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| TITLE: **Hall B CLAS12 Solenoid Cooldown and Cryogenic Operations Procedure** |

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| BY: D. Kashy | DATE: 07 / Feb / 2017 |
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| SUMMARY OF CHANGES FROM PREVIOUS REVISION: | | | | | | | | |

**Introduction:**

The CLAS 12 Solenoid is a superconducting magnet that is part of the CLAS12 Detector system. It is ~2m long and 2m in diameter with a 0.78m open bore. It is surrounded by detectors on all sides. Its central field is 5Tesla and peak field is ~6.6 Tesla. At full current it will store ~20MJoule of energy which is about 50% more than the Torus magnet. The weight of the solenoid cold mass is ~30000lbs. The magnet coils are helium cooled via a 4K primary circuit. Boil off from the magnet cools the radiation shields in both the magnet and service tower. The solenoid cryogenics and power feed come through a vessel called the Solenoid Service Tower (SST). The SST contains most of the control valves involved with the magnet (the rest are in the DBX or in warm piping after the flows leave the SST).

There are two liquid helium reservoirs in the SST. The primary function for each defines the name of the reservoir. One reservoir is called the Lead Reservoir is named such because it houses the VCL’s. The other reservoir is called the Magnet Reservoir and its primary function is to provide steady state cooling for the magnet. The primary reason for splitting the Liquid Helium inventory into two volumes is that it allows the magnet cold mass, if necessary, to be cooled below 4.5K by pumping on the helium in the magnet reservoir. This will give more temperature margin if it is needed to achieve full field.

The lead reservoir is connected to the Distribution Box (DBX) through a set of long flexible U-tubes. These U-tubes allow the magnet to travel on rails along the beam direction w/o requiring disconnection. The primary supply U-tube and the connections inside the DBX allow variable temperature helium gas (300K-80K) or 4K supercritical gas to be brought to the SST. The primary return U-tube mostly functions to return flash gas from the supply U-tube and lead reservoir boil off during steady state operation but allows taking a small trickle flow during cooldown to cool itself. There are 3 other flow connections to the SST. Two are L-tubes that take flow from the VCL’s to an ambient vaporizer and one is a vent for the return from both the shields and the magnet reservoir. All 5 of these lines are Vacuum insulated, but only the primary supply and return U-tubes need to have low heat load because the other 3 lines are returning gas that will be warmed to 300K before returning to the End Station Refrigerator.

The Solenoid magnet has 5 coils. Coils 1 through 4 (C1-4) are mounted on a central bobbin and provide the 5Tesla central field. Coil 5 (C5) has its own bobbin and its function is to limit the external field surround the magnet to low values so that sensitive Detector elements will function properly.

At the center of the C1-4 Bobbin is a helium cooling channel. Finned Copper Buttons that are brazed into this channel conduct heat from the coils into helium in the channel. Copper strips that are epoxied to each coil are in turn brazed to cooling plates and thos are brazed to the copper buttons and form the path to cool the coils. In steady state the channel is fed by a thermal syphon with liquid helium supply from a ½” OD tube from the magnet reservoir. The liquid/gas mix is returned to the magnet reservoir in the SST (Solenoid Service Tower) via a 1-1/4” pipe. Flow in that pipe is used to cool the intercoil conductor splice joints as well as the conductor splice at the interface between the solenoid and the SST. The solenoid and SST heat shields are cooled by boil-off helium from the magnet reservoir. Make up liquid to the magnet is fed to the annulus channel by EV8612 from the lead reservoir.

Multiple PID control loops will be described and setup so that the cooldown can be continuous but will not require 24hr staffing for monitoring or manual intervention. Interlocks will also be implemented to avoid damaging the magnet due to thermal stresses based on design values received from the magnet vendor Everson Tesla Inc.

Cooldown is expected to take ~4 weeks and will be done in two stages, 300-100K using variable temperature gas and 100-4K using 4K gas.

**Scope:**

This document is the cooldown and operating procedure for the CLAS12 Solenoid. Operation of the Torus magnet, the Distribution Can (DBX) and 500 Liter Buffer Dewar are covered in document *B000000901-P007 Hall B Cryogenics DBX and Torus Cool Down and Operating Procedure* . Because the cooling the Solenoid requires the Distribution box and its controls, all those that pertain to the solenoid cooling are described here. NOTE: Setup for some of the controls will be dependent upon the status of other loads on the system. For this draft the procedures are written to be used as if the Torus is operating, i.e. it is cold and could be powered up.

**Valve Control and PID Loops**

A spread sheet that contains all control parameters (PID settings) for each active control device (Valves and Heaters) is attached as Appendix 1. In Appendix 1 there are different **PID Groups** used for different phases of the cooldown process. As the state of the systems pass from one mode of cooldown to another, PID parameters for control elements may change or the control element may go from Normal to Manual. The spread sheet contains two check-list columns which will be filled in after functionality of a Control Loop or control interlock has been tested and found to perform properly. Operators are warned that there may be some states of systems that the controls may not respond as intended, though rare, these can occur due to things as strange as blockages in piping, control read-back failure, or other portions of the system failing (refrigerator, compressor, air system….).

