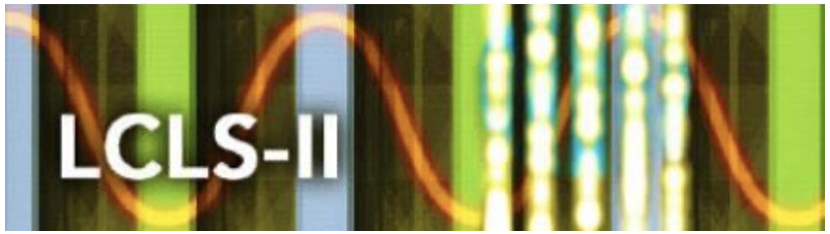


LCLS-II

LCLS-II Cryogenic System Automation

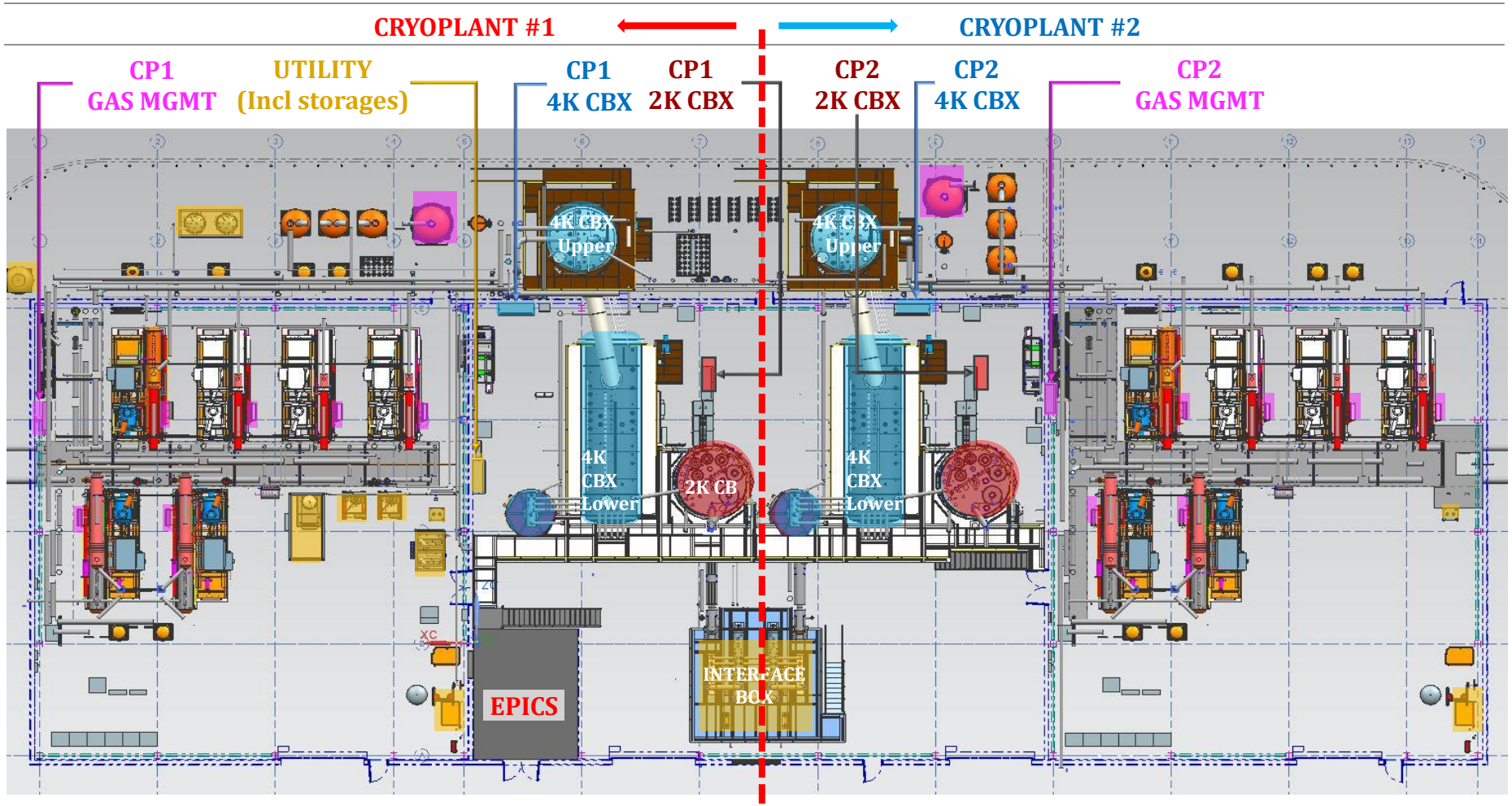
Author: Swapnil SHRISHRIMAL
LCLS-II Cryogenic Process-Control Engineer

Presenter: Dayne ROBINSON
LCLS-II Cryogenic Electrical-Instrumentation Engineer

CEC-ICMC23

Cryogenic Control System Overview

- Total PLCs: 22 [Allen Bradley ControlLogix Controllers]
- Total I/O: ~ 6,000 instruments [Cryoplant + Cryomodule + Cryogenic Distribution System (CDS)]



PLC by Sub-systems:

UTILITIES
- Utility: 1

CRYOPLANT #1
- Compressor Station: 7
- 4K Cold Box: 1
- 2K Cold Box: 1
- LINAC & CDS: 2

CRYOPLANT #2
- Compressor Station: 7
- 4K Cold Box: 1
- 2K Cold Box: 1
- LINAC & CDS: 1

Control System Requirements

- **Operation**
  - 365 days /year uninterrupted operation.
  - 24/7 Staff on site.

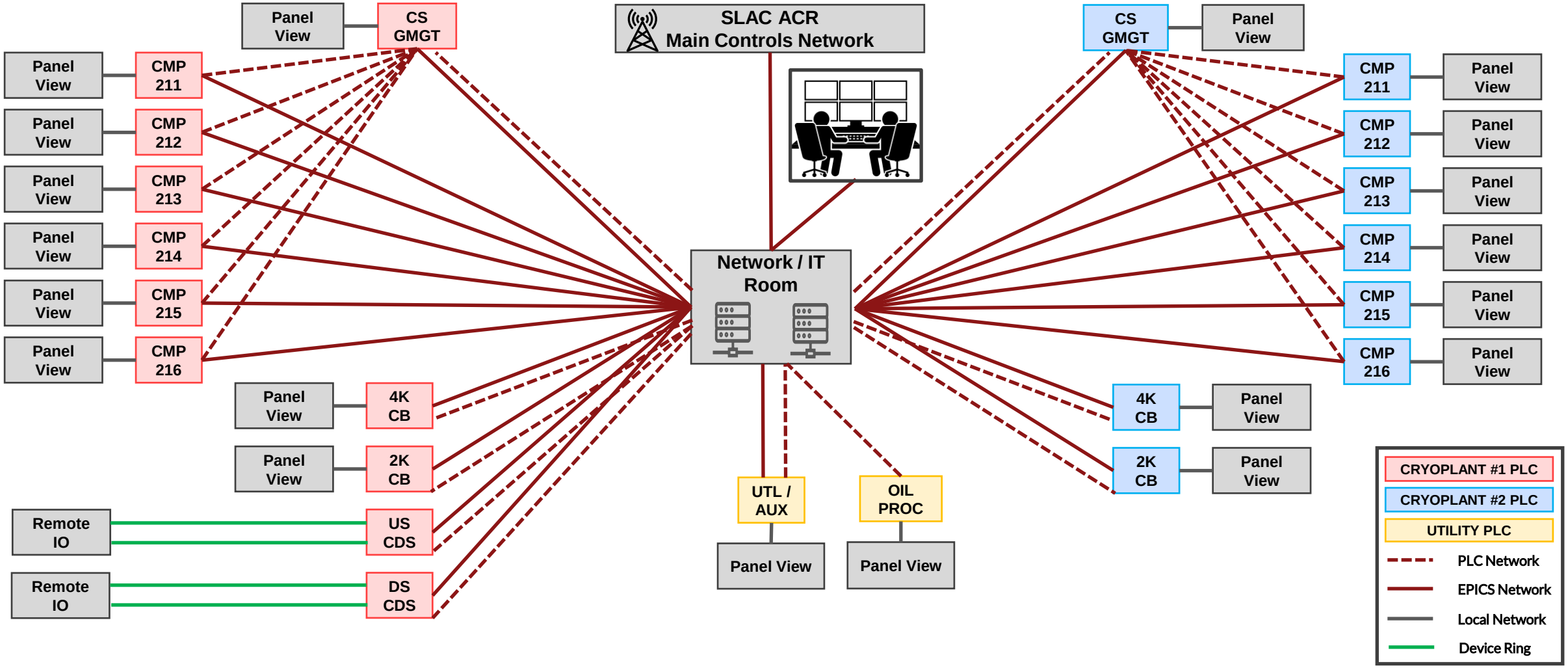
- **Automation**
  - Maximized automation – Minimum operator intervention.
  - Well documented automation: Functional Analysis to Code Traceability.

