LCLS-II-HE CRYOMODULE TESTING AT FERMILAB

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LINAC2022 LIVERPOOL

ABSTRACT

22 Linac Coherent Light Source II (LCLS-II) cryomodules were successfully tested at the Cryomodule Test Facility (CMTF) at Fermilab. Following the completion of the LCLS-II testing program, CMTF has shifted to testing cryomodules for the LCLS-II High Energy upgrade (LCLS-II-HE). The first LCLS-II-HE cryomodule, the verification cryomodule (vCM), was successfully tested and verified the readiness of LCLS-II-HE cryomodule testing at CMTF, and production cryomodule (CM) testing has begun. Presented here are the production CM test acceptance criteria, testing plan, and CM test results so far.

LCLS-II HIGH ENERGY UPGRADE

Having concluded the LCLS-II test program, Cryomodule Test Stand 1 at CMTF is now fully dedicated to LCLS-II-HE CM testing. The infrastructure of the test stand remains largely unchanged. Eight, 7 kW solid state amplifiers have replaced the 4 kW amplifiers used during the LCLS-II test program, which were installed and com-missioned during the final LCLS-II CM test. An EPICS-based controls system has also been implemented to conform with a model like what is used for the accelerator controls at SLAC. CMTF houses a state-of-the-art cryo-genic facility with a cryogenic capacity of 500 W at 2 K. Cavities use 2/0 doping recipe and nominal gradient increased to 21 MV/m.

ACCEPTANCE CRITERIA

Parameter	Value	Minimum acceptable performance during test
Minimum usable gradient for an individual cavity	16 MV/m	Usable gradient – the maximum gradient at which the following 3 conditions are met: • radiation level is below 50 mR/hr, • the cavity can run stably for one hour • 0.5 MV/m below the quench field.
Nominal usable gradient	20.8 MV/m	Individual cavities should reach a nominal usable gradient of 20.8 MV/m.
Minimum Usable CW voltage produced by an individual cryomodule	173 MV	The total CW voltage produced by cryomodule with cavities running at their usable gradients shall be ≥173 MV with all cavities powered simultaneously in GDR/SELAP mode and with the magnet at nominal operating currents for at least one hour with the dark current <30 nA. Additionally, the individual cavity gradients during this run must be recorded.
Stable Operation		For cavities that have a usable gradient above 20.8 MV/m, they must also be shown to be stable (no quenches or trips) at 20.8 MV/m for at least one hour.
Captured dark current	<30 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 ≤30 nA when the cavities are operated in GDR/SELAP mode with the relative phases set to accelerate speed of light electrons. This should be done in such a way to maximize the dark current measured at the Faraday cups.
Individual cavity Q_0		Individual cavity Q_0's must be measured at the expected operating gradient (20.8 MV/m or the usable gradient whichever is lower)
Cryomodule operating duration with RF power during test		Each cryomodule must operate at the minimum CW voltage or greater in GDR/SELAP and with the magnet at operating currents until the coupler temperatures achieve equilibrium or for a minimum of ten (10) hours with 90% operating time, whichever is less, to verify stable operation and confirm acceptable coupler heating.
2 K Dynamic Load at 173 MV voltage		The measured dynamic 2 K heat load of the cryomodule while operating at at total voltage of 173 MV must be ≤ 137 W (equivalent to an average Q_0 of 2.7×10^{10}).
Static heat load at 2 K		The static heat load at 2 K must be ≤7 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
Cavity Microphonics	<10 Hz peak to peak	The microphonics for each cavity must be 10 Hz peak to peak or less, measured over a 1 hour period while at the operating gradient with the JT valve regulating the liquid level (not in a locked position).
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, Bypass valves shall all be verified functional during cryomodule operations by consistency with expectations for operational performance, in particular, no valve or actuator is to have ice form on the room temperature components.
Cavity tuning to resonance during test (coarse tuner)		After cool-down to 2 K, each cavity must be able to be tuned to a resonant frequency of 1300.000 MHz. The tuner on the cavity #1 must be able to change the cavity's frequency from 1299.980MHz to 1300.020MHz. Tuners on cavities #2- #8 must be able to adjust cavity's frequency from 1299.535 MHz to 1300.020MHz.
Fine tuner minimum range	0-500 Hz	

This work was supported by the United States Department of Energy, Offices of Basic Energy Sciences and High Energy Physics under Contracts No. DE-AC05-06OR23177 (Fermilab) and No. DE-AC02-76F00515 (SLAC).