Basic functionality of the main cryogenic control elements is described here:

***DBX Elements***

**PV8563W** provides warm gas (300K) to be mixed with cold gas (80K) to achieve variable temperature gas for cooling either the Torus or Solenoid to 100K. This valve can be controlled on a downstream pressure PT8565, PT8513S, PT8513T, or a calculated pressure P\_CDHE\_8563W\_S, P\_CDHE\_8563W\_T, depending on what other parts of the system are doing. This valve also has a functionality of a PID on its maximum that can be used to limit its maximum position so that it does not overpower the cooling function desired. That is to say it won’t provide so much warm gas that the desired mixed gas temperature can’t be achieved. This can be done by controlling the Max setting on the position of PV8563C.OVAL as that position gets above 90 to 95% then PV8563W max is limited.

**PV8563C** provides helium gas to two heat exchangers. The first is a gas/gas exchanger and the second is a tube in liquid exchanger where the liquid side has liquid nitrogen in it. This LN2 has two primary functions. The first is to provide LN2 for the Torus heat shields and the second is to provide cooling power for helium Cooling (or Warming) the Torus or Solenoid. To provide a stable and controllable temperature there are two critical dependencies. First, the warmer heat exchanger HX8564 is fed only gas. This can only be done if the liquid reservoir LL8554CP/DP is not overfilled. Second the same reservoir level must not get below ~30% and uncover the HX tubing. PV8563C primary PID loop controls the supply temperature to the load (solenoid or torus). It can do this based on a fixed temperature value which must be stepped down or upon a desired DT between the helium and a metal temperature. For the Torus we have used HE\_METAL\_DT or HE\_METAL\_DT2 for the Solenoid we have HE\_METAL\_CD\_DT, HE\_METAL\_CD\_DT2, HE\_METAL\_WU\_DT, HE\_METAL\_WU\_DT2. Again we have a PID for the Maximum position of this valve and it can be used to limit a maximum temperature difference of metals within the load. For the Torus we use METAL4K\_DT\_MAX. For the Solenoid we have several constraints. To allow us to combine these limits we use an algorithm to first calculate each difference then calculate the percentage of each difference from its maximum difference then finally compare each percentage and find the max percentage and use that DT\_MAX\_PCT and we will limit the value to 75%.

**PV8566S** is the variable temperature supply valve to the Solenoid. It is mostly designed as a shut off valve to isolate this source from the 4K temperature supply. It could also be used to either limit the flow to the solenoid by controlling its position on directly on Flow FI8561 or on Liquid level in the N2 pot LL8554CP if it gets low.

**PV8512S** is the 4K supply valve to the Solenoid. It is mostly designed as a shut off valve to isolate this source from the variable temperature supply.

**PV8522SCD** is the cool down valve in the DBX for the Solenoid. It takes return flow from the lead reservoir to HX8524 the large ambient vaporizer on the north wall of Hall B. The flow must return through this valve until the temperature is below 8K so that the 4K supply flow is not warmed in the heat exchanger in the ESMTL. If the heat load of the SST and the U-tubes and the VCL’s is too high then it may be that this valve will be the return path and PV8522SR will remain closed.

**PV8522SR** is the cold return valve for the Solenoid. Flow from the lead reservoir flows through this valve if/when it is below 8K back to the ESR for energy recovery. It can also provide back pressure on the lead flow reservoir to drive the lead flow if the return pressure on the lead return line is a bit too high. Its control input will be PT8620. It can also be throttled if needed to provide pressure to drive flow through EV8612 to the Magnet Reservoir.

***Solenoid Service Tower Elements***

**EV8611JT** is the supply valve for the lead reservoir. Its primary function is to keep the lead reservoir liquid level at a constant value and its input parameter will be either LL8620SC or LL8620DP. It also has a cascade PID on its minimum position that will be used to keep the minimum position open enough to keep the supply temperature TR8610 at or below 6K. During CD this valve will have a small fixed position to allow a small lead flow and the operator can adjust this to keep the 4 sensors on the current leads cooling such that their temperature is lagging the average coil temperature SCOIL\_T\_AVG by less than 50K. Another option which will work is to set the valve to control on FI8621A with a set value below the controller set value. This will then limit the cooling power diverted to the lead reservoir.

**EV8611CD** is the cooldown supply valve. It will remain closed during magnet powering. Its primary function is to provide large flow capability directly to the Magnet Annulus for cooling the magnet from 300K to 4K. During the 300K-100K phase of the CD this valve will be controlled by the flow rate on FI8561 at a value that is acceptable to the cryogenics group depending on the other loads on the system, or as an option it can be controlled on PT8670. During the 100K to 4K phase of the CD it will be controlled on the 4K supply flow to Hall B CFI6711B, or as an option on PT8670. If the Torus is cooling then this flow will be split between the two magnets. During both phases of the cooldown the max of EV8611CD will be controlled by a cascaded PID that will look at the pressure in the Magnet Reservoir PT8670. The Set point of which will be below relief valve RV8670 pressure of 2 atm. It may be necessary to control the flow rate through the magnet based on the ambient vaporizer outlet temperature as it is sized for 3g/s and thus its outlet will likely get iced up if too much flow goes through it. This will create a water drip. If implemented the outlet temperature can be monitored by TP8675. This valve has a double cascade on the maximum position to allow two variables to control its maximum position.

