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LCSL-II CRYOMODULE TESTING AT FERMILAB*

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Abstract

Cold powered testing of all LCLS-II production cryomodules at Fermilab is complete as of February 2021. A total of twenty-five tests on both 1.3 GHz and 3.9 GHz cryomodules were conducted over a nearly five-year time span beginning in the summer of 2016. During this campaign cutting-edge results for cavity Q0 and gradient in continuous wave operation were achieved. A summary of all test results will be presented, with a comparison to established acceptance criteria, as well as overall test stand statistics and lessons learned.

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 status is described elsewhere at this conference [1].

The LCLS-II cryomodule (CM) 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 previously [2].

The scope of this paper focuses on test results only for Fermilab-built cryomodules and is an update to results shared at the most recent SRF conference [3].

TEST RESULTS

Every cryomodule tested was measured against a predetermined set of acceptance criteria adopted by the LCLS-II project and its partners [4,5]. With few exceptions these criteria were met and usually exceeded. Deviation were documented in testing travelers and communicated to the oversight team. Following the end of a CM's test results were shared, discussed, and room temperature warm-up and removal steps were not undertaken without this review and subsequent go-ahead. Only in rare circumstances were extended test runs undertaken.

1.3 GHz

Twenty-two cold tests of 1.3 GHz cryomodules for LCLS-II were conducted at CMTS1. Since the previous report in 2019, an additional four tests were conducted – two remaining production devices and re-test of two rebuilt ones. Figure 1 summarizes the gradient performance of all cryomodules while Fig. 2 shows the average Q0 for each 8-cavity cryomodule; Q0 was measured for each cavity singly. As these data indicate, performance in all respects exceeded specification.

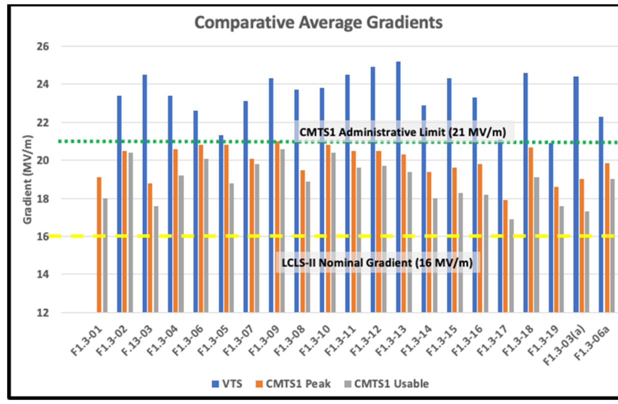

Figure 1: 1.3 GHz gradient summary.

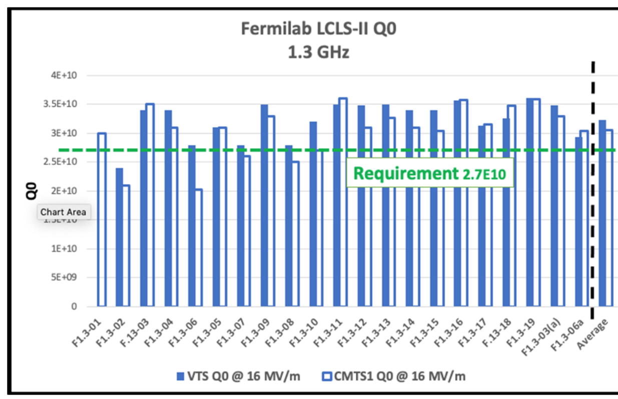

Figure 2: 1.3 GHz Q0 summary.

3.9 GHz

Three 'F3.9' series cryomodules were built for LCSL-II. Two are considered operational units and the third a spare. These proved to perform well above specification like the 1.3 GHz models as noted in Fig. 3 (gradient) and Fig. 4 (Q0).

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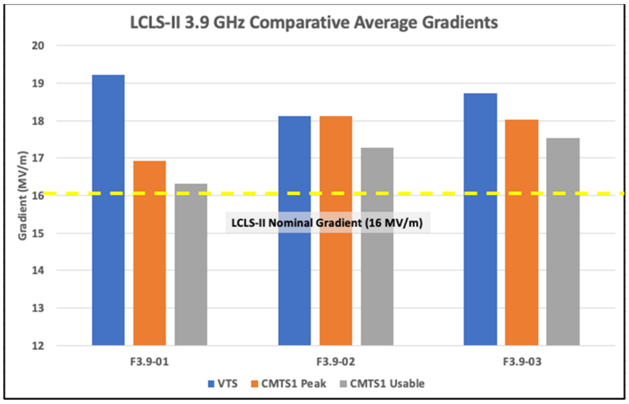

Figure 3: 3.9 GHz gradient summary.

