ISBN: 978-3-95450-211-0 doi:10.18429/JACoW-SRF2019-THP060

EXPERIENCE WITH LCLS-II CRYOMODULE TESTING AT FERMILAB*

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Abstract

The Cryomodule Test Stand (CMTS1) at Fermilab has been engaged with testing 8-cavity 1.3 GHz cryomodules designed and assembled for the LCLS-II project at SLAC National Accelerator Laboratory since 2016. Over these three years twenty cryomodules have been cooled to 2 K and power tested in continuous wave mode on a roughly once per month cycle. Test stand layout and testing procedures are presented together with results from the cryomodules tested to date. Lessons learned and future plans will also be shared.

INTRODUCTION

LCLS-II is a next generation hard x-ray light source based on a superconducting RF electron linac operating in continuous wave regime. Its current status is described elsewhere at this conference [1]. As one of the partner labs Fermilab is responsible for the design of the 1.3 GHz Cryomodules (CM's) as well as assembly and testing for approximately one-half of the specified 1.3 GHz cryomodules. Additionally, Fermilab is designing and will assemble and cold test two 8-cavity 3.9 GHz (third harmonic) cryomodules plus a spare. Both the Cryomodule Test Facility and specifically the CMTS1 test stand and early test results have been described previously [2, 3]. As of this writing (June 2019) nineteen cryomodules have passed through CMTS1 – 18 Fermilab-built ones and the first Jefferson lab assembled one. The scope of this paper will focus on test results only for Fermilab-built cryomodules

The LCLS-II design is cutting edge in terms of continuous wave (CW) operating gradient and Q0. The design work and techniques to achieve such performance is described elsewhere [4].

TESTING STRATEGY

As a guide for qualifying LCLS-II cryomodules, a set of Acceptance Criteria were jointly developed and adopted by the partner laboratories (SLAC, Fermilab, Jefferson Lab) [2]. These form the basis of the testing plan and qualification specifications employed at CMTS1. Figure 1 lists the acceptance criteria and Figure 2 summarizes the performance of each Fermilab built and tested cryomodule against them. As can be seen in the latter figure, with rare exception cryomodules meet, and routinely exceed, these standards.

Parameter	Value	Minimum acceptable performance during test
Minimum acceptable operating gradient for an individual cavity	12 MV/m	Requires radiation associated with the cavity measured outside the CM be < 50 mR/hr and the quench level be at least 0.5 MV/m higher than the operating gradient Usable gradient shall be defined as stable operation for at least 1 hour of c.w. operation.
Minimum CW voltage produced by an individual cryomodule	128 MV	The total CW voltage produced by an individual cryomodule shall be ≥128 MV with all cavities powered simultaneously and an average of cavity gradient ≥15.4 MV/m. If the CM test stand does not support operation of all 8 cavities together then two - 4 cavity runs can be carried out instead.
Minimum cavity gradient at onset of field emission	14 MV/m	The onset of measurable field emission shall be at a gradient of ≥ 14 MV/m
Captured dark current	<1 nA	The dark current as measured by Faraday cups at each end of a cryomodule at the minimum CW voltage as defined above shall be ≤1 nA when the cavities are operated in GDR mode with the relative phases set to accelerate speed of light electrons.
Average cavity Q_0 within a cryomodule	2.7×10^{10}	Average Q_0 of cavities within a CM ≥2.7×10^{10}, measured at 16 MV/m
Cryomodule operating duration with RF power during test		Each cryomodule must operate at the minimum CW voltage or greater until the coupler temperatures achieve equilibrium or for a minimum of ten (10) hours continuously, whichever is less, to verify stable operation and confirm acceptable coupler heating
Cryomodule heat load during test at 128 MV voltage		Dynamic 2 K ≤ 86 W; Dynamic 5 K ≤ 8 W; Dynamic 45 K ≤ 92 W Static 2 K ≤ 7 W; Static 5 K ≤ 17 W; Static 45 K ≤ 123 W Total 2 K ≤ 93 W; Total 5 K ≤ 25 W; Total 45 K ≤ 215 W The impact of end caps in cryomodule testing is estimated to be <1 W
Cryomodule thermometry		All installed thermometry shall be verified functional by observing consistency in output with operational conditions. For sensors measuring identical locations on components within a cryomodule there shall be variation of no more than 0.2 Kelvin under the same conditions at each component and under static load with no power applied to the cavities or magnets
Cryomodule liquid level sensors		Liquid level sensors shall be verified functional by observing liquid levels and changes therein consistent with liquid supply rates and estimated boil-off rates
Cryomodule cryogenic valving		JT valve, CoolDown/Warm up valves shall all be verified functional during cryomodule operations by consistency with expectations for operational performance, in particular, no valve is to have ice form on the room temperature components.
Cavity tuning to resonance during test (slow tuner)		Each cavity must be able to be tuned to a resonant frequency of 1300.000 MHz with a minimum available tuning range of ± 0.02 MHz at 2 K
Fast tuner minimum range	0-500 Hz	
Heater performance		All installed heaters shall be verified functional by measuring resistance of 45±6 Ω at 2 Kelvin. Heaters must be demonstrated functional in a cryomodule as verified by heating of the helium: • Six (6) of the eight (8) heaters on the helium vessels • Two (2) of the three (3) heaters on fill lines • Both heaters on liquid level units
Fundamental power coupler 50 K coupler flange maximum temperature	150 K	
Fundamental power coupler warm part maximum temperature	450 K	
Cavity HOM coupler rejection of 1.3 GHz power		$Q_{ext} \geq 2 \times 10^{11}$, maximum power measured at 1.3 GHz out of a single HOM coupler is 1 W at 16 MV/m
Magnet electrical verification		The magnet package shall be verified electrically to be without shorts or opens, hi-pot test at 500 V with <1 μA under insulating vacuum, <5 μA in ambient pressure, and can be operated at a current of at least 18 A for a minimum of 30 minutes without quenching
BPM electrical verification and signal balance		The BPM shall be verified electrically to be without shorts or opens, with cross-talk between electrodes ≤ -30dB. The difference in S-parameter (S21) between electrodes is < 1dB over a frequency range of 0.5 to 2.5 GHz
Cryomodule vacuum		Cryomodule beamline vacuum prior to cooldown 1×10^{-8} Torr Cryomodule insulating vacuum prior to cooldown 1×10^{-4} Torr Cryomodule warm coupler vacuum prior to cooldown 1×10^{-7} Torr Cryomodule beamline vacuum at 2 K 1×10^{-9} Torr Cryomodule insulating vacuum at 2 K 1×10^{-6} Torr Cryomodule warm coupler vacuum at 2 K 5×10^{-8} Torr