**EV8612** is the Magnet Reservoir supply valve. Its function is to supply make up helium to the reservoir once the magnet is cold. Flow from this valve injects helium into the bottom of the magnet annulus. It will be controlled by PID with an input of the Liquid level in the Reservoir LL8670DP or LL8670SC. One must note that these levels are not equivalent. LL8670DP shows the level of the helium from the bottom of the annulus to the top of the reservoir while LL8670SC shows only the level in the 45L reservoir. This valve will be slightly open in manual mode at ~15% during the 300-100K portion of the cooldown it likely will flow backward from its normal direction because the pressure in the lead reservoir will less than in the magnet reservoir. One will be able to test this by closing EV8611JT and observing the lead flow and or Lead Reservoir pressure PT8620. During the 100K to 4K cooling it will be the primary flow path to the coils. And its position can be limited to look at the flow to the purifiers CFI084 or the DT/Dt of the coils COIL\_DT\_Dt30 or the pressure in the magnet reservoir PT8670. This loop should also have a cascade PID on the max position to control on TP8675 which is the vaporizer outlet temperature. This valve has a double cascade on the maximum position to allow two variables to control its maximum position.

**HTR8620** is a heater in the lead flow reservoir that can be used to assure there is boiloff helium to cool the current leads. So it may be needed to keep PV8522SR from fully closing. This heater has an interlock through the PLC that will disable it when LL8620SC is below 20%

**EV8621A and EV8621B** are lead flow control valves and are not controlled by user inputs but rather the PLC directly controls the flow through the leads based on a minimum of 35.4 slpm per lead when the magnet is at 0 current and a max of 42.5 slpm per lead when the magnet is at full current.

**PV8674** is an isolation valve that is only closed when the magnet is to be disconnected from the helium return (pulling the L-tube to the vaporizer). There may be a failure mode of the future magnet reservoir vacuum pump system that may also require closing this valve.

**EV8670BY** is the shield bypass valve. Its primary function is to bypass flow around the heat shields to allow more cooldown flow if the pressure drop in the shield limits the cooldown flow during cooldown. It may also be used for steady state operations if the shield limits the flow required to keep the magnet reservoir full. During cooldown the control input parameter would be PT8670. The set point will be just above the return pressure PT8675A. This valve has cascaded PID’s on both the min and max position to allow full control flexibility. Another possible input parameter for any of the 3 PID controls for this valve is SHLD\_DP.

**HTR8672** is a set of 3 band heaters attached to the return piping between the Solenoid Annulus helium volume and the Magnet Reservoir. This heater can increase the helium circulation of the thermosiphon and it can also increase the flow through the heat shield. As such it could be driven by one of the magnet temperature sensors or one of the calculated temperatures or temperature averages. It could also be driven by a shield outlet temperature or the average shield outlet temperature. This heater has cascaded PID’s on both the min and max position to allow full control flexibility. Finally this heater has an interlock that will disable it when the LL8670SC is below 20%. It should not have its interlock on LL8670DP unless the set value is quite high since as stated above this sensor monitors the level from the bottom of the magnet Annulus to the top of the magnet reservoir.

**SV8622** is a vent solenoid that allows the lead flow to continue while the solenoid ramps down. It can only be open if the current is above XX amps and the lead flow is below set point for more than XX seconds. (similar to Torus \*\* MUST BE CHECKED)

**SV8675BY** will be user operated but will always remain open during the initial operation. If a sub-atmospheric pumping system is installed the functionality of the valve may be made to respond to pumping system status and magnet reservoir pressure.

**SV8678CR and SV8678DV** are a set of valves that operate together. Either one or the other are always open depending on the cleanliness of return gas. At present there is no automated choice of which is open, thus the operator will select the return path based on input from CHL/ESR operators input. Since both valves are fail closed it is possible that they both close on loss of power or control system. In that case the magnet relief valve will provide the flow path to vent the helium.

**Nomenclature of the Torus and DBX valves and instrumentation**

The nomenclature follows the CND (CEBAF Nomenclature Document) with details described here. Knowing the pattern will help the operator more quickly and correctly identify the hardware and should help to avoid errors in operation.

Typical signals are XXXABCDYYY

XXX is the type of hardware (LL = liquid level, SV = Solenoid Valve, PV = pneumatic valve, EV= electric valve, RV= relief valve, CV= Check Valve, HX=Heat Exchanger, HTR = heater, TD = Diode temperature sensor, TR = Cernox Temperature sensor, TP = Platinum Temperature sensor, PT=PI=Pressure transducer,…)

A is the system locator

(8 is for Hall B, 6 is for ESR)

B is the system detail description

(1 = Torus, 2 = Buffer Dewar and Targets, 5 = DBX, 6 = Solenoid)

C is the process circuit

(1 = 4K supply, 2 = 4K return, 3 = 15K supply, 4 = 20K return, 5 = N2/LN2, 6 = Cooldown Helium 7 = Magnet Reservoir)

D is a counting number that usually increases in the direction of the flow

YYY is usually empty or a set of letters that help to identify function (S = Solenoid, T = Torus C = Cold, W = Warm, BY = Bypass, CD = Cooldown, TR = Torus Return……)

**Prior to use of this procedure the following documents must be read, understood and signed by all operators**

* ENP-16-64298-OSP Solenoid Magnet and Service Tower Cryogenic Operation
* ENP-16-60975-OSP Hall B Distribution Can Operation Procedure