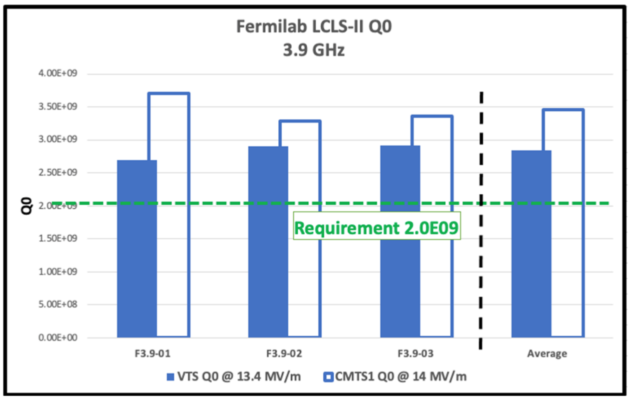

Figure 4: 3.9 GHz Q0 summary.

Compared to their lower frequency siblings, the 3.9 GHz cryomodules had some fundamental design differences including:

- Fixed coupling;
- Fundamental power couplers on alternating sides of the cryomodule to avoid possible coupler induced transverse beam kicks;
- Magnetic shielding internal to the helium vessel which obviated the need for flux expelling thermal cycles and 'fast' cooldowns;
- Blade tuners outfitted with three piezo actuators (for fine frequency adjustment);
- No internal magnet package.

These changes did have some impact on the test stand layout as described below and the test program.

Fixed coupling, for example, required in situ adjustment by means of a combination of waveguide inserts and matching diaphragms at the input coupler to achieve the nominal QL of 2.7E+07 rather than remote adjustment of the antenna penetration as was the case for the 1.3 GHz models. This was carried out iteratively with a combination of room temperature, cold in situ, and cold powered measurements via the LLRF system. An example of the process for F3.9-03 is shown in Fig. 5.

		Q0 @RT		Qext nominal						
		5500		2.70E+07						
	1	2	3	4	5	6	7	8		
3HCM03	3HRI06	3HRI19	3HRI08	3HRI09	3HRI02	3HRI24	3HRI15	3HRI26		
F0, MHz	3900.00	3900.00	3900.00	3900.00	3900.00	3900.00	3900.00	3900.00		F0 - cavity operating frequency
Qext (RT, S11)	2.35E+07	1.50E+07	2.80E+07	1.65E+07	3.20E+07	1.80E+07	1.95E+07	1.45E+07	MC-L00-D34	
Qext (2K, S21)	3.10E+07	2.80E+07	3.10E+07	2.70E+07	3.40E+07	2.80E+07	2.80E+07	2.40E+07	MC-L15-DXX	
QL (2K, decay)	2.50E+07	2.30E+07	2.60E+07	2.40E+07	3.20E+07	2.20E+07	2.40E+07	2.30E+07	WG110-L15-DXX	
QL (4K, S21)	1.90E+07	1.80E+07	1.70E+07	1.70E+07	2.20E+07	1.60E+07	1.80E+07	1.90E+07	WG110-L15-DXX	
Q0 (4K)	7.92E+07	8.28E+07	4.91E+07	5.83E+07	7.04E+07	5.87E+07	7.20E+07	1.09E+08		L - Insert length, mm
L - matching insert	12	12	12	12	12	12	12	12		D - Diaphragm height, mm
D - matching diaphragm, #1	24	20	34	22	34	22	22	18		
D - matching diaphragm, #2										

Figure 5: F3.9-03 measured QL's & adjustments.

TEST STAND SWITCHOVER

In the original design of the cryomodule test stand layout, provisions were made to allow testing for various length TESLA/ILC style cryomodules. LCLS-II 1.3 GHz and 3.9 GHz CMs were specifically designed for testing at CMTS1. To switch from testing 1.3 GHz CMs to 3.9 GHz, the downstream endcap girder must be moved about 5.5 meters closer to the upstream feedcap girder. All ancillary equipment such as system cabling, vacuum, water cooling, waveguide, and cryogenic valve connections must also be relocated to their new locations and modified to accommodate the waveguide on both sides of the CM in the 3.9 GHz design. At the same time, work was performed outside the cave to replace the 1.3 GHz solid state amplifiers (SSA) with smaller 3.9 GHz SSAs and configure 3.9 GHz RF systems. Rather than housing a single cavity amplifier in each cabinet, two 3.9 GHz ones with a peak output of 0.9 kW each are able to fit in each cabinet of the same footprint as the 1.3 GHz housings. The last 1.3 GHz CM before the cave switchover was removed on Nov 9, 2019 and the first 3.9 GHz CM was brought to CMTS1 on Dec 18, 2019, resulting in about 5.5 weeks of work to complete the majority of the physical switchover. No technical or safety incidents occurred during the switch and the first 3.9 GHz CM was aligned and installed without issue; a testament to the excellent execution by the many teams involved.

