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LCLS-II CRYOMODULE PRODUCTION AT JLAB*

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Abstract

The LCLS-II cryomodule construction program leverages the mature XFEL cryomodule design to produce technologically sophisticated cryomodules with a minimum of R&D according to an accelerated manufacturing schedule. JLab, as one of the partner labs, is producing 18 cryomodules for LCLS-II. To meet the quality and schedule demands of LCLS-II, many upgrades to the JLab cryomodule assembly infrastructure and techniques have been made. JLab reconfigured our clean room to provide a dedicated area for LCLS-II string assembly and instituted new protocols to minimize particulate transfer into the cavities during the cryomodule construction process. JLab has also instituted a set of magnetic hygiene protocols to be used during the assembly process to minimize magnetic field impingement on the finished cavity structure. The goal has been to have gradients, both maximum and field emission onset, that do not degrade between the cavity vertical test and final cryomodule qualification, while maximizing the Q_0 of each finished cavity. Results from the prototype cryomodule assembly are presented.

CRYOMODULE PRODUCTION AT JLAB

Jefferson Lab has a long standing core competency in cryogenics and superconducting radio frequency (SRF) systems. It is one of the underlying technologies that enabled CEBAF to provide unprecedented, high quality continuous wave (CW) beams initially at 4 GeV, then 6 GeV and now, with the recent upgrade, 12 GeV.

The primary mission of JLab's SRF enterprise is to maintain and improve the capability of the lab's accelerators for nuclear physics experiments, including developing the next generation of systems for a future electron ion collider (EIC).

A partial list of large cryomodule construction projects to date at Jefferson Lab include:

- Original CEBAF construction 42.25 cryomodules 1987-1993
  - 40 cryomodules plus Injector (2 cryomodules + two cryo-units), totalling 338 five (5) cell cavities
  - During peak production, 2 cryomodules were assembled per month
- SNS cryomodule, fabrication and test of 23 cryomodules built at JLab between 2001-2005
  - 11 Medium Beta , and 12 High Beta
- JLab FEL Project, 3 cryomodules started in 2003
- C50 refurbishment program started in 2006 (12 cryomodules as of 2016)
- 12 GeV, 10 cryomodules built from 2010-2012 using a new 7-cell "Low Loss" cavity design, new tuner, HOM couplers and probe feedthrough, new RF window design, and new cavity processing methods

Jefferson Lab has been in almost continuous cryomodule production for more than 25 years.

LCLS-II CRYOMODULE PRODUCTION

In the fall of 2013 the SLAC National Accelerator Laboratory approached Jefferson Lab to manufacture cryomodules for the LCLS-II free electron laser project being built at SLAC[1]. The schedule for the project is very aggressive and to meet it, the project decided to leverage the existing DESY and XFEL design [2] to produce technologically sophisticated cryomodules while minimizing the initial schedule risk and cost. Further, to reduce the time required to produce the large number of 1.3 GHz cryomodules required for the project, SLAC split the production between Fermi National Accelerator Laboratory (FNAL) and Jefferson Lab. The plan was to produce two identical prototype cryomodules utilizing as much existing hardware as possible to reduce schedule risk and overall cost while verifying the production design and processes [3]. Jefferson Lab and FNAL would share the procurement processes and use identical parts for the production modules, Figure 1. Each will build 17 production cryomodules with the plan that equivalent processes will yield equivalent performance. The goal is for each lab to ship a cryomodule to SLAC every five weeks.

Figure 1: LCLS-II Cryomodule.

The LCLS-II cryomodule also has a very demanding set of specifications [4]. The Q_0 and average gradient without field emission are much greater than previous cryomodules and required JLab to make a careful assessment of our procedures and facilities. As a result of that evaluation and the schedule constraints, several upgrades were made to improve cryomodule construction at JLab.