**Relevant documents:**

* B000000400-R004 Solenoid Magnet Description
* Hall B Warm Gas Piping B00000-09-00-0701
* Hall B Torus Cryogenics P&I Diagram B00000-09-00-0100
* Hall B Cryogenic Distribution Can P&I Diagram B00000-09-00-0500
* Hall B Solenoid Cryogenics P&I Diagram B00000-09-00-0600
* Buffer Dewar 66850-E-02859
* B000000900-S002 Solenoid Magnet Cryo Instruments
* B000000400-R005 Solenoid Load Cells
* B000000901-P006 Hall B Check Lists for Cool Down of Cryogenic Systems

JLAB Cryostat Electrical Documentation (ETI document)

**Initial Conditions**

* B000000901-P006 Hall B Check Lists for Cooldown of Cryogenic Systems.pdf is checked off for all items necessary for the start of cool-down.
* All signal read backs and valve operations verified
* U-tubes between the DBX and SST are installed
* L-Tubes between the SST and the VCL warm up vaporizer are installed
* L-tube from the Magnet reservoir to the ambient vaporizer HX8675 is installed
* System Purified and circulating helium at approximately 3ppm or less
* Set up the PID Control Loops In Appendix 1
* Setup and Test all Alarms for Cooldown

**Main Support Adjustment**

* **The Main Supports Z and R may need to be adjusted before, during and after cooling and before warming the magnet. Follow the vendors procedure as needed to keep the supports properly adjusted throughout the cool down and or warm up processes.**

There will be no preload on the axial supports prior to cooldown. They must be slack at the start. Follow the vendor provided procedure to set the appropriate amount of slack.

Adjustment of the cold mass supports during cooldown is not expected.

For cooldown procedure; the limits for the supports are listed below   
  
    \* Radial supports alarm at 65kN; load not to exceed 100kN   
    \* Axial supports alarm at 5kN; load not to exceed 7.5kN

**PID/Interlock Initial Verification**

Test the PID Control Loops with appropriate perturbations, initialing the “PID Verified” to Work Cells in the spread sheet (Appendix 1).

NOTES:

MOST PID Control Loops will need to be fine-tuned during the initial cooldown.

Some PID loops and may also need to be tuned differently depending on the phase of the operation.

Interlocks in general will not need to be changed. If interlocks need to be changed, D. Kashy or R. Fair must be contacted.

Upon successful verification of PID Loop/Interlock basic functionality, cooldown may begin. Basic functionality includes:

1. Controlled Device moves the full amount required in both manual and normal (“PID”) modes
2. Controlled Device moves in the correct direction to an offset in the set value vs actual value of the PID input
3. Controlled Device if it has any cascades is receiving its proper min/max from the cascaded PID
4. If Controlled Device has an interlock, the interlock has been dummy loaded and confirmed to act properly to shut the device if proper operating conditions do not exist, AND the actual trip value is reinstated into the PLC

At each phase of the cooldown verify the PID loops for that phase are working properly and fine tune as needed. D. Kashy (or his alternate) should be contacted if PID loops are not reacting properly or need fine tuning.

**Critical things to monitor or observe:**

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| System Parameter(s) | Operator Action |
| Monitor strain gauges and load cells for signs of unusual differential thermal contraction | Call Expert if values change into an alarm state (yellow or red) |
| Temperature difference between the full 4k cold mass and the shields. (50K to start) SHLD4K\_DT\_MAX | Reduce control temperature DT (input of PV8563C.MAX). Increase flow rate. |
| Time rate of change of the cold mass should be kept below 1K/hr COIL\_DT\_Dt30 or DT120 or DT600 | Reduce control temperature DT (input of PV8563C.MAX) |
| Maximum temperature difference in the Coil 5 assembly C5BOB\_DT\_MAX at 20K |  |
| Maximum temperature difference in the Coil 1-4 and Bobbin Assembly C14ASY\_DT\_MAX at 25K | Reduce control temperature DT (input of PV8563C.MAX) |
| Maximum temperature difference in the full 4K cold Mass assembly CM\_DT\_MAX at 40K | Reduce control temperature DT (input of PV8563C.MAX) |
| Ambient vaporizers getting iced past ½ of last series finned tube and or outlet temperature of Magnet Reservoir vaporizer TP8675 drops below 285K | Determine source(s) of flow and reduce flow as needed |
| Vacuum Jackets of Solenoid, TL, DBX, or U-tubes, sweating or icing | Call Expert, stop or slow cooldown, add pumping capacity or start pumping on static vacuum spaces |



LHe Annulus Channel

C1

C2

C4

C3

C5

CLAS12 5T Solenoid Magnet - Cross section of coldmass  
Conduction cooled from LHe via Cu sheets and ‘fingers’

(ETI Drawing)



Expected Solenoid Magnet Cool-Down Profile  
Bill Schneider/ Tom Willard

(12 June 2014)

**Contacting the Cryogenics Operators:**

* During normal working hours contact CHL control room at ext 7405 or the guard shack ext 5822
* During off hours contact is through the guard shack ext 5822
* Mat Wright 715-1167
* David Schleeper771-4491
* Johnathan Creel 869-8910

