19th Int. Conf. on RF Superconductivity
ISBN: 978-3-95450-211-0

SRF2019, Dresden, Germany

JACoW Publishing
doi:10.18429/JACoW-SRF2019-THP056

CURRENT RESULTS FROM ACCEPTANCE TESTING OF LCLS-II CRYOMODULES AT JEFFERSON LAB*

M. Drury†, E. Daly, N. Huque, L. King, A. Solopova, Jefferson Lab, Newport News, VA, 23606
J. Nelson, B. Ripman, L. Zacarias SLAC, Stanford, CA, 94309, USA

Abstract

The Thomas Jefferson National Accelerator Facility is currently engaged, along with several other Department of Energy (DOE) national laboratories, in the Linac Coherent Light Source II project (LCLS-II). The SRF Institute at Jefferson Lab is currently building 21 cryomodules for this project. The cryomodules are based on the XFEL design and have been modified for continuous wave (CW) operation and to comply with other LCLS-II specifications. Each cryomodule contains eight 9-cell cavities with coaxial power couplers operating at 1.3 GHz. The cryomodule also contain a magnet package that consists of a quadrupole and two correctors. Most of these cryomodules will be tested in the Cryomodule Test Facility (CMTF) at Jefferson Lab before shipment to SLAC. Up to three of these cryomodules will be tested in a test stand set up in the Low Energy Recovery Facility (LERF) at Jefferson Lab. Acceptance testing of the LCLS-II cryomodules began in December 2016. Twelve cryomodules have currently completed Acceptance Testing. This paper will summarize the results of those tests.

INTRODUCTION

The LCLS-II main linac 1.3 GHz cryomodule is based on the XFEL design, including TESLA-style superconducting accelerating cavities, with modifications to accommodate CW (continuous wave) operation and LCLS-II beam parameters. [1]

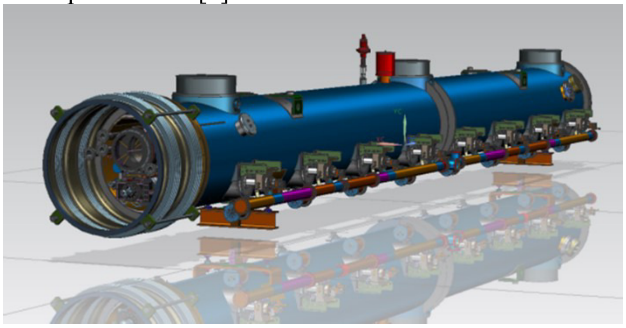

Figure 1: LCLS-II Cryomodule

Each cryomodule contains a string of eight 9-cell 1.3 GHz TESLA type cavities that have been nitrogen doped in order to reach a high quality factor (Q_0) of at least $2.7x10^{10}$ at the operating gradient of 16 MV/m. Power is delivered to the cavities through a TTF-3 coaxial power coupler that has been modified for CW operation and for the higher Qext's ($4x10^7$) required for LCLS II operations. Figure 1 shows a rendering of the LCLS II cryomodule.

Tuning of the cavities is accomplished using a lever-style tuner, consisting of the frame, two piezo actuators and a Phytron stepper motor. [2]

During Acceptance testing, the cavity string is cooled in superfluid helium to temperature near 2 K and each cavity is characterized in terms of gradient reach, field emission, and Q_0. Mechanical and piezo tuners are also characterized. The Qext's of the two HOM couplers are measured. In some cases, the notch frequencies of the HOM couplers are measured. The power couplers must be tunable to a Qext of $4x10^7$ and have a range from $1x10^7$ to $6x10^7$. The magnet package is operated to ensure that currents up to 18 A can be sustained without quenches.

CRYOMODULE TEST FACILITY

The CMTF at Jefferson Lab has been in operation for about 28 years. A variety of cryomodule designs that includes all of the designs in use at Jefferson Lab, the SNS cryomodules and now the LCLS-II design have been tested in this facility.