CRYOMODULE ASSEMBLY PROCESS

The assembly process begins with cavities arriving from industrial vendors and being inspected. After cavity inspection, each cavity is individually tested in the

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Table 1: LCLS-II Cryomodule Specifications

Quantity	Nom
$Q_{external}$, FPC is tunable	$4x10^7$
Average Cavity gradient, MV/m	>15.4
Field Emission Onset Gradient	>14
Dark Current, nA	<10
Total Cryomodule Accelerating Voltage, MeV	>124
Q_0, Measured at 16 MV/m	$>2.5x10^{10}$
HOM Q_{ext} at 16 MV/m	$>5x10^{11}$

Vertical Test Area (VTA) to confirm cavity performance prior to inclusion in a cavity string. The JLab VTA has two dewars which are used to test LCLS-II cavities and a third which is large enough to test up to three LCLS-II cavities at a time. All of the dewars in the VTA have the capability to tune the magnetic field in the dewar to avoid misleading Q_0 measurements. Once a cavity is qualified, it is placed, hermetically sealed and evacuated, on a rack in the clean room until enough cavities are available to assemble a complete string. Cavities are slowly bled up to atmospheric pressure using an automated system and assembled on a mobile rail using a set of "lollipop" supports. After assembly, the string is evacuated and leak checked and then rolled out of the cleanroom on the mobile rail to begin cryomodule assembly. The mobile rail system is unique amongst the partner labs.

The mobile rail rolls the completed string out of the clean room and mates to the Thomson rails that are part of work station 2, Figure 2. The assembled string is transferred off the mobile rail onto the fixed rails at work station 2. This second work station starts the process of instrumenting and attaching the helium piping to the string. The mobile rail is then taken to be cleaned and prepped for the next string assembly in the clean room. JLab uses two identical work stations 2 and 3. Figures 2 and 3 show the work stations schematically and in use at JLab. The schedule risk that a problem with an individual cryomodule during assembly would delay successor modules is mitigated by utilizing multiple identical workstations, on parallel assembly lines. If such an issue should arise, successor modules would be pushed to the parallel assembly rail until the issue could be evaluated and a plan for correction devised.

At work station 2, the cavity string has the split quadrapole magnet attached and aligned. The cavity heaters are attached to the helium vessels. The Berry bolts to support the cold couplers against the vacuum load are installed; this is done outside the clean room since the hardware for these supports, generates particles. The 2-phase piping tying the Tee's on the cavities together is welded on and leak checked. The first layers of Multi Layer Insulation (MLI) and magnetic shielding are installed, and cavity instrumentation is installed.

A pair of new overhead support fixtures, "4 posters", with integrated Thomson rails were built and attached to the existing pair of work station 2 Thomson assembly rails. This allows strings from work station 2, to roll directly under the support fixture and to be mated with the suspended Upper Cold Mass (UCM) assembly. Each of the two overhead support fixtures also are work station 3. By breaking up the work into separate work stations, the cryomodule assembly work can be broken into smaller, well defined tasks which can be described by Travelers within the JLab Pansophy system [5]. The traveler for work station 3, the four poster, describes discrete tasks such as alignment and tuner installation. At work station 3, the string is supported from the UCM on a set of needle bearings which allow the string to be aligned to less than 0.25 mm. The cavity tuners are then installed. The tuners use both a cold motor drive and a piezo drive and testing for cavity frequency changes during nominal operation using a network analyzer is noted in the traveler. After the tuners are installed and tested, the final instrumentation and heat stationing is done, and the 50 K shields are welded on.

Once the cavity string is mated to the UCM and all instrumentation, magnetic and thermal shields are installed, the cold mass is crane lifted into a new forty foot long cantilever support fixture where the cold mass has MLI applied and the cold mass is mated to the de-Gaussed vacuum vessel. This acts as work station 4 with a detailed traveler describing the assembly sequence.

After the cold mass is insulated and installed in the vacuum vessel, the cold mass is aligned to the vacuum vessel to set the coupler positions. The entire assembly is then craned to work station 5 where warm couplers, instrumentation flanges and the JT valves are welded into the helium circuits. Pressure tests of helium circuits, instrumentation checks, and warm coupler vacuum manifold installation all occur at work station 5. From work station 5, the completed cryomodule is rolled into the Cryomodule Test Facility (CMTF) for testing. The CMTF is the rate limiting factor for construction of LCLS-II cryomodules at JLab, with a five week turn around for cooldown, test and warm-up of the module.