**Initiation of cooldown:**

1. Verify the supports for the cold mass have been set to safely allow cooldown
2. Verify that interlocks and appropriate alarm set points have been entered and tested
3. Make a Solenoid Log entry titled with the Time, Day, Month and Year of cool down. (Make entries for all steps, there cannot be too many entries) the electronic log book is at: https://logbooks.jlab.org/book/hbtorus
4. Confirm data logging is activated – including Fast DAQ- (Contact Wesley Moore or Ruben Fair)
5. Start plots of critical signals relevant to the stage of the cooldown, in general these will be flows, pressures, temperatures and valve or heater positions of active control parameters for that stage of cooldown/operation, these usually are the inputs/outputs of active PID loops and temperatures, pressures, and flow rates in the flow stream

**300-100K Cooling of the Solenoid Magnet and its Heat Shields**

**PID Group S1**

***Discussion:***

Variable temperature helium gas is used to cool the solenoid. The control temperature for this helium should be set at a value (40K to 75K ) below the maximum metal temperature in the magnet SCM\_T\_MAX. This temperature difference (HE\_SMETAL\_CD\_DT or HE\_SMETAL\_CD\_DT2) set value may need to be changed to depending on what the actual temperature profile of the coils and bobbins look like and also the time rate of change of the coils. The cooldown analysis showed that it will take several days to develop the full gradient in temperature profile. So the starting value should be 40K. Watching the Coil 1 to 4 gradient develop to see how it responds prior to making the differential temperature sepoint larger.

As stated above the variable temperature is achieved is by mixing helium at 300K with helium at 80K. To create 80K helium 300K helium passes through two heat exchangers (HX8564 and HX8565) in the distribution box. The amount of 80K helium controlled by PV8563C and the amount of 300K helium is controlled by PV8563W. The PID for PV8563C uses temperature for its set point and PV8563W uses a pressure for its set point.

It is important to monitor the inlet temperature to the Torus to verify it is not warming when this variable temperature gas flow commences. Valves that are cold can often leak through because their seats are hardened by the cold temperatures. So besides having valve PV8566T ( the variable temperature gas to the Torus) closed, we will prevent flow from leaking through to the Torus by keeping the supply pressure to the Solenoid lower than PT8513T (the 4K helium supply pressure to the Torus). The simple way to do this is to pick a setpoint well below PT8513T as the input for PV8653W. A more complex way but may be nice and necessary to maximize flow is to use a value which is the difference between PT8513T and PT8565 named (P\_CDHE\_8563W\_S) as the input for PV8563W More information on these variables is available on the PID spread sheet (Appendix 1).

Cooldown stresses are limited mostly by temperature differentials. But since not all portions of the magnet are instrumented, we may also need to limit the time rate of change of the cold mass. This can be done by limiting the flow rate. The flow rate is controlled by the valve positions of the three inlet valves EV8611JT, EV8611CD and EV8612. Since most of the mass that needs to be cooled is the coils, most of the flow will be through the cooldown valve EV8611CD.

To limit the cooldown stresses generated we will limit the temperature differentials in the magnet. Each coil has two temperature sensors and they are mounted as a pair so we do not have temperature differences in individual coils. Four temperature differences will be compared as a percent of their allowable maximum, whichever is highest will be used to trip the cooldown valve interlock.

* DT\_MAX\_PCT = Maximum percentage of the allowed values for differential temperatures. These are
  + Temperatures on the C1-C4 and Bobbin Assembly at 25K
  + Temperatures on C5 Bobbin Assembly at 20K
  + Temperatures of the full 4K cold Mass assembly at 40K
  + Temperatures of the full cold mass (shield and 4K cold mass) at 50K

For details on the calculations for these values see the PID spread sheet (appendix 1)

* There are no alarms on the above signals once the magnet is below 50K
* Interlocks will shut the warm and cold mixing valves PV8563W and PV8563C if the DT gets above their Major Alarm Condition and this will require expert intervention to reset the interlocks and resume the cooldown