- **Equipment Protection**

  Three layers of equipment protections are used:
  - **Alarms**: Inform operators of Off-Nominal Conditions.
  - **Interlocks**: Take pre-emptive actions: Supersede Operator or other PLC Command.
  - **Trips:** Return System to Fail condition [Fail Safe].

Network Architecture

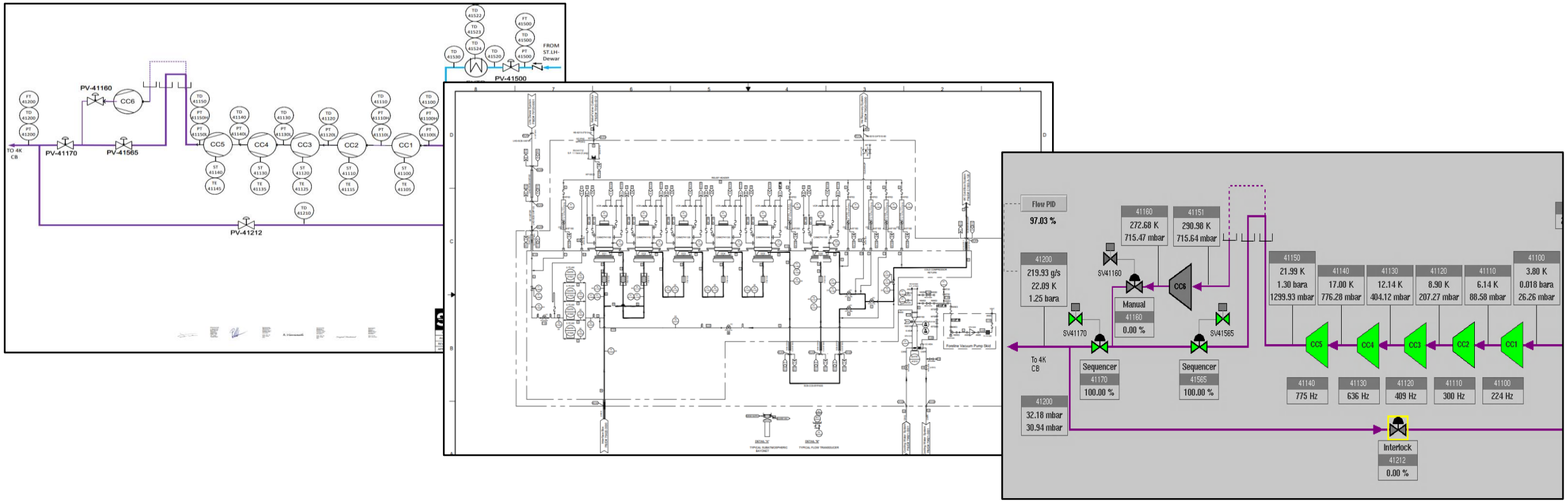
- Communication between PLCs is performed through PLC-PLC STAR network via produced & consumed tags and Common Industrial Protocol (CIP).
- Communication to the rest of the SLAC controls system is through a Channel Access (CA) gateway which allows specific access to SLAC network.



Controls Development Process

PROCESS	Process Flow Diagrams (PFD) Piping & Instrumentation Drawings (P&ID) EPICS HMI View
INSTRUMENTATION	Electrical & Instrumentation Drawings Instrumentation List Wiring Drawing
AUTOMATION	Coding Rules Functional Analysis (FA) PLC code & EPICS Development
COMMISSIONING	Bench Test System commissioning

Process

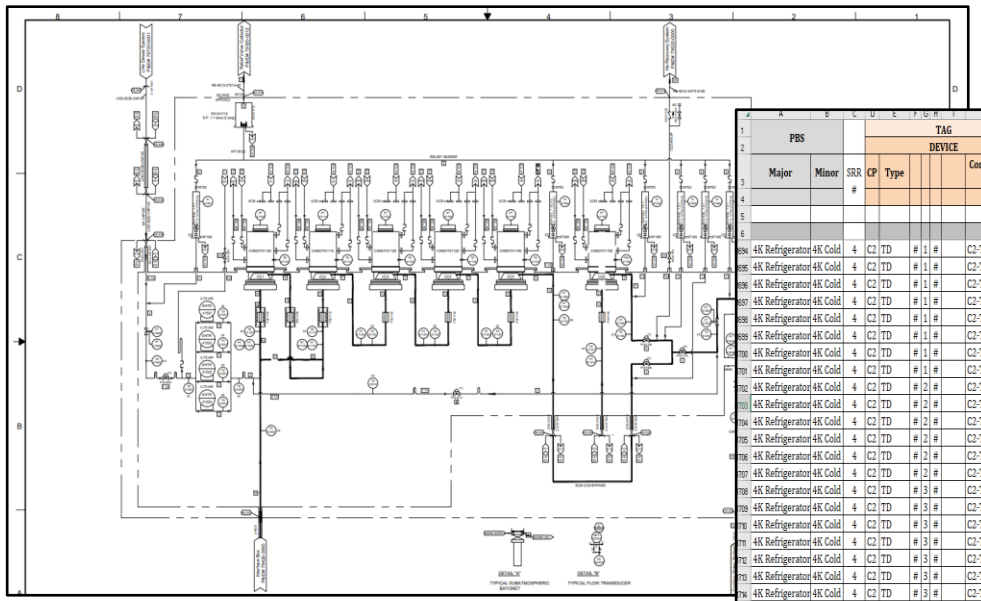


Process Flow Diagrams (PFD)

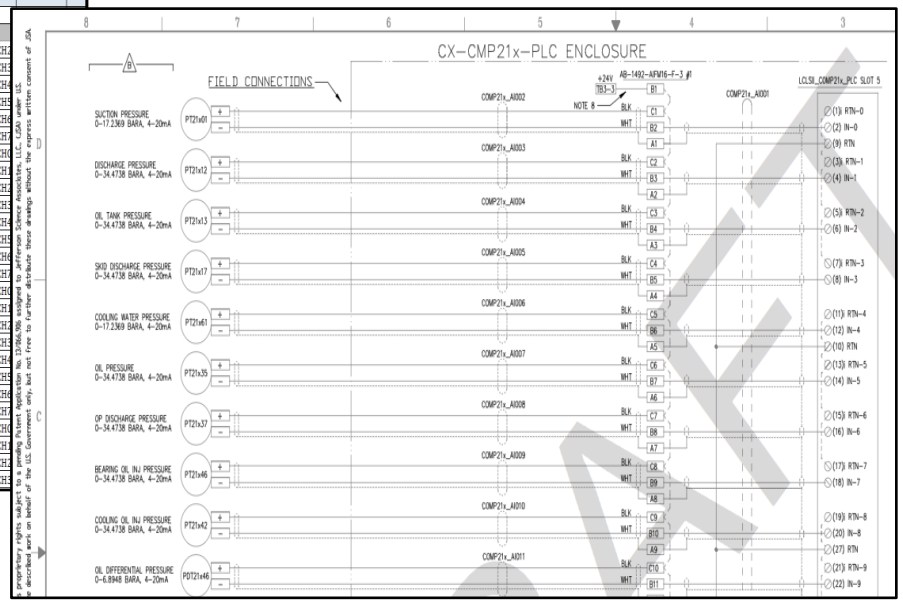
Piping & Instrumentation Diagrams (P&ID)