The CMTF consists of a shielded "cave" that houses the cryomodule and an adjacent Control Room. RF power sources such as klystrons and solid state amplifiers (SSA's) are located on a mezzanine above the cave. Concrete walls that are 4.5 ft. thick and a 3 ft. thick concrete roof provide radiation shielding. Magnetic shielding inside the cave maintains a controlled environment for testing with magnetic fields of 50 mG or less. Eight 3.8 kW SSA's deliver individual power to the cavities in each LCLS II cryomodule through a combination of coaxial hard-line and waveguide. A closed loop 2 K helium refrigerator, known as the Cryogenic Test Facility (CTF), provides cooling. The CTF can deliver 7-8 g/s of 4 K helium to the primary circuit for cool downs and 2-3 g/s for steady state operations. The CTF can also delivers several g/s to the 50K shield circuit. End Caps were fabricated specifically to connect these cryomodules to the CTF system.

New digital field control chassis, interlock chassis and resonance control chassis have been installed to test the LCLS II cavities. A variety of instrumentation including six channels of peak power measurement, ten channels of Geiger-Mueller (GM) tubes, a Faraday cup, various signal analysers and scopes are controlled and monitored through a combination of EPICS and Labview software packages. Figure 2 shows an LCLS II cryomodule installed in the Test Facility

---

* This work was supported by the LCLS-II Project and the U.S. Department of Energy, Contract DE-AC02-76SF00515.
† drury@jlab.org

Figure 2: LCLS II cryomodule in test cave.

LERF TEST STAND

The LCLS-II Test Stand is located in the LERF Vault. The Vault is a below-ground concrete enclosure located in the LERF building that provides radiological isolation for the control room and laser laboratories above. The Vault was originally designed to house the Jefferson Lab Free Electron Laser. The accelerator that was originally installed in the Vault consisted of an injector and an energy recovering linac (ERL) that contained 3¼ CEBAF design cryomodules.

The original linac has been dismantled leaving only 1¼ cryomodules in the first two RF zones of the original linac.

The LERF vault presented an opportunity to relieve schedule pressure on the CMTF by acting as a parallel testing facility. Further, the vault is a large enough space that two LCLS-II cryomodules could be installed and joined together using an interconnect unit in a configuration similar to that of the L1 segment of the LSCS-II accelerator. With one of the two Central Helium Liquefiers providing cooling, the LERF Test Stand presents opportunities for testing that are closer to the operational environment in the LCLS-II accelerator.

A two cryomodule vertical slice was installed in the LERF that consists of the two cryomodules with an end-can that contains cryogenic connection. High Power RF is supplied from sixteen 3.8 kW Solid State Amplifiers (SSA's). The SSA's along with four LLRF control racks two magnet control racks and cryogenic controls were supplied by the LCLS-II project and are identical to the hardware installed at the LCLS-II accelerator. The EPICS controls provided by LCLS-II are using the identical process variables and naming conventions that are planned for the L1 section of the LCLS-II linac. [3] Figure 3 shows the position of the LCLS-II cryomodules in relation to the original ERL beamline.

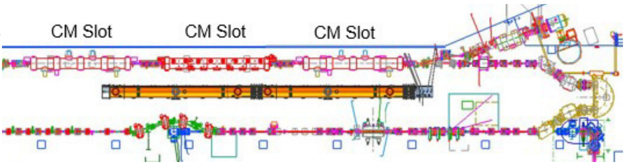

Figure 3: LCLS-II cryomodules installed in the LERF.

To date, one full test cycle has been completed with a cryomodule pair consisting of J1.3-05 and J1.3-12. A second pair, J1.3-05 and J1.3-16 have just begun their test cycle.

TEST RESULTS

Gradient Reach

Maximum gradients for the LCLS-II cavities are determined in the following manner. An initial set of measurements are made to determine the Q_{ext} of the Fundamental Power Coupler (Q_{ext}FPC), the Q_{ext} of the field probe (Q_{ext}FP), the frequency and gradient calibration. Q_{ext}'s of the Higher Order Mode (HOM) couplers are also measured. Gradients are then raised, using an automated script, in pulsed RF mode until a limit is reached.

The automated gradient ramping may be interrupted by attempts at either quench processing or field emission processing.

Once a limit is reached in pulsed mode, the limit is tested with CW RF in self excited loop (SEL) mode. In a few cases, heating issues in the FPC or in an HOM coupler become evident while running CW RF. Heating issues may result in lower gradients than are possible with pulsed RF.