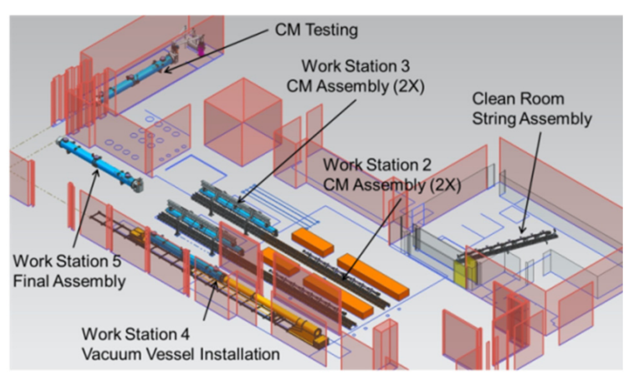

Figure 2: The work stations and work flow for LCLS-II cryomodules.

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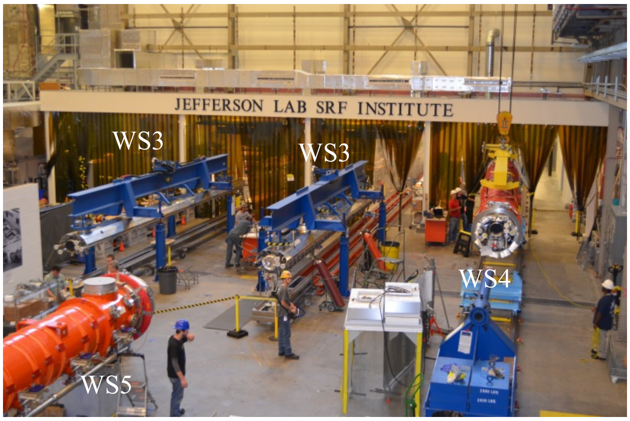

Figure 3: Actual work stations with two cryomodules at work station 3, one at work station 5 and one being craned out of work station 4.

When testing is complete, the module is removed from the cave and readied for shipment. Cryomodules are transported the 3,000 miles from JLab to SLAC over road on a custom modified flatbed trailer. The cryomodule itself is installed in a steel truss structure equipped with helical isolator springs. The springs are designed to attenuate large shocks from bumps etc. on the road. Two shipping caps are installed at either end of the cryomodule; these caps enclose the insulating vacuum space, and have features that restrain the inner piping of the cryomodule to further limit chances of damage. During each trip, accelerometers will record shock loads on the cryomodule, and vacuum gauges will monitor the condition of the beamline vacuum. After the first test of the prototype cryomodule in the CMTF, it was shipped on several trips of up to 300 mile distance to evaluate the effectiveness of the shipping structure [6]. The prototype cryomodule was then retested in the CMTF.

UPGRADES TO THE JLAB FACILITY

Within JLab's existing ISO4 clean room, an 1800 square foot area was sectioned and dedicated for LCLS-II string assembly. The area is isolated from other activities using clean room soft walls. To achieve ISO 4, the area maintains 100% ultra-low particulate air (ULPA) filtration coverage producing laminar flow with raised flooring and side-wall return. The sectioned area is directly coupled to a forty-foot garage door style air lock which is used to transfer assembled cavity strings out of the clean room into the cryomodule assembly stations. The strings are transferred using a mobile rail system which is unique to the JLab infrastructure. Process tools and High Pressure Rinse (HPR) are bulkheaded through the walls, Figure 4.

The "garage door" and plenum allow completed, 40 foot long strings to be rolled out after assembly. To best utilize that feature, a mobile rail system was procured which allows completed strings to be guided into the assembly path which best fits the schedule and available resources.

