the strings to lower. Occasionally, the ice can take much longer to melt out and it will take longer for the strings to melt through them (> 10 minutes), but waiting and retrying will still melt through them, given enough time.

Detector Guide Tubes When the inner source strings begin to reach the detector guide tube region, the strings can become obstructed and experience "ratcheting". When this occurs, the string becomes obstructed as normal, but upon retracting the string to try again, the string becomes obstructed again right at where the string was retracted. This process will continue until the string is sufficiently outside of this "ratcheting" region, usually when the bottom of the string is at the TSP. A string becoming obstructed this way in the detector guide tube region can be very difficult for an observer to catch, and the plateau interlock will likely miss due to the slow speeds. Thus, we currently find these issues by having the strings undergo a raise command every 5 once they reach the problematic zone. When the raise command happens, if the string does not raise, then string has become obstructed and will not go down any further. The resolution is to raise the string up until it regains tension and then to let that be its final deployment position.

Table 3: Known issue locations during deployment. The start and end positions list roughly where the issue has been seen previously

String	Issue Type	Start Position	End Position	Resolution Comments
All	Ice in S-Tubes	-350	-250	Waiting for melting or retrying
1M	Ratcheting	1500	1700	Leave at position when regains tension
2T	Ratcheting	1500	1850	Leave at position when regains tension
4T	Ratcheting	1800	1950	Leave at position when regains tension
4B	Ratcheting	1600	1900	Leave at position when regains tension

6.7 String Extraction Problem Areas

S-Tubes While in the S-tubes, the strings will encounter the same ice that they had to pass through to be deployed down into the cryostat. This ice generally does not pose a problem on extraction, as the ice will be pushed through. This shows up as short-lived increases in tension as the string is raised, but the tension will drop back down before the software stops the motion. Occasionally, however, the ice will cause enough tension for the software to stop the motion of the string. If this happens and then the tension returns back to the nominal value, then motion can be continued, otherwise the string needs to be lowered slightly and then raised again for another attempt.

Issues Below the Thermalizer We have observed some issues with raising a couple of the strings (4B and 3B) inside the cryostat. These issues seem to be mechanical in nature and not due to ice, and the solution outlined above has not always been able to fix this issue. Activating the Thermalizer has been able to solve this issue, the method of which is described in Section 7.

Table 4: Known issue locations during extraction. The start and end positions list roughly where the issues have been seen previously.

String	Issue Type	Start Position	End Position	Comments
All Strings	Ice in S-Tubes	-250	0	Solved with multiple lower/raise
4B	Stuck in Thermalizer	900	880	Solved by Thermalizer
3B	Stuck at TSP	1420	1400	Solved by Thermalizer

6.8 Broken Thermalizer Grounding Contact Signal

The Thermalizer contact does not reground when the Thermalizer for MB 2 is fully closed. This was caused by accident while adjusting the thermalizer tension, but the thermalizer seems to be fully closing properly, just no longer regrounding when not squeezing on a capsule.

6.9 Motion Box 2 Proximity Sensor

The proximity sensor on Motion Box 2 is malfunctioning and does not work properly. Because of this, the capsule count does not increment when the string moves up or down through the proximity sensor. This is not too much of an issue during deployment, although it does increase the position uncertainty on strings in Motion Box 2.

6.10 String 2M Position

For an unknown reason, the position on string 2M does not return to its original value when lowered into the cryostat and back to the home position. It consistently needs to be raised 3-4 cm beyond where we would have expected the string to return to home, seemingly uncorrelated with how far down the string has progressed into the cryostat. After inspection of the string in early 2018, it was determined that, while there does not seem to be anything wrong with the string, the speed at which the string deploys and raises is not the same (when the same speed is input to the string through the MAX software). This causes the difference in the position that is observed during deployment and extraction. It is still unclear what causes the difference in speed, but the string is able to be deployed and extracted.

7 Expert Shifting

These steps should only be taken by an expert shifter!

Unplugging cables When plugging or unplugging any DCS components, always turn off the motion controller boxes or gauge that the component is plugged into. Hot plugging/unplugging will damage DCS components! If the cables are being unplugged on the cryostat, be careful not to disturb other cables or the cryostat itself. If the cables are being unplugged on the rack, be careful to hold the mating nuts with a wrench as you unscrew them, as they may come loose otherwise.

