Cryogenics – The Basics

Lesson 3

D. Kashy

Lesson 3 - Objectives

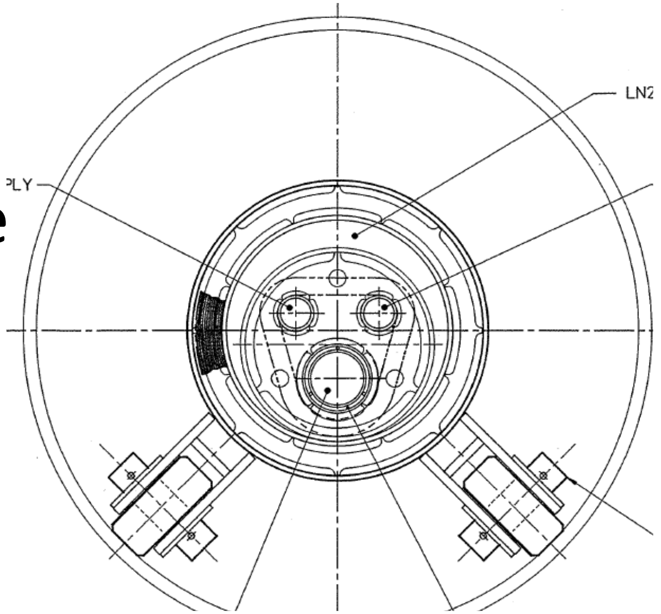
- Go through Hall B Cryogenic Hardware
  - Distribution Box (DBX)and ESMTL
  - TORUS – Helium and Nitrogen circuits
  - SOLENOID – Helium primary and shield circuits
  - 500 liter HELIUM BUFFER DEWAR
  - SACLAY CYROTARGET
- Discuss how PID control loop work
- Discuss PID tuning
- Look at a basic PID that controls the Torus Lead Reservoir Pressure

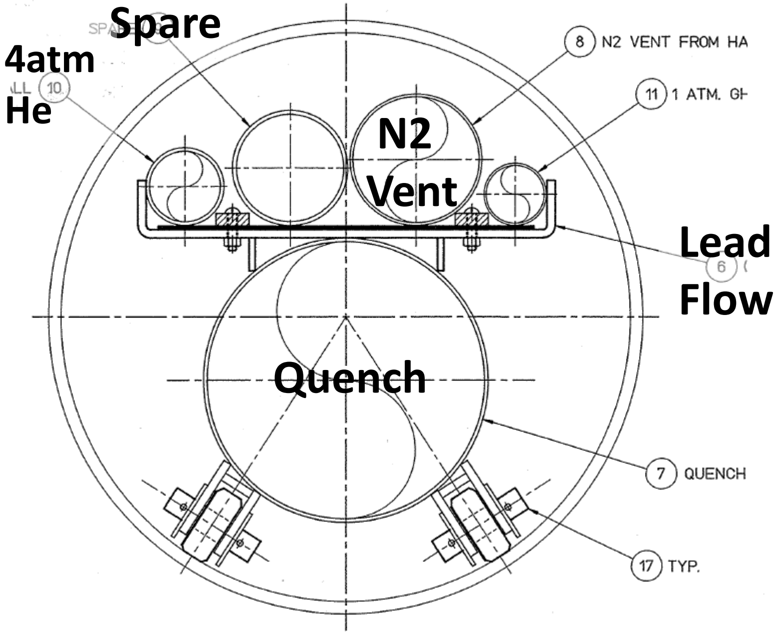
Lesson 2 – Review and Questions

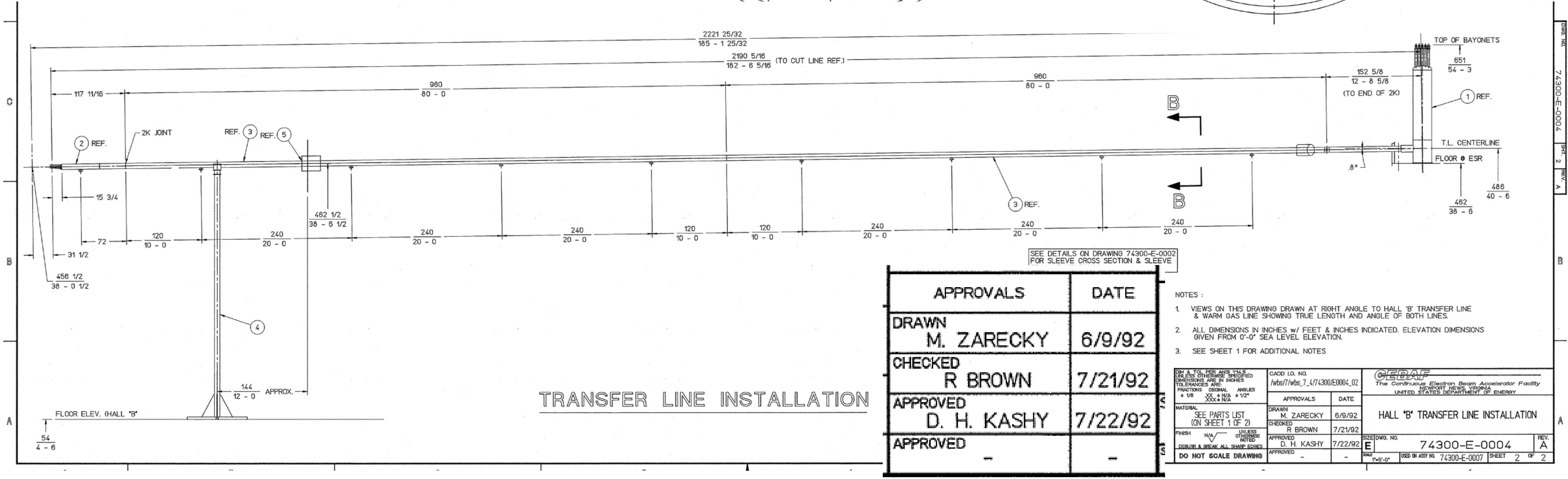
- Any questions from Lesson 2?
  - Followed the Atoms/Molecules from arrival on site on their trips through the cryogenic refrigeration plant
  - Learned a bit about the END STATION REFRIGERATOR (ESR)
  - Discussed Instrumentation Nomenclature and the CND
  - Learned a bit about expansion engines and a property called Entropy

TL and Warm Gas

- 185ft of TL at 0.8 degree slope
- Vacuum break in the Hall
- CVI POV's in Hall B and at ESR
- DBX welded to end of TL

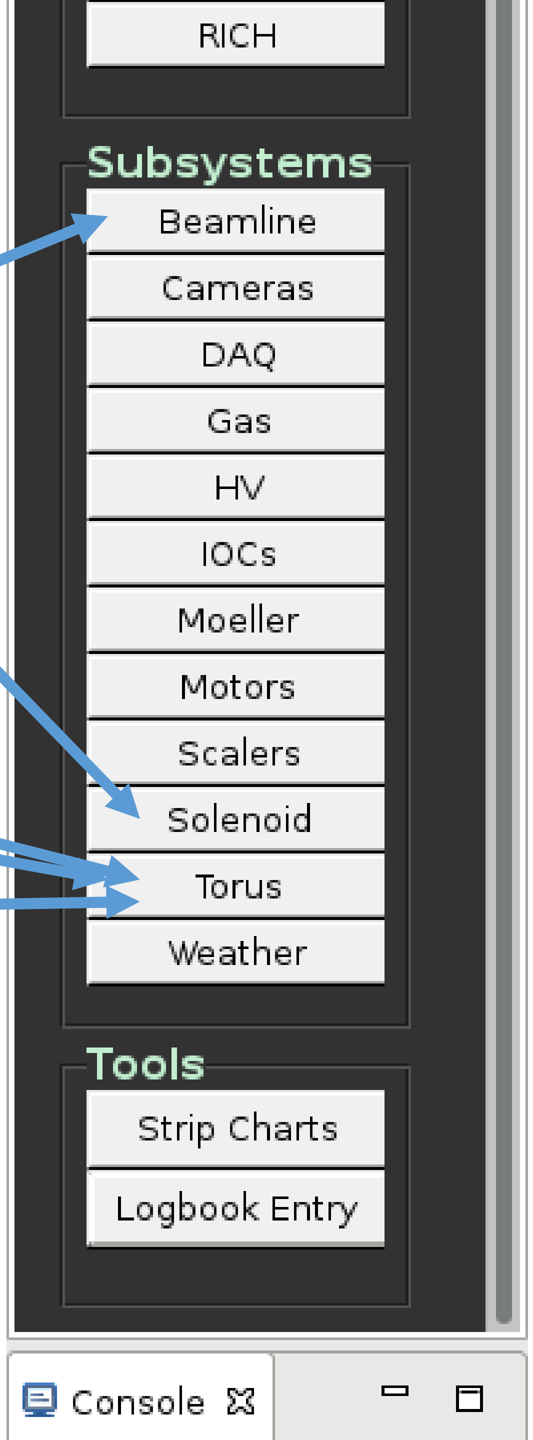


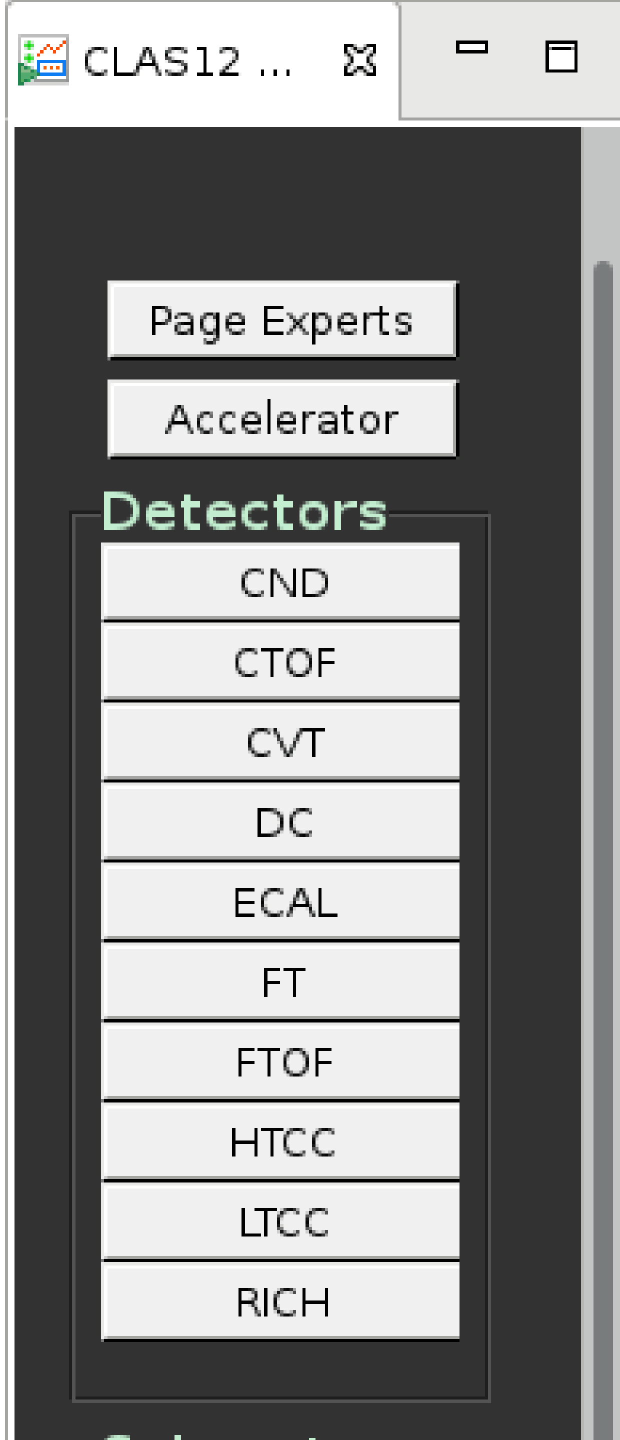




Hall B Main Menu

- Target is in Beamline
- Solenoid systems are in Solenoid
- DBX is in Torus
- Buffer Dewar is in Torus
- Torus systems are in Torus