JLab performs an HPR on every cavity, including LCLS-II, immediately prior to assembly into a string. To improve that process, JLab procured a new, state of the art, high pressure rinse (HPR) tool which has been incorporated into JLab's suite of cavity processing equipment. The new HPR tool provides up to 10 gallons per minute of ultrapure water (UPW) at pressures up to 1500 psig. The tool has the capability of high pressure rinsing with both ambient and 80°C UPW.

Figure 4: LCLS-II string in JLab clean room.

Utilizing the new HPR to clean cavities immediately prior to string assembly and leaving the string hermetically sealed and under vacuum while the cryomodule is assembled, particulate transfer into the cavities is minimized. However, to keep the cold couplers under vacuum during assembly, a new fixturing system using "Berry" bolts was developed to prevent the bellows from collapsing. The Berry bolts hold the coupler flange at the correct position as the string is assembled and placed under vacuum. The bolts can then be removed during warm coupler installation, Figure 5.

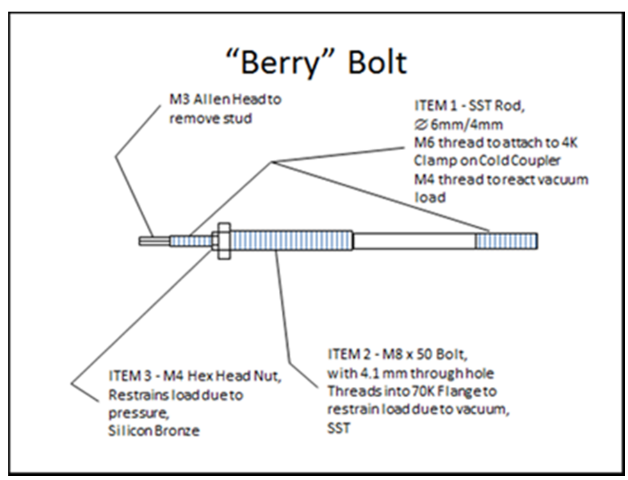

Figure 5: Berry bolts restrain the cold coupler flange against the vacuum load during assembly.

The CMTF was upgraded with a set of 8 digital Field Control, Interlock and Resonance Control Chassis for control of the rf system. This allows the cavities to be operated in generator driven resonance (GDR) mode. In addition, eight new 1.3 GHz solid state amplifiers were installed to allow simultaneous operation of all eight cavities during testing. A new temperature measurement and fluxgate magnetometer monitoring system was also added to monitor fast cooldown and magnetic expulsion

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of the cavities as they pass through T_c; both technologies are key to achieving the high Q_0's required from the cavities.

The CMTF cryogenic system was upgraded to handle the third 5 K helium circuit used in the LCLS-II cryomodules through the addition of a heat exchanger, a vaporizer and several new JT valves. In addition, a new cold box using turbines has been installed with the intent to increase the availability of 4 K liquid helium.

UPGRADES TO THE JLAB PROCEDURES

JLab and FNAL have instituted a set of magnetic hygiene protocols [7] to be used during the design and assembly process to minimize magnetic field impingement on the finished cavity structure. During design, substitutions of lower permeability materials, where possible, were made. Fluxgate magnetometers were placed on the cavities in

Figure 6: De-Gaussing of Prototype cryomodule. Cart in foreground is monitoring magnetometers in cryomodule during the process.

the prototype to measure the changes in incident magnetic flux on the cavities of different processes and environment during the assembly process. 10 Gauss was set as the maximum surface field for tooling used in close proximity to the cavity string. Small parts and tools are measured and demagnetized prior to use as part of the traveler process. The vacuum vessel itself is magnetically mapped and then wrapped with a set of coils and degaussed using a computer controlled power supply. These same coils are used as a final de-Gauss step for the completed cryomodule immediately prior to testing in the CMTF, Figure 6.

Specific new procedures were put in place to minimize the negative change in field emission onset voltage typically seen between the cavity test in the VTA and the cryomodule test in the CMTF. Besides keeping the string evacuated and hermetically sealed during assembly, a new portable cleanroom with separate gowning section was procured for the job of replacing the beamline pieces outside the string's gate valves with pumping tees and Faraday cups for the test in the CMTF. The techniques and tools used by the string assembly group were duplicated including a slow bleed up and pump down system and cleaning and bagging all parts prior to use. The goal of these tools and procedures is to minimize the introduction and motion of particles in the string during the beam tube change process.