1. Set up cooldown plots of pertinent signals for
   1. DBX: LL8554CP,PT8565, PT8513T TP8565, TD813S, TP8567, TP8564, TD8522SR, PV8563W, PV8563C, FI8561, TD8522DR
   2. Solenoid SST: EV8611CD, EV8611JT, EV8612, EV8621A, EV8621B, EV8670BY, PV8674, TR8674, TR8672, TR8673, TR8611, PT8620, TR8671, TR8670, PT8670
   3. Solenoid Coil, Bobbin and Shield temps: COIL\_T\_AVG, COIL\_T\_MIN, COIL\_T\_MAX, C14\_DT\_MAX, C5BOB\_DT\_MAX, SHLD\_T\_MAX, DT\_MAX\_PCT
   4. Solenoid Support Loads: AL01 through AL08; RL01 through RL08 do we need to update these to ZS8610US\_BR\_B etc,?
   5. Buffer Dewar: LL8210, TD8211, TD8210
   6. Torus: LL8120DP, TD8111, TD8120
2. Check the pressure of the Supercritical helium to the Torus on PT8513T and PT8111 (it is assumed that the Torus is running at 4K) and observe if there is a difference. Choose an offset value big enough to assure that the supply pressure to the Solenoid as read on both PT8565 and PT8513S are below the SC helium supply by 0.2-0.3atm, this will be the input for PV8563W either directly at the set value for PT8565 or the more complex control programing with direct offset (see PID sheet) P\_CDHE\_8563W\_S
3. Verify the primary supply and return valves for the solenoid, PV8512S and PV8522SR are in manual mode and closed
4. Open PV8522SCD 100% in manual mode
5. Verify that Warm Helium Interface valve MV6031B at ESR to the Purifiers is open (the cryogenics group will assist here and could choose to change to MV6030B and take the flow to the ESR main compressors)
6. Open the Magnet Reservoir return valve PV8674
7. Put the shield bypass control valve EV8670BY in manual mode with a set value of 100%
8. Open valves SV8675BY and SV8678CR which allow return flow to the quench header and confirm the dirty gas vent valve SV8678DV is closed
9. Contact the cryogenics group and ask that the 4atm helium supply to Hall B be turned on (open MV6010B and to verify that a warm return path is open MV6031B to purifiers or MV6030B to ESR compressors
10. Verify helium mixing valves in the DBX are closed PV8563C and PV8563W
11. Verify MV8561V is closed and open MV8002 and MV8561 and MV8562. Then verify that PT8561 is at least 3.0 atm
12. Set the differential pressure amount to 0.3 atm by entering 0.3 into variable PV8563\_DP\_OFFSET on the DBX control screen
13. Open EV8611CD in manual mode to 20% and EV8611JT 20% and EV8612 to 15% in manual mode
14. Manually open PV8563W to 5%. Check the supply pressure PT8565 to see how it is responding. If it is below 2 atm and above 1.4 atm then make the max of PV8563 5% and the min 5%. Put PV8563W in Normal mode. Slowly increase the max and lower the min while tuning the Warm supply valve PV8563W to control the supply pressure of the mixed helium gas below the Torus supply pressure by 0.2 to 0.3 atm either using PT8565 directly at a set point of 2.0 or using calculated pressure signal P\_CDHE\_8563W\_S (this signal may need lots of filtering)
15. Put PV8563C in Manual Mode and slowly open it a few percent at a time. Have someone up at the valve to report back when the valve actually moves and once it does quickly throttle it (unless it moves from the first attempt). Make the input TD8513S and the setpoint 290K (or 10K below the average coil temperature). Watch the temperature gradient develop through the magnet.
16. Flow rate can be adjusted by opening EV8611CD in manual mode
17. Watch the magnet reservoir pressure PT8670 and the Solenoid Shield pressure drop SSHLD\_DP. Setup PV8670BY to keep the shield flowing and cooling. To do this the value of the shield pressure drop must be above 0.0 atm. The amount is not clear and as the shield cools the amount of pressure drop to keep flow going through it will decrease. Setup the PID for PV8670BY to keep SSHLD\_DP at 0.1 to start and revisit this as the cooldown proceeds.
18. Setup PV8563C to control on the helium to metal DT HE\_SMETAL\_CD\_DT2 and make the starting value 10K. This will slowly be stepped up as the cooldown gets going and gradients develop and understood
19. Setup PV8563C Max position PID to control on the max percentage allowable of the DT’s specified at 90%
20. With a tight range on the Min and Max position put EV8611CD in Normal mode and tune it to control the flow rate FI8561 or set to control on PT8670. A PID on the max position should also be implemented to be sure we do not blow RV8670. If PT8670 is the control parameter then TP8675 can be used as the cascade PID on the maximum position.
21. Verify that lead flow controllers EV8621A and B are working and that manual valves MV8621A and B are open and setup EV8611JT to control on FI8621A at a set value of 10. This will establish a trickle flow through the lead reservoir.
22. Check the heaters on the lead flow to make sure they are working and keeping ice growth minimal
23. Check both reservoir pressures PT8670 and PT8620. PT8670 should be higher as more flow will be going through that path. Very slightly open EV8612 to establish a bit of flow through this line. The manual position of 15% set above should be sufficient. The flow will likely be backward, that is from the magnet annulus to the lead reservoir but that is fine.
24. When the coils get below 150K it may be that PV8563C can’t provide enough flow to keep the pressure up. (not its primary function) Thus it may be necessary to put a new PID max control on PV8653 to control it based on PV8563C.POS, this will allow the temperature to continue to cool as the flow through PV865W will be reduced to keep PV8653C from going full open.
25. When the coils get below ~120K PV8563W will be closed and its air supply isolated and 80K helium will flow through the solenoid.
26. When the coils get below ~100K the next phase of the cooldown can begin.

**Solenoid 4K Mass cooldown 100K to 4K**

**PID Group S2**

***Discussion:***

This phase of the cooldown is done with 4K helium. 4K helium flow from the ESR to the DBX will have already been established when cooling the ESMTL and the Buffer Dewar. There are two distinct phases of this portion of the cooldown. The first will be Cooling and Filling of the Lead Reservoir. This phase will happen very quickly because there is very little mass in the Lead Reservoir. In parallel but much slower will be cooling of the magnet and the magnet reservoir and heat shields.

Because the lead reservoir will cool and fill quickly we should be able to use the liquid feed valve EV8612 to the magnet annulus. This will reduce the complexity of the switch to 4K operations and also the likelihood of blowing the relief valve RV8670.

