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COMMISSIONING THE JLAB LERF CRYOMODULE TEST FACILITY*

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Abstract

The JLAB Low Energy Recirculating Facility, LERF, has been modified to support concurrent testing of two LCLSII cryomodules. The cryomodules are installed in a similar fashion as they would be in the L1 section of the LCLSII linac, including the floor slope and using all of the LCLSII hardware and controls for cryomodule cryogenics, vacuum, and RF (SSA and LLRF). From the start, it was intended to use LCLSII electronics and EPICS software controls for cryomodule testing. In effect, the LERF test facility becomes the first opportunity to commission and operate the LCLSII LINAC hardware and software controls. Support for specific cryomodule high level test applications like Qo and HOMs measurements, are being developed from the basic cryomodule control suite. To support the testing, 2 K He is supplied from the CEBAF south linac cryogenic system, where care must be taken when using the LERF test facility to not upset the CEBAF cryogenics plant. This paper discusses the commissioning of the hardware and software development for testing the first two LCLSII cryomodules.

INTRODUCTION

The LERF began life as the JLAB free electron laser facility where it produced coherent CW 14 kW IR light. It has since become a multipurpose facility supporting nuclear physics experiments, isotope production and now cryomodule testing. The concept for testing LCLS-II cryomodules was twofold. First, as an additional test facility to keep JLAB cryomodule production on schedule, and second, as test bed for LCLS-II linac hardware and controls. An added benefit of the LERF over the Cryomodule Test Facility (CMTF) was the potential for a more reliable and stable He supply. In addition from the start it was decided to minimize the role of external software (Labview) and test equipment for cavity testing, relying on built in EPICS applications in the RF and cryogenic controls.

To accommodate two cryomodules the building and existing systems had to be modified. The existing FEL LINAC RF system was partially removed, such that 16 four kW solid-state amplifiers (SSA) could be installed in the equipment gallery. The existing WR650 waveguide between gallery (upstairs) and the vault below was repurposed for this project. Additionally, all new waveguide was installed in the vault to connect the two cryomodules. Figure 1 shows the cryomodule and waveguide installed in the vault along with the SSAs in the equipment gallery.

Figure 1: LCLS-II cryomodule in the LERF vault and four kW solid state amplifiers in the equipment gallery.

The LCLS-II project provided all of the controls software and instrumentation for the cryomodules [1]. This included the four kW RF amplifiers, Low Level RF (LLRF) control chassis, resonance, interlocks and racks, cryomodule cryogenic PLCs and racks, and vacuum controls. The EPICS controls provided by LCLS-II is using the identical process variables and naming convention that are planned for the L1 section of the LCLSII linac. The idea being the controls software can be ported back to SLAC as tested and commissioned.

A key portion of the cryomodule test facility is the cryogenic connection to the central helium liquefier (CHL) that supplies 2 K He for the CEBAF accelerator. A new cryo-connection was designed to make it minimally invasive while operating the CHL during CEBAF operations. The LERF cryogenic system is an extension of the CEBAF "south" linac He supply which is connected to one of the two CHL plants. Once connected the CEBAF linac and the LERF are cooled down from 4K to 2K together. To accommodate the two LCLSII cryomodules two of the three FEL cryomodules were removed. Attaching to the existing U tubes is a cryogenic transfer line with bayonet stubs that is then connected to the "Cryo Can" which contains the valves and piping to supply the LCLSII cryomodules [2]. The piping inside the cryo can allows the LERF cryomodules to be "bumped" up in

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temperature and for fast warms ups. Figure 2 shows the short transfer line connecting the U tubes to the cryo can. The two cryomodules initially installed in the LERF were J1.3-12 and J1.3-5. J1.3-12 was tested last winter and has since been shipped to SLAC for installation in their tunnel. J1.3J-5 is to be reconditioned to fix cryogenic performance issues identified during early cryomodule tests. Presently J1.3-16 is installed and undergoing testing.

SYSTEM READINESS

All of the hardware and controls were tested before the initial cryogenic cool down and RF being applied to the cavities. The three major systems, EPICS controls, cryo and RF had written procedures for initial check out and tests. These and remote development procedures were then presented at a system readiness review before system start up.

Figure 2: Showing the U tube, transfer line and cryo can connecting to the first cryomodule.