Simultaneously a new low level RF (LLRF) system based on the LCLS-II design was installed and commissioned. Thus, testing of F3.9-01 was reminiscent of the prototype cryomodule test in that testing and commissioning new systems proceeded in parallel. Advanced planning minimized the impact so that the overall duration was in line with subsequent tests.

Once F3.9-03 testing was ended, the stand was reverted back to its original configuration in support of the final 1.3 GHz CM test as well as prepare for future support of the LCLS-II HE project. In this case new 7 kW amplifiers, with the same footprint as previously installed 4 kW amplifiers, were put in place. Some re-work was necessary given the different RF distribution hardware. Again, the installation duration prior to cooldown (45 days) was longer than nominal (~15 days), but pre-planning kept the extra time to a minimum.

NOTABLE ACHIEVEMENTS

In support of the test program, there were some novel achievements during the latter stages of the testing program worthy of mention:

- Quench detection;
- Multiple LLRF platforms; and
- EPICS implementation.

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Quench Detection

Early on it was recognized that a desirable feature would be a means to detect quenches so as to inhibit the RF power automatically without operator intervention, especially to prevent possible cavity damage and emptying the helium inventory. While a 'cryo permit' exists to disable RF power when the inlet temperature, helium pressure, or liquid levels fall outside of prescribed limits, this a slow responding system, on the order of tens of seconds. Unfortunately, resources limited R&D on the initial LLRF system.

Beginning with F1.3-13, however, parasitic study time was used to gather waveforms and investigate algorithms using the RF interlocks system. While integrated to the low-level RF system, it is a completely independent hardware platform. The basic premise is to employ a technique identified for pulsed RF systems and customize it for cw operation [6]. Rapid changes to the digitized RF transmitted power signal are sensed and trigger a system fault. The signal is filtered using an 8 tap FIR filter and then subtracted. The subtraction is looking for fast changes in the signal akin to one seen during a quench. Circular buffers were implemented for raw signal, filtered signal, and subtracted signal. The recorder captures 50 counts past the quench detection. Figure 6 is an example of this scheme while Fig. 7 complements it with a show of an RF inhibit due to the quench indication.

Although rudimentary, this scheme was demonstrated in multiple instances and eventually deployed to all cavity interlock systems, but not until F1.3-19 testing was begun.

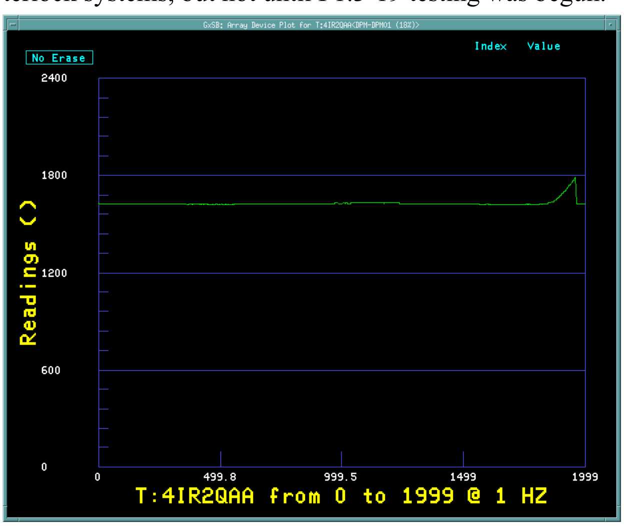

Figure 6: Indications of a quench using digitized RF powers available to the RF interlocks chasses.