The lead flow reservoir will be back pressurized by the solenoid warm return valve PV8522SCD to ~1.6atm in the DBX to allow driving flow to the magnet reservoir through EV8612. As the Lead reservoir starts to collect liquid helium the return from this reservoir will be switched over to Cold return PV8522SR and the flow will go back to the refrigerator. The ice that collected on HX8524 (not a lot compared to the Torus Cooldown) will start to melt and the area below this ambient vaporizer should be roped off. The lead flow controllers will control the lead flow to limit heat load into the reservoir.

To continue the magnet and shield cooldown, liquid helium will be drawn from the lead reservoir and injected at the bottom of the magnet reservoir through EV8612. This flow will return to the ambient vaporizer HX8675 through PV8674 and PV8670BY as needed to keep the pressure in the magnet annulus below the pressure in the Lead Reservoir. Flow will be limited to 10 g/s or less depending on available capacity from the End Station Refrigerator and the warming power of HX8675. Flow may also be limited to assure that other Hall B loads (Torus and Buffer Dewar) stay operational if they are needed for ongoing operations.

To assure that the no warm helium gas mixes into the 4K helium supply, the warm supply will be isolated from the cold supply and its pressure will be vented to 2 atm (below the nominal 3atm 4K helium pressure). This is done by venting through MV8561V.

When TD8522SR is between 7 and 8K the process to switch to cold return and away from ambient vaporizer HX8524 can begin. Because all the piping in the Solenoid and in the DBX is cold the switch to cold return can be done fairly easily if the ESR operators agree. The basic method is to first setup PV8522SCD to be a back pressure valve with a set point of 1.3atm. Then with EV6721B at ESR open, slowly open PV8522SR fully while watching TD672 and other key refrigerator parameters as well as the supply temperatures to the Torus and Solenoid TD8513T and TD8513S. Once PV7522SCD is fully closed the Solenoid Lead reservoir is on cold return and it can be re-pressurized by settings its control PID to control PT8620 at ~1.6atm to continue to drive flow through the magnet

1. Change Alarm State for HE\_SMETAL\_CD\_DT and DT2 from Minor and Major to No Alarm for these signals.
2. Close the Warm Gas Supply Control Valve PV8563C and manual valves MV8562 and MV8561. The warm valve PV8563W should have already been closed at the end of the previous 300-100K cooldown phase
3. Slowly depressurize the volume between MV8562 and MV8561 using MV8561V to between 1.5 and 2 atm (7-15psig) while monitoring local pressure gage PI8561.
4. Depressurize PT8563 by cracking PV8566S then closing it while PT8513S is less than 1.5 atm. Watch to see that PT8563 stays lower than PT8513S and less than PT8651
5. Verify that the warm return valve from the solenoid PV8522SCD is full open and that cold return valve PV8522SR is closed.
6. **Establish 4K supply flow to the Solenoid** by: setting EV8611JT to 100% in manual and EV8612 to 100% and slowly open PV8512S. Watch the supply flow rate CFI6711B, TD8513S and PT8513S. Use PV8512S in manual mode to keep the flow rate to the solenoid from going above a couple grams/second, (amount that CFI6711B changes) , and also to keep the Pressure PT8620 between 1.3 and 1.6 atm while TR8610 drops to below 10K.
7. When the Solenoid inlet temperature TR8610 drops below 10K the flow throttling function should be transferred to EV8611JT. Slowly decrease EV8611JT position and at the same time PV8512S can then be slowly opened opened to keep it from dropping the pressure. When the temperature at TD8610 is below 6K the PID’s for EV8611JT may be enabled. The primary loop controls the helium level on LL8620SC at 70%. The Min PID loop will keep the JT open enough to keep the U-tube from warming with a set value of ~5.5K so if the level is satisfied and the valve wants to go closed it will be forced to stay slightly open to keep the system flowing and stable. The Max Position Loop for EV8611JT may be controlled on CFI6711B but more likely it will be set in Manual mode with a fixed value.
8. When the Lead reservoir has ~40% liquid level and the return temperature at TD8522SR is below 7K the switch to cold return can commence. One must watch the Supply temperature to the Torus, Buffer Dewar and Solenoid as this is done. Alert the Cryo group that we have collected liquid in the Solenoid Lead reservoir and would like to switch to cold return. With PV8522SCD controlling on back pressure at 1.3 to 1.6 atm slowly crack open PV8522SR. Have someone at the DBX to see that the valve is actually moving as it could be stuck. Continue to open PV8822SR and watch PV8522SCD close. Once PV8522SCD is fully closed put it in manual mode and put PV8522SR on pressure control of the solenoid lead reservoir on PT 8620.
9. The cooldown operator will need to choose the flow path to the Magnet reservoir. Either EV8610 CD or EV8612 can be used.
10. Helium will flow through EV8612 or EV8610CD and into the magnet annulus. Temperatures in the Magnet and heat shield will continue to fall. EV8612 should be controlled on PT8670 between 1.4 and 1.7 atm but could be controlled by CFI60DLP (the ESR dirty line flow rate) or CFI084 (purifier flow) if we are connected to that and there are no other loads or DT/Dt or the magnet reservoir . The cascade loop on EV8612 max ( or EV8610CD) position should be controlled on the vaporizer outlet temperature TP8675A at 285K
11. As the shield cools its pressure drop should decrease as the density of the helium will increase. This should allow PV8670BY to close if it is controlling on the calculated pressure drop SSHLD\_DP
12. As the density of the helium increases it should start to show on the helium level sensor LL8670DP since this sensor measures the pressure difference between the top and bottom of the magnet and since cold helium density is significant when compared to liquid helium.
13. When liquid starts to show up on LL8670SC go to PID Group 3