EPICS

Instrumentation



PBS			TAG							Technical information			Controls							
Major	Minor	SRR #	CP	Type					Concatenated TAG	Manufacturer	Type	Model #	PLC	Type	Rack	Slot	Channel		Cable #1	PR #
4K Refrigerator	4K Cold	4	C2	TD	#	1	#		C2-TD22140	Lakeshore	Diode temperature	DT-670A-SD-QL36-2	4K	CRYOCON	5	2		4K PLC:RACK_SLOT5_CH2		
4K Refrigerator	4K Cold	4	C2	TD	#	1	#		C2-TD22147	Lakeshore	Diode temperature	DT-670A-SD-QL36-2	4K	CRYOCON	5	3		4K PLC:RACK_SLOT5_CH3		
4K Refrigerator	4K Cold	4	C2	TD	#	1	#		C2-TD22160	Lakeshore	Diode temperature	DT-670A-SD-QL36-2	4K	CRYOCON	5	4		4K PLC:RACK_SLOT5_CH4		
4K Refrigerator	4K Cold	4	C2	TD	#	1	#		C2-TD22180	Lakeshore	Diode temperature	DT-670A-SD-QL36-2	4K	CRYOCON	5	5		4K PLC:RACK_SLOT5_CH5		
4K Refrigerator	4K Cold	4	C2	TD	#	1	#		C2-TD22189	Lakeshore	Diode temperature	DT-670A-SD-QL36-2	4K	CRYOCON	5	6		4K PLC:RACK_SLOT5_CH6		
4K Refrigerator	4K Cold	4	C2	TD	#	1	#		C2-TD22190	Lakeshore	Diode temperature	DT-670A-SD-QL36-2	4K	CRYOCON	5	7		4K PLC:RACK_SLOT5_CH7		
4K Refrigerator	4K Cold	4	C2	TD	#	1	#		C2-TD22191	Lakeshore	Diode temperature	DT-670A-SD-QL36-2	4K	CRYOCON	6	0		4K PLC:RACK_SLOT6_CH0		
4K Refrigerator	4K Cold	4	C2	TD	#	1	#		C2-TD22193	Lakeshore	Diode temperature	DT-670A-SD-QL36-2	4K	CRYOCON	6	1		4K PLC:RACK_SLOT6_CH1		
4K Refrigerator	4K Cold	4	C2	TD	#	2	#		C2-TD22225	Lakeshore	Diode temperature	DT-670A-SD-QL36-2	4K	CRYOCON	6	2		4K PLC:RACK_SLOT6_CH2		
4K Refrigerator	4K Cold	4	C2	TD	#	2	#		C2-TD22230	Lakeshore	Diode temperature	DT-670A-SD-QL36-2	4K	CRYOCON	6	3		4K PLC:RACK_SLOT6_CH3		
4K Refrigerator	4K Cold	4	C2	TD	#	2	#		C2-TD22240	Lakeshore	Diode temperature	DT-670A-SD-QL36-2	4K	CRYOCON	6	4		4K PLC:RACK_SLOT6_CH4		
4K Refrigerator	4K Cold	4	C2	TD	#	2	#		C2-TD22245	Lakeshore	Diode temperature	DT-670A-SD-QL36-2	4K	CRYOCON	6	5		4K PLC:RACK_SLOT6_CH5		
4K Refrigerator	4K Cold	4	C2	TD	#	2	#		C2-TD22247	Lakeshore	Diode temperature	DT-670A-SD-QL36-2	4K	CRYOCON	6	6		4K PLC:RACK_SLOT6_CH6		
4K Refrigerator	4K Cold	4	C2	TD	#	2	#		C2-TD22249	Lakeshore	Diode temperature	DT-670A-SD-QL36-2	4K	CRYOCON	6	7		4K PLC:RACK_SLOT6_CH7		
4K Refrigerator	4K Cold	4	C2	TD	#	3	#		C2-TD22332	Lakeshore	Diode temperature	DT-670A-SD-QL36-2	4K	CRYOCON	7	0		4K PLC:RACK_SLOT7_CH0		
4K Refrigerator	4K Cold	4	C2	TD	#	3	#		C2-TD22352	Lakeshore	Diode temperature	DT-670A-SD-QL36-2	4K	CRYOCON	7	1		4K PLC:RACK_SLOT7_CH1		
4K Refrigerator	4K Cold	4	C2	TD	#	3	#		C2-TD22372	Lakeshore	Diode temperature	DT-670A-SD-QL36-2	4K	CRYOCON	7	2		4K PLC:RACK_SLOT7_CH2		
4K Refrigerator	4K Cold	4	C2	TD	#	3	#		C2-TD22382	Lakeshore	Diode temperature	DT-670A-SD-QL36-2	4K	CRYOCON	7	3		4K PLC:RACK_SLOT7_CH3		
4K Refrigerator	4K Cold	4	C2	TD	#	3	#		C2-TD22386	Lakeshore	Diode temperature	DT-670A-SD-QL36-2	4K	CRYOCON	7	4		4K PLC:RACK_SLOT7_CH4		
4K Refrigerator	4K Cold	4	C2	TD	#	3	#		C2-TD22389	Lakeshore	Diode temperature	DT-670A-SD-QL36-2	4K	CRYOCON	7	5		4K PLC:RACK_SLOT7_CH5		
4K Refrigerator	4K Cold	4	C2	TD	#	3	#		C2-TD22390	Lakeshore	Diode temperature	DT-670A-SD-QL36-2	4K	CRYOCON	7	6		4K PLC:RACK_SLOT7_CH6		
4K Refrigerator	4K Cold	4	C2	TD	#	3	#		C2-TD22392	Lakeshore	Diode temperature	DT-670A-SD-QL36-2	4K	CRYOCON	7	7		4K PLC:RACK_SLOT7_CH7		
4K Refrigerator	4K Cold	4	C2	TD	#	3	#		C2-TD22393	Lakeshore	Diode temperature	DT-670A-SD-QL36-2	4K	CRYOCON	8	0		4K PLC:RACK_SLOT8_CH0		
4K Refrigerator	4K Cold	4	C2	TD	#	4	#		C2-TD22425	Lakeshore	Diode temperature	DT-670A-SD-QL36-2	4K	CRYOCON	8	1		4K PLC:RACK_SLOT8_CH1		
4K Refrigerator	4K Cold	4	C2	TD	#	4	#		C2-TD22430	Lakeshore	Diode temperature	DT-670A-SD-QL36-2	4K	CRYOCON	8	2		4K PLC:RACK_SLOT8_CH2		
4K Refrigerator	4K Cold	4	C2	TD	#	4	#		C2-TD22432	Lakeshore	Diode temperature	DT-670A-SD-QL36-2	4K	CRYOCON	8	3		4K PLC:RACK_SLOT8_CH3		



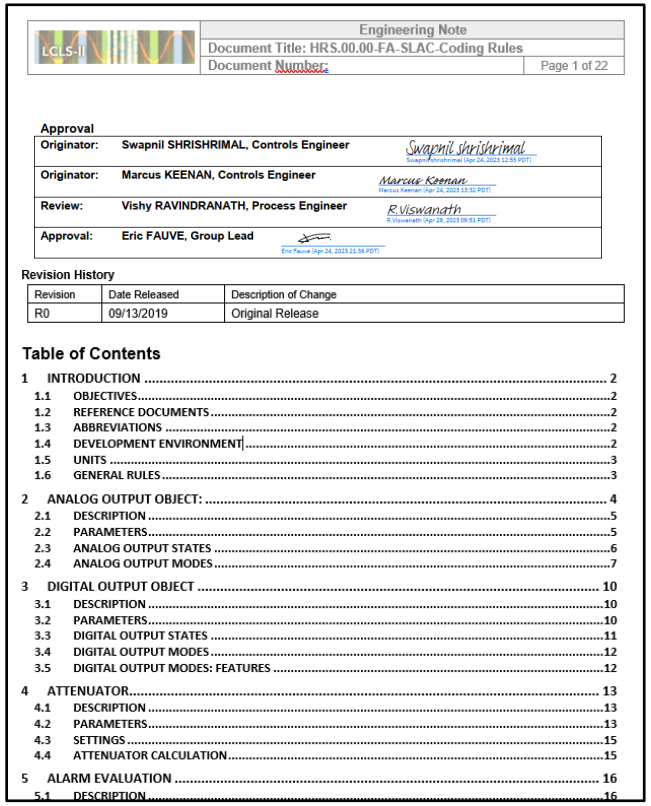
Piping & Instrumentation Diagrams (P&ID)

Instrumentation List

(Excel Sheet)

Electrical Wiring Drawings

Automation



Engineering Note

Document Title: HRS.00.00-FA-SLAC-Coding Rules

Document Number: Page 1 of 22

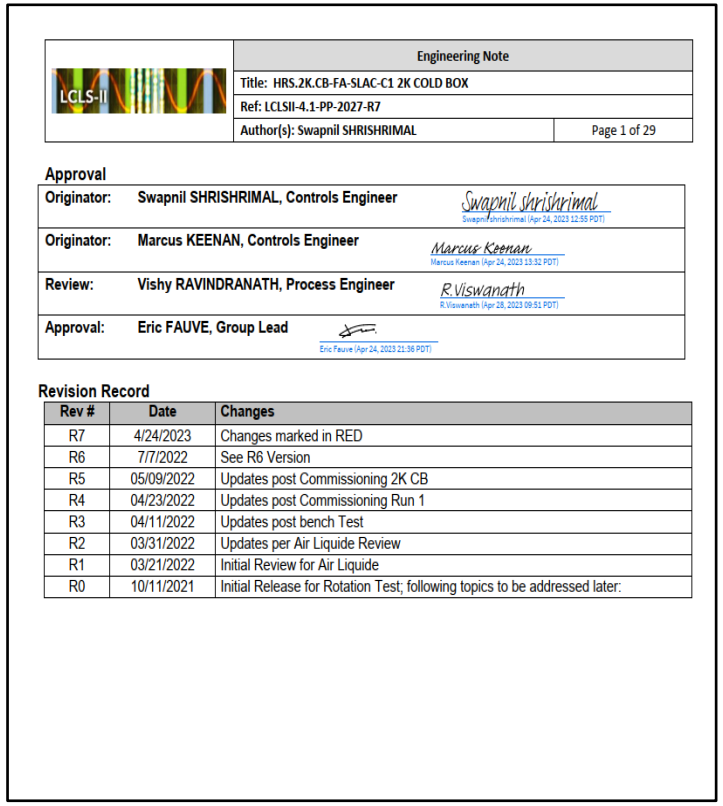
Approval

Originator:	Swapnil SHRISHRIMAL, Controls Engineer	Swapnil Shrishrimal (Apr 24, 2023 12:55 PDT)
Originator:	Marcus KEENAN, Controls Engineer	Marcus Keenan (Apr 24, 2023 13:32 PDT)
Review:	Vishy RAVINDRANATH, Process Engineer	R.Viswanath (Apr 28, 2023 09:51 PDT)
Approval:	Eric FAUVE, Group Lead	Eric Fauve (Apr 24, 2023 21:36 PDT)

