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LCLS-II CRYOMODULE AND CRYOGENIC DISTRIBUTION CONTROL*

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Abstract

The new superconducting Linear Coherent Light Source (LCLS-II) at the SLAC National Accelerator Laboratory will be an upgrade to LCLS, the world's first hard X-ray free-electron laser. LCLS-II is in an advanced stage of construction with equipment for both cryogenic plants (CryoPlants) as well as more than half of the 37 cryomodules onsite. Thomas Jefferson Lab (JLab) is a partner lab responsible for building half of the LCLS-II cryomodules. The Low Energy Recirculation Facility (LERF) at Jefferson Lab (JLab) was used to stage and test LCLS-II cryomodules before shipping them to SLAC. The testing was done by setting up two cryomodules at a time, cryocontrols instrumentation racks, Programmable Logic Controllers (PLC) controls and Experimental Physics and Industrial Control System (EPICS) Input/Output Controllers (IOCs) at LERF with the intention of developing cryogenic controls for LCLS-II. The cryogenic controls developed at LERF would then be replicated for controlling all 37 cryomodules via an EPCIS user interface. This paper discusses the cryogenic controls developed at LERF for implementation in the LCLS-II project.

INTRODUCTION

The LCLS-II project provided funding for all the instrumentation and controls software [1]. This includes RF amplifiers, Low Level RF (LLRF) control equipment and Cryogenic Controls racks with PLCs. EPICS is used for supervisory control of the cryogenic systems while the control logic was developed in Allen Bradley PLCs. Field instrumentation is connected as Distributed I/O communicating over an EtherNet/IP based Device Level Ring (DLR). The subsystem controls included electric heaters, pressure transducers, Resistive Temperature Detectors (RTDs) and liquid level monitors. Cryogenic valves are controlled using Profibus Process Automation (PA) and Profibus Decentralized Peripheral (DP) communication protocols [2]. The test facility included 16 four kW solid state amplifiers (SSA) and new wave guides were installed to connect the two cryomodules. Low Level RF chassis were installed for controls and interlocks, along with vacuum controls. Figure 1 shows the LERF cryomodules in the vault and cryocontrols racks in the gallery.

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The Central Helium Liquefier (CHL) at JLab provides 2K Helium for the CEBAF accelerator. A cryogenic-connection to CHL was designed and installed to supply helium to the new LERF cryomodule test facility. This connection to one of the CHL cryoplants allows the CEBAF Linac and LERF to be cooled down from 4K to 2K without interrupting the CEBAF operations. The first two cryomodules installed and tested at the LERF were J1.3-12 and J1.3-5. Cryomodule J1.3-12 was installed at SLAC while J1.3-5 was reconditioned to remedy cryogenic performance issues identified during initial testing.

Figure 1: LCLS-II cryomodule in the LERF vault and cryogenic controls instrumentation racks in the gallery.

CONTROLS ARCHITECTURE

The final cryogenic control system architecture to be implemented for LCLS-II was developed in collaboration with input and feedback from partner labs. The cryogenic plant supplies helium through upstream and downstream distribution boxes. The upstream distribution box supplies 17 cryomodules with helium while the downstream distribution box supplies 20 cryomodules. The LCLS-II cryomodule control system will be designed using off-the-shelf hardware and will closely mirror the mechanical design. Redundant PLC processing will be done in centralized locations using ControlLogix 1756-L83E processors. The cryomodule PLCs will communicate to EPICS and the cryogenic plant PLCs. Figure 2 illustrates the redundant architecture.

The controls architecture at the LERF replicated the proposed LCLS-II design by using two of the controls rack intended for LCLS-II with all the same instrumentation and

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distributed I/O. The 5069-L330ER CompactLogix processor was used for processing the cryomodule monitoring and control signals. The cryomodule installation at LERF included a 0.5% slope to replicate the actual SLAC tunnel and the associated control challenges due to this slope.

