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PERFORMANCE OF THE FIRST LCLS-II CRYOMODULES: ISSUES AND SOLUTIONS

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Abstract

LCLS-II 4 GeV linac consist of 35 (+5 spares) of 1.3 GHz cryomodules (CM) and three of 3.9 GHz CM's including one spare. Fermilab responsible for the CM design and share responsibility with JLAB for module assembly and testing. CM production is almost on the middle of production stage. Paper will overview the performance of the CM's tested at Fermilab, lessons learned and modifications in design to improve performance.

INTRODUCTION

All cryomodules after assembly are transported to the test facility, CMTS-1, for cold testing. The baseline testing program addresses acceptance criteria with additional tests to address special topics as the schedule allows. Special studies have included: microphonics measurement and mitigation, Q0 dependence on cooldown rate and remnant magnetic field, LLRF system performance, resonance control, and cryogenic performance. The first pre-production CM, called pCM or F1.3-01 was equipped with more thermometry and magnetic field diagnostics to compare with production CM's and provided more details in its studies. The baseline testing schedule goal is 28 days including installation and cooldown (13 days), testing (8 days) and removal (7days). This agressive schedule was nearly achieved in the three recent CM tests: 34, 32 and 29 days.

The list of acceptance criteria are shown in Figure 1 [1].

Parameter	F1.3-01	F1.3-02	F1.3-03	F1.3-04	F1.3-06	F1.3-05	F1.3-07	F1.3-09
Operating gradient > 12 MV/m	✓	✓	👎	✓	✓	✓	✓	✓
Cryomodule voltage > 128 MV	✓	✓	✓	✓	✓	✓	✓	✓
FE onset > 14 MV/m	✓	✗	👎	✗	✗	✗	✓	✗
Dark current < 1 nA	✓	✓	👎	✓	✓	👎	✓	✓
Average Q0 > 2.7x1010	✓	👎	👎	✓	👎	✓	✓	✓
Unit test	✓	✓	✓	✓	✓	✗	✓	✓
Heat load acceptable	✓	✓					✓	✓
Thermometry	✓	✓		✓	✓	✓	✓	✓
Liquid level sensors	✓	✓	✓	✓	✓	✓	✓	✓
Cryogenic valving	✓	✓	✓	✓	✓	✓	✓	✓
Slow tuner	✓	✓	✓	✓	✓	✓	✓	✓
Fast tuner	✓	✓	✓	✓	✓	✓	✓	✓
Heater performance	✓	✓	✓	✓	✓	✓	✓	✓
Coupler flange temperatures	✓	✓	✓	✓	✓	✗	✓	✓
HOM's	✓	✗	✓	✓	✓	✗	✓	✓
Magnet performance	✓	✓	✓	✓	✓	✓	✓	✓
BPM	✓	✓	✓	✓	✓	✓	✓	✓
Vacuum (warm & cold)	✓	✗	✓	✗	✗	✓	✓	✓

✓ - pass
✗ - partial credit
👎 - fail

Figure 1: LCLS-II acceptance criteria and CM test results.

CAVITY GRADIENT, Q0 AND FIELD EMISSION

The LCLS-II project specifies an average cavity gradient of 16MV/m and $Q0 = 2.7 \cdot 10^{10}$ as baseline parameters. Acceptance criteria for the dressed cavity after vertical test stand (VTS) is a gradient of 18 MV/m and $Q0 \geq 2.7 \cdot 10^{10}$. For production CM's the minimum acceptance criteria for cavity performance in the module is shown in table 1.

Table 1: Performance Acceptance Criteria for a CM

Parameter	value
Cavity operating gradient	>14 MV/m
Cryomodule voltage	>128 MV
Field Emission onset	> 14 MV/m
Dark current	< 1 nA
Average Q0	$>2.7 \cdot 10^{10}$

Cavity Gradient

After cooldown and calibration of the cavity field probes we raise the gradient to the maximum, but not higher than the administrative limit, 21 MV/m. Cavities exhibiting field emission (FE) activity or gradient less than 21 MV/m are processed with 40ms-long pulses, reaching the maximum gradient with little or no radiation. In many cases processing helps to reach higher gradient in cw mode. The average cavity gradient in each tested CM is shown in Fig.2. "Usable gradient" refers to peak gradient limited by measured FE of 50mR/hour or Dark Current above 1nA at either end. One can see that performance has improved over time as clean room assembly techniques are improved.