Hall B DBX
(distribution box)

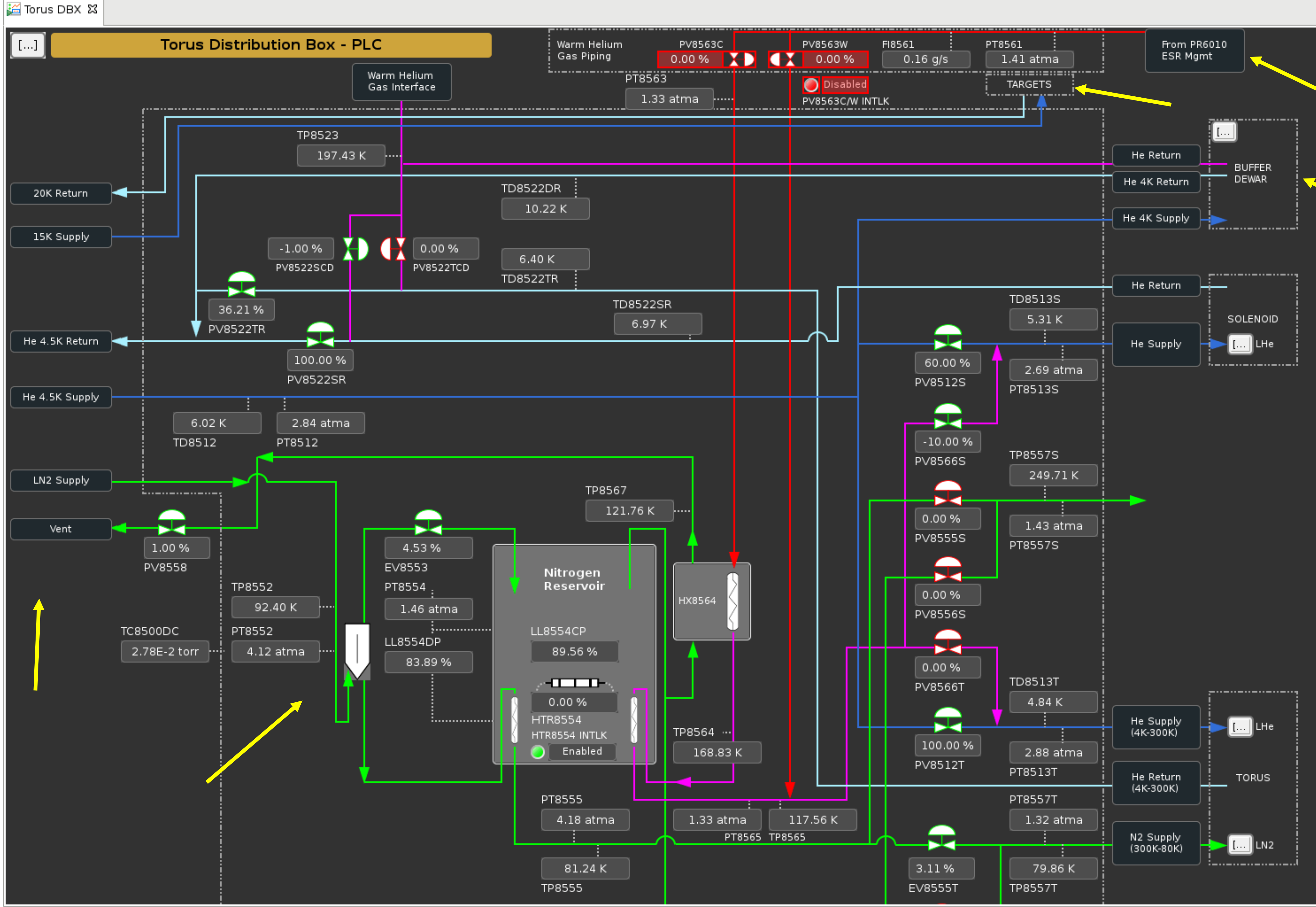
Bayonets for Warm Return and HP Targets

Bayonets for Torus

Bayonets for Solenoid and Dewar

Transfer Line and DBX

- DBX can create variable temperature gas to allow "gentle" cooldown
- Supply up to 4 different loads
- Has Cold and Warm returns
- LN2 used for Torus shields and for Magnet cooldown/warm up



CLAS12 - TORUS Magnet

Update – March 15, 2017 – JLab Team

The CLAS12 Toroid is based on six super-conducting coils around the beam line to produce a field primary in the azimuthal (f) direction. The choice of this configuration leads to an approximate toroidal field distribution around the beam axis. The Torus design was driven by the following physics requirements:

- Large acceptance for forward going particles (50% particle acceptance in detectors at 5 degrees from beam axis)
- Good momentum resolution
- 6 fold symmetry around the beam axis
- Large bore to allow passage of scattered primary beam

TECHNICAL PARAMETERS

PARAMETER	DESIGN VALUE
Magnet Type	Toroidal Field Geometry
Number of Coils	6
Coil structure	Double pancake potted in Aluminum Case
Warm bore ∅ (mm)	124
Total weight (Kg)	25,500
Number of turns per pancake	117
Number of turns per coil	234
Conductor	SSC outer dipole cable soldered in 20 mm x 2.5 mm Cu channel
Turn to Turn Insulation	0.003" E-Glass Tape ½ Lap
Nominal current (A)	3770
Ampere turns (-)	882,000
Peak Field (T)	3.58
Peak Field Location	Inner turn near warm bore adjacent to cooling tube
B-Symmetry	Yes
∫Bdl @ nominal current (Tm)	2.78 @ 5 degree , 0.54 @ 40 degree
Inductance (H)	2.00
Stored Energy (MJ)	14.2
Quench Protection/Dump Resistor	Hard wired quench detector / 0.124 Ω dump resistor
Coil Cooling	Conduction Cooled by SC Helium
Supply temperature (K)	4.6
Temperature margin (K)	Min 1.52 (@5.3 K) to Generation temperature 6.82
Heat Shield Cooling	LN2 Thermo-Siphon

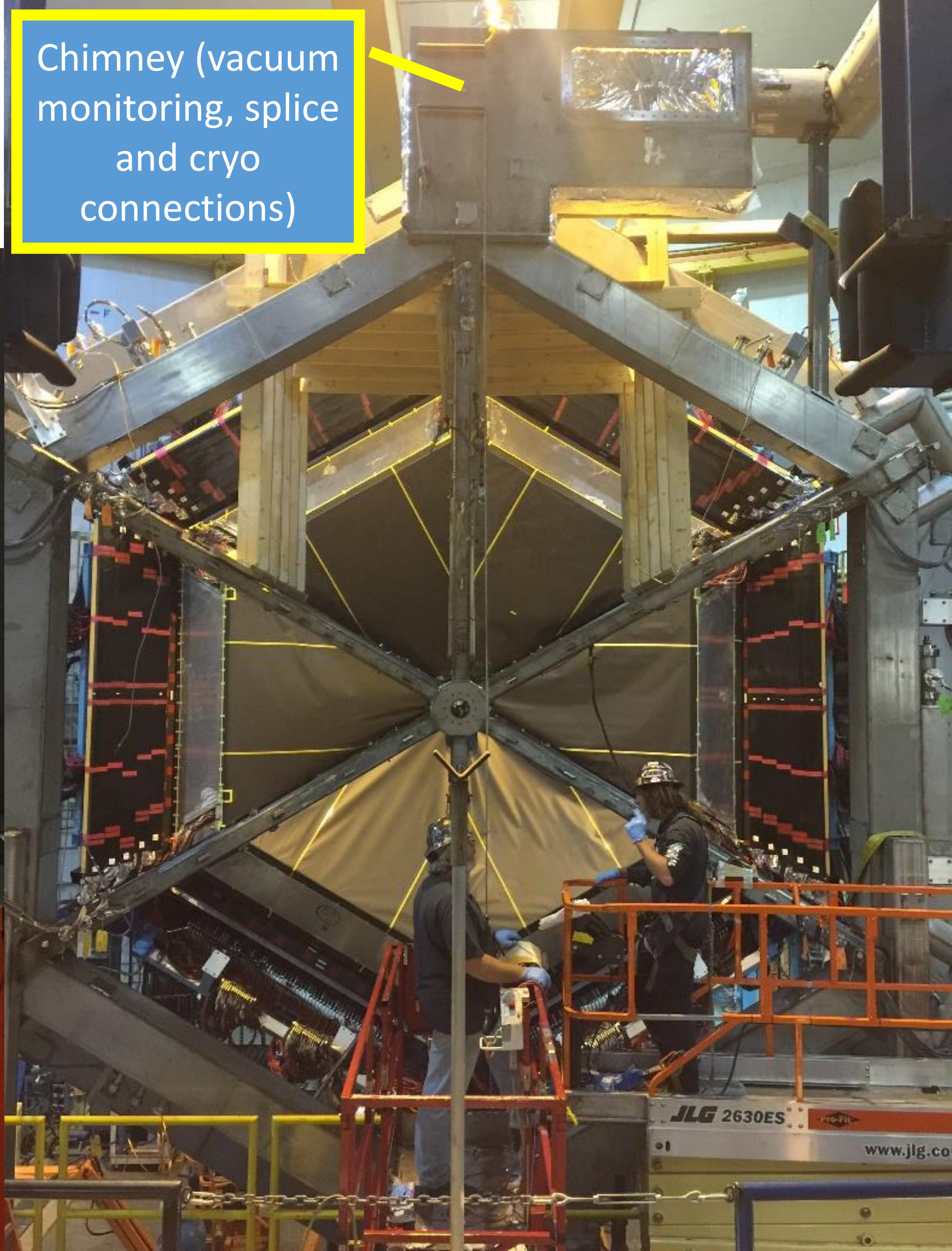
- **Construction Strategy:**
  - ❑ JLAB leads the design effort
  - ❑ JLAB procures the soldered conductor
  - ❑ FNAL manufacture 8 coils and pot them in the coil cases (CCMs)
  - ❑ JLAB will assemble each coil into cryostats in an on site factory
  - ❑ All 8 coils will be tested at 80K
  - ❑ The six coil torus will be assembled and tested as a magnet in HALL B