Revision History

Revision	Date Released	Description of Change
R0	09/13/2019	Original Release

Table of Contents



Engineering Note

Title: HRS.2K.CB-FA-SLAC-C1 2K COLD BOX

Ref: LCLSII-4.1-PP-2027-R7

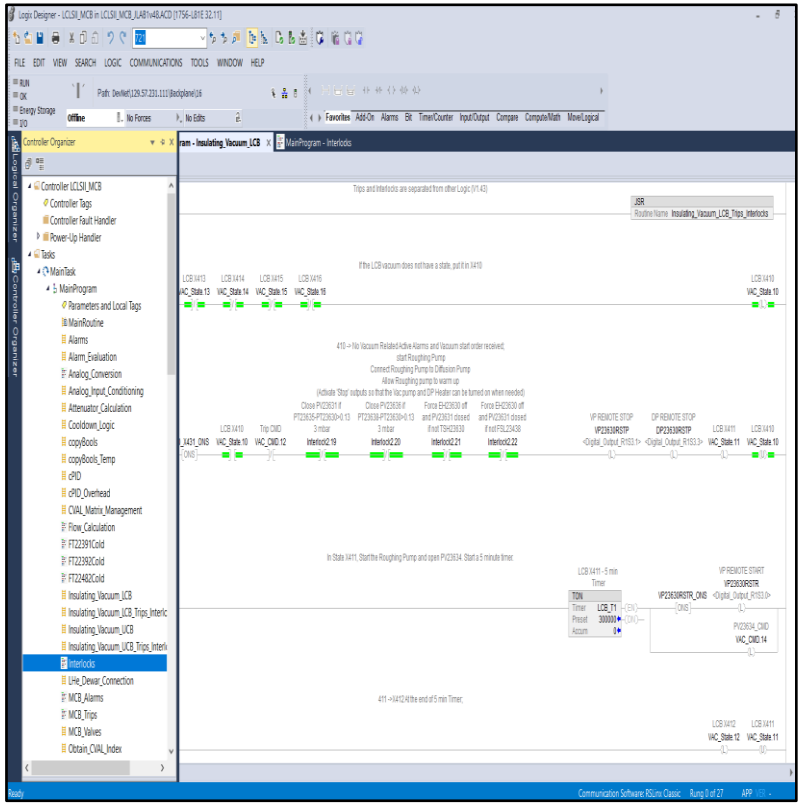
Author(s): Swapnil SHRISHRIMAL Page 1 of 29

Approval

Originator:	Swapnil SHRISHRIMAL, Controls Engineer	Swapnil Shrishrimal (Apr 24, 2023 12:55 PDT)
Originator:	Marcus KEENAN, Controls Engineer	Marcus Keenan (Apr 24, 2023 13:32 PDT)
Review:	Vishy RAVINDRANATH, Process Engineer	R.Viswanath (Apr 28, 2023 09:51 PDT)
Approval:	Eric FAUVE, Group Lead	Eric Fauve (Apr 24, 2023 21:36 PDT)

Revision Record

Rev #	Date	Changes
R7	4/24/2023	Changes marked in RED
R6	7/7/2022	See R6 Version
R5	05/09/2022	Updates post Commissioning 2K CB
R4	04/23/2022	Updates post Commissioning Run 1
R3	04/11/2022	Updates post bench Test
R2	03/31/2022	Updates per Air Liquide Review
R1	03/21/2022	Initial Review for Air Liquide
R0	10/11/2021	Initial Release for Rotation Test; following topics to be addressed later:

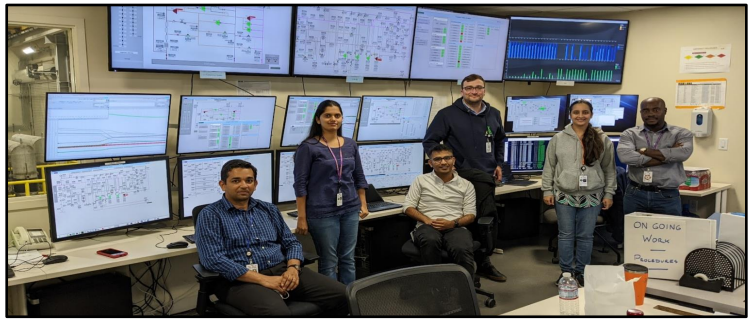


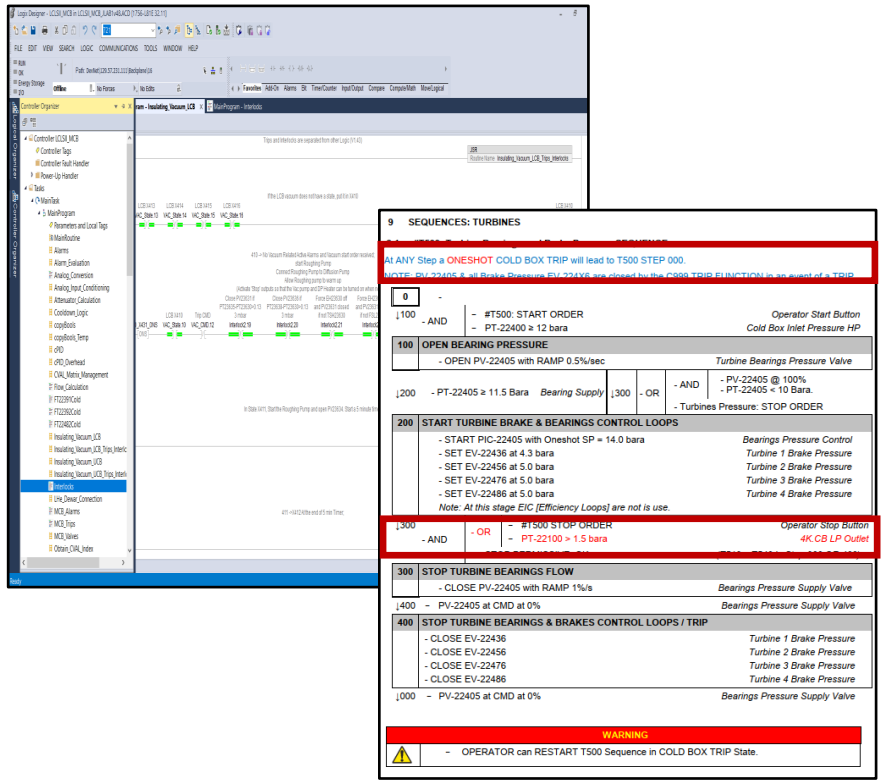
Coding Rules

Functional Analysis (FA)

PLC Code

Commissioning





Bench Test

Commissioning

Track Changes (Code + FA)

Coding Rules

Defines

Programming PLCs & EPICS

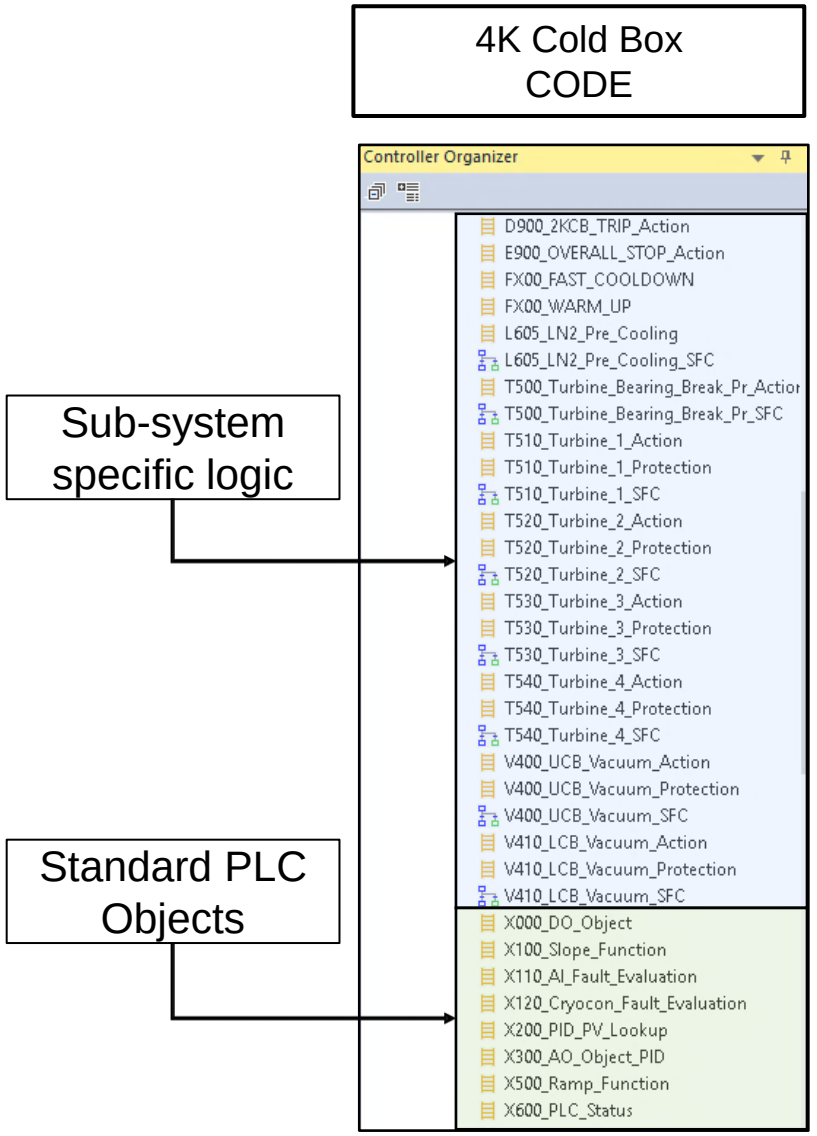
- All Automation Logic is programmed within PLC
- Control, monitoring & data archiving is performed using EPICS