Figure 1: LCLS-II 1.3 GHz Cryomodule Acceptance Criteria.

CMTS1 SCHEDULE

Cryomodules are tested on a roughly 28-day cycle with 11 days planned for installation and leak checking, 3 days for cooldown from room temperature to 2K, 7 days for cold, powered testing, and 7 days for warm-up and removal. With the exception of the first cryomodule which

* This manuscript has been authored by Fermi Research Alliance, LLC under Contract No. DE-AC02-07CH11359 with the U.S. Department of Energy, Office of Science, Office of High Energy Physics.
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ISBN: 978-3-95450-211-0 doi:10.18429/JACoW-SRF2019-THP060

necessarily took longer time due to CMTS1 commissioning and remediation of thermoacoustic oscillations, cryomodules on average pass through CMTS1 in less than 45 days.

Installation & Removal

Cryomodule installation and removal at CMTS1 consumes the bulk of the 28-day testing schedule with 12 days allotted for installation and cooldown and 7 days for warmup and removal. This schedule was not consistently hit until about the tenth cryomodule to pass through the test stand. This is mostly due to improvements in task scheduling and sequencing, fewer assembly issues with incoming cryomodules as production hit stride, and tasks becoming more routine. As tasks became routine, workers learned who to contact for the next job in their area, relieving the burden on a central coordinator and also removing that coordinator as a possible bottleneck in the process.

Two improvements to increase throughput were made that may seem simple but had a large effect. First, all the appropriate tools for each job were bought and hung on the cave wall to avoid wasted time searching around for the correct tool for each job. Re-usable materials such as MLI and shielding are stored around the cave near their respective jobs. Second, people are cross-trained so that delays due to personnel unavailability are minimized.

COLD TESTING

The 7 days of cold testing generally follow a prescribed sequence once 2 K is achieved:

- Cavities are set to 1.3 GHz resonant frequency, tuner operation verified,
- 30-minute initial microphonics data capture
- QL set to nominal 4.1E+07
- Initial cw power rise to 16 MV/m in parallel with Low Level RF (LLRF)/gradient calibration
- Power rise to peak achievable gradient, limited administratively to 21 MV/m
- Field emission onset and dark current evaluation
- Usable Gradient (one-hour continuous operation) determination
- Warm-up to 50 K followed by 'fast' (minimum 32 g/s) cooldown for magnetic flux expulsion
- Single cavity Q0 measurements at nominal (16 MV/m) gradient
- Unit test – all cavities operating at nominal for at least 8 hours, magnet coils energized at 20 A each, evaluation of fundamental power coupler heating, microphonics data capture, attempts to operate cavities in Generator Driven Resonance (GDR) mode.