The cryogenic controls were also thoroughly tested prior to cool down. Items tested included: control of all 16 cavity heaters, all of the temperature diodes, all four of the pressure transducers, and all four cryo valves (JT and RT). Figure 3 shows the control screen for the cryomodule controls.

The RF system's four kW solid state amplifiers were operated into waveguide shorts for initial check out and power calibrations. Each amplifier was tested to 4 kW using the LLRF system as the source, while checking the forward and reverse power levels against the factor SSA settings. This ensured that the amplifiers internal interlocks were operational and as a check on the forward power calibrations. Since cavity testing would rely on the LLRF receivers for gradient and Q_L measurements these were given additional scrutiny.

The LLRF systems were calibrated in a test stand and then installed into their racks at SLAC. From there they were shipped to JLAB. At JLAB the LLRF receiver's calibrations were checked again.

Early on, remote development and checkout was identified as a key to success since much of the hardware and controls were being developed at other laboratories. Policies and procedures were developed such that systems could be safely developed and tested remotely. There were two concerns driving this. First that a remote developer could harm a production cryomodule, and second, a remote user could inadvertently harm the CHL which is providing both 2 K He to the LERF cryomodules and the operating CEBAF accelerator.

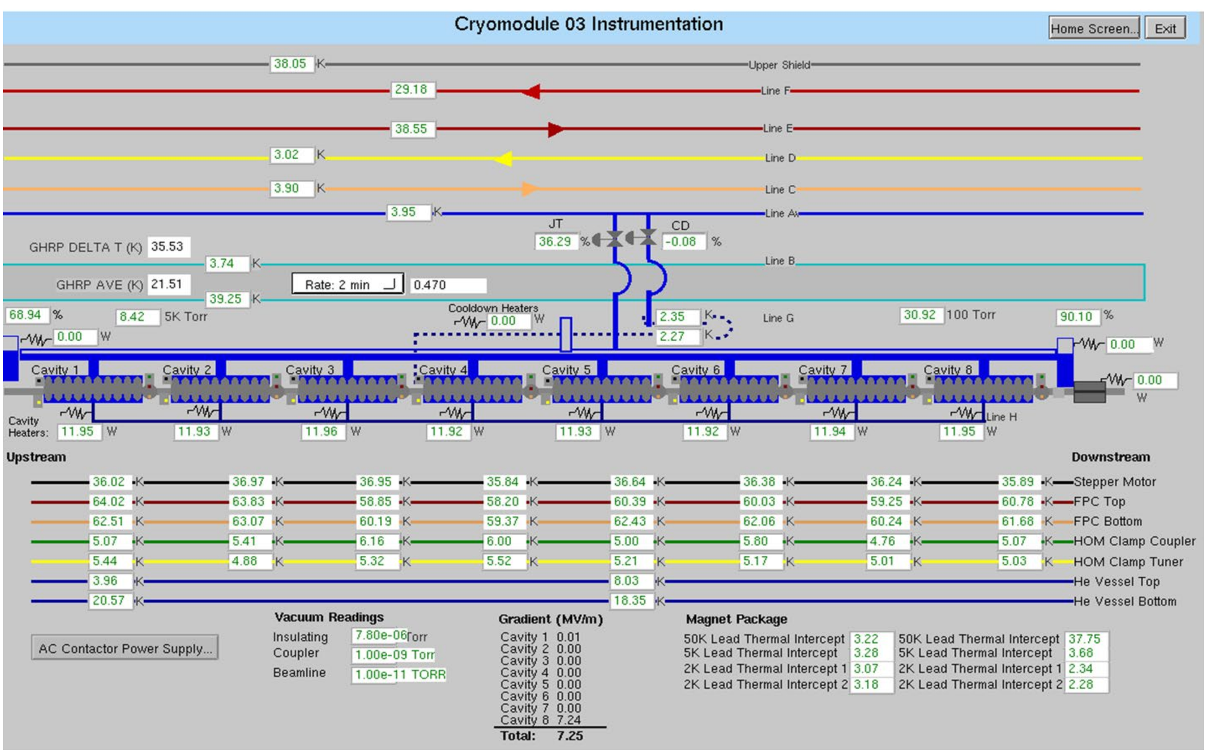

Figure 3: LCLS-II cryomodule EPICS cryo-control controls. Showing valves, heaters and temperature sensors.