KEY PARAMETER DIFFERENCES: LCLS-II & LCLS-II-HE

Parameter	LCLS-II	LCLS-II-HE
Nominal Cavity Gradient [MV/m]	16	21
Max. Cavity Gradient [MV/m]	21	26
Min. CM Voltage [MV]	132	173
Multipacting Processing [Days]	1-2	4-5

TESTING SEQUENCE

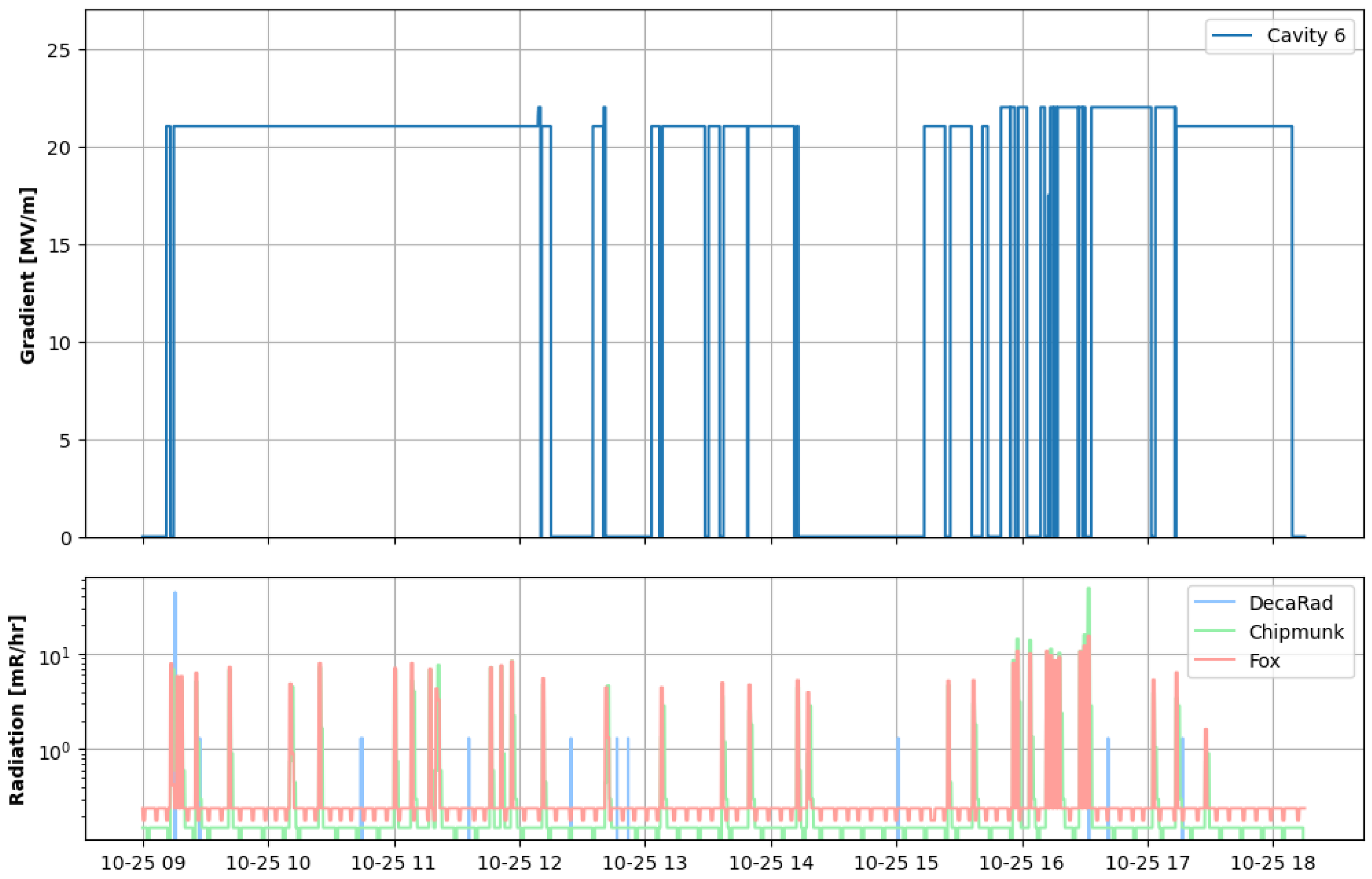
- Installation – 11 days
- Cooldown, 24hr soak at 2 K – 5 days
- Power rise, MP processing – 5 days
- Thermal cycle/fast-cooldown – 1 day
- Q_0 measurements – 2 days
- Unit Test – 1 day
- Pre warmup review, warmup, removal – 4 days