Maximum gradients continue to be limited mainly by cavity quenches and an administrative limit at 21 MV/m.

Once the maximum gradient is defined, an attempt is made to operate the cavity for at least an hour in CW SEL mode. If the cavity is limited by quenching or a machine protection fault, the gradient is lowered by 0.5 MV/m before starting the run. In a few cases, further gradient reductions may be necessary in order to complete a one-hour run. The gradient at which a successful one hour run is completed is known as the maximum usable gradient or the maximum gradient for steady state operations.

When the one-hour run is complete, field emission is characterized. Note that the LCLS-II project's minimum acceptance criteria places a 50 mR/hr limit on radiation from a single cavity. This may lead to further reductions in the maximum usable gradient for cavities with field emitters.

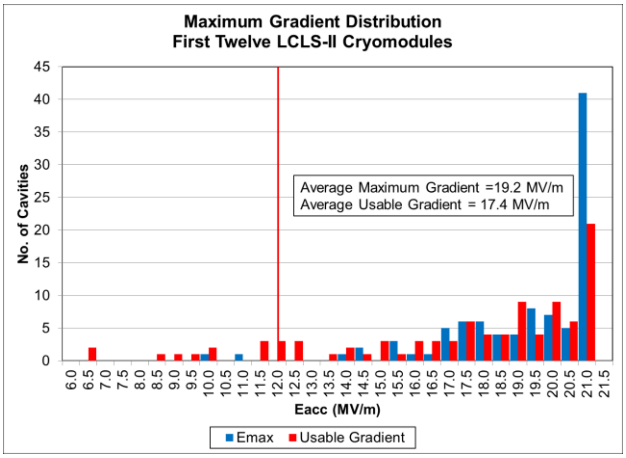

Figure 4: Maximum gradient distribution.

Figure 4 shows the distribution of maximum gradients for the 12 cryomodules tested so far. The average usable gradient is 17.4 MV/m. The minimum acceptable operating gradient for LCLS II cavities is 12 MV/m. Only twelve cavities have failed to meet this requirement.

Table 1 lists five cavities limited by end group quenches. These events may be the result of improperly tuned HOM couplers. Higher than normal heating in couplers with HOM Q_{ext}'s that did not meet the minimum requirement of $2x10^{11}$ appear to have resulted in quenches. This type of quench tends to manifest as a delayed quench. It is thought that at some constant gradient, some component such as the HOM coupler, begins to heat up eventually reaching a temperature that causes the cavity to quench. The tuning problem appears to have been solved by the time that J1.3-03 was tested. The last end group quenches were observed during the testing of J1.3-04. Four HOM Q_{ext}'s have failed to meet the requirement since J1.3-03 was tested. Each of these couplers were re-tuned after testing and before shipping.

Cavities listed as having FE related limits are cavities that had radiation levels high enough to set off the Personnel Safety System radiation monitors.

One cavity is listed as having an HOM Heating limit. In this case, an HOM coupler was incorrectly heat stationed leading to abnormal heating.

Table 1: Gradient Limits

Limit	Number of Cavities
Quench	48
Admin	29
FE related	11
End Group Quench	5
Coupler Vacuum / Heating	2
HOM Heating	1

Each cryomodule must deliver a minimum usable CW voltage of 128 MV. Figure 5 shows the predicted CW voltage for each of the cryomodules tested so far. Only one of the cryomodules tested, J1.3-08, have failed to meet this requirement.

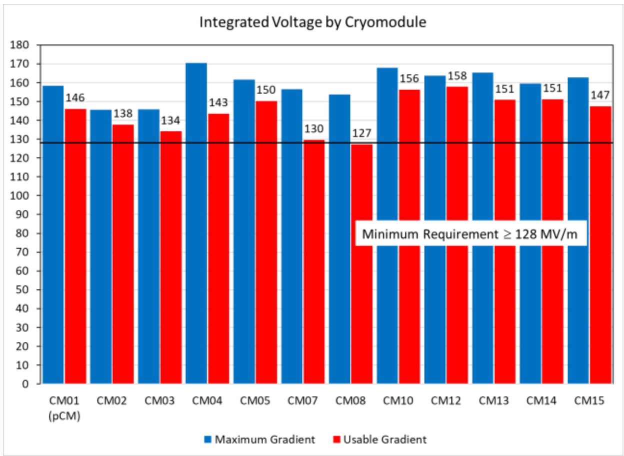

Figure 5: Integrated voltage by cryomodule.