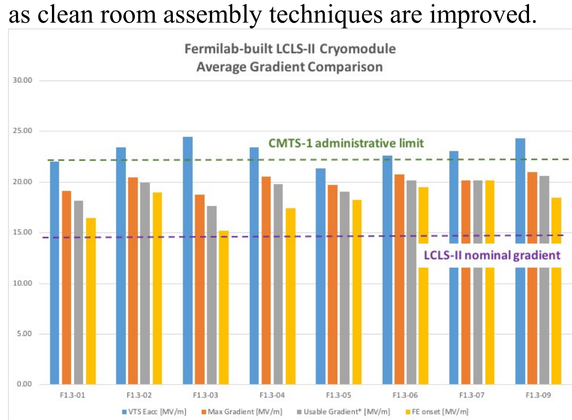

Figure 2: Cavity average gradient in the CM.

Q0 Performance

LCLS-II is the first project where the newly-developed nitrogen doping technique for cavity processing was implemented to reduce the cryogenic heat load of the superconducting linac. This technology allows an increased Q0 of niobium 1.3 GHz cavities by a factor of two to four compared to the traditional protocol such as that used in the EuXFEL project. One drawback of this new approach is a factor of three higher sensitivity to the residual magnetic

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field. To achieve the required magnetic field suppression at the cavity surface to the level < 5mG, a double magnetic shielding for the cavity was designed using non-magnetic material around the cavity. Demagnetization of the cryomodule is a powerful tool to achieve even lower fields, as low as ~1mG with 2.5 mG considered acceptable as measured by fluxgate sensors on selected cavities. The best Q0 performance is achieved when a 'fast' cooldown process (from ~50K to <9K) expels a major fraction of the magnetic flux from the surface. During early cavity production it was realized that niobium sheets from a specific vendor reproducibly exhibit poor flux expulsion. Increasing the cavity annealing temperature from 800C to 900-950C helps improve flux expulsion. Comparison of the average Q0 measured for all cavities tested in the vertical cryostat (VTS) to those in the cryomodule is shown in Figure 3. Cryomodules 6 and 7 with lowest Q0 contains many cavities made of poor magnetic expulsion material [2].

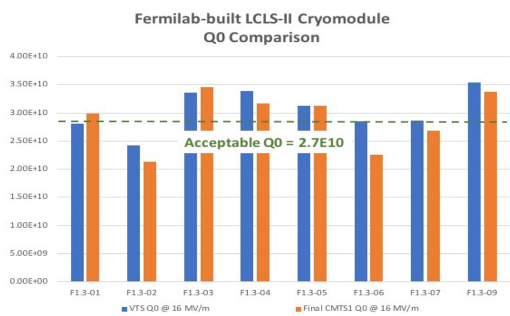

Figure 3: CM average Q0 comparison.

Field Emission, Radiation and Dark Current

CMTS-1 is equipped with an extensive array of detectors for field emission and dark current (DC) detection. The layout of radiation diagnostics is illustrated in Figure 4. Additionally an ArCO2-filled ion chamber and fiber optics detectors run the length of the cryomodule test stand to provide integrated radiation signals.

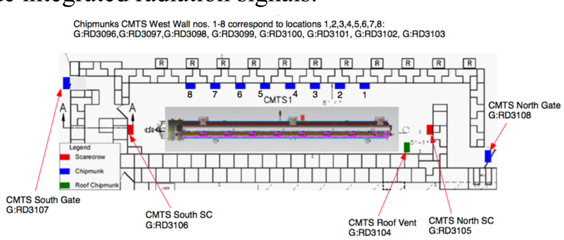

Figure 4: Layout of radiation and dark current diagnostics in the cave.