In parallel to the above steps, ancillary subsystems are also checked against their acceptance criteria. These include:

- Magnet checkout
- BPM cross-talk
- HOM spectrum measurements
- HOM power and heating
- Fine (piezo) tuner checkout
- Microphonics evaluation (described below)
- Cryogenic system thermometry and heater checks
- Vacuum levels
- Fundamental Power Coupler (FPC) heating.

In the infrequent instances where performance specifications have not been met, cryomodules have been partially disassembled and mitigation steps taken. These steps have included re-tuning HOM's, replacing FPC sections or re-tightening loose joints, and in one case of loss of beam line vacuum, re-building the cavity string.

Cryo-module #	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17
Gradient	ok	n/a	x	ok	ok	ok	ok	ok	ok	ok	ok	ok	ok	ok	ok	ok	ok
CW Volts	ok	ok	ok	ok	ok	ok	ok	ok	ok	ok	ok	ok	ok	ok	ok	ok	ok
FE onset	ok	x	x	x	x	x	ok	ok	x	ok	ok	ok	ok	ok	ok	ok	x
Q0	ok	ok	ok	x	ok	x	ok	x	ok	ok	ok	ok	ok	ok	ok	ok	ok
Unit Test	ok	ok	x	ok	x	ok	ok	ok	ok	ok	ok	ok	ok	ok	ok	ok	ok
Instr.	ok	ok	ok	ok	ok	ok	ok	ok	ok	ok	ok	ok	ok	ok	ok	ok	ok
Tuners	ok	ok	ok	ok	ok	ok	ok	ok	ok	ok	ok	ok	ok	ok	ok	ok	ok
Couplers	ok	ok	ok	ok	x	ok	ok	ok	ok	ok	ok	ok	x	ok	ok	ok	ok
HOMs	ok	x	ok	ok	x	ok	ok	ok	ok	ok	ok	x	ok	ok	ok	ok	ok
Magnet	ok	ok	ok	ok	ok	ok	ok	ok	ok	ok	ok	ok	ok	ok	ok	ok	ok
BPM	ok	ok	ok	ok	ok	ok	ok	ok	ok	ok	ok	ok	ok	ok	ok	ok	ok
Vacuum	ok	x	ok	ok	ok	ok	ok	ok	ok	ok	ok	ok	ok	ok	ok	ok	ok

Figure 2: Summary of achievement of Acceptance criteria. Green/'ok' indicates satisfactory performance while red/'x' is outside of acceptable bounds.

Gradient Determination

The gradient of each cavity is determined by means of the forward power technique:

$$E_{acc} = 2\sqrt{\left(\frac{R}{Q}\right)Q_L P_f}(1 - e^{-\frac{\omega t}{2Q_L}})/L$$

The forward power, P_f, is measured very close to the output of the 4 kW Solid State Amplifier (SSA) driving the cavity to minimize the directional coupler signal deviation due to reflected power. During the early stages of testing, this technique was compared against the technique based on the cavity field and the former was determined to provide a more accurate and reproducible means of determining the gradient at CMTS1 by approximately a factor of two. Calibration checks, including by means of a calorimetric load, and regular re-calibrations of the power meters prior to each test have ensured continued good accuracy.

Pulsed Processing/multi-pacting/peak Gradient

For 1.3 GHz cavities, the multi-pacting band is in the range of 17-23 MV/m, coincidentally where determination of the peak gradient occurs. During the peak power rise, multi-pacting is exhibited by cavity quenches beginning at 17 to 18 MV/m. Switching from cw to pulsed mode with pulse lengths varying from 40 to 90 milliseconds at a 1 Hz repetition rate and gradually increasing the drive voltage as the incidence of quench disappears allows cavities to be processed through the band and typically achieve maximum gradients at or close to the administrative limit of 21

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MV/m. Ensuring that any detected radiation remains well below acceptable personnel exposure limits outside of the shielded test cave drives the administrative gradient limit. Processing takes anywhere from a few minutes to nearly an hour in extreme cases and is often accompanied by field emission which subsides when cw operation is restored.

