Experience With LCLS-II Cryomodule Testing at Fermilab

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Abstract

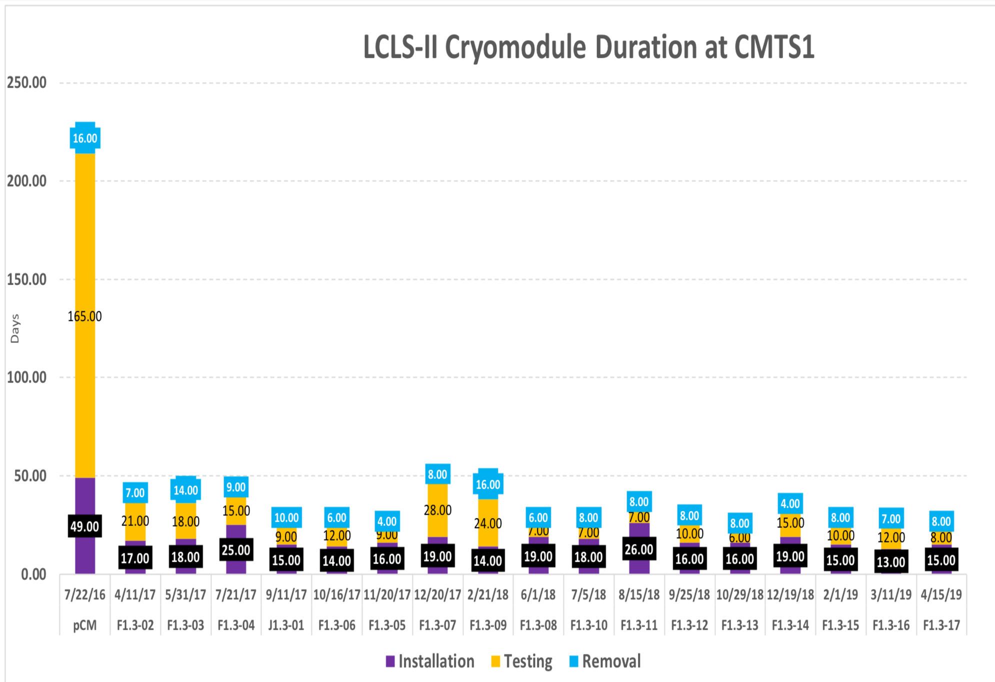
The Cryomodule Test Stand (CMTS1) at Fermilab has been engaged with testing 8-cavity 1.3 GHz cryomodules designed and assembled for the LCLS-II project at SLAC National Accelerator Laboratory since 2016. Over these three years twenty cryomodules have been cooled to 2K and power tested in continuous wave 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. 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. As of this writing (June 2019) nineteen cryomodules have passed through CMTS1 – 18 Fermilab-built ones and the first Jefferson lab assembled one.

The LCLS-II design is cutting edge in terms of continuous wave (CW) operating gradient and Q0.

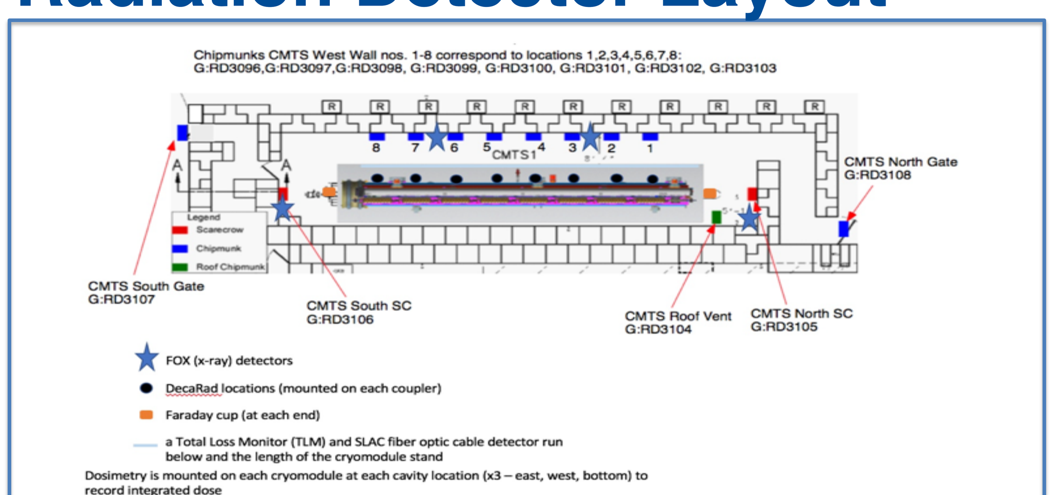
Timeline



Cryomodules are tested on a roughly 28-day cycle

- 11 days for installation and leak checking
- 3 days for cooldown to 2K
- 7 days for cold, powered testing
- 7 days for warm-up and removal