Coding Structure

- Naming Convention for I/O, Sub-Routines, UDT, etc.
- Standardized objects
  - Analog Output, Digital Output, Slope function, etc.
- PLC language use
  - Objects: Ladder Logic
  - Sequences - State & Transitions: Sequential Flow Chart (SFC)
  - Sequences - Sequence Actions: Ladder Logic

EPICS Display

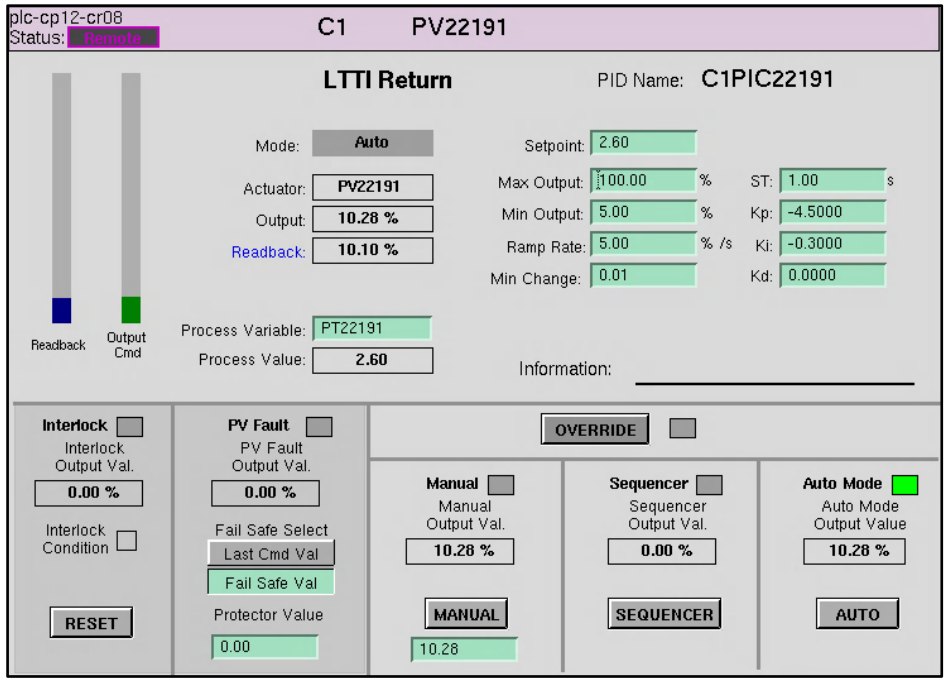
- Standardized object Faceplates
- Sequence and Associated Commands
- Alarm Management



Standardization

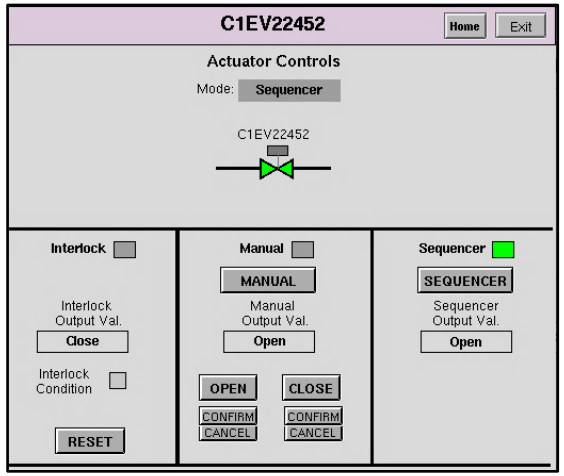
Analog Output Object

- Used for each Analog Output.
  - Pneumatic Valve, Heater Controller, etc.
- Includes PID Algorithm [Velocity form].
- Includes Attenuators / Functions.
- Defines Actuator Modes:
  - Manual: Command from Operator
  - Sequencer: Command from Code
  - Auto: Command from PID Controller
  - PV Fault: Fail Safe when in Auto and Sensor Fail
  - Interlock: Highest Priority for Machine Protection



Digital Output Object

- Used for each Digital Output.
  - Heater On-Off, Solenoid Valves, Equipment On-Off, etc.
- Defines Actuator Modes
  - Manual: Command from Operator
  - Sequencer: Command from Code
  - Interlock: Highest Priority for Machine Protection



Functional Analysis (FA)

Defines

Process Details:
- Notes and Warnings
- Process Schematics

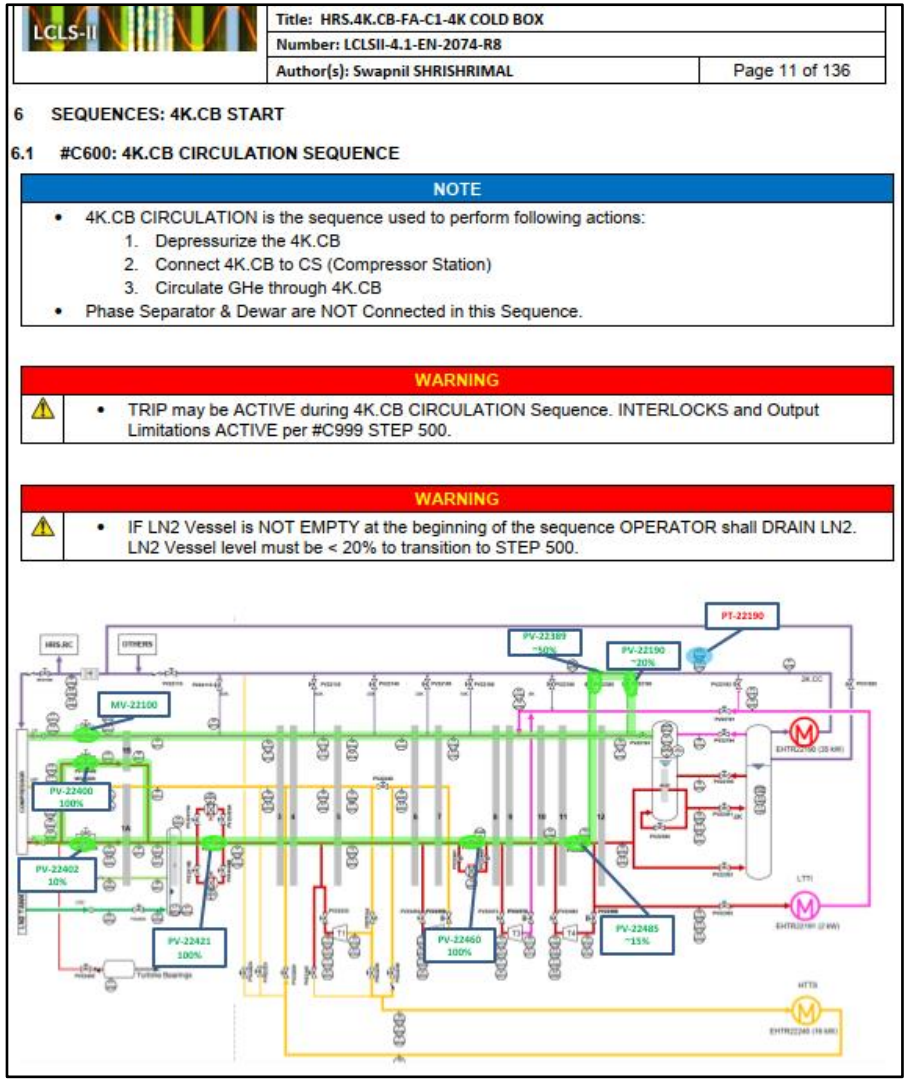
Control Logic:
- Functions
- Control Loops
- Sequences: Actions & Transitions
- Machine Protections: Alarms, Interlocks, TRIPS

Instrumentation:
- I/O information

1-1 traceability from FA → PLC / Code → EPICS / HMI

~20 FA (~1000 pages) in TOTAL: 1 FA per Sub-system

About ~ 2000 hours required for FA [including author & review]



LCLS-II

Title: HRS.4K.CB-FA-C1-4K COLD BOX
Number: LCLSII-4.1-EN-2074-R8
Author(s): Swapnil SHRISHRIMAL | Page 11 of 136

6 SEQUENCES: 4K.CB START

6.1 #C600: 4K.CB CIRCULATION SEQUENCE

NOTE
- 4K.CB CIRCULATION is the sequence used to perform following actions:
  1. Depressurize the 4K.CB
  2. Connect 4K.CB to CS (Compressor Station)
  3. Circulate GHe through 4K.CB
- Phase Separator & Dewar are NOT Connected in this Sequence.