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Before the first cool down, the procedures were implemented and refined to make remote modifications as seamless and safe as possible.

CRYOGENIC COOL DOWNS

The initial cool down of the cryomodules went very smoothly with no issues. The LERF is cooled down at the same time as the cryomodules in the CEBAF south linac. Cool downs are scheduled around the CEBAF operation schedule so that it is minimally invasive to the Nuclear physics program.

The cryo system in the LERF does allow for temperature bumps and cool downs independently of the CHL. To start a bump the LERF first uses the eight cavity helium vessel heaters to bring the cryomodule to atmospheric pressure, and then gas at 300K to warm the cavities to 40K. All return flow is directed to the recovery header. From 40 K the cool down rate is limited to ~ 15.1 K/min [2]. The fast cool down in the LERF is not limited by a lack of flow through the cryomodules but by the effects of sudden increase in flow through the 2K sub-cooler at the CHL. Therefore the flow into the cryomodules must be dialed back to keep the pressure manageable so not to trip the CHL.

CRYOMODULE COMMISSIONING

The J1.3-12 cryomodule underwent the full performance qualification testing that other cryomodules received at the other test facilities (JLAB and FNAL). These tests have been extensively described elsewhere, but include Qo, maximum useable gradient, field emission onset, along with tests that ensured the cavities and cryomodule met their performance specifications [3, 4]. Figure 4 shows the Qo's and gradients measured from J1.3-12.

Cavity	Serial #	QextFPC	Emax VTA	Emax LERF	Usable Gradient	FE Onset	Qo VTA	Qo @ 16MV/m	Material	Limit CM
1	L2-0254	4.15E+07	20.6	16.2	16	N/A	3.00E+10	3.00E+10	TD900	HOM Heating
2	L2-0278	4.20E+07	25.1	19.5	18.5	N/A	2.20E+10	2.90E+10	TD900	Quench
3	L2-0156	4.25E+07	23.5	21	21	N/A	2.60E+10	2.30E+10	TD900	Admin
4	L2-0155	4.34E+07	22.3	21	21	N/A	3.40E+10	2.10E+10	TD900	Admin
5	L2-0165	4.21E+07	25.4	21	21	20	3.20E+10	3.40E+10	TD900	Admin
6	L2-0166	4.36E+07	27	21	21	N/A	2.30E+10	3.10E+10	TD900	Admin
7	L2-0152	4.15E+07	24.7	19	18.5	N/A	2.90E+10	3.40E+10	TD900	Quench
8	L2-0153	4.10E+07	20	18.9	15	11.4	3.20E+10	3.00E+10	TD900	Quench
		Average		19.7	19			2.90E+10		
		Total Voltage (MV)		163.6	157.8					

Figure 4: J1.3-12 Qo and maximum useable gradient.

To facilitate these tests the LLRF system have built-in applications that measures the cavity Q_L and calibrates the gradient from the emitted reverse power. This made cavity commissioning easier since external test equipment was not needed or used (like in the older CMTF).

A different Qo measurement (than what is used in the JLAB CMTF) was developed and implemented in the LERF using the He liquid level. The measurement compares the dLL/dt, the rate of change of the He liquid level between a known electric heat and the RF heat when a cavity is at a specific gradient. Unlike pulsed SRF systems CW SRF systems must have electric heaters connected to each cavity in order to balance the cryo-plant load between RF on and off. This measurement takes advantage of these heaters using them in a calibrated fashion to measure the cavity Qo. Figure 5 shows the results of that measurement.

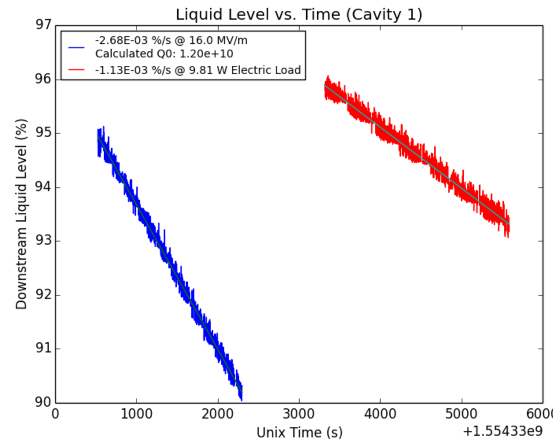

Figure 5: Qo Measurement: He Liquid level vs. electric heat and RF heat.