Radiation Detector Layout



Acceptance Criteria

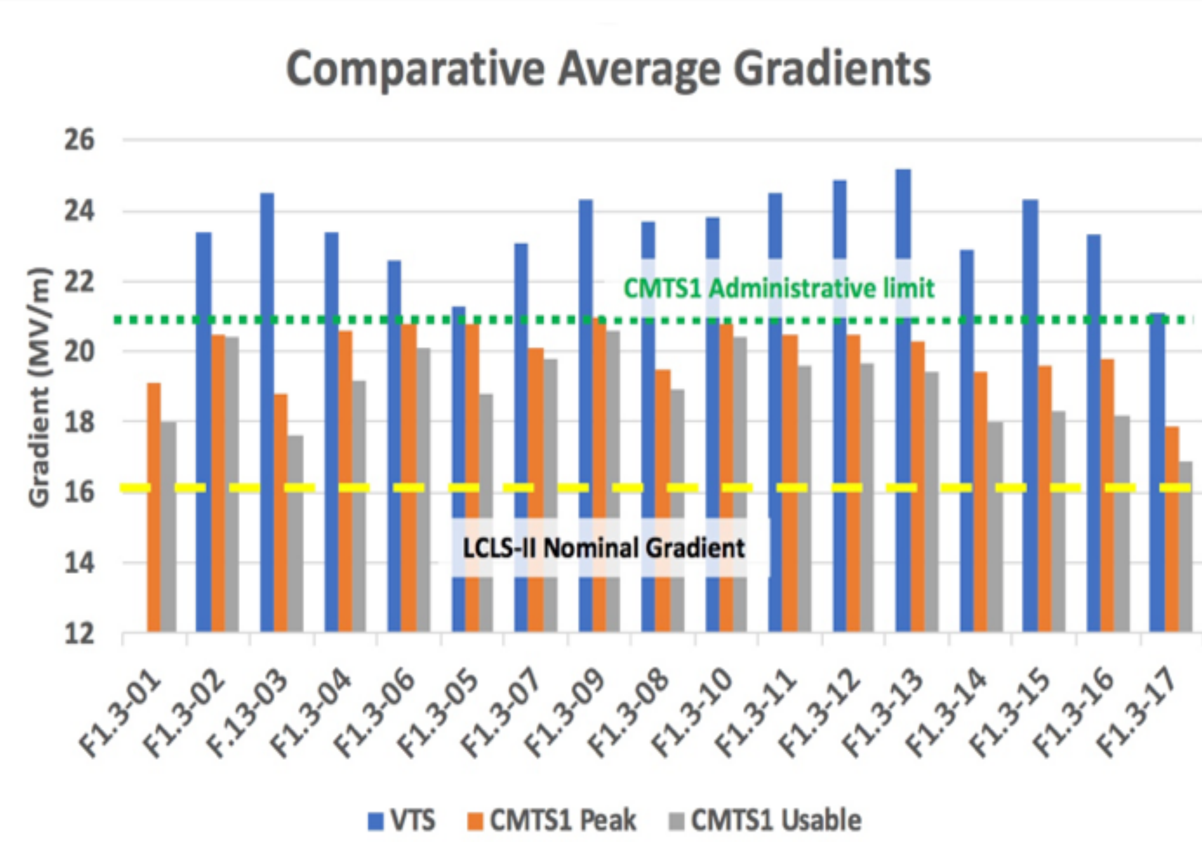
Parameter	Value	Minimum acceptable performance during test
Minimum acceptable operating gradient for an individual cavity	12 MV/m	Requires radiation associated with the cavity measured outside the CM be < 50 mR/hr and the quench level be at least 0.5 MV/m higher than the operating gradient. Usable gradient 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	$2.7x10^{10}$	Average Q_0 of cavities within a CM $\geq 2.7x10^{10}$, 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		$Q_{ext} \geq 2x10^{11}$, 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 $1x10^{-8}$ Torr Cryomodule insulating vacuum prior to cooldown $1x10^{-4}$ Torr Cryomodule warm coupler vacuum prior to cooldown $1x10^{-7}$ Torr Cryomodule beamline vacuum at 2 K $1x10^{-9}$ Torr Cryomodule insulating vacuum at 2 K $1x10^{-6}$ Torr Cryomodule warm coupler vacuum at 2 K $5x10^{-8}$ Torr