WARNING
- TRIP may be ACTIVE during 4K.CB CIRCULATION Sequence. INTERLOCKS and Output Limitations ACTIVE per #C999 STEP 500.

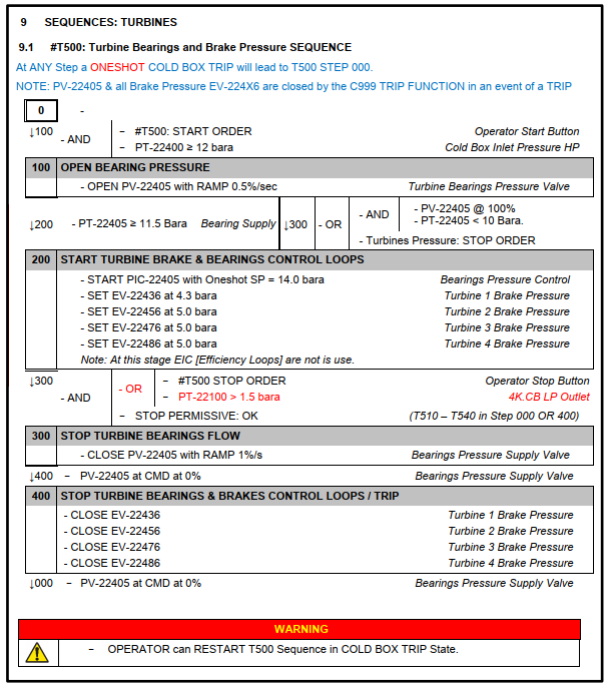
WARNING
- IF LN2 Vessel is NOT EMPTY at the beginning of the sequence OPERATOR shall DRAIN LN2. LN2 Vessel level must be < 20% to transition to STEP 500.

Programming

Sequence Programming

- State & Transitions — Sequential Flow Chart (SFC)
- Sequence Actions — Ladder Logic

1-1 traceability from FA → Code → EPICS UI



9 SEQUENCES: TURBINES

9.1 #T500: Turbine Bearings and Brake Pressure SEQUENCE

At ANY Step a ONESHOT COLD BOX TRIP will lead to T500 STEP 000.

NOTE: PV-22405 & all Brake Pressure EV-224X6 are closed by the C999 TRIP FUNCTION in an event of a TRIP

0 -

↓100 - AND
- #T500: START ORDER — *Operator Start Button*
- PT-22400 ≥ 12 bara — *Cold Box Inlet Pressure HP*

100 OPEN BEARING PRESSURE
- OPEN PV-22405 with RAMP 0.5%/sec — *Turbine Bearings Pressure Valve*

↓200 - PT-22405 ≥ 11.5 Bara *Bearing Supply* | ↓300 | - OR | - AND
- PV-22405 @ 100%
- PT-22405 < 10 Bara.
- Turbines Pressure: STOP ORDER

200 START TURBINE BRAKE & BEARINGS CONTROL LOOPS
- START PIC-22405 with Oneshot SP = 14.0 bara — *Bearings Pressure Control*
- SET EV-22436 at 4.3 bara — *Turbine 1 Brake Pressure*
- SET EV-22456 at 5.0 bara — *Turbine 2 Brake Pressure*
- SET EV-22476 at 5.0 bara — *Turbine 3 Brake Pressure*
- SET EV-22486 at 5.0 bara — *Turbine 4 Brake Pressure*

Note: At this stage EIC [Efficiency Loops] are not is use.

↓300 - AND | - OR
- #T500 STOP ORDER — *Operator Stop Button*
- PT-22100 > 1.5 bara — *4K.CB LP Outlet*
- STOP PERMISSIVE: OK — *(T510 – T540 in Step 000 OR 400)*

300 STOP TURBINE BEARINGS FLOW
- CLOSE PV-22405 with RAMP 1%/s — *Bearings Pressure Supply Valve*

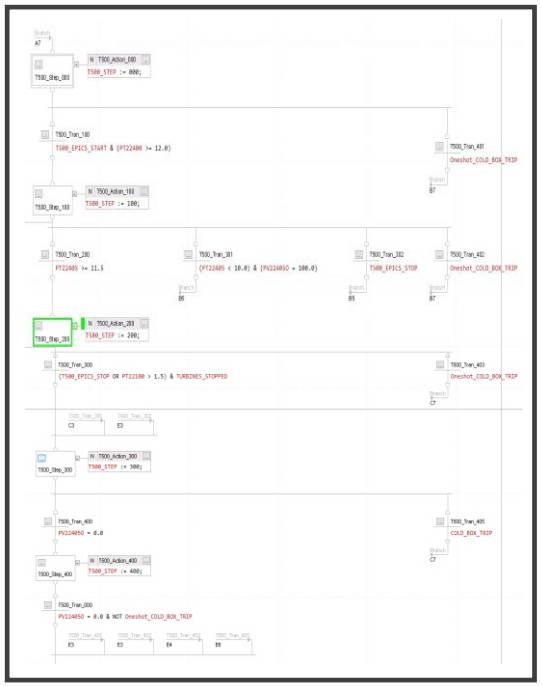
↓400 - PV-22405 at CMD at 0% — *Bearings Pressure Supply Valve*

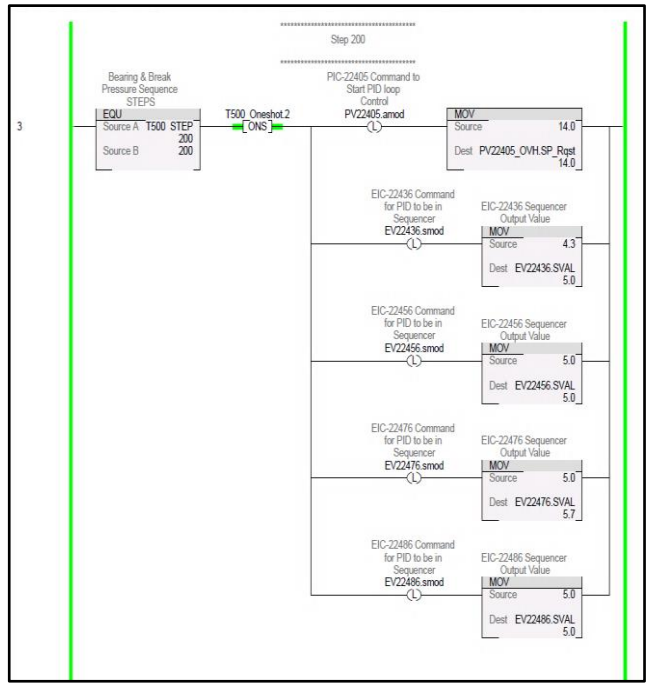
400 STOP TURBINE BEARINGS & BRAKES CONTROL LOOPS / TRIP
- CLOSE EV-22436 — *Turbine 1 Brake Pressure*
- CLOSE EV-22456 — *Turbine 2 Brake Pressure*
- CLOSE EV-22476 — *Turbine 3 Brake Pressure*
- CLOSE EV-22486 — *Turbine 4 Brake Pressure*

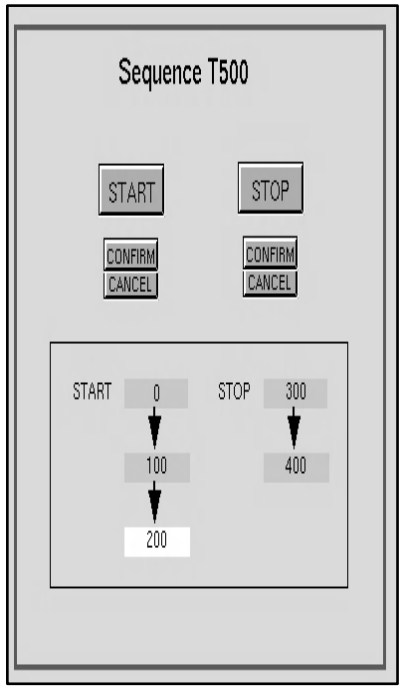
↓000 - PV-22405 at CMD at 0% — *Bearings Pressure Supply Valve*

WARNING

⚠ - OPERATOR can RESTART T500 Sequence in COLD BOX TRIP State.