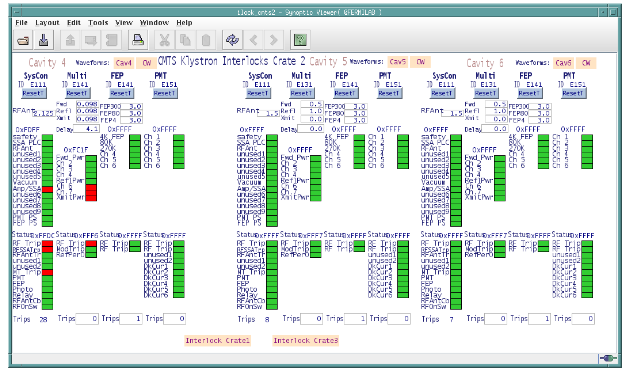

Figure 7: Indication of an amplifier trip consistent with the quench indication of Fig. 6.

LLRF & EPICS

Given time constraints imposed by the project, the initial low-level RF (LLRF) system at CMTS1 was based on an existing platform developed at Fermilab interfaced to the legacy ACNET control system and LabView™. Over time the maturity of the EPICS-based system specifically designed for LCLS-II progressed sufficiently to install it consistent with testing of the 3.9 GHz cryomodules. Thus LLRF hardware and user displays were also installed and ported during the 1.3 GHz to 3.9 switchover. Commissioning of the system at CMTS1 was begun with F3.9-01.

To maintain a full suite of tools including plotting, alarms, and archiving, a hybrid ACNET/EPICS platform was realized. EPICS user screens of the LLRF were the primary user interface to control the cavities while high level amplifier control and other the user interfaces continued via ACNET. The primary LLRF Process Variables (PVs) were bridged into ACNET to allow for shared data and archiving. This proved to be overall successful with of order twenty PVs per cavity resident in both EPICS and ACNET. Successful implementation would not have been possible with the close cooperation, availability, and as needed rapid response of the entire LCSL-II LLRF team sited at SLAC, LBNL, Jefferson lab, and Fermilab. Valuable experience in EPICS-based control was gained by the Fermilab team both in mastering user interfaces and implementing an EPICS-based system. This achievement was in large measure due to hands-on guidance by EPICS experts.

In the course of switching over LLRF systems, comparisons were made between the measured powers and gradients derived by each system. Initially gradient differences of up to 19.5% (10.4% on average) were observed for single cavities. In part this was due to different algorithms being implemented. In the case of the Fermilab system, gradient was determined by measuring the forward power at the output of the amplifier and applying correcting factors for waveguide loss. In the case of the LCLS-II system, probe power was the fundamental source to measure gradient. That said, even discrepancies in measured powers were observed. Systematic evaluation of possible sources and mitigation of same eventually reduced the discrepancy to of order less than 4% on average as seen in Fig. 8.

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Another subtle outcome of this venture was to validate two platforms for consideration for future LLRF projects.

cavity #	Power Meter Gradient (MV/m) from FWD	Remeasured Ql	Power Meter Gradient (MV/m) from FWD	LLRF Gradient (MV/m) from Probe	LLRF FWD recalibrated	LLRF Gradient (MV/m) from FWD	Percent diff
1	20.18	(3.1 -> 2.53) E+07	18.24	19.46	1.01	17.64	3.31
2	16.51	(2.8 -> 2.31) E+07	15.00	16.20	1.04	14.96	0.25
3	19.08	(3.1 -> 2.56) E+07	17.35	18.64	1.06	17.44	0.52
4	14.94	(2.7 -> 2.38) E+07	14.04	16.74	0.94	15.18	8.13
5	18.03	(3.4 -> 3.2) E+07	17.48	19.62	1.01	18.26	4.45
6	15.95	(2.8 -> 1.6) E+07	14.00	14.60	1.04	13.06	6.73
7	15.55	(2.8 -> 2.37) E+07	14.31	15.64	1.05	14.77	3.22
8	15.81	(2.4 -> 2.29) E+07	15.42	16.05	1.05	16.03	3.91

Figure 8: LLRF calibration discrepancy.

FIELD EMISSION

A common concern of SRF cavity operation is field emission (FE) – the gradient onset, mitigation steps, and overall management. The 1.3 GHz CMs and 3.9 GHz ones which had not been tested prior to the previous report showed behavior consistent with their predecessors. Of a total of 168 single cavity tests conducted, only 11 cavities failed to meet the field emission onset limit of 14 MV/m. 93% of the cavities tested thus met or exceeded this specification.

In the case of the 3.9 GHz CMs, only one cavity of the twenty-four tested showed FE below the onset limit of 14 MV/m and only one other cavity showed any indication of detectable field emission whatsoever, a ratio consistent with that of the 1.3 CMs. This behavior is a testament to the care put forth by the CM assembly and CMTS1 installation crews in maintaining a particle-free environment.