Fixing Obstructed Strings - Deployment When a string is stuck going down, this requires very delicate operation to get the string to continue deploying. Check Section 6.6 to see if this position and string has been previously noted with a problem/fix. If the string becoming stuck has been caught by the shifter/software (has not had the chance to unspool), then leaving the string at the position in which it was stuck may be enough for the string to clear the obstruction or melt any ice that has formed on a tube and the load cell reading will return to the correct tension. If this happens, then double check this by raising the string a few cm to see that the tension is okay, and then lowering back through the position where the string had been caught. If the string passes through the same position without having the load cell drop, then the obstruction has been cleared (and note the position in Section 6.6). The load cell on a string that became obstructed that was raised and became unobstructed is shown in Figure 19.

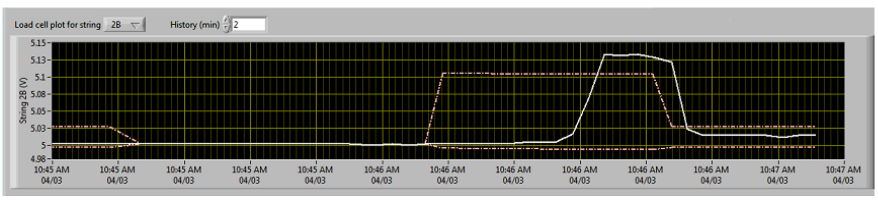


Figure 19: The string here had become obstructed. Raising the string took a short time to remove the slack in the string, and then the string was able to redeploy correctly. In particular, note that the voltages on the left-hand side of the rise are lower than the voltages on the right-hand-side.

Manually Opening Gate Valves Occasionally, if the gate valve control is not working from the software, the gate valves can be opened and closed manually. On the gate valve, there are two buttons, one on top of the gate valve, and one on the bottom of the gate valve. A small hex wrench works well to press these buttons, which are shown in Figure 20

Blown UMI Box Fuse If a cable has been plugged/unplugged while a UMI box is own, it is likely that the fuse has blown in the UMI box. To fix this issue, unplug all the cables on the problematic UMI box and then remove it from the rack and onto a table. Next, open up the top of the box and replace the fuse shown in Figure 21 and Figure 22.

Looking Inside a Motion Box Viewport All of the motion boxes are outfitted with viewports that allow for watching the strings in the region from the spool to the teflon covering the global stop switch. Looking inside this region can be helpful for watching for string tension to become slack or if the string has become unspooled, a dangerous situation.

Generating Load Cell Profiles In the case of the current load cell profiles not being adequate, new load cell profiles can be generated with data from previous runs of the DCS. To do this, there are multiple python scripts that, when run, will produce new load cell profiles for the DCS strings. The scripts are located in the cuore-dcs github under the scripts directory. The steps to create a profile are as follows:

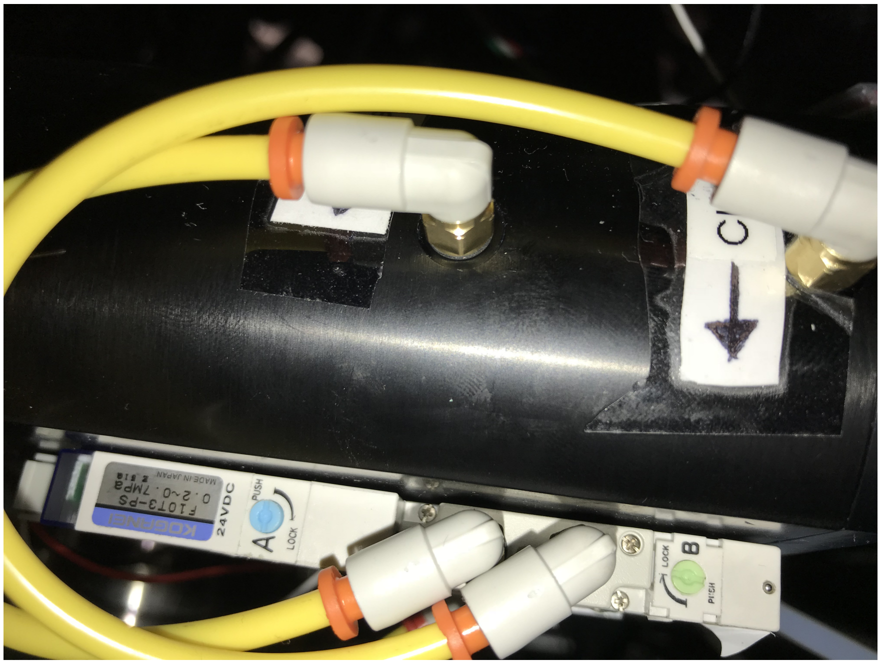


Figure 20: A picture of the side of the gate valve with the manual push buttons. The blue button, labeled A, (closest to the motion box) opens the valve, while the green button, labeled B, closes the valve. The buttons are currently covered by bottle caps as they can be accidentally pressed, creating a significant problem. The buttons can also be locked by twisting after depressing, although that prevents remote activation.

Figure 21: The fuse, marked with an (A), is shown here on the UMI box. The fuse here can be quickly replaced, if needed.

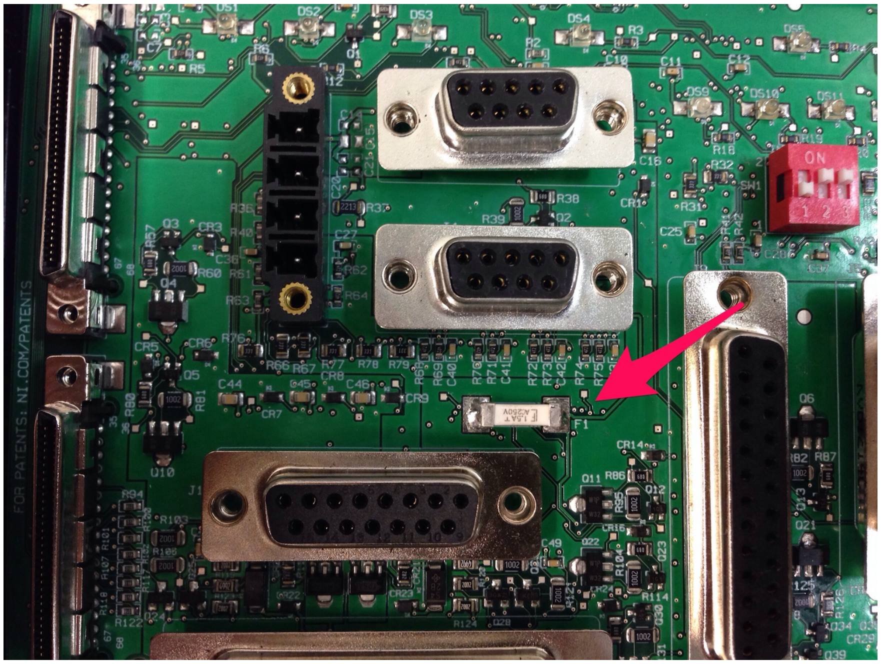


Figure 22: The fuse location on UMI boards that have not had the addition of the external fuse. This fuse is much more difficult to replace.

1. Determine the run numbers for the extraction and deployments for each string you want to make a profile of.
2. Open cmd.exe on the DCS machine.
3. Run *ExtractLoadCellDataForProfile.py* and follow the usage notes.
4. Collect the data extracted from the database by the script and check to make sure the data looks good (Excel works well after you move to the data to your own machine).
5. Apply an offset to each run such that the fiving position (check this position for each string) is also 5 V in the profile.
6. Copy all the runs (one for DOWN and one for UP) into a tab-delimited text file with the format: *“⟨position⟩\t⟨voltage⟩”*
7. Run *MakeLoadCellProfile.py* and find a good value for the fitting algorithm (0.02 - 0.05 work well). A good value catches general changes, but not too much of the small-scale variations that may change in different runs.
8. On the DCS machine, run *InsertLoadCellProfileIntoDB.py*, giving the profile a clear, helpful name.
9. The profile will be there in the software the next time the software is run.

Opening a Motion Controller Box In case of an issue such as a blown fuse inside the motion control box, it may become necessary to open up the faulty box to make a repair. The inside of the motion box is shown, with labels, in Figure 23.