- **Significant dates**
  - ❑ August 1, 2013 - 7 conductor spools soldered
  - ❑ December 1, 2013 - Practice coil delivery to JLAB
  - ❑ January 2, 2014 - Prototype coil fabrication start
  - ❑ Oct 17, 2014 - Begin erection of the Torus assembly tooling in Hall B
  - ❑ Nov 1, 2014 - Complete coil fabrication process (Practice CCM001)
  - ❑ Nov, 2014 - First CCM delivered to JLab for Cryostating
  - ❑ February 6, 2015 - First coil delivered to Hall B
  - ❑ May 11, 2015 - 4th Coil installed on Installation Spit
  - ❑ June, 2015 - Last CCM delivery to JLAB
  - ❑ June, 2015 - 6th Coil installed on Torus
  - ❑ January, 2016 - Magnet Assembled and off the Assembly Spit
  - ❑ August 2016 - Cooldown Starts
  - ❑ September 2016 - Torus at 4 Kelvin
  - ❑ November 2016 - Torus commissioned and field mapped

Lets do some math

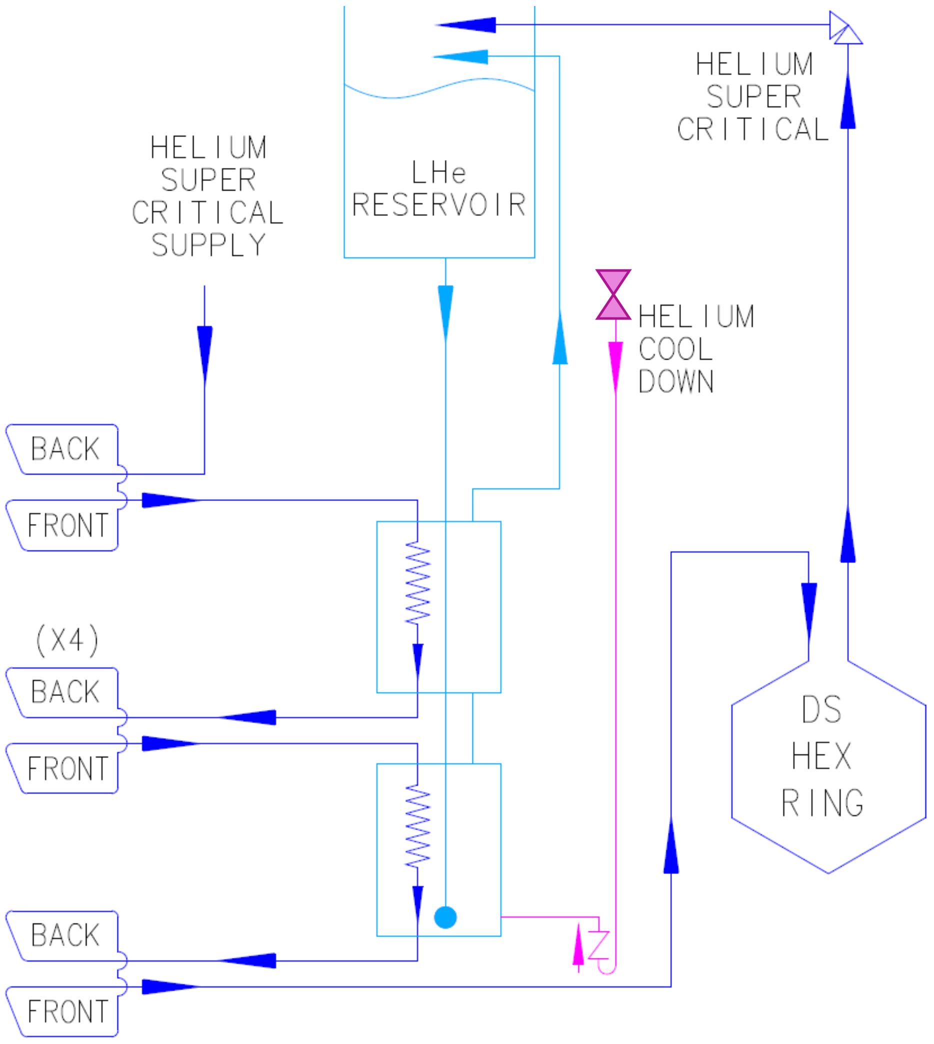
- Toyota Sequoia weight is ~6000 lbs: 6000lbs/2.2(lb/kg)= 2700kg
- Freeway speed is 75mph: 75mph*.447(m/s)/mph = 33.5m/s
- Kinetic Energy $KE=1/2*M*V^2$ = $1,515,037 kg*m^2/s^2$ = 1.5MJ
- So the Torus stored energy is more than 9 Sequoias going 75mph
- One Sequoia would have to go 230mph to get the same level of energy
- 14.2MJ = 6.8lb of TNT
- If/when we fast dump the Torus its average temperature goes to 34K