Dosimetry strategically installed on all CMs tested from F1.3-09 onwards measured integrated doses per test interval that varied between minimal and 18147 mR for a heavily field emitting cavity. An average integrated dose was 3357 mR. Fast neutron production was detected in two of the cryomodules tested, consistent with significant field emission.

TESTING DURATION

In general, the time required to install, cooldown, test, warmup and subsequently remove each cryomodule was in line with early estimates. Table 1 summarizes the average time duration for each step with separate counts for the 1.3 and 3.9 GHz CMs.

Table 1: Average Testing Durations (Days)

CM type	Installation & cooldown	Cold testing	Warmup & re-moval	Total days at CMTS1
1.3 GHz	18	14	8	43
3.9 GHz	19.75	38	6	104*

Notable is the time that the 3.9 CMs, particularly F3.9-02 spent at CMTS1. F3.9-02 alone spent 184 days at CMTF while -01 and -03 spent 55 and 72 days there respectively. This duration was exaggerated by the work stoppage in early 2021 associated with the covid-19 pandemic. Testing time was also impacted due to the need to limit on-site staffing once the work stoppage was lifted.

RELIABILITY

Overall, there was little lost time during cryomodule testing due to component or infrastructure failure. The RF solid state amplifiers exhibited excellent reliability with virtually no system failures. The cryoplant, once in routine operation, behaved similarly.

Rogue trips of RF interlocks were at times beyond a nuisance. Anecdotally extraneous RF noise sources were the prime culprit, but no concrete source was ever identified.

Cold cathode gauges had a definite lifetime limit of some hundreds of hours and when approaching end of life would generate spurious faults. Fortunately, their end of life was often anticipated and could be replaced between cryomodule tests.

During the switchover to 3.9 GHz testing careful attention was given to areas where frequent connect/disconnects occurred. A fair number of RF connectors to the cryomodule flanges were replaced – both power cables and the BPM ones. Excessive power supply voltage and corrosion was also evident on the magnet leads to the cryomodule which also prompted a re-work of those electrical connections.

When the operator workstations in the CMTF control began to serve double duty as both ACNET and EPICS consoles, computer memory issues, leading to at times frequent crashes and restarts, became more apparent.

LESSONS LEARNED

The full scope of testing is now completed on two distinctive, yet similar types of cryomodules. The world-wide pandemic added an interesting wrinkle to the testing schedule and protocol. Given these realities, some observations can be made:

- Written down and discussed test plans were invaluable in assuring there were no overlooked steps;
- Supporting documentation such as troubleshooting procedures, system fault recovery, etc. was not as robust, and would have been helpful;
- Quench detection, even for manually operated systems, but especially when automation is implemented, needs to be implemented from day one;
- RF calibration from test to test was fairly consistent, but significant reorientations require a complete re-calibration;
- Close coordination is vital especially when resources are shared. For much of the time, CMTS1 was the sole user of the cryoplant. Operation of the PIP-II Injector Test, a separate test bed in the same building, required an extra level of planning to ensure needs of test programs were met;
- Schedules are helpful for planning purposes, but reality rules;
- Vigilance is necessary particularly for a long duration effort spanning many years;
- Operational Readiness Clearance protocols are vital to ensure smooth turn on and identification of potential problems particularly when frequent (monthly) changeovers are anticipated;

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- Systematic inspection and maintenance on 'consumable' components e.g. vacuum gauges and seals on a regular schedule assure efficient switch-on and operation;
- Sharing expertise from multiple institutes/laboratories is a model for future large projects. Such a collaborative model for specialized disciplines seems to be the clear path forward.

SUMMARY/CONCLUSION

The campaign to cold test all cryomodules built at Fermilab for LCLS-II has come to a successful conclusion and all devices are now delivered to SLAC having met and oftentimes exceeded performance specifications. The design choices made in adapting TESLA style cryomodules for cw operation were validated. The experience gained with these series of tests will benefit LCLS-II commissioning and operation and are already informing follow-on projects, especially SRF-based ones. Most significantly this effort was carried out safely with only one technical incident affecting the cryoplant occurring.

ACKNOWLEDGEMENTS

The authors acknowledge that these results and successful completion of this effort on behalf of LCLS-II 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 nor would the timely transition from test to test been accomplished.

Special note goes to the LCLS-II LLRF collaboration at SLAC, LBNL, Jlab, and Fermilab without whom the successful transition to a new platform and EPICS would have been possible.

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