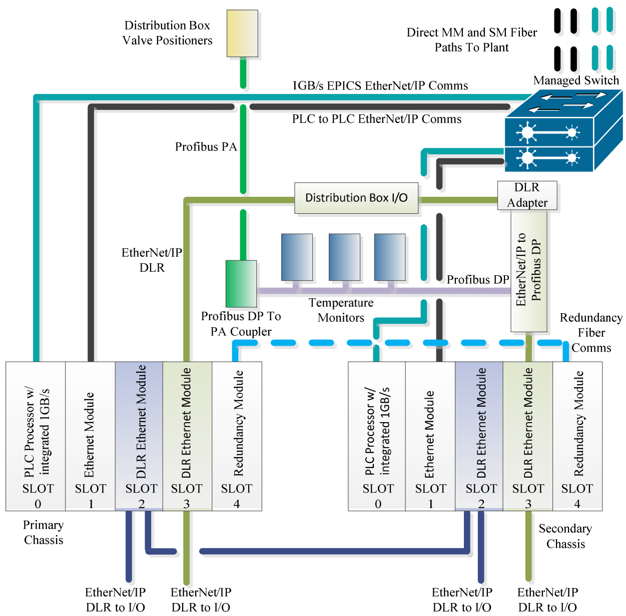

Figure 2: Centralized PLCs with redundancy.

SYSTEM READINESS

All hardware and software controls were tested prior to the initial cryogenic cool down and before RF was applied to cryomodule cavities. Checkout procedures were developed and used to test the PLC cryogenic and EPICS controls as well as the RF system. Given the fact that a significant amount of hardware and controls was being developed at partner laboratories, there was a requirement to have remote software development and checkout capabilities. Policies and procedures were developed for managing remote access needed for support and safe development of the Cryo software controls. A JLab readiness review prior to system start up validated whether or not the new cryomodule test facility was ready to transition from engineering and development to operations. An extensive saftey review was done to identify the possible risks of remote operations and to determine how best to mitigate those risks. The primary risks involved a remote user harming the CHL which would be providing 2K Helium to the CEBAF accelerator and LERF. Secondly a remote user could potentially damage a production cryomodule.

Extensive testing of the cryogenic controls was carried out prior to the initial cool down. Instrumentation that was tested included 70 temperature diodes, 4 pressure transducers, 16 cavity heaters and 4 Joule-Thomson valves (JT and Cool down). The RF system was tested to verify that the internal interlocks of the amplifiers were operational. Figure 3 shows an EPICS cryomodule control screen.