Venting a Motion Box In the case that a motion box needs to be vented, there is a valve on MB 1 that allows for this to occur. THIS SHOULD ONLY BE DONE WHEN THE GATE VALVES ARE CLOSED! As only MB 1 has this valve, any time another motion box needs to be vented, MB 1 will also be vented in the process. It is best to vent to a dry gas, such as nitrogen, as water takes a very long time to desorb from surfaces in the motion box.

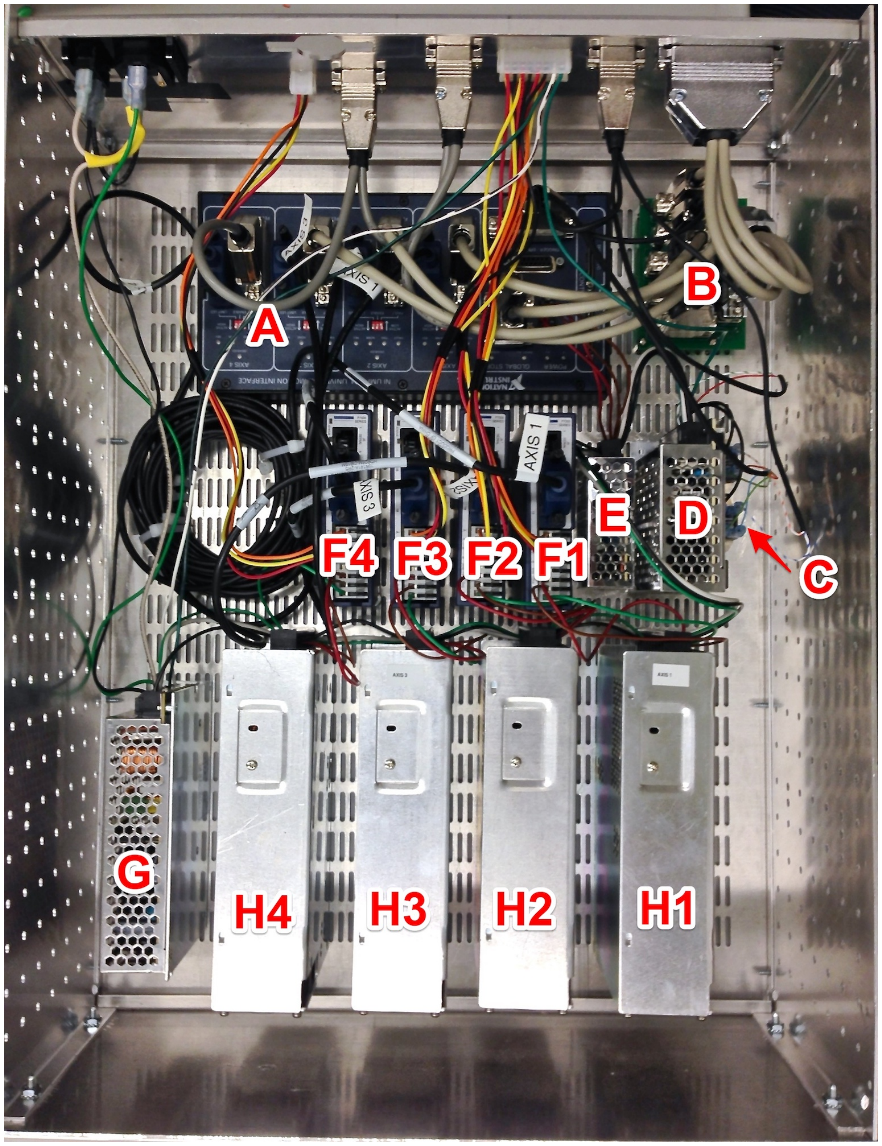


Figure 23: The inside of a motion control box. (A) is the UMI board, (B) is the PCB, (C) is the gate valve relay, now replaced with mechanical relays, (D) is the gate valve power, (E) is the UMI power, (F1-4) are the controls for each motor: top, middle, bottom, and linear actuator, respectively, (G) is the preamp power, and (H1-4) are the powers for each motor, similarly labeled as (F).