1.3 GHz (fundament mode) signals from the higher order modes (HOM) couplers were also automated within EPICs. A commercial "off the shelf" system (power meter and switch matrix) was assembled such that all 16 HOM couplers (both polarizations) could be monitored and measured for 1.3 GHz bleed through.

Multiple Cavity Operations

After the cryomodules were performance tested, all 16 cavities in the LERF were operated all at once. This was done in a two-step process, first turning on all eight cavities in J1.3-12 to 16 MV/m. The cavities were to operate in GDR, but some issues in the feed-back control firmware made this problematic and they were operated in SELA which only has amplitude lock. The initial eight cavity run of J1.3-12 went smoothly with no CHL issues. The heat load was manually balanced with the electric heat so the effective LERF cryo-load was stable.

After the success with J1.3-12, the eight cavities in J1.3-5 were turned on. This was more problematic. An issue with a personal safety system "area radiation monitor" tripped off all of the RF solid state amplifiers. This was traced to a field emitting cavity in J1.3-5. This cavity was left off for the remainder of the run. An additional issue is that J1.3-5 had not been put through a fast cool down, so the Qo's were higher than expected leading to more heat on the cryo system. Therefore several cavities were operated at a lower gradient to keep the heat load at a manageable lever. Even with these shortcomings both cryomodules achieved an accelerating voltage of 230 MV with no issues seen at the CEBAF CHL.

LLRF SYSTEM COMMISSIONING

The LCLS-II RF system footprint is designed to support the SLAC gallery to cryomodule layout [5]. The footprint for the LERF RF system is almost identical, where each

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cryomodule is divided between two LLRF control racks, such that four cavities are controlled from each rack. The LCLS-II RF system is a single amplifier, single LLRF controller per cavity. LLRF control is intelligently divided between a precision receiver chassis (PRC) which processes four cavity signals, and the RF station that processes the forward and reverse power and provides the drive signal to the SSA. Each RF station controls two cavities. Resonance control is provided by a stepper motor and a piezo tuner.

The RF system controls and functionality were fully tested during the first LERF operations. The LLRF system, on startup, performs a number of routines to measure the coupler loaded Q and RF amplifier linearity. Figure 6 shows an EPICS LLRF waveform screen, during a gradient calibration. All aspects of the hardware, firmware and software were tested against their performance goals. This also included testing of the cavity resonance controls and the cavity interlocks.

A key performance parameter for the LLRF system is the very tight phase and amplitude, 0.01° and 0.01% control which the LLRF must maintain for less than 1 second.

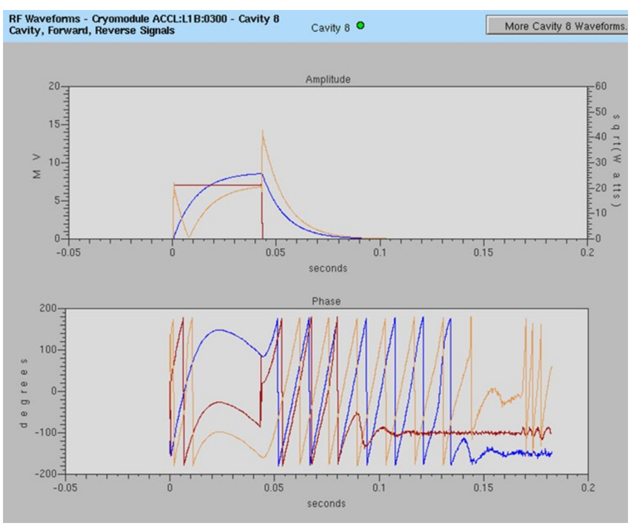

Figure 6: Cavity waveforms during QL and cavity probe Q measurements.

To that end the LLRF system was tested first in self excited loop (SEL) mode and then in generator driven resonator (GDR) mode, where it is locked both in phase and amplitude. Figure 7 shows a phase noise plot of the cavity field while the system is in GDR. The phase control measured was 0.05°, which is larger than specification, and is attributed to the local oscillator (LO) used in the LERF. Using the LCLS-II LO reference the phase rms cavity phase will fall below the specification.