FA | SFC State & Transitions | Sequence Actions | EPICS

What was Automated?

#E900: OVERALL CRYOGENIC SYSTEM STOP

Compressor Station

- # G900 STOP OVERALL CS
- # G100 START OVERALL CS
  - #C200 CMP21X START
  - #C400 CMP21X STOP
  - #C900 CMP21X TRIP

Where X: CMP 1 – 6

4K Cold Box

- #C600: 4K.CB GAS CIRCULATION
- #C610: 4K.CB COOLDOWN - START
- #C900: 4K.CB STOP
- #C999: 4K.CB TRIP
  - #L605: LN2 PRE-COOLING
  - #C671: RETURN LINE - COOLDOWN
  - #C672: RETURN LINE - NOMINAL
  - #C620: PHASE SEPARATOR START
  - #C630: DEWAR START
  - #T500: TURBINE BEARING & BRAKES
  - #T5X0: TURBINE X

Where X: Turbine 1 – 4

2K Cold Box

- # D500 2K.CB START - PUMPDOWN
- # D500 2K.CB STOP / TRIP
  - #L000 LINAC HEATER CONTROLS

LINAC & Distribution System

- # L900 LINAC TRIP
- #F100 D1 LINAC WARM-UP
- #F200 D2 LINAC WARM-UP
- #F300 D1 LINAC FAST COOLDOWN
- #F400 D2 LINAC FAST COOLDOWN

Where:

GLOBAL SEQUENCES

Acts on

HIGH LEVEL SEQUENCES

Acts on

LOW LEVEL SEQUENCE

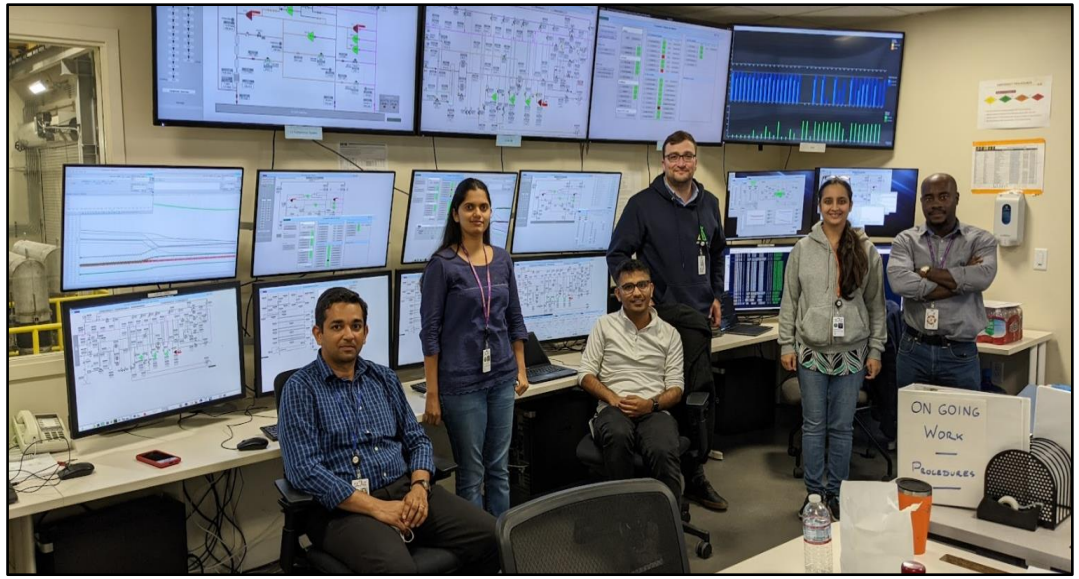
HMI: Overview

HMI: EPICS (Experimental Physics and Industrial Control System)

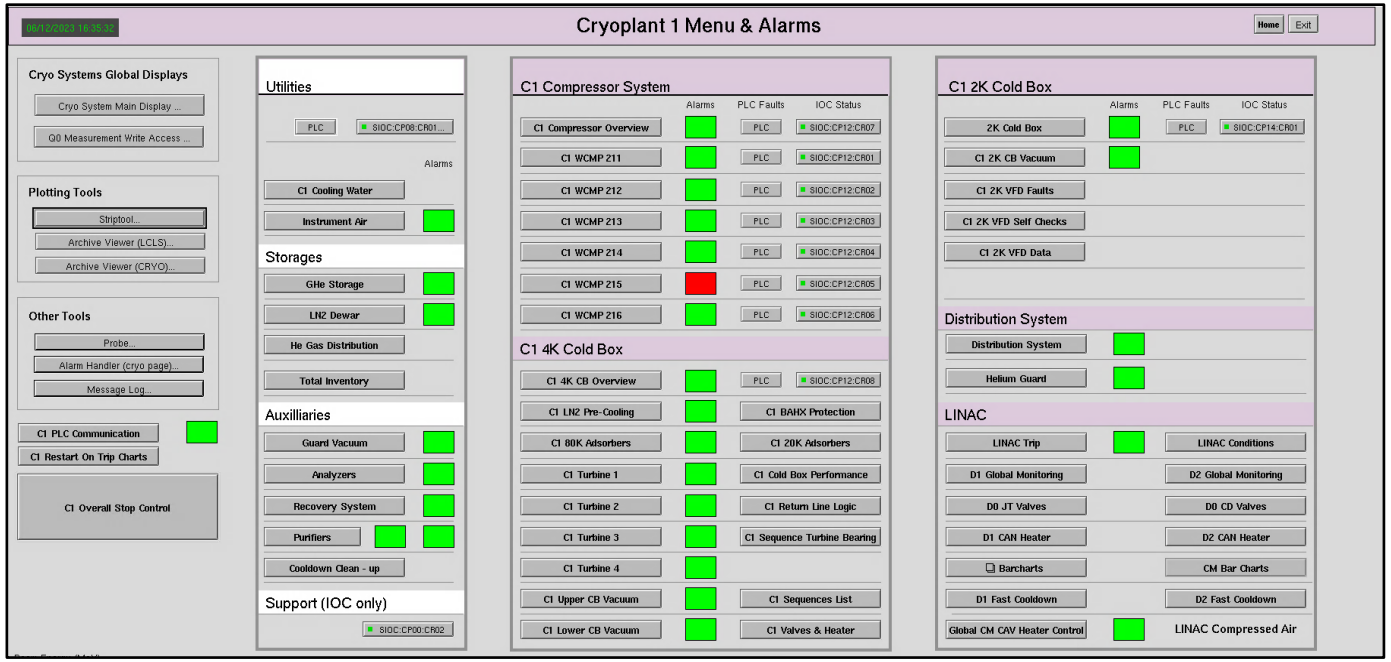
- Widely used in national laboratories within USA.
- Infrastructure was available at SLAC with decades of expertise.
- Only used for Monitoring, Controlling & Data Archiving – NO control logic

SLAC Cryogenic System is nominally operated remotely via control rooms.

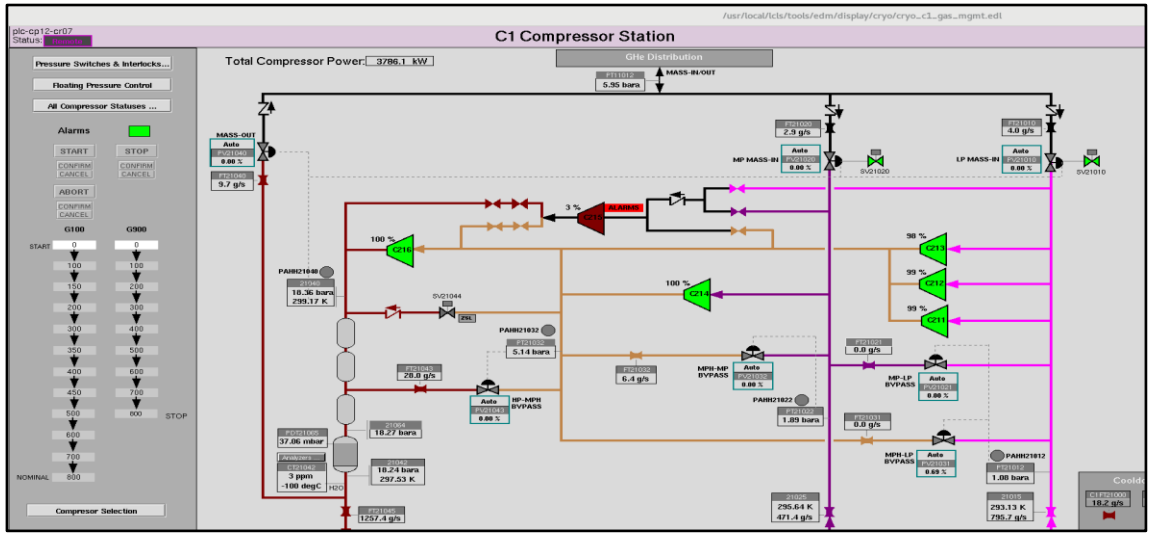
A Global Menu & Alarms screens provides operator a single UI to operate & monitor the cryogenic system.