A few cavities have been able to reach the 21 MV/m limit without processing, but recently as a matter of practice, all cavities are processed for at least 10 minutes after their quench limit is reached.

Usable Gradient

As a final test of gradient performance, each cavity's 'Usable Gradient' is determined. This is the value at which a cavity operates for one hour continuously with detected radiation ≤50 mrem/hour. In case of a quench limit, the value is set at 0.5 MV/m below the measured quench field. On average the Usable Gradient is within 95% of the peak gradient.

Gradient Summary

Figure 3 provides a summary of the average Peak, Usable, and VTS measured Gradient for the seventeen cryomodules which have undergone a complete test cycle at CMTS1. VTS values are well above due to there being no limit on achievable gradient. Performance is on average comfortably above the nominal gradient (16 MV/m) and well in excess of the acceptance limit of 12 MV/m, not to mention the field emission onset limit of 14 MV/m.

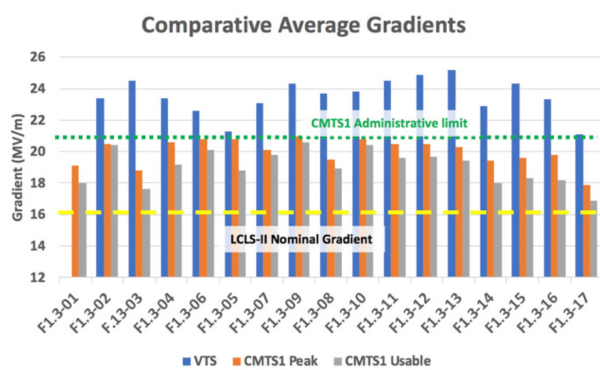

Figure 3: Average Cryomodule Gradient Performance. The dotted yellow line indicates the LCLS-II nominal specification of 16 MV/m. The green line denotes the 21 MV/m administrative limit at CMTS1.

Field Emission & Dark Current

An extensive array of radiation detecting sensors are employed in CMTS1 to measure both field emission (x-rays measured transversely to the longitudinal axis of the cryomodule) and dark current. Faraday cups are installed at each end of the test stand to detect dark current produced. Supplemental systems in addition to the required personnel protection detectors have been added over time and their layout is portrayed in Fig. 4. These include:

- Fermilab-built Total Loss Monitor (TLM)
- Prototype SLAC optical fiber-based loss detector
- G-M tube 'DecaRad' system courtesy of Jefferson Lab
- Fermilab-built 'FOX' x-ray detectors
- Dosimetry (TLD badges).

This suite of detectors provides extensive coverage using complementary detectors. All of these systems are interfaced to the CMTS1 controls system allowing for both real time monitoring and archiving capability.

Overall only 14 of the 144 cavities tested to date have exhibited detectable field emission and or dark current production. The majority of occurrences are with the first four cryomodules assembled and appear to be due to cleanliness issues during string assembly. Mitigation steps are described elsewhere at this conference [5,6].

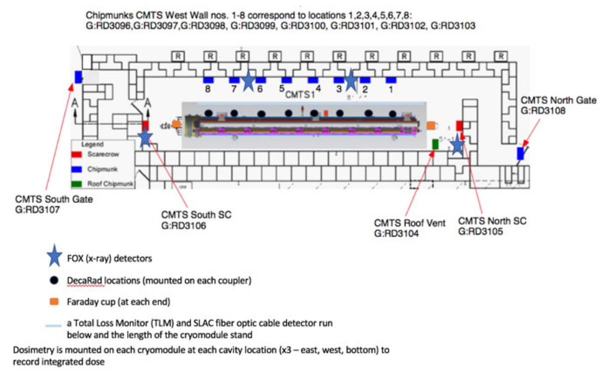

Figure 4: CMTS1 Radiation Detector Layout.

Dosimetry has been installed at 26 locations around the cryomodule to assess integrated doses during the entire test sequence since the onset of F1.3-09 testing. An array of three dosimeters are placed longitudinally in the eight locations corresponding to the location of the FPC's. Placement of the three are circumferentially at the 3, 6 (bottom) and 9 o'clock locations.

A representative distribution from cryomodule F1.3-16 is shown in Fig. 5. No cavity exhibited field emission during cw operation; what is shown here was likely produced during pulsed processing. Note that when a dose is detected, the maximum is typically from the bottom, 6 o'clock.