For dark current detection, Faraday cups are installed on both ends of the test stand together with Fermilab-built X-ray (FOX) detectors for correlation measurements. Dark current response was detected on a total of five cavities in three cryomodule with only a fraction of a nA detected in most cases. The worst response was on F1.3-05 and is correlated to in situ replacement of a broken HOM feed-through on this CM. Field emission (FE) was found on at least one cavity of every CM except for F1.3-07. The location and magnitude varies. Several cavities have FE onset below 14MV/m (see Figure 5), defined as the acceptance criteria. This criterion for LCLS-II cryomodules operating in the cw regime corresponds to about 18-20 MV/m in the pulsed regime as for E-XFEL modules with a factor of 100 times less duty cycle [3].

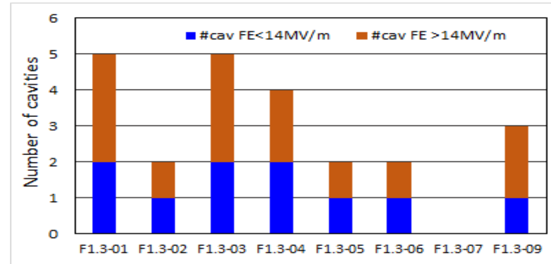

Figure 5: Number of cavities with detectable Field Emission per cryomodule tested.

MAIN COUPLER PERFORMANCES

The LCLS-II fundamental power coupler is based on a modified EuXFEL design with increased thickness of copper plating on the warm section inner conductor assembly from 30 to 150 micron. This allows for reduced heating of the inner conductor at the maximum designed RF power for LCLS-II (6.4 kW). Thermal connection of the coupler intercept points at 5K and 50K was also improved for better control of thermal regime of the coupler. Couplers are tuned to provide a nominal QL=$4.1 \cdot 10^7$ with measured tuning range from $1 \cdot 10^7$ to $5 \cdot 10^7$.

The acceptance criteria for the coupler specifies the maximum temperature of the 50K flange to be <150K and the maximum temperature inside the coupler < 450K at 3kW with full reflection. During coupler heating tests at CMTS-1 between 3 and 3.2 kW of RF power at full reflection is applied to each cavity. To keep the cavity gradient in a safe range, ~10 MV/m, the QL is tuned to ~1.e+7. This level of RF power reproduces the heating regime expected for operation with 6.4kW of power with a beam current of 0.3mA as is expected for future LCLS-II operation.

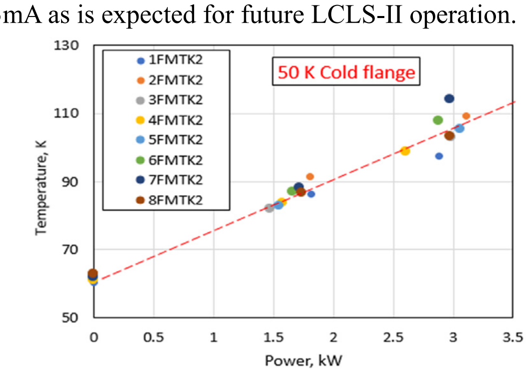

Figure 6: Temperature of the 50K flange vs. RF power, measured at F1.3-09 cryomodule test.

Coupler heating has a long time constant; it can take of order10 hours to reach the equilibrium temperature on the 50K flange, while the 5K and 300K zones reach their equilibrium temperature faster. During prototype cryomodule testing the temperature of the 50K flange was ~200K above the acceptance criteria. The problem was fixed after changing the location of the thermal strap connection to the 50K sink. For production CM's the strap is attached directly to

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the 50K return pipe instead of lower 50K shield. Typical temperatures at the coupler 50K flange are shown in Figure 6. Data are taken from testing of F1.3-09 module for two RF power levels: ~1.6kW (unit test, duration ~24 hours) and ~3 kW (coupler heating test, duration ~12 hours).

Temperature of the warm ceramic window as measured by infrared sensors (IR) do not exceed 50C. The temperature of the inner conductor in the warm section of the coupler as measured by IR sensor is <340K which meets the acceptance criteria.