**Steady State Solenoid Operation at 4K**

**PID Group S3**

***Discussion:***

To achieve stable temperature of the Coils will require stable pressure in the Lead reservoir and the Magnet reservoir. The lower the pressure in the magnet reservoir the cooler the coils will run to some point. But if the heat shield warms up it may be better to push more flow through the shields at a cost of running the liquid in the magnet reservoir at a higher pressure. This will lower the heat shield temperature which will have the most dramatic effect on Coil 5 but will help all coils since they are all cooled by conduction of the copper fingers. The first step increasing the pressure is to close or throttle EV8670BY and force all or some of the boil off of the magnet through the shields. If this is not enough we can turn on heaters in the Magnet Reservoir circuit HTR8672 and control them on the pressure in the circuit or the shield outlet temperature.

A small amount (< 1g/s) of the 4K helium gas generated in the Solenoid is used to cool the Vapor Cooled Leads (VCL’s). Vapor cooled leads are designed to transmit the high current (2500A) from water cooled buss bars to the superconductor of the magnet. Helium “vapor” starts at 4K and warms as it flows up the leads and warms due to absorbing heat from the I2R loss of the conducting filaments in the lead. 400Watt heaters HTR8621A and HTR8621B will help to limit the ice ball size. After those heaters are ceramic breaks that have helium on the inside and air on the outside.

There are male bayonets with Teflon circulation flow dampers inside to minimize the cooling of the ceramics. The flow then proceeds through vacuum insulated lines that then connect to ambient vaporizers that are designed to ice up on the outside and warm the gas to room temperature. That warm gas then goes through the flow controllers, one for each lead. Flow is controlled based on mass flow and this mass flow is a pre-programed function of current in the magnet, 35.4slpm (0.096g/s) at no current and 41.3slpm (0.112g/s) at full 2416 amps.

With the proper amount of flow, the heat load to the 4K system is minimized and the lead is protected from overheating. If the lead reservoir is not stable because the heat loads of the solenoid and the U-tubes are too low or if there is not enough boil off gas to cool the vapor current leads, we can activate heater HTR8620 to increase the pressure in the reservoir. We can make the control parameter of this heater the position of the cold return valve PV8522SR and require it to be some percent open while regulating the pressure in the Lead reservoir at about 1.3 atm.

1. Verify stability of the Lead Reservoir (1.2 Atm Tank) helium level. The PID for controlling the liquid level for the primary supply valve EV8611JT can be fine tuned. This will be a very slow loop and the valve will only need changes every few minutes (sample time long).
2. Flow from this reservoir will return cold via the Solenoid cold return valve PV8522SR. This valve will be set up to control the pressure of liquid helium in 1.2 atmosphere helium reservoir in the magnet. The set point will likely be 1.2 to 1.35 atm. If the pressure PI8620 is not enough above the warm return pressure CPI603QB, the lead flow controllers will go full open and if they still can’t provide enough flow the leads may warm and the magnet will ramp down (if energized).
3. The lead flow control valves EV8621A and EV8621B should be enabled and their flow rate set point should be set by the PLC.
4. Heaters on the lead exhaust will need to be set up to control on a temperature on the lead. Enable and tune set points and PID loops for HTR8121A and HTR8121B.
5. Monitor Coil temperatures and check the system stability.
6. Tune EV8612 as needed to control the helium level in the magnet reservoir
7. Once the magnet has soaked at temperature for several hours (all temperatures are changing less than 0.05K) One should see if any fine tuning of the PID’s is advantageous

NOTE: LL8670SC only measures the amount of liquid in the Magnet Reservoir while LL8670DP measures the amount of liquid in the magnet and reservoir combined and the volume per height is not linear. The nominal values for LL8670DP (based on ~0-16” of H2O) are:

* ~14% Magnet Annulus is empty
* ~40% Magnet Annulus is full
* ~85% piping to reservoir is full but Reservoir is empty
* 96% helium is at the bottom of magnet return pipe and the thermosiphon stops and the magnet the return pipe to the shield supply and magnet cooldown line

NOTE: the distance from the bottom of the Annulus to the top of the reservoir is ~128” with helium having a density of 125g/l this gives a pressure head of 16” of H20 but the transducer is a 0-25” of water so the value of LL8670DP must take this (and the density of 4K gas helium) into account to give proper readings.

Future Sections

**Parking the magnet at ~80K**

The Solenoid parking can be done by flowing 80K helium that is cooled by LN2 through the magnet and its shield. The setup should be similar to the flow during the last stage of the 300K to 100K cooldown (section 1 above). The major difference between the solenoid and other JLab spectrometer magnets is that the radiation shields are not cooled by LN2 so a loss of helium supply will prevent 80K parking.

**Warm up to 300K**

Warm up will be done similar to cooldown in reverse

**APPENDIX 1 - PID Control Loops**

(Excel filename: Solenoid and DBX PID’s 5\_2\_17dk)

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**APPENDIX 2 - Specialty Variables and Limits**

(Excel filename: Solenoid and DBX PID’s 5\_2\_17dk)





Do we want to append any other info? Like the info from Renuka





