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LCLS-II CRYOMODULES PRODUCTION AT FERMILAB*

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Abstract

LCLS-II is a planned upgrade project for the linear coherent light source (LCLS) at SLAC. The LCLS-II Linac will consist of thirty-five 1.3 GHz and two 3.9 GHz superconducting RF continuous wave (CW) cryomodules that Fermilab and Jefferson Lab are currently producing in collaboration with SLAC. The LCLS-II 1.3 GHz cryomodule design is based on the European XFEL pulsed-mode cryomodule design with modifications needed for CW operation. Two prototype cryomodules had been assembled and tested. After prototype cryomodule tests, both laboratories have increased cryomodule production rate to meet the challenging LCLS-II project installation schedule requirements of approximately one cryomodule per month per laboratory. Fermilab is at the halfway point for the production, meaning that eight cryomodules are fully assembled and tested. This paper presents LCLS-II cryomodule assembly and production experience at the halfway point, emphasizing the challenges and the mitigations.

INTRODUCTION

The LCLS-II main linac 1.3 GHz cryomodule is based on the XFEL design, including TESLA-style superconducting accelerating cavities, and with modifications to accommodate CW (continuous wave) operation and LCLS-II beam parameters. Fermilab has completed the assembly of eight cryomodules (CM) and all eight cryomodules have been tested at the Cryomodule Test Stand (CMTS) at Fermilab. F1.3-1 is the prototype CM that was assembled in 6 months duration at Cryomodule Assembly Facility (CAF) and tested at CMTS to shake down the established infrastructure, to develop assembly travelers and to assess the needed manpower resources [1]. F1.3-2 through F1.3-4 were assembled in a pseudo-parallel assembly mode to ramp-up the production throughput. During ramp-phase, we hired and trained additional manpower, refined assembly travelers, developed manufacturing bill of material (MBOM aka parts kits) Starting from F1.3-5, peak production throughput of 1 CM per 4~5 weeks is reached.

CHALLENGES & MITIGATIONS

During testing of the F1.3-1 through F1.3-3 at CMTS, we have experienced excessive field emission (FE). The field emission specification requires the onset of measurable field to be above a gradient (Eacc) of14 MV/m for all cavities. Starting from F1.3-5, we started to increase quality oversight during cavity string assembly in the CAF cleanroom, and the FE problem started to improve significantly. During the F1.3-7 cavity string assembly, the cavity beamline vent procedures were optimized. F1.3-7 is the first cryomodule tested with no measurable FE. During F1.3-9 cavity assembly, an external expert audit was conducted by Stephane Berry from CEA/Saclay. Audit recommendations (infrastructure and assembly processes improvements) are currently being implemented gradually to achieve consistent FE performance. F1.3-9 is the last cryomodule currently being tested at CMTS. Fig. 1 shows the FE performance of the tested cryomodules at CMTS [2].

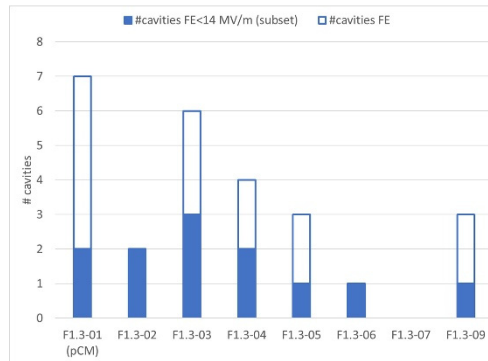

Figure 1: Field Emission Performance. No FE was measured for F1.3-07.

During F1.3-1 testing, microphonics detuning exceeded the specification [3]. Thermal acoustic oscillations (TAO) in the cryogenic valves internal to the cryomodule were found to be the main culprit. Design and assembly modifications to reduce microphonics were immediately introduced during F1.3-2 assembly. During F1.3-2 testing, microphonics problems were reduced but cavity string position #1 still did not meet the requirements of the LCLS-II project. Additional design and assembly modifications were done for F1.3-3 through F1.3-7. These modifications reduced the microphonics detuning. F1.3-7 is the first module where all the cavities met the microphonics requirements [3]. The most significant modifications are shown at Fig. 2 and Fig. 3.

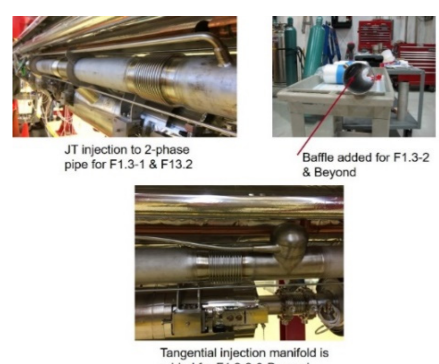

Figure 2: Better Liquid Management and Microphonics Optimization

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F1.3-1	F1.3-2	F1.3-3 & Beyond
JT and CD valve stems do not have wiper rings (TAO issue) - retrofit during CMTS tests	JT and CD valve stems have wiper rings	JT and CD valve stems have wiper rings
JT and CD valves are welded with standard (as designed configuration)	JT and CD valves are welded with reverse configuration	JT and CD valves are welded with reverse configuration

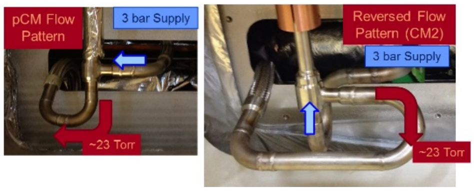

Figure 3: Optimizations to reduce TAO

During F1.3-2 final beamline vacuum pump down and leak check (done at the final assembly work station before transporting the module to CMTS for testing), the cold valves were found to be leaking through. Both cold gate valves were installed onto F1.3-2 cavity string in the cleanroom, and the cavity string successfully passed the helium mass spectrometry leak check after installation.