Torus during Assembly in Hall B



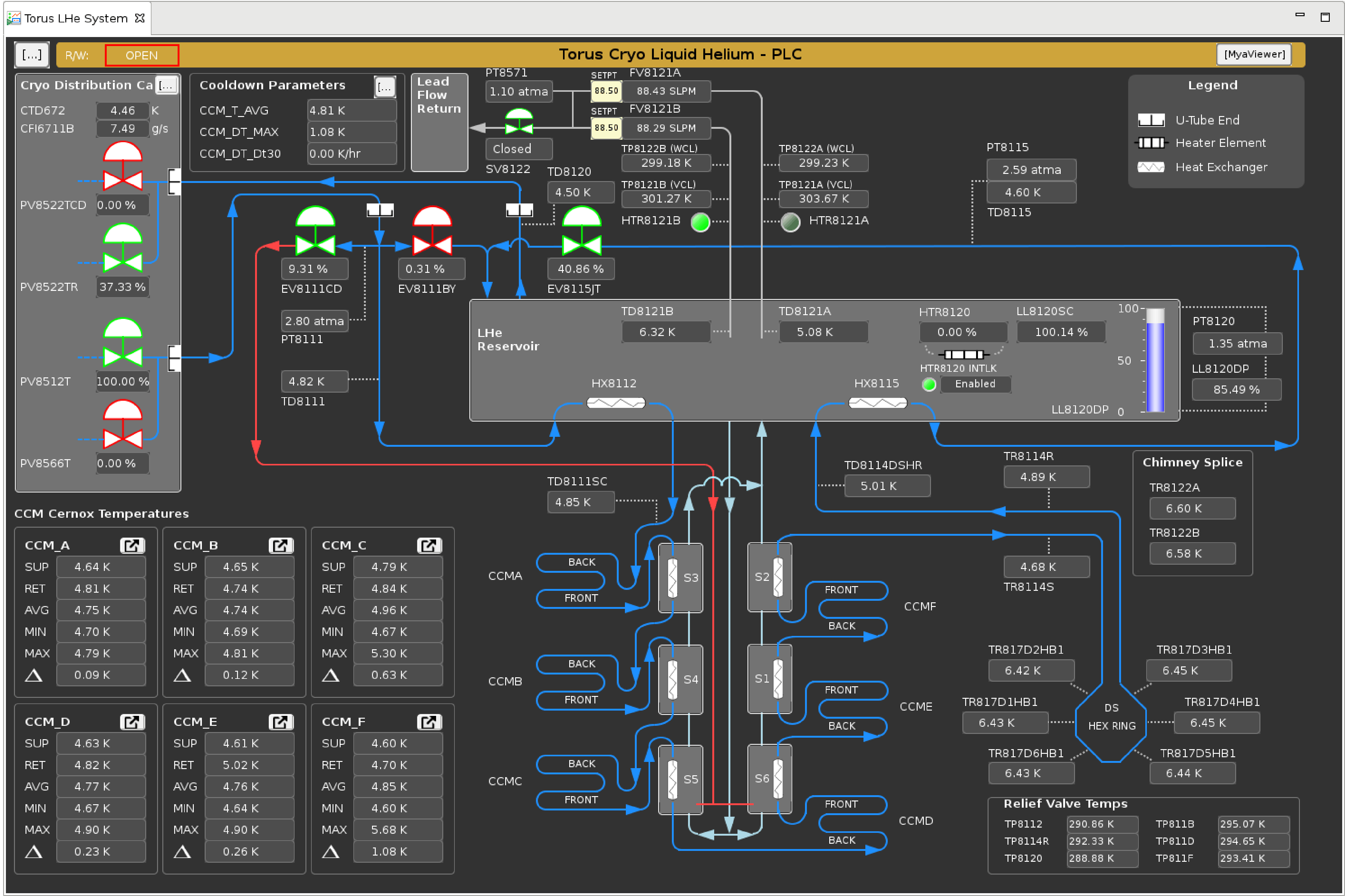
Simplified Torus Helium Schematic

- Recoolers located in US hex ring
- Recooler bottom fill (CD) line
- JT valve



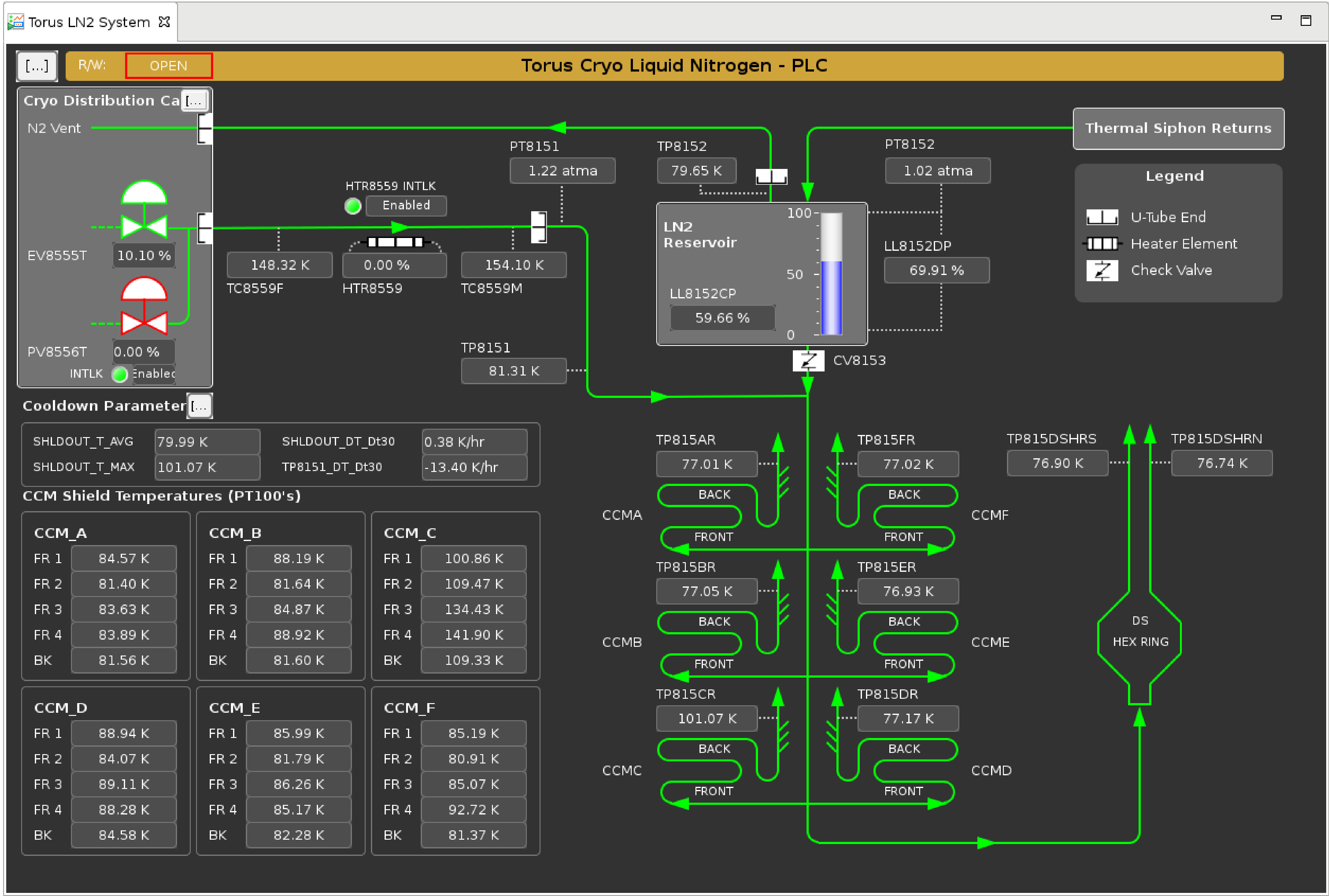
Hall B Torus - Helium

- Flow path for Helium
- CD Parameters
- LL Probes
- Relief Valve temperatures



Hall B Torus - LN2

- Themo-siphon cooling
- Flow path for Nitrogen
- CD Parameters
- LL Probes
- CCM C warm shield



CLAS12 –Solenoid Magnet

The CLAS12 Solenoid is a self-shielded (actively shielded) super-conducting magnet around the beam line to produce a field primary in the beam direction. It has been driven by the following physics requirements:

- Provide field for magnetic field for tracking of central particles
- Moeller electron shield
- Uniform field ($\Delta B/B < 10^{-4}$ in ϕ2.5x4 cm cylinder) for polarized target operation

Solenoid - TECHNICAL PARAMETERS

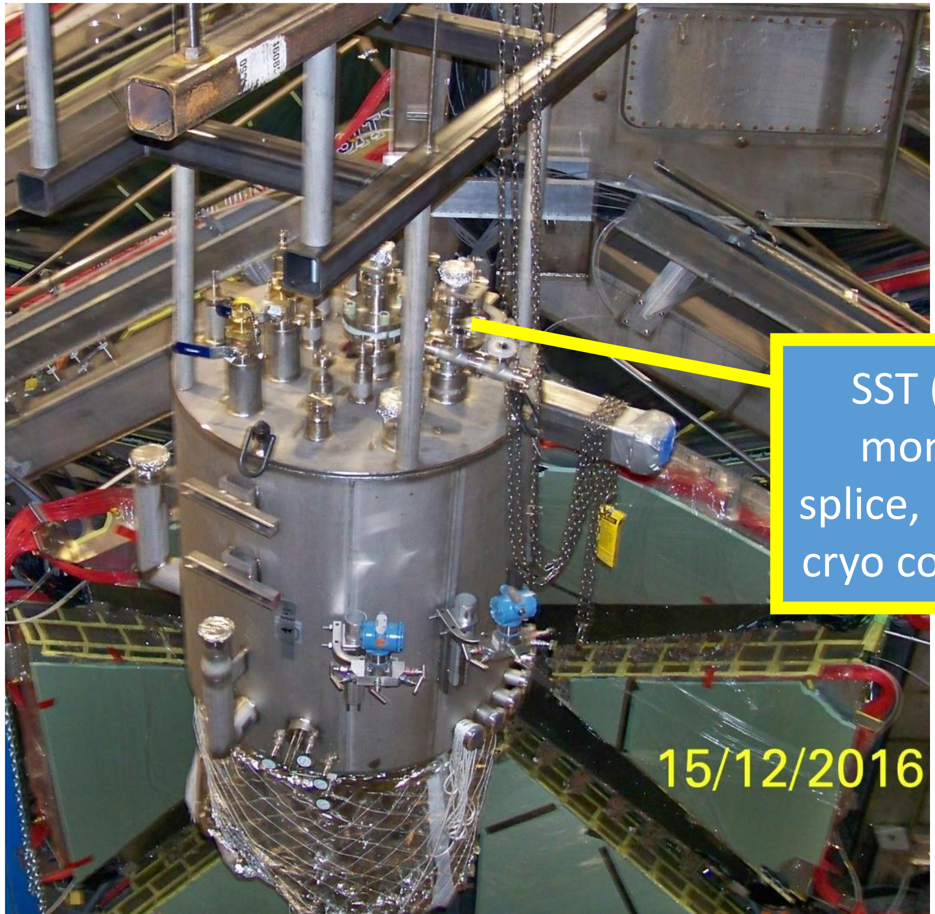
PARAMETER	**DESIGN VALUE**
Magnet Type	Solenoid
Number of Coils	5
Coil structure	Layer wound
Number of turns in main coils	3704 (2 x 840 + 2 x 1012)
Number of turns in shield coil	1392
S.C. cable	SSC 36 strands
Nominal current (A)	2416
Central field (T)	5.0
Peak Field (T)	6.56
Field homogeneity in ϕ2.5x4 cm cylinder	1 x 10^{-4}
Peak Field Location	Inner turn near warm
B-Symmetry	Yes
∫Bdl @ nominal current (T-m)	7.0
Inductance (H)	5.89
Stored Energy (MJ)	< 20 MJ
Warm bore ∅ (mm)	780
Total weight (KG)	18800
Cooling mode	Conduction cooled
Supply temperature (K)	4.2
Temperature margin	Min 1.5
Conductor Used	SSC outer dipole w 17 mmx2.5mm copper channel
Turn to Turn Insulation	0.004” Glass Tape ½ Lap

- **Construction strategy:**
  - Magnet has been designed and is being fabricated by Everson Tesla Inc. (ETI). ETI is responsible for electromagnetic, thermal, mechanical designs, and quench analysis. In addition, ETI shall provide all QA/QC associated with the manufacturing and assembly of the cryostat.
  - ETI will have an active role in start-up and commissioning the magnet at JLab
  - JLab responsibilities:
    - Provide the SSC cable soldered in Cu Stabilizer to ETI
    - Design the instrumentation, power and control system for the magnet
    - Shipping and delivery of the solenoid magnet to Hall B
    - Install and commission the magnet in Hall B
    - Design & fabrication of cryogenic supply/return system – SST (solenoid-service-tower) for the magnet

- **Significant Dates:**
  - Mar. 2014: FDR at ETI
  - Dec. 2014: MRR (Coil) at ETI
  - Jun. 2015: Inner Coils Wound & Potted
  - Dec 2015: MRR of Cold Mass Assembly
  - Jan. 2016: Intermediate Coils Wound & Potted
  - Jun. 2016: Shield Coil Wound & Potted
  - Dec. 2016: Cold Mass assembly complete
  - Apr. 2017: Factory testing
  - June 28 2017: Arrived to JLab
  - Sept 30, 2017: Magnet cooled and powered

Solenoid Assembly in Hall B

Arrived on lowboy trailer

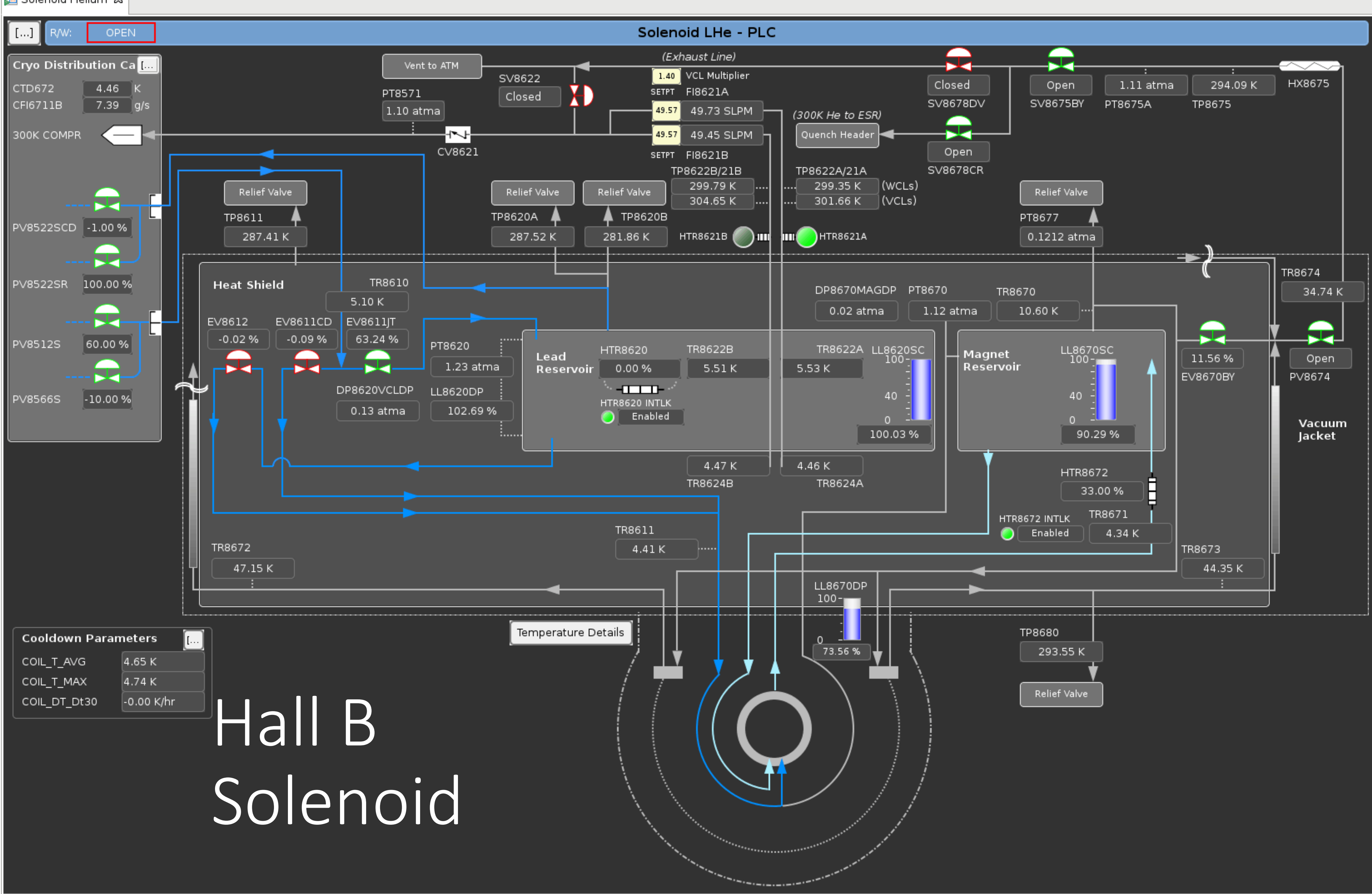


SST (vacuum monitoring, splice, power, and cryo connections)