OTHER SYSTEMS

HOM Couplers

Notch frequencies of the HOM couplers are tuned at the last stage of CM assembly at room temperature. The tuning technique is presented in [4]. It should provide small leakage of the operational mode in cw regime. The LCLS-II project specifies HOM power <0.5 W at 16MV/m (Q_{HOM}>5.4·10^7). The HOM power of all cavities measured at CM tests is shown in Figure 7. CM02 showed some HOM signals above specification due to an error in the tuning process. It was fixed for the following cryomodules and out of specification HOMs were re-tuned inside F1.3-02 after the testing.

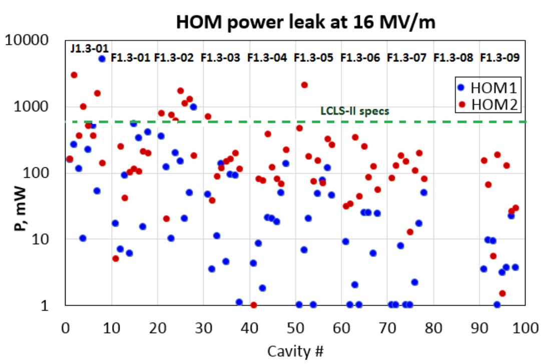

Figure 7: HOM power leak at 16MV/m.

Detuning from Microphonics

LCLS-II has a tight specification for the cavity detuning due to microphonics, less than ±10 Hz. In the first (pCM) test this requirement was not achieved due to strong thermal acoustic oscillation (TAO) in the cryogenic valves. After intensive microphonics studies, several modifications to the cryo-valves and two phase pipe design were done to eliminate TAO and reduce microphonics to the specified level as measured on all cryomodules tested since. More details on microphonics and mitigation steps are reported previously [5].

Issues and Solutions

Several others issues have been identified during cryomodule testing. Immediate actions were applied to solve these deficiencies including changes in the design, procedure or work flow.

- Cavities from one vendors not meeting gradient or Q0 specification. Actions: increase vendor oversight, improved procedures, changed processing recipe, and rework cavities to meet requirements.
- Large level of microphonics. Actions: JT valve change including addition of thermal 'wipers,' flow reversal, and gas-guarding; modifications in the two-phase pipe and cavity1 to gate valve interface.
- HOM Tuning: a few HOMs were out of specification. The tuning procedure was reviewed and improved. .
- Field emission in CM. Action: changes in the High Pressure Rinse technique, cleanroom audits leading to improved performance.
- Power coupler overheating at 70K flange. Action: connect thermal straps to 50K return pipe directly instead of connection to low part of 50K thermal shield.

CONCLUSION

To date Fermilab has tested cryomodules and the preproduction cryomodule built by JLAB, J1.3-01. The first cryomodules exhibited issues like gradient limitations due to FE, coupler heating, HOM power leak above specification, low Q0 and large microphonics detuning. This provided feedback for improving the design, cleaning and assembly procedures, correcting travellers, etc. This learning curve has helped to improve cryomodule performance to meet and frequently exceed the minimum acceptance criteria. Table 2 summarized the average value of key parameters as demonstrated in tested modules.

Table 2: Fermilab Tested CM Performance

CM#	Avg Q0	Usable Voltage (MV)	Flow Rate (g/s)	Cavity Material
pCM	$2.93{\cdot}10^{10}$	145.3	80	WC/800
F1.3-02	$2.12{\cdot}10^{10}$	159.7	80	TD/800
F1.3-03	$3.38{\cdot}10^{10}$	141.0	30	TD/900
F1.3-04	$3.11{\cdot}10^{10}$	158.4	30	TD/900
F1.3-05	$3.00{\cdot}10^{10}$	148.4	80	6-TD,2-NX
F1.3-06	$3.00{\cdot}10^{10}$	161.4	60	1-TD,7-NX
F1.3-07	$3.00{\cdot}10^{10}$	161.1	80	2-TD,6-NX
F1.3-09	$3.35{\cdot}10^{10}$	171.3	80	5-TD,3-NX

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