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.

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

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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.

**Gradient Determination**

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

\[ E_{acc} = 2 \sqrt{\frac{R}{Q}} Q_f P_f (1 - e^{-20t})/L \]

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 MV/m.
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.

**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 ‘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].

**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 $2.7 \times 10^10$, a world-class level. At CMTS1 Q0 is determined on a cavity-by-cavity.
basis using the mass flow technique to determine the dynamic heat load:

\[ Q_0 = \frac{E_{\text{acc}}^2 L^2}{R/Q P_c} \]

\( P_c \) 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 \( Q_0 \) 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 \( \leq 25 \) mGauss. Less than \( 1 \) mG is routinely achieved and maintained during a test cycle.

Since \( Q_0 \) 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 \( Q_0 \).

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 \( Q_0 \)’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 \( Q_0 \) and are documented [7].

Microphonics

Cavity detuning is monitored at several points during cryomodule testing. Early tests showed significant amounts of cryomodule-externally 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...
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 microphonic 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 $Q_0$ 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 $Q_0$ measurements made.

REFERENCES