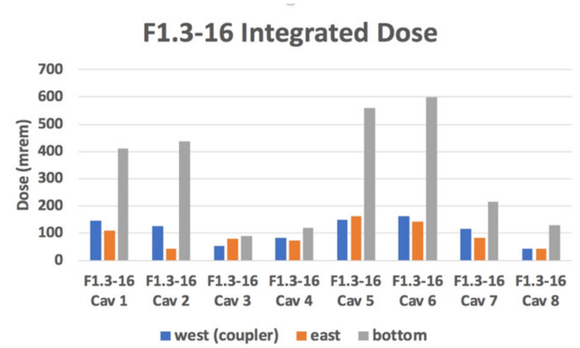

Figure 5: F1.3-16 dosimetry results. Peak doses are almost exclusively detected at the bottom of the cryomodule.

Single Cavity Q0 Determination

LCLS-II operation will depend greatly on maximizing the Q0; the attendant acceptance criterion specifies an average value for a cryomodule of 2.7E+10, a world-class level. At CMTS1 Q0 is determined on a cavity-by-cavity

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basis using the mass flow technique to determine the dynamic heat load:

$$Q0 = \frac{E_{acc}^2\ L^2}{R/Q\ P_c}$$

P_c is determined by comparing helium mass flows with a fixed helium feed for three states:

- No heat load (static)
- Heater at fixed value (calibration)
- Each cavity at nominal gradient.

Care is taken to ensure that conditions exist to assure as high a measured Q0 as possible within schedule constraints. Minimizing the ambient magnetic field and expelling any residual magnetic flux are important steps. This is accomplished first by demagnetizing each cryomodule immediately prior to cooldown from room temperature. Flux sensors installed within each cryomodule are monitored to ensure a field <= 25 mGauss. Less than 1 mG is routinely achieved and maintained during a test cycle.

Since Q0 data gathering follows power rise tests which invariably results in cavity quenches, a 'thermal bump' is performed in order expel the magnetic flux. This is accomplished by first warming the entire cavity string to 45-50 Kelvin, maintaining that temperature for of order an hour, then re-cooling the string to 4 K at rates of at least 32 g/s, a so-called 'fast' cooldown. Pump down to 2 K follows. A thermalization or 'soak' period, typically 24 hours, follows before static and dynamic heat load measurements to determine P_c begin. Gathering data for each of the eight cavities is accomplished over a 16-hour period. A standard sequence of steps completes this set of measurements:

- Lock the Joule-Thomson helium supply valve to a fixed position ensuring that the liquid level remains relatively stable with no heat load,
- Measure the static mass flow with no heat load applied for up to 45 minutes,
- Perform a static heat load by measuring the mass flow with a liquid level probe heater on at approximately 8 Watts,
- Measure the helium mass flow/static heat load with each cavity at 16 MV/m for of order 45 minutes each,
- As needed re-fill the cavity string if the liquid level drops close to its lower limit,
- Intersperse cavity runs with static and as needed additional heater calibration runs.

45 minutes of data collection time assures good statistics and includes settling time which is typically not factored into the data analysed. Once all data is gathered, off-line analysis is carried out with at least two independent checks of the results performed. Real-time results, albeit with less precision, are generated, displayed, and archived to provide a real-time 'sanity check' and as a third check of the data. Periodic fluctuation in the measured mass flow and occasional random movement of the J-T valve, even when locked, can result in a greater than desired uncertainty of the measured Q0.

Figure 6 shows the results for the seventeen cryomodules already tested. As can be seen, all but three cryomodules have met or exceeded the acceptance limit. These less than optimum results correlate with cavities demonstrating low Q0's at the Vertical Test Stand (VTS); cavities fabricated with material known to have poor flux-expelling properties.

Limited time was available to study the impact of variations in cooldown rate, 'soak' time on flux expulsion and resulting Q0 and are documented [7].

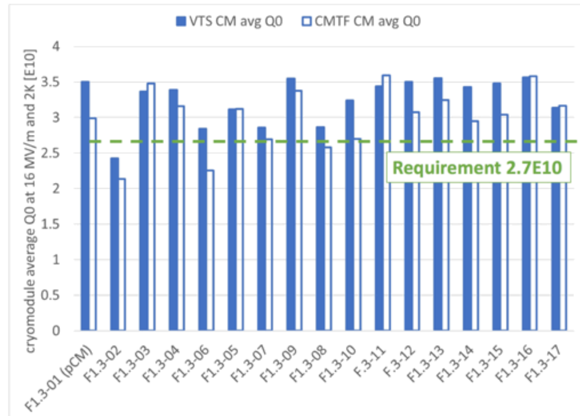

Figure 6: Average Q0 for cryomodules tested to date (through F1.3-17).