RESULTS

The prototype cryomodule (pCM) was tested in the CMTF. Due to difficulties with the new cryogenic equipment, Q_0 data was not available. The pCM was then removed from the CMTF and reconfigured for shipping tests. The module returned from its 300 mile 'road trip' and was reconfigured for reinstallation into CMTF for retesting. Concerns were raised over the additional beamline tube reinstallation generating additional particles and whether the shipping test had moved existing particles in the module leading to lower field emission onset gradients. Results before and after the shipping test are shown in Table 2 [8].

The maximum gradient achievable did not change significantly between the VTA and first test and only cavity six was lower by more than 5% after the shipping test with several cavities' E_{max} actually improving. Field emission onset gradient, a strong indicator of particulate contamination of the cavities, did not change, pre and post trip, with 7 of the 8 cavities showing no field emission at all. Cavity 8 bears special mention because its FPC could not reach 4×10^7. It did not have a valid E_{max} during the first test and was power limited during the post

Table 2: Preliminary Cavity Performance Data, Pre and Post Shipping Tests

	Emax, MV/m			FE Onset Gradient, MV/m			
Cavity	**VTA**	**Pre-Trip**	**Post- Trip**	**VTA**	**Pre-Trip**	**Post- Trip**	**Limit CM**
1	19.8	16.7	17.1	15.3	No	No	Quench
2	23.7	20.8	19.8	No	No	No	Quench
3	21	19	20.5	No	No	No	Quench
4	23	18.8	20.5	No	No	No	Quench
5	21.3	16.2	21	No	No	No	Quench
6	20.2	20.5	18.3	16.4	12	12	Quench
7	19.8	20.8	19.9	No	No	No	Quench
8	16.7	-	18.8	No	No	No	Fwd Pwr Lim

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shipping test to 18.8 MV/m. The integrated gradient of the cryomodule at the cavities' field emission onset gradient,after the shipping test is just under 150 MeV for this module.

SUMMARY

The LCLS-II cryomodules have started production at Jefferson Lab as the latest in a series of cryomodule production projects. The specifications and production schedule for the LCLS-II cryomodules are very challenging and the JLab infrastructure and procedures have been upgraded to meet the challenge.

REFERENCES

[1] J.N. Galayda, "The New LCLS-II Project: Status and Challenges," Proceedings of LINAC 2014, Geneva, Switzerland, 2014, paper TUIOA04, pp.404-406.

[2] T.O. Raubenheimer. "LCLS-II: Status of the CW XRay FEL Upgrade to the SLAC LCLS Facility." Proceedings of FEL 2015, Daejeon, Korea, 2015, paper WEP014, pp.618-624.

[3] M. Ross, "SRF Linac for LCLS-II: Design Approaches, R&D, and First Test Results," presented at SRF2015, Whistler, Canada, Dec 2015, paper MOBA01, unpublished.

[4] A. Burrill, "1.3 GHz Cryomodule Performance Requirements and Minimum Acceptance Criteria", SLAC Document# LCLSII-4.5-PP-0670-R1.

[5] V. Bookwalter *et al.*, "Pansophy, a JLab SRF Engineering Data Management System, Supporting Data Collection, Retrieval and Analysis Utilized by LCLS-II," presented at SRF2017, Lanzhou, China, July 2017, paper MOPB043, this conference.

[6] N. Huque *et al.*, "LCLS-IICryomodule Transport System Testing," presented at SRF2017, Lanzhou, China, July 2017, paper MOPB112, this conference.

[7] G. Cheng *et al.*, "Magnetic Hygiene Control on LCLS-II Cryomodules Fabricated at JLab," presented at SRF2017, Lanzhou, China, July 2017, paper MOPB044, this conference.

[8] M. Drury, private communication, Jun. 2017