Field Emission

The CMTF uses a ten-channel GM tube system known as a decarad to monitor field-emitted radiation generated by the cavities under test. The tubes are positioned so that there is a tube located at each coupler and at the beam pipe at either end of the cryomodule. Ion chambers that are a part of the Personnel Safety System are also monitored. A Faraday cup was recently installed at the downstream end of the cryomodule. Table 2 lists the Acceptance Requirements associated with field emission.

Table 2: Field Emission Requirements

Parameter	Value
Field Emission Onset	≥ 14 MV/m
Maximum radiation	50 mR/hr
Maximum dark current	< 1 nA

The maximum dark current is to be measured with all eight cavities in operation and phased to accelerate in gradient driven resonator (GDR) mode. Table 3 lists some statistics on the field emitting cavities tested so far.

Table 3: Statistics of Field Emitting Cavities

No. Field Emitting Cavities	29
No. Failing Onset Requirement	21
No. Failing Minimum Gradient Requirement	12

Field emission onset gradients for the 29 cavities varied from 3.7 MV/m to 20.0 MV/m with an average onset at 11.7 MV/m.

The Faraday Cup was first tested successfully on the single field-emitting cavity in J1.3-05 while running in SEL mode. Due to the limiting capacity of the CTF, it has not been possible to operate an LCLS-II cryomodule in the configuration necessary to determine if a cryomodule meets the dark current specification. The correct configuration is now possible in the LERF and J1.3-16, which has just begun its test cycle, will be the first cryomodule to undergo a measurement of dark current with all cavities running in GDR at 16 MV/m.

Q_0 Measurements

The LCLS-II project has set the minimum acceptable requirement for Q_0 at no less than $2.7x10^{10}$ at a gradient of 16 MV/m and a temperature of 2.0 K. In the CMTF, Q_0's are calculated using a calorimetric measurement of the power dissipated by the cavity into the helium bath. This is accomplished by isolating the cryomodule from the helium transfer lines and measuring the rate of rise of helium pressure with RF off, a known heater power, and finally with RF on. [4]

This method is not feasible for cryomodules installed in the LERF due in part to the joining of two cryomodules that does not allow for the necessary isolation from the helium supply. Instead a method of measuring rates of change in the liquid helium level in the cryomodule under different conditions has been developed. The supply valve is locked open at a predetermined position while heaters and RF are turned on and off. The varying rates of changes in the liquid level allow for a calculation of the RF heat load.

In order to achieve Q_0's as high as required by the LCLS-II project, fast cool down rates (dT/dt) through the superconducting transition temperature, T_C are necessary to ensure magnetic flux expulsion from the cavities. The necessary cool down rate appears to require 4 K helium delivery rates of about 30 g/s. As noted above, the CTF is able to deliver 7-8 g/s for cool downs. Several modifications have been made to the 4K supply hardware in an attempt to deliver higher mass flow. These included a temporary change in the u-tube configuration that bypassed the pressure drops associated with certain systems. [5] Further improvements that would include modification of the 4K-2K heat exchanger led to the first successful fast cool down during acceptance testing of J1.3-08.

Figure 6 illustrates the difference in cavity Q_0's once successful fast cool downs were achieved.

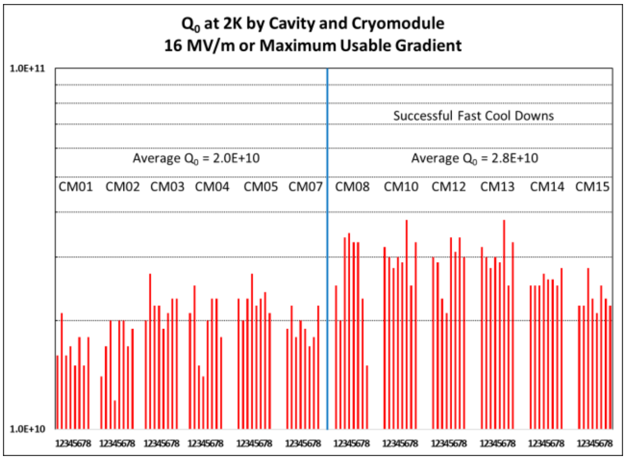

Figure 6: Q_0 by cavity and cryomodule.