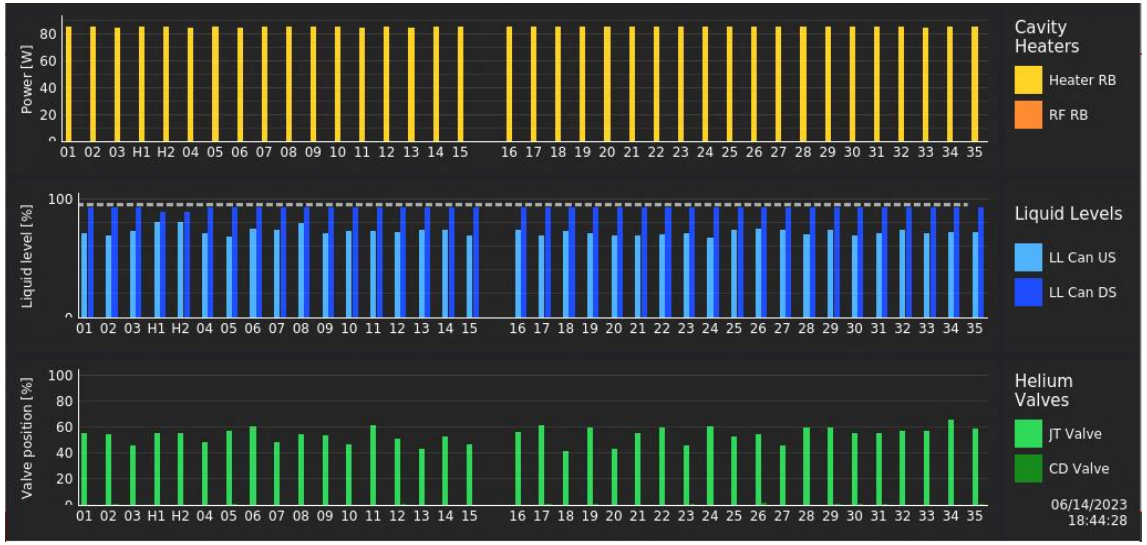
Cryogenic Control Room @ SLAC



HMI

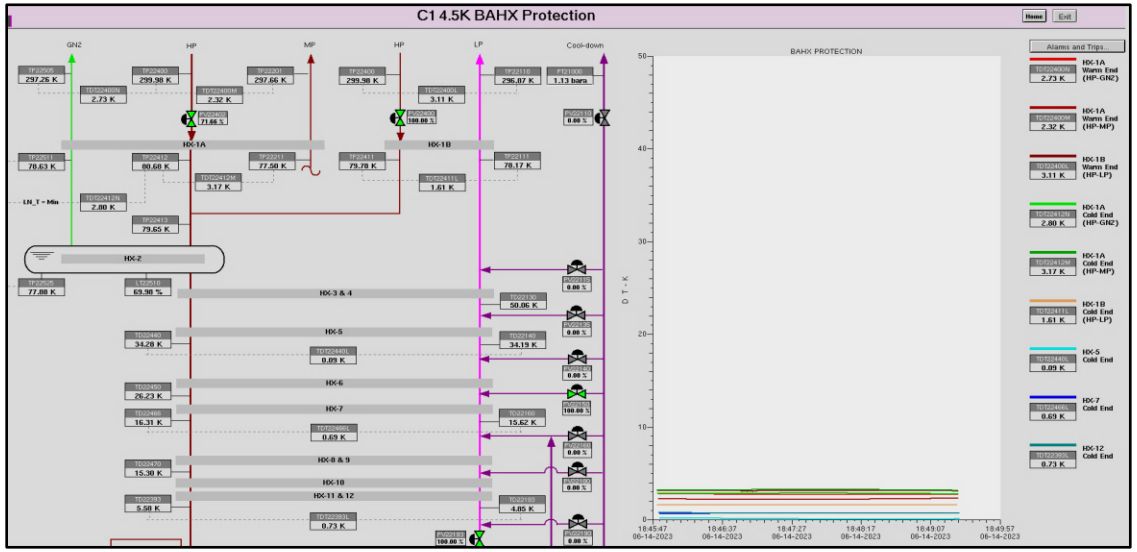


- Compressor Station
  - Visual based on PFD
  - Sequence State
  - Quick view of the Alarms
  - Quick glance of compressor parameters
  - Compressor Bypass valves status
  - Mass-in Mass-out valve status

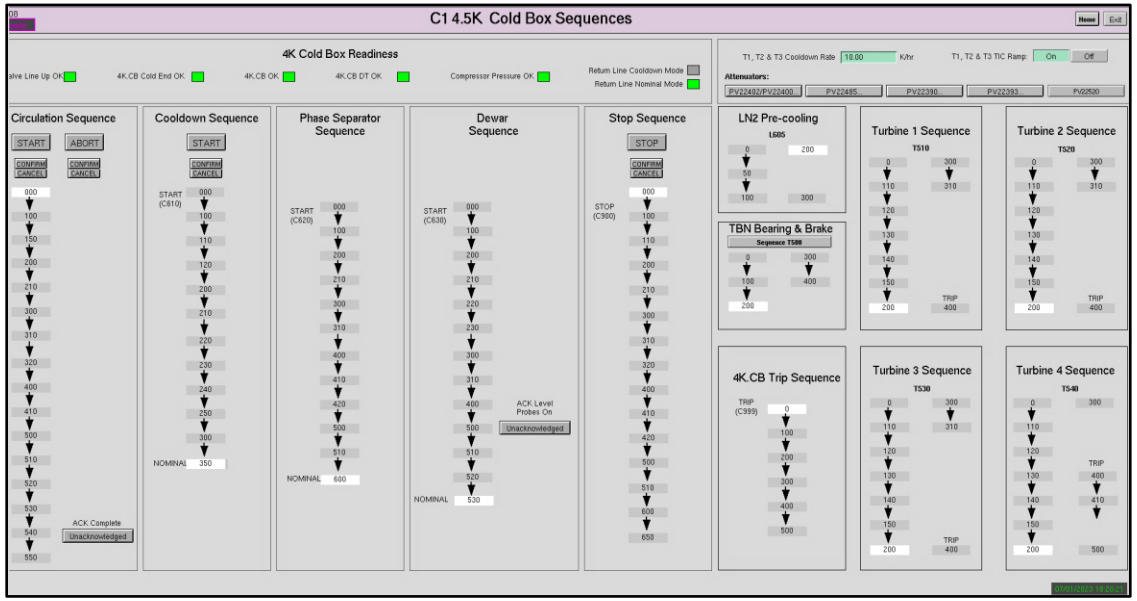


- LINAC Status Monitoring
  - Quick view of LINAC critical data
  - Glance to identify odd Cryomodule
  - Numbers vs graphical data
  - Provide information on:
    - RF & Cavity Heater
    - Upstream & Downstream Liquid Levels
    - JT & CD Valves

HMI



- 4K.CB Heat Exchanger DT Monitoring
  - Visual based on PFD
  - Preconfigured Trends
  - Quick identification of historical trend
  - Quick view of the critical data



- 4K.CB Cold Box Sequences
  - Quick view of all sequence states
  - Monitor and observe automation with FA

Lessons Learned

What we did well:

- Good documentation:
  - Well organized Electrical & Instrumentation Diagrams.
  - Detailed Functional Analysis to define Automation.
  - Detailed Coding Rules for homogenous Code Development.
  - Traceability to Code, with 100% Tests.
- Automation at PLC Level:
  - All Automation at PLC Level, EPICS used for Data archiving and Human Machine Interface Only.
  - Online editing feature offered by Allen Bradley PLC was extremely helpful during commissioning.
- The Same Institution leading Process Control Development and Commissioning
  - Commissioning requires frequent PLC Code update.
  - The Institution/Group in charge of Commissioning shall own the PLC Code.
- Standardization helps quick on-boarding of operators / engineers.
- Automation helps simplifying procedures, and accelerating execution.

Lessons Learned

What we would do differently:

- Centralizing & minimizing the number of PLCs simplifies controls / automation.
- Network architecture: Ring should be preferred.
- Readily available SCADA – Industrial Options should be evaluated against EPICS.

Conclusions

- SLAC & Jefferson Lab collaboratively developed LCLS-II Cryogenic Control System.
- The SLAC cryogenic system is extensively automated.
- Documentation & 1-1 traceability provides quick troubleshooting & tracking of process modification.
- Control system automation & flexibility provides the means to the operator, to easily transition between different modes of operation.
- Automated Operation helps in:
  - Minimizing the human error and increasing system reliability & repeatability.
  - Providing Fast Response in the event of Emergencies while limited staff on-site.


Thank you