Crows Nest for safe access to SST

Hall B Solenoid Helium

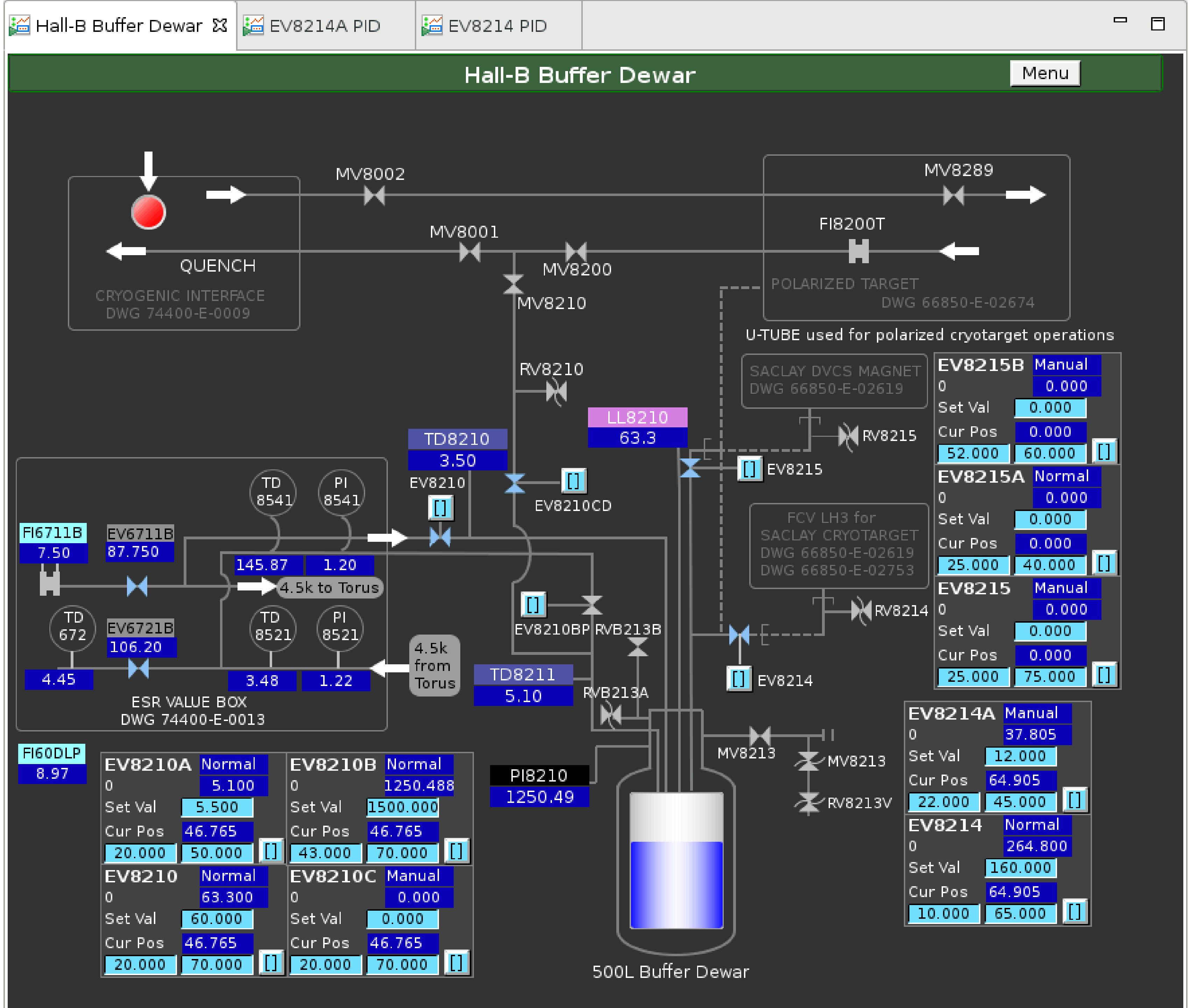
- Flow path for Helium
- CD Parameters
- LL Probes
- Leaky CD valve



Hall B Solenoid

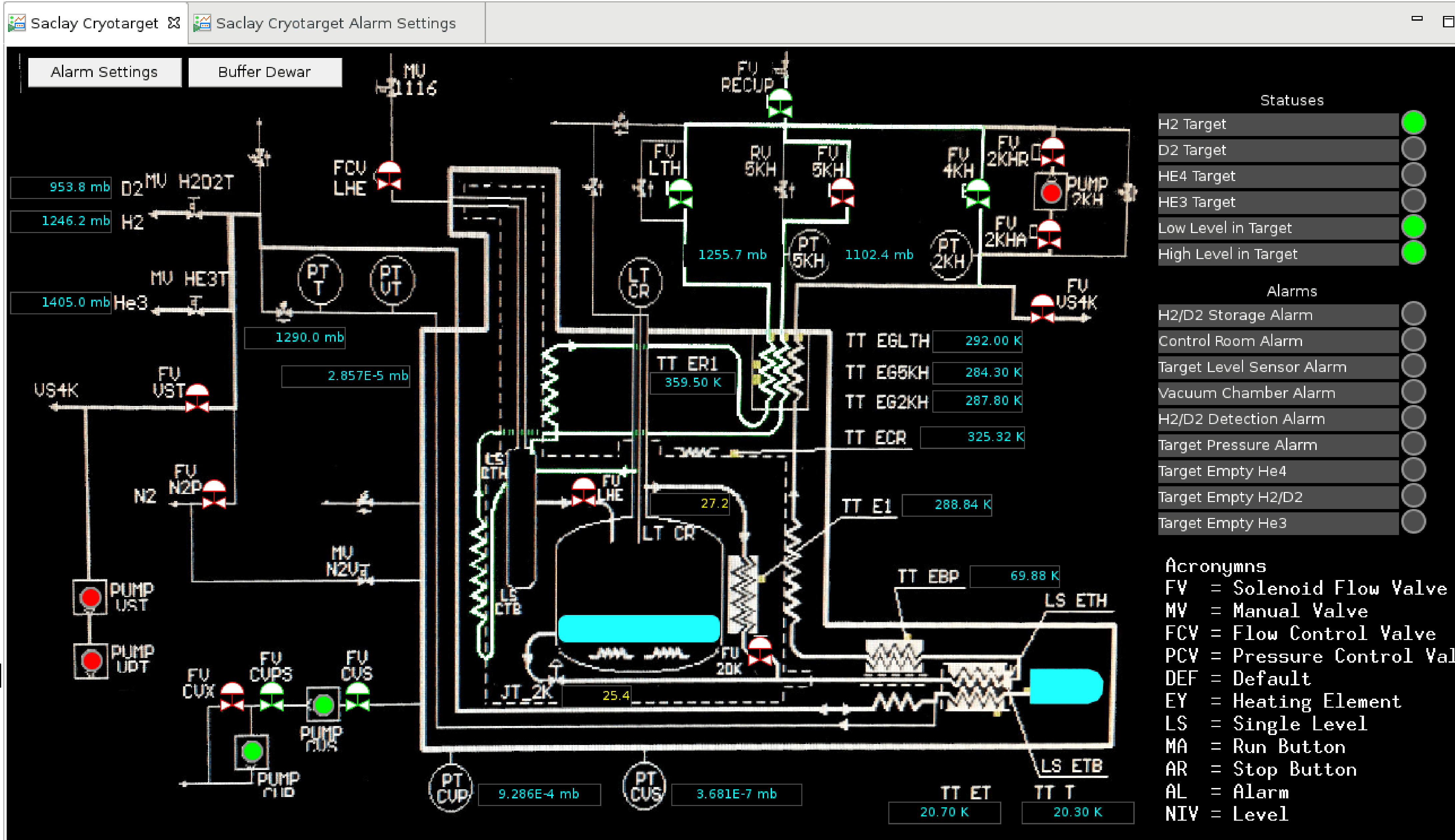
Hall B Buffer Dewar

- Flow path for Helium
- Errors in this graphic – Flow is not on the 15K/20K circuit
- Back pressure control
- Helium withdrawal



Hall B Cryotarget

- Flow path for Helium
- Target gasses and modes
  - H2, D2, He4, He3
- LL Probe
- Cryogenic load ~0.3g/s liquefaction



Control loops - PID’s

- PID stands for Proportional, Integral and Differential control
- You yourself are pretty good PID at PID type control
  - Say you want to fill your coffee cup. You follow a set of steps:
  - First you start to pour slowly to be sure that you don’t miss the cup and that it does not splash
  - Then you pour faster to get the cup full
  - Then as the cup approaches its ideal level you slow then stop the pouring
  - Each of these steps require looking at a PV (amount of splash, amount of spill, and level) and then making adjustments to the pot location and angle

PID Loop Control

- Loops are used to control what are called a Process Variable
  - Pressure
  - Temperatures
  - Liquid levels
- They use signals to adjust devices such as:
  - Valve positions
  - Heater power
  - Possibly pump speed (some target systems…)
- They can also operate in Manual Mode

Basic PID control loop

Device to be controlled

Control Mode
(Manual or Normal)

Input Signal (Process Variable)

Process Variable Setpoint
(desired value)