Figure 7 shows the distribution of Q0's measurements at 2.0 K. The average measured Q0 for all tested cavities is 2.4x1010 with the highest Q0 at 3.8x1010. This group of measurements includes the highest Q0's ever measured in a cryomodule at Jefferson Lab.

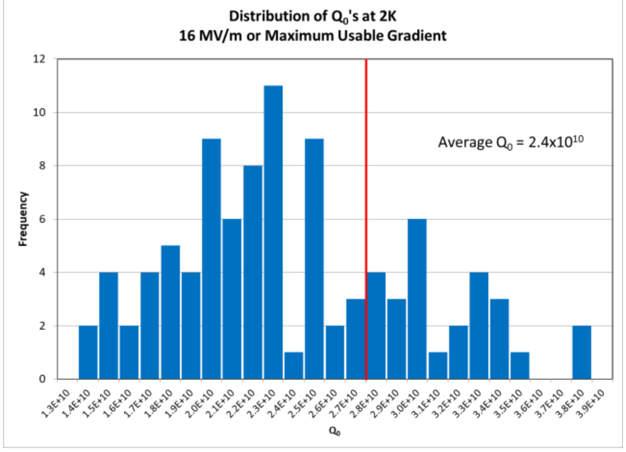

Figure 7: Q_0 istribution.

Other Testing

The magnet package is also checked out during Acceptance testing. The current for each of the three magnets is ramped up in steps to 18 A. The magnets must be operable at 18 A for at least 30 minutes without quenching. In the CMTF the magnets are run for at least 45 minutes. All of the magnets, with one exception, have passed this test. A corrector magnet in J1.3-07 failed. This was due to an open circuit in the wiring that has since been corrected.

Piezo and mechanical tuners are also tested. Mechanical tuners must demonstrate a range of ± 20 kHz around the operating frequency. Piezo tuners must have a range of 500 Hz. All of the cavity tuners tested so far have met or exceeded these requirements.

SUMMARY

Twelve LCLS II cryomodules have been tested in the CMTF at Jefferson Lab. All but twelve cavities have met or exceeded the minimum gradient requirement. The average maximum usable gradient for all of the cavities tested is 17.4 MV/m. Less than a third of the cavities in the twelve cryomodules exhibited field emission during testing. Twelve of those cavities had radiation levels high enough to limit usable gradient to below the minimum acceptable requirement. Cavity Q_0's for the first six cryomodules did not meet the requirement of $2.7\text{x}10^{10}$. The development of a successful fast cool down method, however, has led to improved Q_0 results. The average Q_0 for the last six cryomodules has increased by 40% to a value of $2.8\text{x}10^{10}$. All but one of the cryomodules have exceeded the minimum voltage requirement of 128 MV.

REFERENCES

[1] T. Arkan *et al.*, "LCLS-II 1.3 Ghz Design Integration for Assembly and Cryomodule Assembly Readiness at Fermilab", in *Proc. 17th Int. Conf. on RF Superconductivity*, pp. 895-897 (SRF 2015), Whistler, Canada, Sept 2015.

[2] N. Huque *et al.*, "Accelerated Life Testing of LCLS II Cavity Tuner Motor", in *Proc. 17th Int. Conf. on RF Superconductivity,* pp. 1257-1261 (SRF 2015), Whistler, Canada, Sept 2015.

[3] C. Hovater *et al*, "Commissioning the JLab LERF Cryomodule Test Facility", presented at 19th Int. Conf. on RF Superconductivity (SRF 19), Dresden, Germany July 2019, paper THP049, this conference.

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

[5] N. Huque *et al*, "Upgrades to Cryogenic Capabilities for Cryomodule Testing at JLab", presented at 19th Int. Conf. on RF Superconductivity (SRF 19), Dresden, Germany July 2019, paper THP051, this conference.