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ACCEPTANCE TESTING OF THE FIRST GROUP OF LCLS II CRYOMODULES AT JEFFERSON LAB*

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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 17 cryomodules for this project. The cryomodules are TESLA style cryomodules that have been modified for continuous wave (CW) operation and for other LCLS II specifications. Each cryomodule contains eight 9-cell cavities with coaxial power couplers operating at 1.3 GHz. The cryomodules also contains a magnet package that consists of a quadrupole and two correctors. These cryomodules will be tested in the Cryomodule Test Facility (CMTF) at Jefferson Lab before shipment to the Stanford Linear Accelerator (SLAC). Acceptance testing of the LCLS II cryomodules began in December 2016. Seven 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]

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 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 (4x107) required for LCLS II operations. Figure 1 shows a rendering of the LCLS II cryomodule.

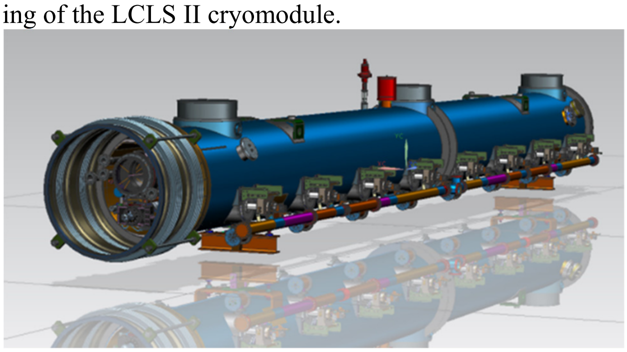

Figure 1: LCLS II Cryomodule

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 cryomodule is cooled to 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 notch frequencies and Qext's of the two HOM couplers are measured. The power couplers must be tunable to a Qext of $4x10^7$. The magnet package is operated to ensure that operation up to 18 A is possible 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.

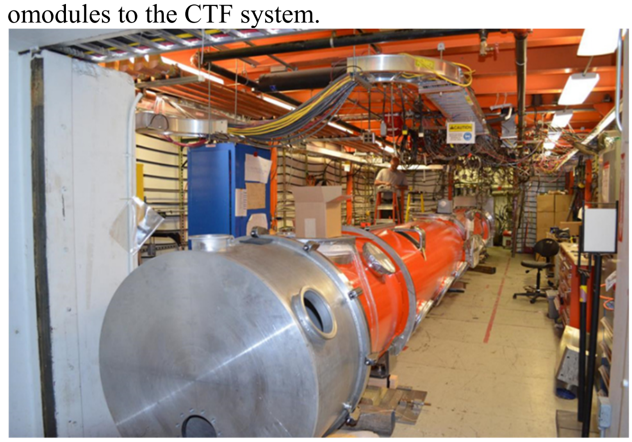

Figure 2: LCLS II Cryomodule in Test Cave

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

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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

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 Qext of the Fundamental Power Coupler (Q_{ext}FPC), the Q_{ext} of the field probe (QextFP), frequency and gradient calibration. Q_{ext}'s of the Higher Order Mode (HOM) couplers are also measured. Gradients are then raised in pulsed RF mode until a limit is reached.

Maximum gradients have so far been limited mainly by cavity quenches and the administrative limit at 21 MV/m.

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 in CW, resulting in end group quenches, for example, and further reduction in the maximum gradient.

Once the maximum gradient is defined, an attempt is made to operate the cavity for at least an hour in CW mode. If the cavity is limited by quench or a machine protection fault, the gradient is lowered by 0.5 MV/m before starting the run. In some cases, further gradient reductions may be necessary in order to complete a one-hour run. The gradient at which a successful one hour 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, depending on the magnitude, radiation may place further limits on usable gradient.

Figure 3 shows the distribution of maximum gradients for the six cryomodules tested so far. The average usable gradient is 16.8 MV/m. The minimum acceptable operating gradient for LCLS II cavities is 12 MV/m. Only eight cavities have failed to meet this requirement.

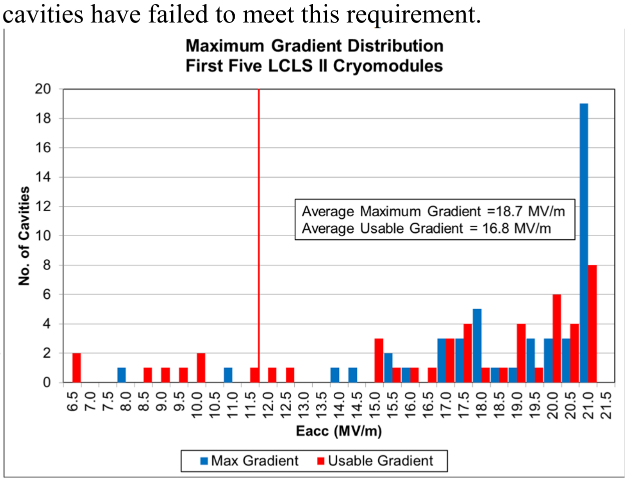

Figure 3: Maximum Gradient Distribution

Table 1 lists the various limits on maximum gradient.