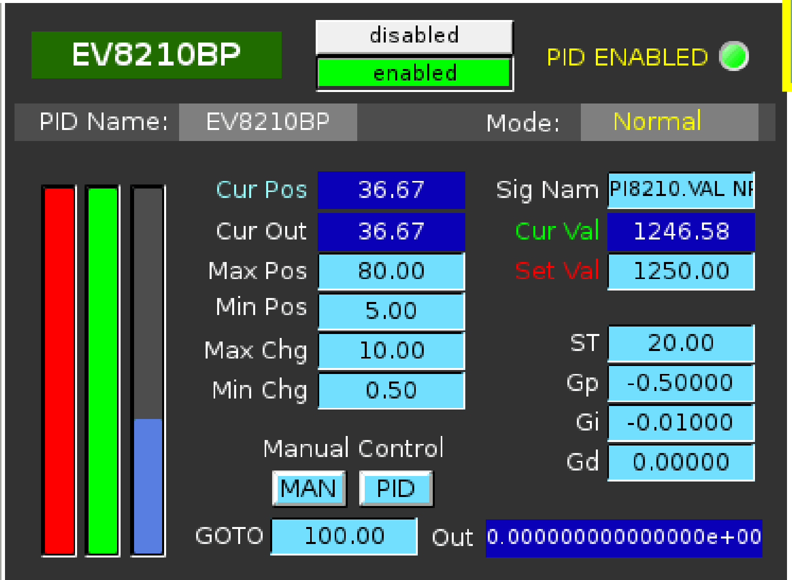
Process Variable Measured
(current value)

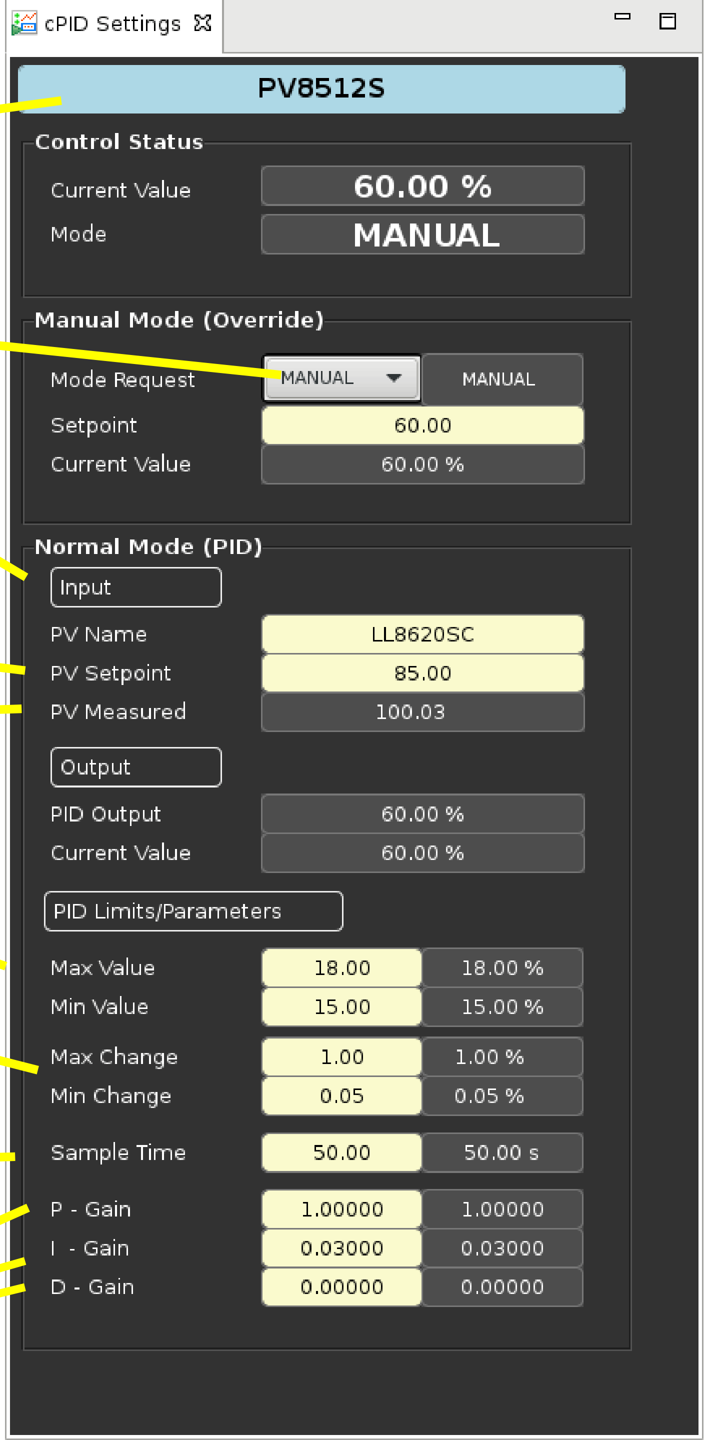
Min and Max value
(not necessarily full range)

Min and Max Change
(per Sample time)

Sample Time

Gains





PID Gains

- Gains can be positive or negative
- All gains should have the same sign (+ or -) or be zero
- Depending on the effect desired one may want a valve to close or open to effect the process variable being controlled
- Examples
  - One could use a valve to control the pressure in a reservoir
    - If it is a supply valve then it must open to fill and pressurize the volume
    - If it is a return valve then it must close to pressurize the volume

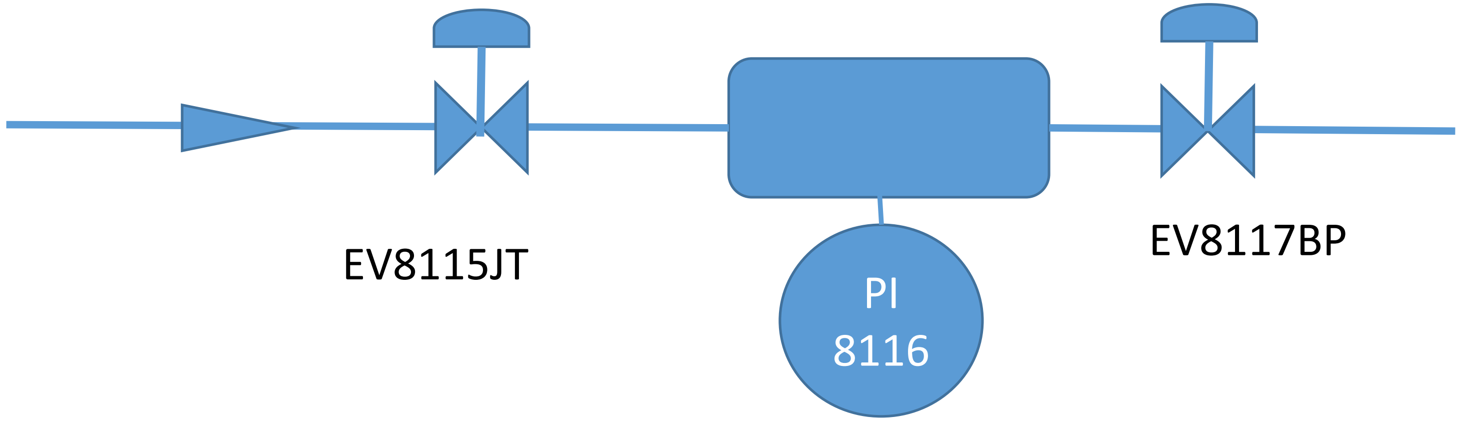
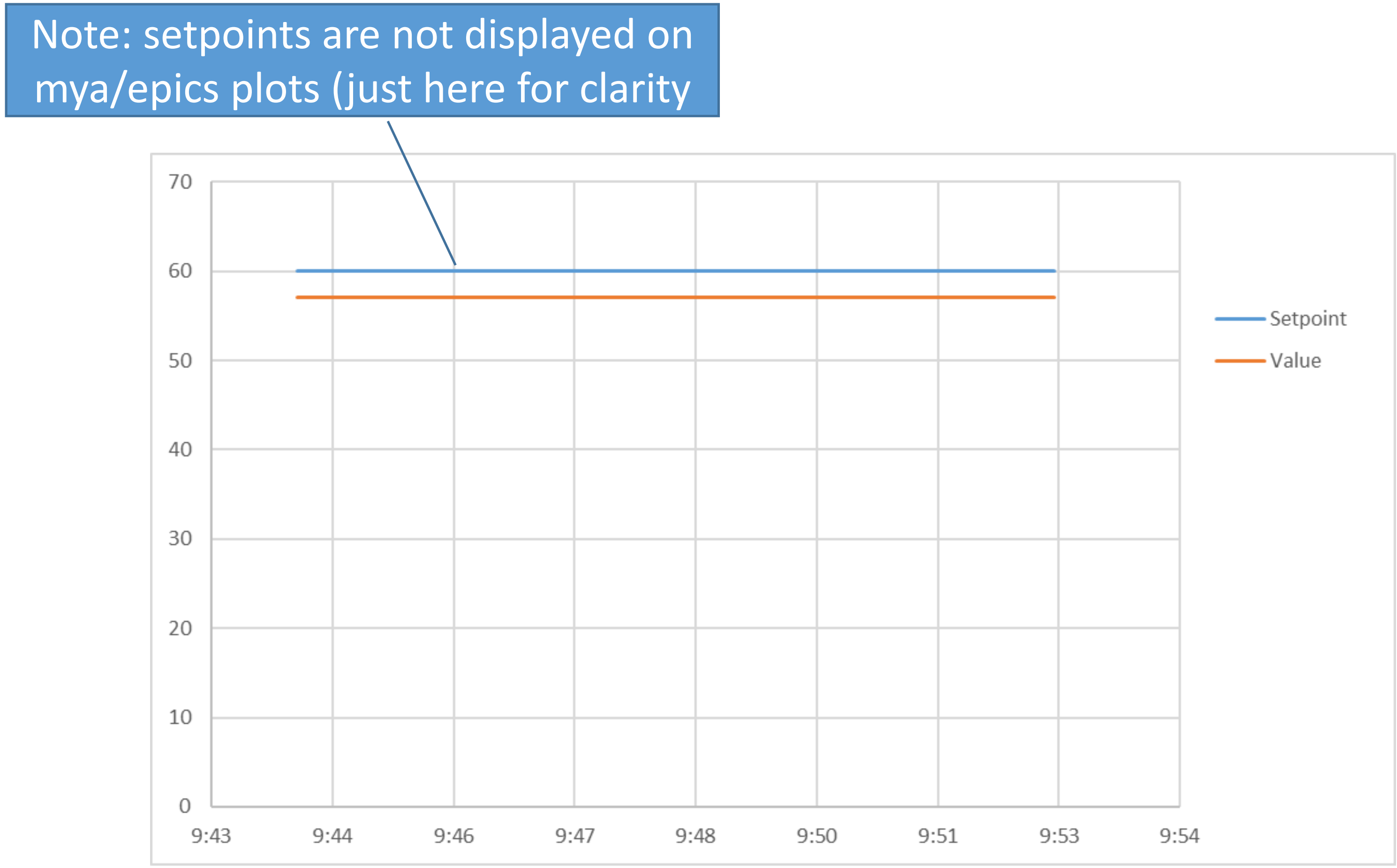


Chart with setpoint and offset

- Example:
- Helium pressure set to be 60 psig but it is at 57 psig, Feeding with a JT valve
- Need to open the valve
- PV is low and not changing



So which gain corrects offsets?