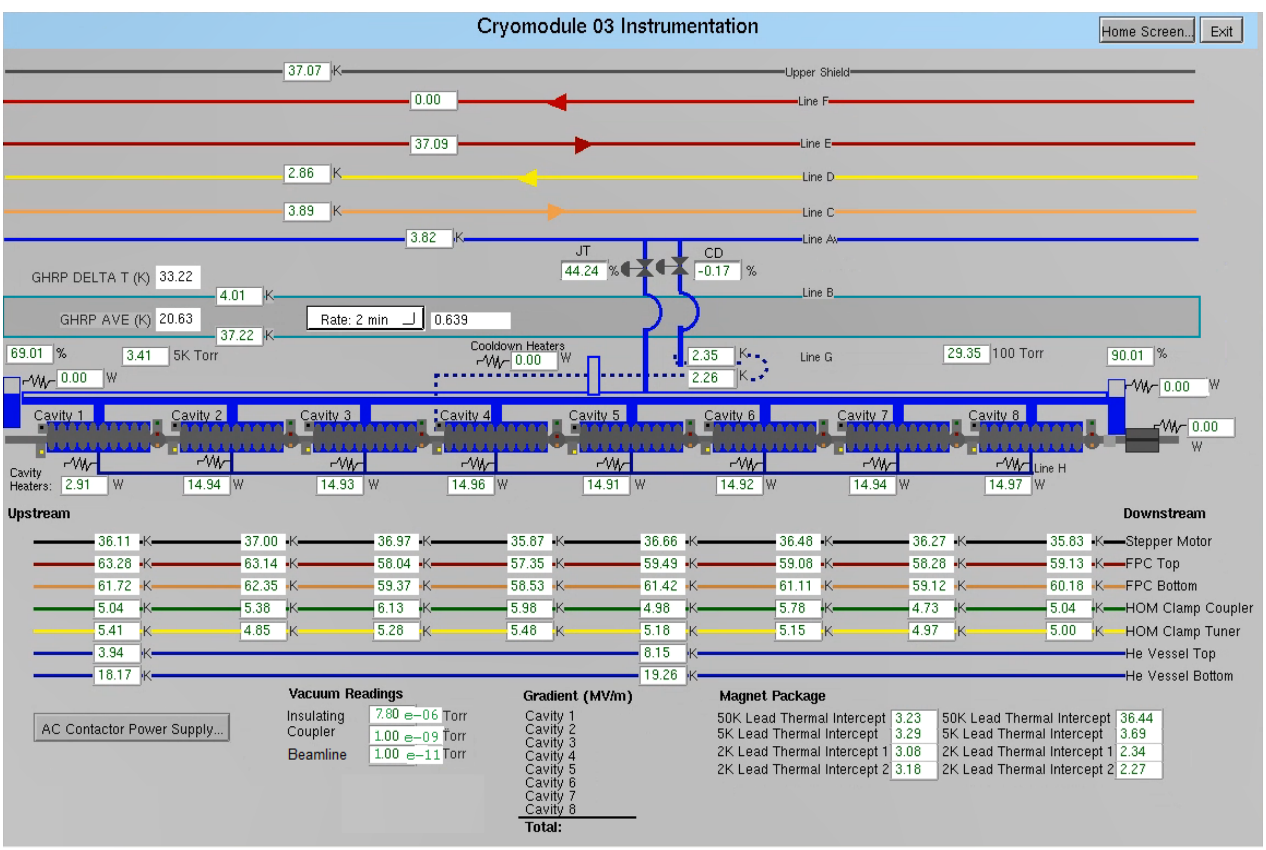

Figure 3: LCLS-II cryomodule cryo-controls EPICS display showing temperature sensors, heaters and valves..

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Heater Control

Several heaters are required for managing heat loads in the cryomodules. There are 8 cavity strip heaters per cryomodule affixed to the bottom of the vessel bath. Each heater is individually driven by a linear power supply with current shunts placed in series with the heaters to monitor current draw. Depending on the mode of operation, LLRF sends a gradient reading to the PLC, which is used to regulate the heaters. The End Can heaters are two cartridge heaters with current transducers internal to the regulated power supplies. PLC Logic was developed to automatically control the heaters by implementing a “PID-like” algorithm. The logic calculates the likely heater read-back current based on the known shunt resistance and PLC commanded output voltage. The current readback is then used to control the heater output by adding or subtracting to the PLC commanded output voltage. This is automatically done until the heater read-back is within an acceptable range for the target set point power. Controlling the heaters in this way was found to take too much time, so a faster logic control method will be tested at LERF. Cryomodule temperatures are monitored using the Lakeshore 240-8P temperature monitors, which communicate over Profibus DP. Figure 4 shows the EPICS faceplates for controlling the heaters and monitoring temperatures. A cryo-operator is able to enable, disable and enter set points and alarm values for each heater and temperature monitor from the faceplate.

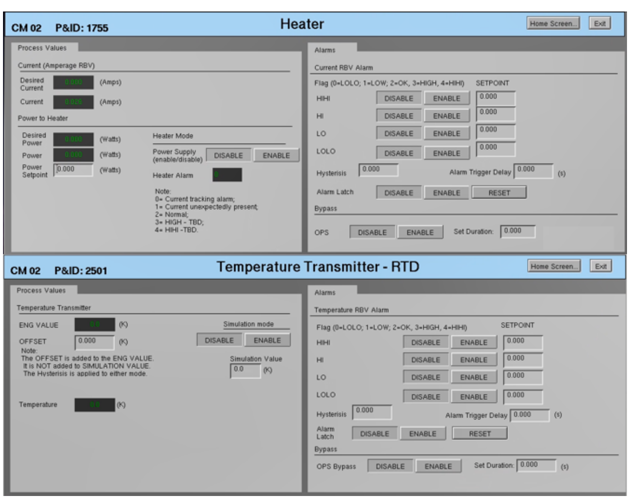

Figure 4: EPICS faceplates for Heaters and Temperature.

Valve Control

The JT valve is the expansion valve on each cryomodule which operates to fill the bath containing RF cavities with helium. The Cool-down valve regulates helium from the Cryoplant used for initial cryomodule cooling. Both valves are controlled using the PLC’s built-in enhanced PID algorithm to regulate the valve actuator position in order to maintain Helium liquid level at the desired set point in each cryomodule. The PLC logic monitors two liquid level probes in each cryomodule which are manufactured and customized by AMI. One probe is located at the upstream end and the other at the downstream end of the cryomodule.

The tunnel at SLAC has an approximately 0.5% slope and hence the downstream probe of the cryomodule will always indicate a higher liquid level than the upstream probe. This slope illustrated in Figure 5 increases the complexity of the control strategy required for controlling the Helium levels.