Table 1: Gradient Limits

Limit	Number of Cavities
Quench	22
Admin	14
FE related	8
End Group Quench	5
Coupler Vacuum / Heating	1

Table 1 lists five cavities limited by end group quenches. These events appear to be due to improperly tuned HOM couplers. Abnormal heating in couplers with HOM Q_{ext}'s that did not meet the minimum requirement of $2x10^{11}$ appear to have resulted in quenches. The tuning problem appears to have been solved by the time that J1.3-03 was tested. End group quenches have ceased in J1.3-05 and J1.3-07. Only one HOM Qext failed to meet the requirement in the last three cryomodules.

Each cryomodule must deliver a minimum CW voltage of 128 MV. Table 2 lists the predicted CW voltage for each of the cryomodules tested so far. All of the cryomodules tested have exceeded this requirement.

Table 2: Cryomodule Voltage

Cryomodule	Average Usable Gradient (MV/m)	CW Voltage (MV)
J1.3-01	17.3	143.3
J1.3-02	16.6	137.5
J1.3-03	16.2	134.5
J1.3-04	17.3	143.3
J1.3-05	18.1	150.3
J1.3-07	15.6	129.5

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 3 lists the Acceptance Requirements associated with field emission.

Table 3: Field Emission Requirements

Parameter	Value
Field Emission Onset	$\geq$ 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 4 lists some statistics on the field emitting cavities tested so far.

Table 4: Statistics of field emitting cavities

No. of Field Emitting Cavities	14
No. Cavities Failing Onset Requirement	10
Number with Usable Gradients Reduced	10

Nine of the fourteen field emitting cavities experienced what appear to be the creation of new field emitters during the initial gradient ramp up. These events manifested as a

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quench followed by significant increases in radiation production. This group of cavities tend to have the lowest onset gradients and highest radiation levels. Onset gradients for all fourteen cavities varied from 5.0 MV/m to 19.3 MV/m with an average onset at 11.1 MV/m.

The Faraday Cup was first tested successfully on the single field-emitting cavity in J1.3-05 while running in SEL mode. The ability to run all eight cavities phased together in GDR mode was achieved for the first time on J1.3-07. It is expected that, in future tests, dark current measurements as specified by the project will be possible.

Q_0 Measurements

The LCLS II project has set the minimum acceptable requirement for Q_0 at no less than 2.7×10^{10} at a gradient of 16 MV/m and a temperature of 2.0 K. During the Acceptance testing process, 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. [3]

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 at 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 modifications were tested on the last two cryomodules tested and appeared to supply 4K helium at ~30 g/s. However, Q_0 measurements made before and after the attempted fast cool down were approximately the same. Analysis of cool down date afterwards showed that dT/dt near T_C was only ~2 K/min. A cool down rate this low is expected to "significantly impede flux expulsion on JLab measured cryomodules". [4]

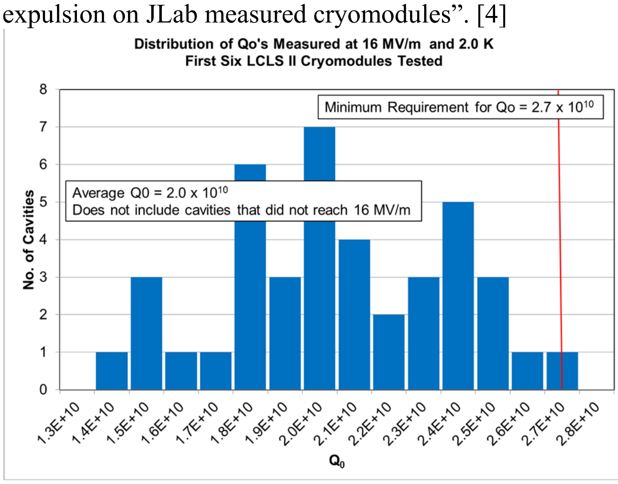

Figure 4: Q_0 Distribution

Work will continue on methods to facilitate a cool down that will achieve the necessary flux expulsion.

Figure 4 shows the distribution of Q_0's measurements at 16 MV/m and 2.0 K. It does not include measurements on cavities that could not reach 16 MV/m. This group includes seven cavities and are a subset of the group of cavities that experienced the creation of new field emitters during testing. The average measured Q_0 is 2.0×10^{10} with the highest Q_0 at 2.7×10^{10}. This group of measurements includes the highest Q_0's ever measured in a cryomodule at Jefferson Lab.

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

Six LCLS II cryomodules have been tested in the CMTF at Jefferson Lab. All but eight cavities met or exceeded the minimum gradient requirement. The average usable gradient for all of the cavities is 16.8 MV/m. Fourteen cavities exhibited field emission during testing. Ten of those cavities did not meet the minimum requirement for onset gradients and had radiation levels high enough to limit usable gradient. Cavity Q_0's, as measured in the CMTF, do not meet the requirement of 2.7×10^{10}. This, however, is due to the limitations of the CTF refrigerator and not to the quality of the cavities. All of the cryomodules have exceeded the minimum voltage requirement of 128 MV.

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