Venting and/or Calibrating the Vacuum Gauges If the vacuum gauges need to be recalibrated, the vacuum in the motion box that's being recalibrated needs to be at atmospheric pressure. This should only be done when the gate valves are closed!To do so, use the leak up valve on MB1 to make the vacuums seen by the motion boxes on the gauge(s) of interest, and then recalibrate them from the Varian vacuum controller on the front of the DCS rack.

Adjusting Thermalizer Tension The thermalizer tension can be adjusted by hand if the thermalizer is not able to cool down the sources properly. This can be done by adjusting the height of the washer and nuts (see Figure 18 for reference) to make it so that the mass is freely hanging when the thermalizer is closed. If the adjustment needed is too large for threading, there are other loops on the string that can be used. It is dangerous to do this adjustment as access to the hanging masses is quite restricted, so care is needed here. It is also important that the string remains under tension, so tape is used to hold the string while the mass is being adjusted. Also, return the masses down softly so that the tension in the string does not change suddenly as this can damage components.

Global Stop Defeater Cable When Global Stop signal is on, the software cannot move the motors at all. This can be overriden by the global stop defeater cable, but this should only be done by the Yale DCS team, not even by an expert shifter. This cable allows for the global stop signal to be overridden and the software will be able to continue moving the motors. Naturally, this can be extremely dangerous, and extreme caution needs to be taken as to not damage or break a string.

Adjusting Proximity Sensor The proximity sensor sensitivity can occasionally need adjusting. This can be done with a small screwdriver and adjusting the sensitivity until the orange light (meaning that the proximity sensor is triggered) is off when there are no capsules and is on when there are capsules in the sensor. Note that there is some hysteresis in this system, so this is not as simple as it sounds.

Global Constants File On occasion, it may be necessary to edit the Global Constants.ini file in the software. This is possibly needed when the strings are obstructed or there is a change in the magnitude of load cell drift and the profile spread may need to be larger/smaller. Note: changing the size of the load cell profiles for downward motion is a MAJOR change. Editing the size for upwards motion is much less so. It may also be necessary to change the load cell limits to higher than the nominal value of 5.5, but be careful not too raise them much higher as the global stop can engage (depending on factors like the speed of the extraction) before the software can stop the motion, and this causes a significant delay in the operation of the DCS.

Removing a Drive Spool If for whatever reason, e.g. replacing strings, a motion box needs to be opened for a drive spool to be removed, first vent the motion boxes to atmosphere, using the leak up valve on MB1, making sure that the gate valves are closed on all the motion boxes!. Then unplug all the cables leading into the drive spool, after making sure that the DCS rack is turned off. Afterwards, remove the conflats from the motion boxes that contain the drive spools, taking care to catch the copper gaskets as the conflats are removed and to keep the drive spools steady. Then, to remove the drive spool, slowly pull the spool out of the box, minimizing any bumping of the components inside on the motion box. Once the drive spool is removed from the motion box, mount it on a motion box test stand, which is stored in the DCS cabinet on-site. From there, work can be done on the spool while it is resting on the stand.

Replacing a Source String After a drive spool has been removed from a motion box, the source strings can then be replaced. To do this, reconnect the cables to the drive spool on the test stand (note: you will likely need to perform this activity while close to the original motion box). Then, you can unscrew the teflon cover over the global stop switch and the cover over the spool itself to remove the string. If the string is not unusable or if it had mis-spooled around the wrong part of the drive spool, it is advisable to use the motor to unwind the source string and manually wind it around another external spool for storage. Otherwise, you may just remove the source string. When putting the new string in, first connect the back end of the string (opposite of the teflon ball) into the slot on the spool mounting and then wind the string under tension with the motor onto the spool. Do not attempt to wind the string manually without the motor as it is critically important to have the string under tension in order to provide smooth operation. Note that for new strings, new profiles will likely need to be taken in order to properly account for the tension during subsequent deployments.

Inserting a Drive Spool After removing a drive spool, it naturally needs to be reinserted in order to restore normal operation of the DCS. To do so, unplug all the cables, if any, from the drive spool on the test stand and slowly and carefully reinsert the drive spool back into the motion box, being careful to not bump parts of the spool against the motion box, particularly the load cell. Once the drive spool is back in place, then insert a fresh copper gasket and tighten the conflat. Then pump down the motion box, taking care to check to see if any leaks were introduced during this operation.