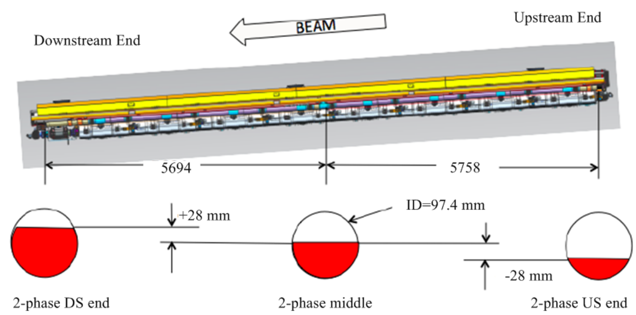

Figure 5: Cryomodule Liquid He level due to tunnel slope.

The PLC logic is designed to monitor and control the valves using the downstream liquid level. Figure 6 shows the EPICS faceplates for controlling the JT valve and monitoring liquid level. A cryo-operator is able to enable, disable and enter set points, PID and alarm values for each valve and level monitor from the faceplate.

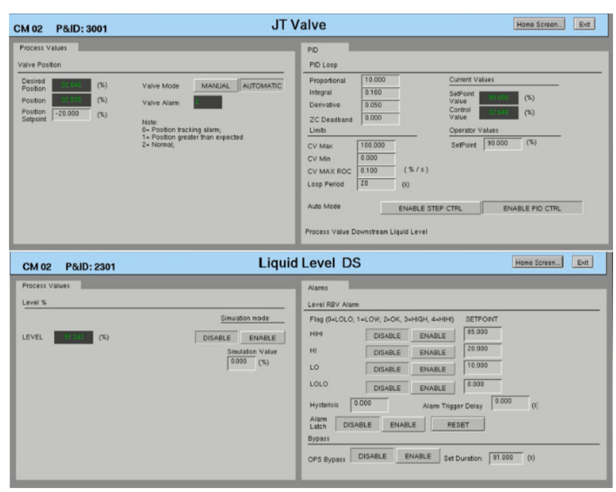

Figure 6: EPICS FACEPLATES for JT valve and Liquid Level.

A hardwired interlock to the downstream level monitor is designed to open the JT valve and shutdown LLRF if the cavity helium liquid level goes too low. This helium low level interlock was successfully tested.

Pressure

There are two pressure transducers per cryomodule. These pressure signals may be used for manipulating the control of a valve or heater based on the cryoplant and cryomodule mode of operation. Pressure readings from strain gauges at the end of the cryomodule strings are used for providing diagnostics [3, 4].

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CRYOMODULE COMMISSIONING

Both J1.3-5 and J1.3-12 cryomodules at LERF underwent full performance qualification testing similar to cryomodules received at the other test facilities at JLAB and FNAL. These tests included Qo, maximum useable gradient and other tests to ensure that the cryomodules and all their cavities met their performance specifications. After performance testing all 16 cavities were simultaneously operated. This was coordinated using a two-step process. First an initial run of the J1.3-12 cavities was done successfully with no issues. The heat load was balanced manually with the electric heaters to ensure that the effective LERF cryo-load was stable. Next, the J1.3-5 cavities were turned on. Problems occurred with this cryomodule as RF SSAs were tripped off. Eventually several cavities were operated at a lower gradient and an acceptable accelerating voltage was achieved without affecting the CEBAF CHL [5].

LESSONS LEARNED

A significant amount of time was needed for termination of field wiring in the cryocontrols racks and for doing end-to-end instrument loop checks for all PLC I/O. During checkout of the equipment, several wiring errors were found in the field and in the design. While doing checkout, wiring errors caused electrical damage to instrumentation that had to be replaced. Catching the wiring errors at LERF allowed us to make changes to the design prior to the large build of cryocontrol racks. We will take the opportunity to integrate heater control with LLRF in future LERF runs.

SUMMARY

The cryomodule test facility at the LERF has been successfully commissioned including the cryomodule cryogenic controls. The facility has fulfilled its mandate of providing an alternate cryomodule commissioning facility and providing a test-bed for pre-commissioning the LCLS-II linac cryogenic hardware and software controls. The controls for Cryo, RF and Vacuum have been successfully tested and will be continuously improved by onsite personnel in tandem with remote support and development.

OUTLOOK

Further development work will be done to improve the LCLS-II cryogenic controls software at LERF for implementation on LCLS-II. The U.S Department of Energy Mission Need (CD-0) has been established for the LCLS-II- High Energy (LCLS-II HE) upgrade and the conceptual design is now under review. This upgrade would potentially require an additional 20 cryomodules. The cryomodule test facility at the LERF will be beneficial for developing and testing future cryomodules.

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