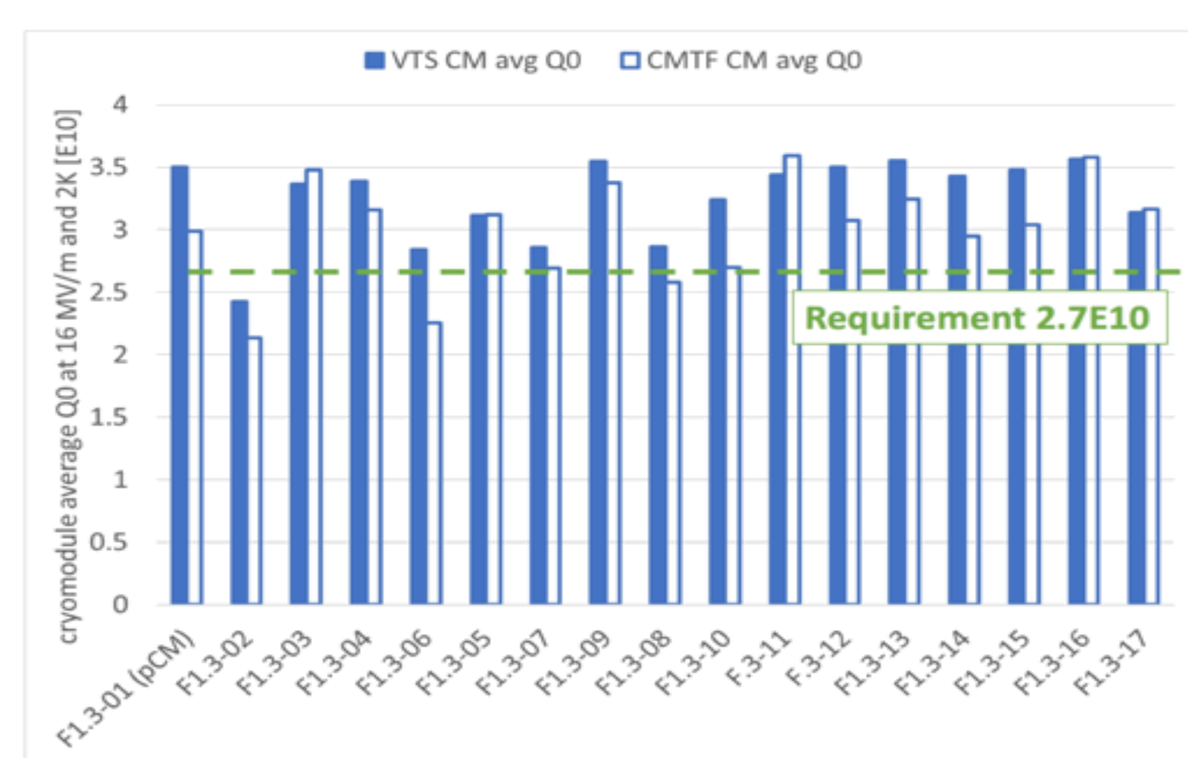
Cryo-module #	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17
Gradient	ok	n/a	x	ok	ok	ok	ok	ok	ok	ok	ok	ok	ok	ok	ok	ok	ok
CW Volts	ok	ok	ok	ok	ok	ok	ok	ok	ok	ok	ok	ok	ok	ok	ok	ok	ok
FE onset	ok	x	x	x	x	x	ok	ok	x	ok	ok	ok	ok	ok	ok	ok	x
Q0	ok	ok	ok	x	ok	x	ok	x	ok	ok	ok	ok	ok	ok	ok	ok	ok
Unit Test	ok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

Acceptance Criteria were jointly developed and adopted by the partner laboratories (SLAC, Fermilab, Jefferson Lab. These form the basis of the testing plan and qualification specifications employed at CMTS1.

Fermilab-built cryomodules meet and routinely exceed these standards.

Performance





For the 17 cryomodules tested to date, average achievements (compared to specification) are:

Maximum voltage = 166 (128) MV, 'Usable Voltage' = 158.7 (128) MV

Q0 = 2.99 (2.7) E+10

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.

Related papers at SRF '19

MOFAA1	MOP090
MOP092	MOP093
TUP038	TUP039
TUP096	TUP097
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