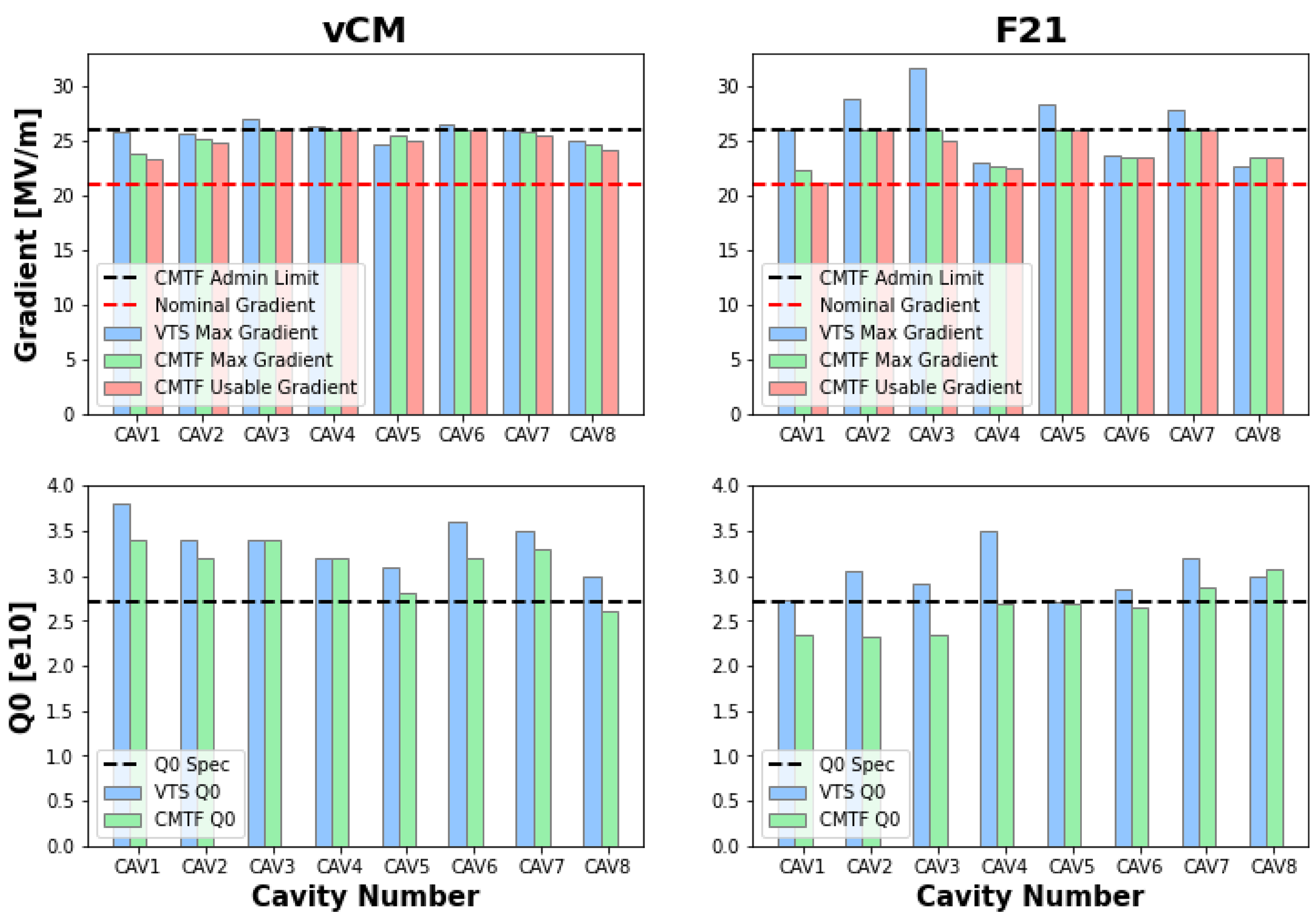
MULTIPACTING PROCESSING

Operating gradient for LCLS-II-HE cavities, 21 MV/m, lies within multipacting (MP) band, necessitating processing of cavities. MP typically presents as: sporadic quenching, radiation spikes, combination of the two. MP seen in both vertical cavity test as well as CM test.

Procedure:

- Increase gradient until quench.
- Return power to cavity until stable.
- Repeat process until quench field or admin. limit, whichever comes first.
- Long runs (2-4hr) at 21 MV/m <u>before</u> Unit Test.





TEST RESULTS WITH COMPARISON TO ACCEPTANCE CRITERIA

Parameter	Spec	vCM	F21
Average Q_0 @ 21 MV/m [e10]	2.7	3.12	2.62
2 K Heat Load @ 21 MV/m [W]	< 137	119	141
Max. CM Voltage [MV]	N/A	211	203
Usable CM Voltage [MV]	173	208	201
Field Emission @ 16 MV/m [mR/hr]	< 50	0	1

CM TEST RESULTS

Two CM have been fully tested and qualified. Third production CM set to be tested Aug. 2022.

Verification Cryomodule (vCM)

- First LCLS-II-HE CM (prototype)
- Tested April – October 2021, fully qualified
- Record performance for CW machine: 211 MV max. voltage
- 4 cavities plasma processed:
  - No cavity degradation
  - No MP observed for processed cavities

First Article CM: F1.3-21 (F21)

- First LCLS-II-HE production CM
- Fully qualified, but some nonconformance observed:
  - 2 K dynamic heat load over spec – contribution seems to be lower Q0 from LCLS-II cavities (not 2/0 recipe)
  - Three cavities with microphonics > 10 Hz
- No MP observed at 21 MV/m after processing

Related LCLS-II-HE contributions:

- MOPOPA13
- TU1AA03
- THPOJO19
- THPOJO20
- THPOGE15
- THPOGE21

Please also see:

- S. Posen et al., "High gradient performance and quench behavior of a verification cryomodule for a high energy continuous wave linear accelerator", Phys. Rev. Accel. Beams 25, 042001 – Published 4 April 2022
- B. Giaccone et al., "Plasma Cleaning of LCLS-II-HE verification cryomodule cavities", arXiv:2201.09776 [physics.acc-ph], https://doi.org/10.48550/arXiv.2201.09

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