Microphonics

Cavity detuning is monitored at several points during cryomodule testing. Early tests showed significant amounts of cryomodule-internally driven acoustic noise, resulting is detuning a factor of ten over the 10 Hz specification. Significant testing effort was spent diagnosing and mitigating the sources of this detuning including weeks of cold testing time, additional expert personnel effort, and infrastructure to support the detuning data capture and analysis. The major mitigations include modifications to the cryogenic valves on the module to suppress Thermoacoustic Oscillations, modification of the upstream beamline vacuum valve support, and a host of smaller 'best practices' modifications/improvements to assembly [8].

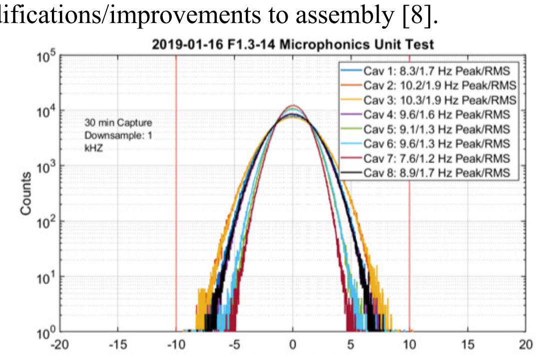

Figure 7: Results of microphonics data capture for F1.3-14 ten days after initial cooldown to 2 K. The vertical bars indicate the +/- 10 Hz acceptance limit.

The LLRF system at CMTF allows capture of all eight cavities simultaneously and synchronously for an extended period of time. This powerful diagnostic tool is used to

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capture detuning at the beginning and end of each cryomodule test as well as during high-power unit testing.

Final modifications to the cryomodule design for microphonics improvement were made on F1.3-05, and since then the tests have shown consistently good detuning environments with most cavities below specification as seen in Fig. 7. Transient thermalization effects on detuning are significant, however. Testing shows that detuning above specification is expected to be due to the short testing cycle and attendant lack of complete thermalization.

LESSONS LEARNED

With nearly three years of testing experience gained, some observations can be made:

- Developing a mindset that prioritizes production/schedule over R&D requires time and discipline,
- An unambiguous set of acceptance criteria is a necessity as are coherent test plans and procedures,
- Automation of testing sequences, though highly desirable, can be challenging to implement given the dynamic nature of the test environment. Significant pre-planning together with an appropriate labor pool are vital to achieve success in this regard.
- Adhering to a fairly regular cycle of testing enhances efficiency, reduces the incidence of errors, of virtually all aspects of the test sequence.

FUTURE CONSIDERATIONS

Once initial production series cryomodule tests are completed, anticipated to be later this summer, CMTS1 will go into a multi-week hiatus as the cryogenic distribution systems for the Fermilab PIP-II Injector Test (PIP2IT) is tied into the CMTF cryogenics system. Following this, cryomodules that required rebuild due to performance deficiencies or manufacturing or transport problems will be retested. Once this is completed, CMTS1 will be reconfigured to support testing of the three 3.9 GHz cryomodules being built at Fermilab for LCLS-II. Longer terms plans call for CMTS1 to be configured back for testing 1.3 GHz cryomodules for the proposed LCLS-II High Energy Upgrade.

SUMMARY

The majority of the 1.3 GHz cryomodules built at Fermilab for the LCLS-II project have now been successfully cold tested – seventeen to date with F1.3-18 testing nearing completion. By and large, performance specifications have been met, and in the majority of cases, exceeded. This bodes well for future LCLS-II operation.

Generally excellent reliability of all subsystems and rapid response to identified issues, has allowed the testing program to proceed close to schedule and in general not impede the production and delivery rate of cryomodules to SLAC.

In light of endeavouring to complete testing within stringent schedule demands these results have been gratifying. Of particular note is the achievement of unprecedented Q0 levels which have required careful planning of the test sequence and attention to detail during a cryomodule's time at CMTS1.

ACKNOWLEDGEMENTS

The authors acknowledge that the results to date reflect the dedicated efforts of a large number of people both at Fermilab and the other LCLS-II partners labs, as well as the international SRF community. The world class performance of these LCLS-II cryomodules is due to the collaborative nature of the community.

Particular mention is made of the technical staffs in the Fermilab Accelerator and Applied Physics & Superconducting Technology Divisions without whom these cryomodules and test stand would perform so well. Members of the Accelerator Division Operations crews are also recognized for their contributions to the quality Q0 measurements made.

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