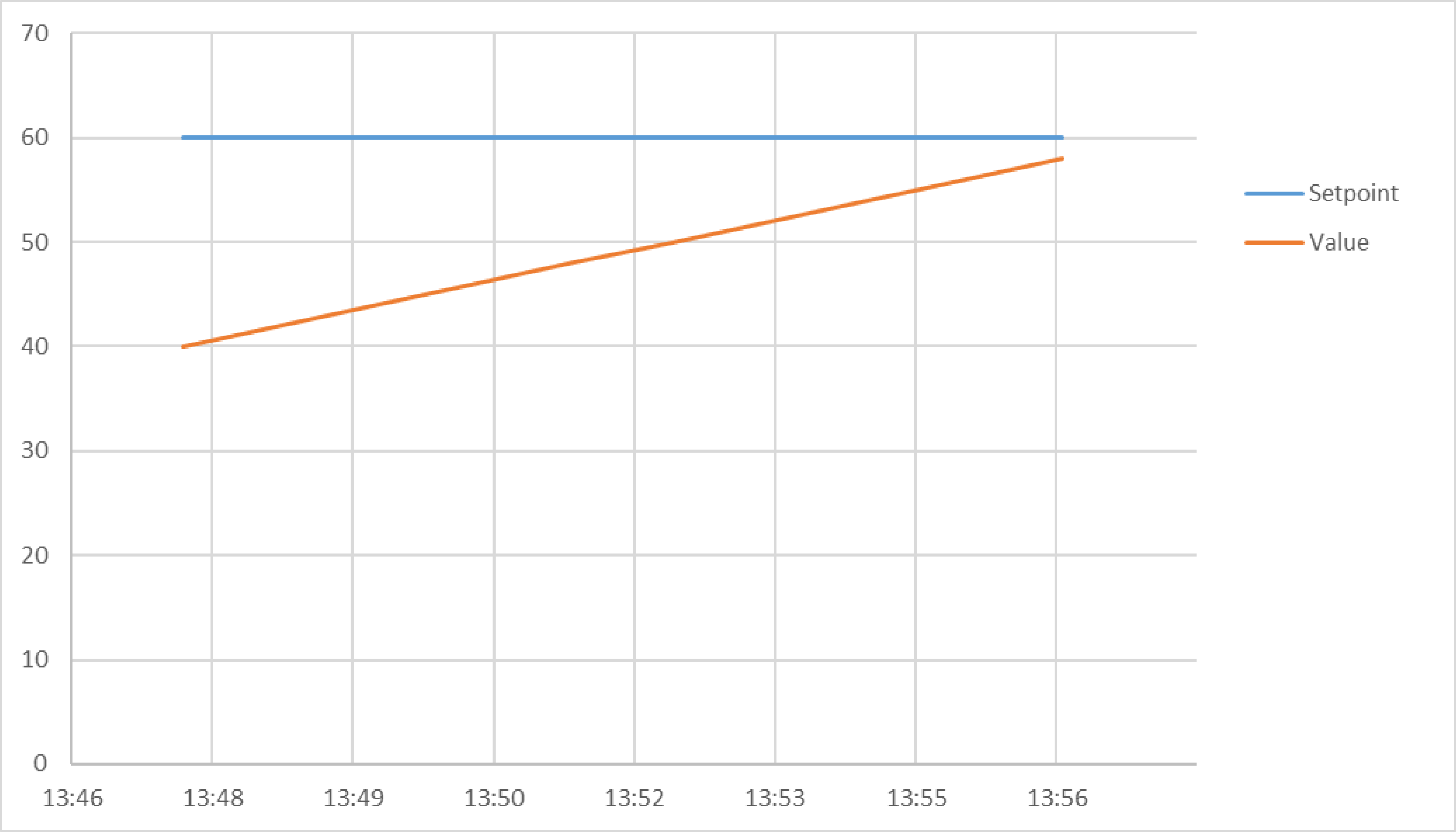
- Options are P-Gain, I-Gain, D-Gain
- To correct offsets one needs the I-Gain
  - This type gain looks at the signal and determines a change needed to make the offset get smaller.
  - The PID calculates a change
  - It compares the calculated change to the min and max change allowed
    - If the calculated change is less than the min change then no change is made (you may want a bigger (I-gain)
    - If the calculated change is bigger than the max change then the max change would be used
  - The device to be controlled is changed after a sample time has passed. New calculations are performed depending on the comparison between PV actual value and its setpoint

What sign should we select for the “I” gain?

- Sticking with the same case
- e = PV – SP (error is readback of PV – setpoint of PV)
- If the value of the error is positive then the signal is too high already and if it is negative then the signal is too low (our present case)
- To get more to flow into the system we need the supply valve to open when the PV readback is less than the setpoint
- This requires positive gains: It is called “reverse acting”
- Negative gains are for “direct acting”

Chart with sloped line

- Here the PV signal is approaching the setpoint, but it is still below.
- I-gain will tell the controller to make a correction that may not be helpful
- P-gain can counter act the I-gain to get the system not to overshoot



P-gain : Proportional Gain

- Most on-line literature says that P-gain is for offsets, but here at JLab I have always found that it works on the slope of the line to counteract the “offset I-gain”
- For more on programing PID’s see: https://epics.anl.gov/EpicsDocumentation/AppDevManuals/RecordRef/Recordref-16.html#HEADING16-0

D-gain – Derivative Gain

- It is supposed to be useful for large systems with lots of “inertia”.
- It works on rate of change of an error (something like second derivative)
- Here at JLab, I have not found it useful (EVER!), but it could be…
- I think there are now a few PID loops used by the cryogenics group that have non zero D-gains

Other important inputs on PID loops

- ST – Sample time, must be appropriate for the system.
  - Too fast and the device will make changes before the system reacts
  - Too slow and the system will not be stable and may cause it to go beyond normal operating range
- Min and Max Change
  - These set limits of how much change the PID gains can effect the output of the loop on each sample time update
  - Min change is normally used on electric valves to keep them from making very small changes and wearing out part of the drive motor by oscillating in one small portion of the winding (0.2 is usually fine for min change on JLab EV’s)
  - Max change can help especially in very noisey signals or random spikes to assure the system does not cause a huge output request and can save a system from quickly dumping something like the ESR…

Other important inputs on PID loops (continued)

- Min Value- important if you don’t want a full shutoff
  - Maybe if a line needs to have a gas source to keep it clean or cold
- Max Value- important to keep from putting in too much flow or heater power

Not all Control Devices work the same

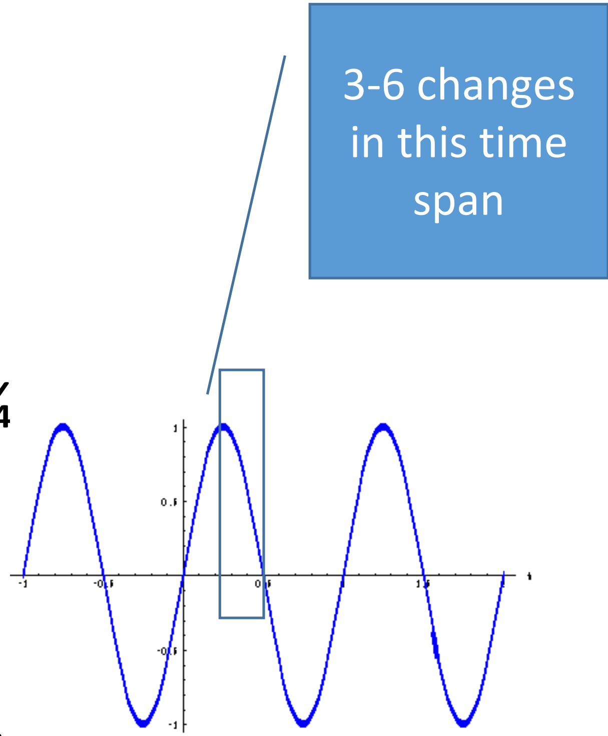
- JLab EV’s have LVDT’s (linear variable differential transformer’s) that give an actual position.
  - The EV gets a 24V pulse for a certain amount of time that is determined by the PID
- Most PV’s at JLab do not have LVDT’s so the PID is programmed to give a certain amount of electrical signal that then is fed into the actuator which has an I to P transducer and air pressure is used to force the valve to its position (against a spring)
- Electric Heaters (at JLab) also don’t have a “readback” and the PID just sends a % of full power request

Setting Gains – Tuning PID loops

- Proper choice of input variable is critical: one must choose a “dependent” variable
- Tuning is somewhat a trial and error exercise
- Experience and copying other PID’s can help get to a set that works well for large ranges of inputs quickly
- Once a set of gains is picked they need to be tested
  - Changing the setpoint is one possible way to perform tests
- Plotting parameters is very useful in tuning PID loops
  - PV (input variable)
  - Control Parameter position (usually like EV8115JT.ORBV)
  - Also at time especially with EV’s one can plot the requested value EV8115JT.OVAL)
  - Other things like flow rates of flow streams, temperatures in the process line, and pressures in the process line

Setting Gains – Rules of Thumb

- Each system has its own frequency response
  - A 500 liter dewar will not see a very quick level rise while a small piping system can see its pressure or temperature change quickly
- One would like to see ~3-6 changes of the PID output every ¼ cycle of a "sinusoidal" oscillation this helps set the sample time
- The ratio of the P-gain/(ST*I-gain) should be between 3 and 10 in most to cases (most of the time 3 is perfect, but could be up 20 but not often this high)
- Gains should be small enough to not request max changes on each sample time