The resonance control system worked as expected. The stepper motor interface easily tuned the cavities to within +/-20 Hz of 1.3 GHz. A frequency counter application was added in the middle of the commissioning run that extended the visible detuning range beyond 10 kHz when in SEL. The piezo controller, while capable of using a more sophisticated algorithm, only used an integrator for this run. The cavity microphonics in the LERF were small and the integrator controller had no trouble keeping up with the small He pressure drifts.

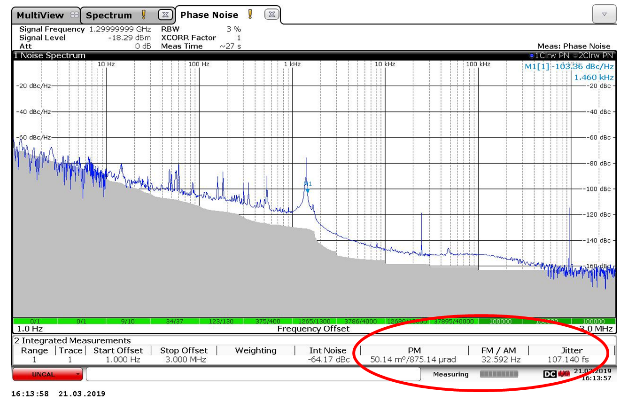

Figure 7: Phase noise plot of the cavity field.

An aspect of the commissioning that was extremely beneficial was the opportunity to test and turn on all of the RF applications before they are installed in the LCLS-II linac. No system is perfect at the start, and the LLRF controls were no different. LLRF experts would test aspects of the LLRF system locally, communicating "real" time with the remote developers. Modifications and improvements many times were made immediately, or at the worst, overnight. At the end of the run a list of improvements to the LLRF controls were made and for the most part are now being implemented during the present LERF commissioning run. The RF system as a whole will be ready on day one at SLAC to control a cryomodule and accelerate beam.

SUMMARY

The LERF Cryomodule test facility has been successfully commissioned. It has fulfilled both goals, first as an alternate commissioning facility for cryomodules, and second, as a place to "pre"commission the LCLS-II linac hardware and software. Two LCLS-II cryomodules have undergone commissioning, and a third is now being tested. The LCLS-II linac hardware and controls (RF, Cryo, and Vacuum) have been tested and are undergoing continuous refinements. CEBAF operations have not been affected by the testing, and remote development of the software and tools has been wildly successful.

REFERENCES

[1] J. N. Galayda, "The LCLS-II: A High Power Upgrade to the LCLS", *in Proc. 9th Int. Particle Accelerator Conf. (IPAC'18)*, Vancouver, Canada, Apr.-May 2018, pp. 18-23. doi:10.18429/JACoW-IPAC2018-MOYGB2

[2] N. A. Huque, E. Daly, and T. Wijeratne, "Upgrades to Cryogenic Capabilities for Cryomodule Testing at JLab", presented at the 19th Int. Conf. RF Superconductivity (SRF'19), Dresden, Germany, Jun.-Jul. 2019, paper THP051.

ISBN: 978-3-95450-211-0 doi:10.18429/JACoW-SRF2019-THP049

[3] M. Drury *et al*., "CEBAF Upgrade: Cryomodule Performance and Lessons Learned", *in Proc. 16th Int. Conf. RF Superconductivity (SRF'13),* Paris, France, Sep. 2013, paper THIOB01, pp. 836-843.

[4] M. Drury *et al.*,"Current Results From Acceptance Testing of LCLS-II Cryomodules at Jefferson Lab", presented at the 19th Int. Conf. RF Superconductivity (SRF 19), ' Dresden, Germany, Jun.-Jul. 2019, paper THP056.

[5] C. Serrano *et al.*, "RF Controls for High-Q Cavities for the LCLS-II", in *Proc. 9th Int. Particle Accelerator Conf. (IPAC'18)*, Vancouver, Canada, Apr.-May 2018, pp. 2929-2933. doi:10.18429/JACoW-IPAC2018-THYGBE3