PID Parameter Tracking

PID Group:	Phase of Operation:
10-SH1	4K Operation of Torus

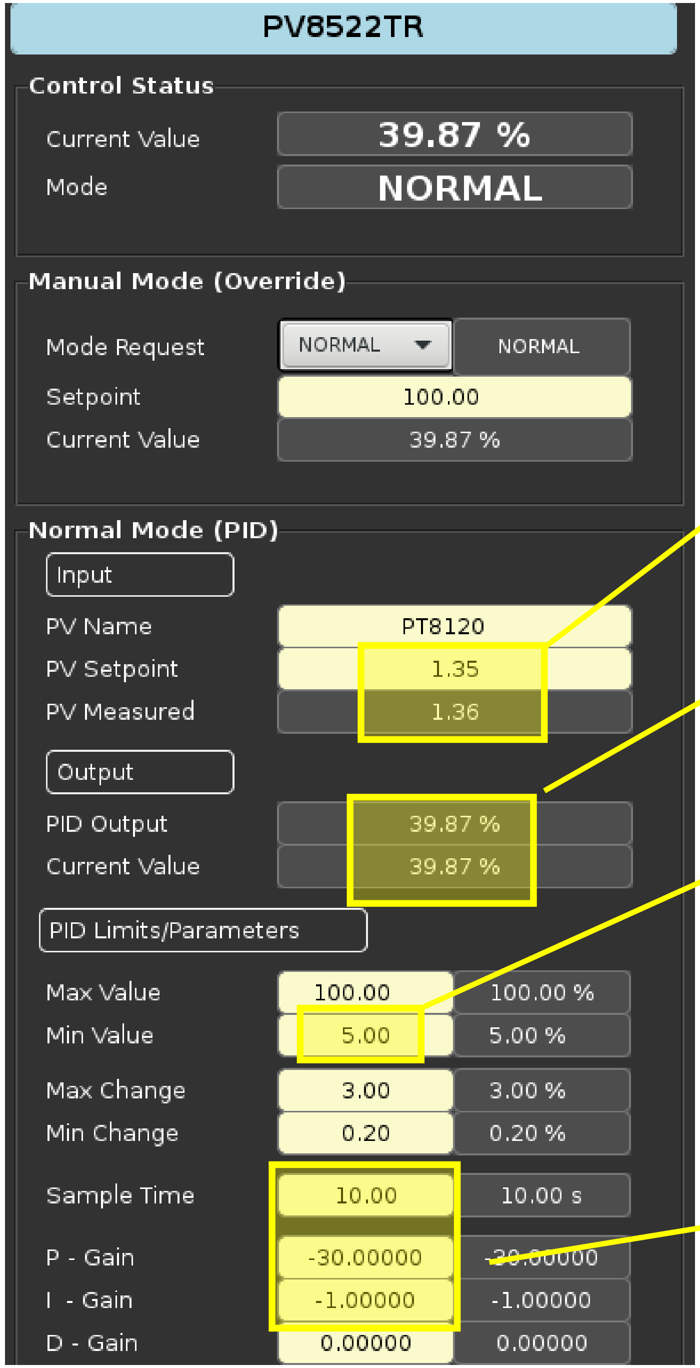
Device to be controlled	Description	Mode	Manual Position	Input	Set val	Reverse or Direct or interlock	Max Pos	Min Pos	Max Chg	Min Chg	Sample Time (sec)	Kp	Ki	Kd	Gain Ratio Kp/(Ki*ST) (typ~3)	Date PID Verified to work	Verifying Persons Initials	Comments
CEV6721B	4K Return Valve at ESR to Hall B	Manual	100															
CEV6711B	4K Supply Valve at ESR to Hall B	Manual	100															
PV8522TR	Torus Cold Return Valve	Normal	-	PT8120	1.35	Direct	100	5	3	0.2	10	-30	-1	0	3.00	9/20/2017	DHK	This valve in the DBX controls the pressure in "1.2 atm" helium reservoir tank in the Torus The lower the pressure the colder the coils, but the pressure must be high enough to get enough VCL flow
PV8522TCD	Torus Cooldown Return to Vaporizer	Manual	0	PT8120	1.48	-	100	0	2	0	6	-20	-1	0	3.33	9/20/2017	DHK	This valve is open to keep the return line positive pressure
PV8512T	4K Supply valve to Torus	Manual	100	-	-	-	-	-	-	-	-	-	-	-		9/26/2016	DHK	
EV8115JT	Torus JT valve	Normal	-	LL8120DP	75	Reverse	From PID	From PID	3	0.2	50	5	0.02	0	5.00	1/10/2018	DHK	
EV8115JT_Min	Torus JT valve	Manual	410	-	-		-	-	-	-	-	-	-	-		9/26/2016	DHK	
EV8115JT_Max	Torus JT valve	Manual	65	PT8115	2.5	Direct	50	43	1	0.2	50	-20	-0.1	0	4.00	9/20/2017	DHK	

CAUTION

- Changing PID controls can be risky and dangerous to your system and to other systems too.
- If you don’t feel a bit nervous about making a change then you probably should not be making a change!
- One must think very far upstream and downstream along the system to determine what impact the controls will have on other things. It is not always obvious.
  - One might think that opening a valve will supply more flow, but if there is another valve upstream that limits the flow then opening the downstream one could just cause the upstream valve to throttle
  - Warm gas from one load may mix into a flow path and effect the supply temperature or the pressure drop in a system, and of course the total heat load.
- So knowledge of the entire system is important before making any changes, communication between groups can help avoid issues
- ***Use the mailing list esr-users@jlab.org*** when making adjustments that could effect other ESR users or the ESR

One example PID from the Torus

(this is a back pressure vlave)

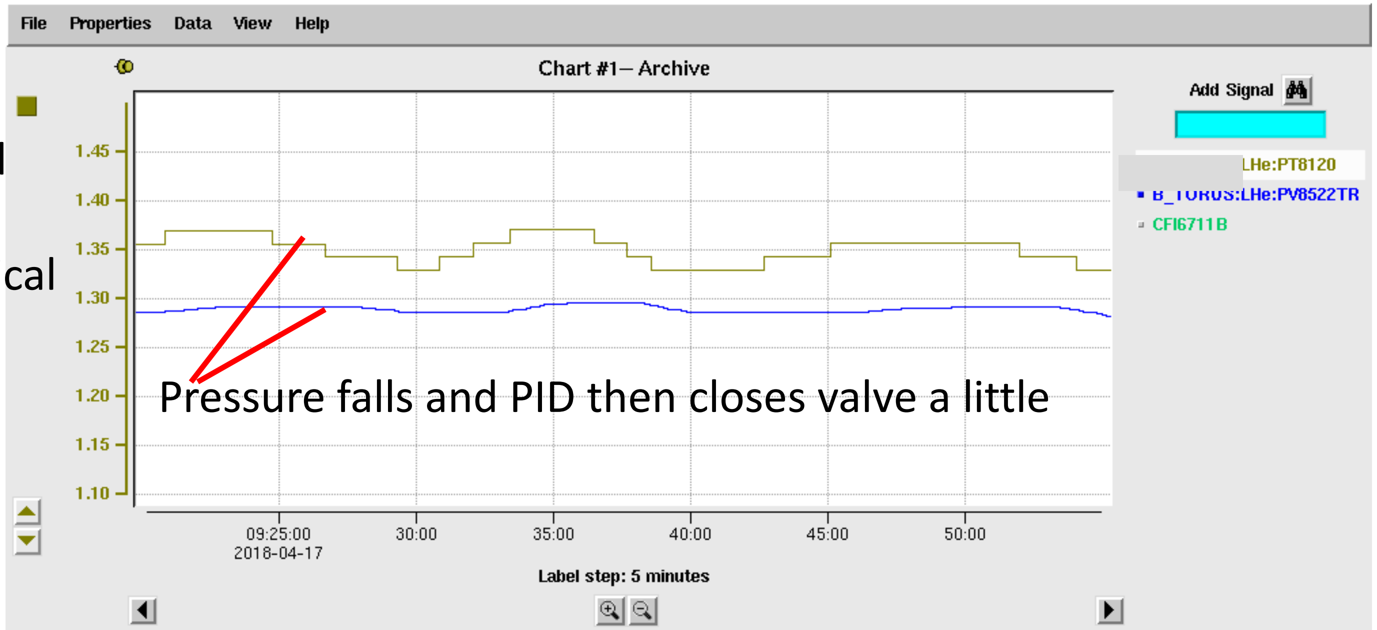


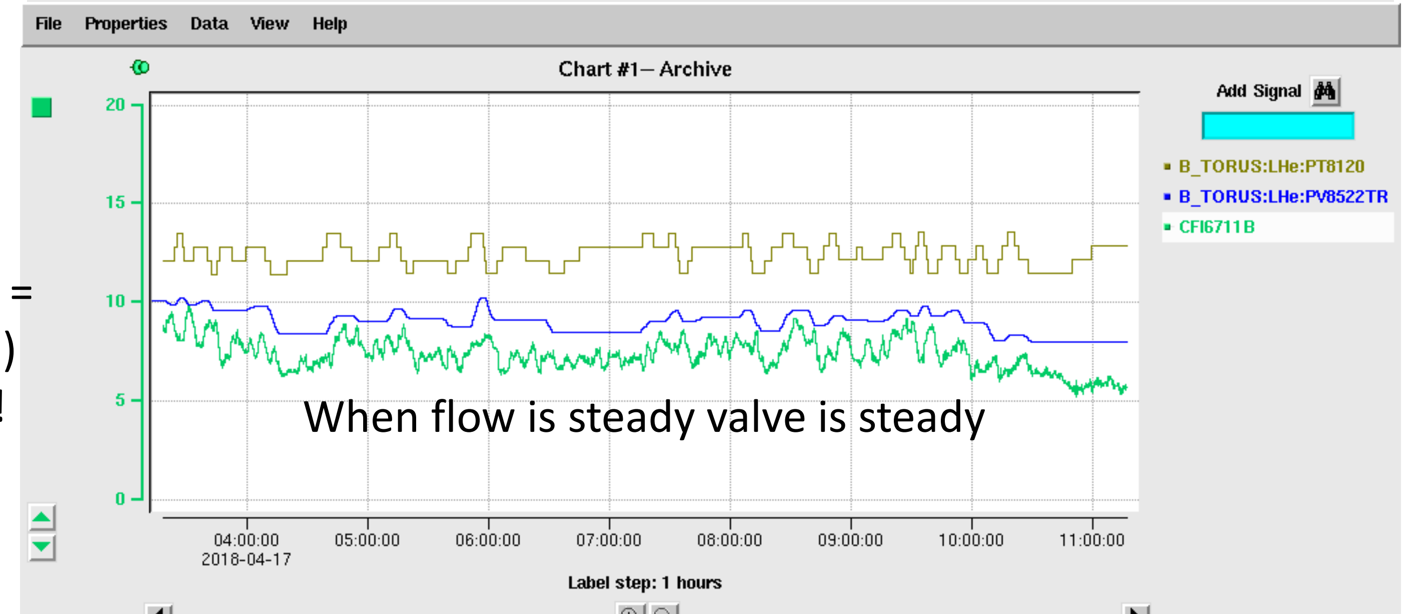
Setpoint and Measured nearly identical

No LVDT so Output and Position match

Min position always allows flow

Gain Ratio = -30/(10x-1) =3.0 good!





That’s it for Today

- Next Lessons:
  - More on Hall B PID control for steady state operation
  - Cascaded PID’s
  - Effect of Heat load and more
  - Hardware
    - What is a bayonet and why do we need them?
    - What kinds of valves are used in cryogenics?
    - Relief valve or rupture disc, which should I choose?
  - Thermal Contraction of materials
  - Thermal Conductivity

Questions?

Thanks for listening