The gate valves were leak tight to air, but the gate does not close properly and this leak through phenomenon cannot be diagnosed with a standard helium mass spectrometry leak check. Corrective actions that were immediately introduced: leak check gate valves and right-angle valves individually before installation onto the cavity string. We started to perform this leak check with F1.3-5. See Fig. 4. The valve vendor was contacted to report this non-conformance, but for schedule and efficiency, the problematic gate valve was not disassembled nor returned to the vendor, and no further action has been taken. No other leak through problems were experienced after F1.3-2.

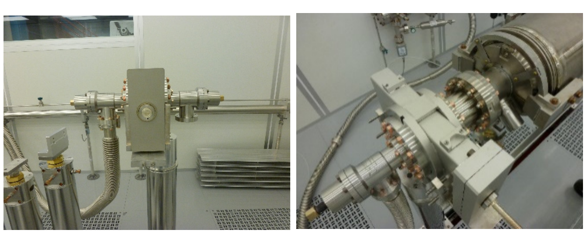

Figure 4: Valves leak check and Assembly

During the testing for F1.3-3, the cavity at string position 3 experienced end group heating [2]. Further diagnosis was done at CMTS after warm-up by accessing the thermal intercepts for the high order mode (HOM) for this end group via using the access ports on the side of the vacuum vessel. There are 7 access ports on the opposite side of the fundamental power coupler (FPC) ports which are designed mainly for tuner access. These access ports have proven to be very useful to repair several other problems and eliminated the needed to pull the cold mass off the vacuum vessel for many repairs. The thermal intercept clamp installed on the HOM connector was installed with indium and torqued to specified value with specified sequence, but a bad thread of the used fastener caused a false torque reading and resulted a loose thermal intercept installation during cryomodule assembly. Corrective actions that were immediately introduced: extra QC steps such as checking the assembled thermal intercepts by wiggling the clamp, sink and giving more attention to the torqued fasteners by peers, lead techs and the responsible engineer.

Fig 5 shows the repair done in-situ at CMTS while F1.3-3 was warm but still on the test stand.

Figure 5: Thermal intercept repair

After the testing of F1.3-3, during warm-up, a beamline leak developed. This cryomodule is disassembled at CAF for further diagnosis and to pinpoint the leak location. The leak was located at beam position monitor (BPM). 3 of the 4 electrical feedthrough flange connections to the BPM body developed leaks. Fasteners which were torqued to 12 N-m specification during string assembly were loose. After the fasteners were tightened to 12 N-m, two flanges stopped leaking. Other still leaking flange was torqued to 16 N-m and the leak was eliminated. Based on the findings, the root cause of the BPM leak was deemed to be insufficient torque on the fasteners and loosening of the fasteners after thermal cycle. Corrective actions that were immediately introduced: increase the torque for the BPM electrical flanges from 12 N-m to 16 N-m and introduce a formal torque specification for all the cavity string fasteners. Starting from F1.3-7, travelers are revised to specify the torque values and torque wrench use.

After testing of F1.3-5 and F1.3-7, during insulating vacuum venting to atmosphere to expedite warm-up, 5 Torr partial pressure of helium was introduced to insulating vacuum space before venting with nitrogen to atmosphere. When helium was introduced to the insulating vacuum space, a residual gas analyser (RGA) on the cavity string beamline vacuum was monitored and a very small leak (E-8 mbar x liter / second) was observed for both cryomodules. Based on the cryomodule internal temperature sensors, helium was introduced at 275 Kelvin which is slightly below room temperature. When these cryomodules were leak checked upon their return to CAF, no leaks were found. This small beamline leak experienced at CMTS could not be found later during further diagnosis at CAF on these 2 modules and it is not well understood.

F1.3-6 is the first cryomodule that Fermilab shipped to SLAC for the LCLS-II. F1.3-6 was tested successfully at CMTS, and no vacuum leak during were observed during or after the test. The shipping configuration: beamline is under vacuum (not actively pumped, not actively monitored/recorded). Warm end FPC vacuum/pumping

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line is under vacuum (not actively pumped, not actively monitored/recorded). Insulating vacuum is pressurized to 4.3 psig with boiled off nitrogen gas.

During incoming quality control checks, it was found that the beamline vacuum integrity was compromised. Further investigation showed that the BPM electrical feedthrough flange which faces down lost 2 out of 8 fasteners. One fastener was fully disengaged and fell; the other fastener was hanging in only by a thread. See Fig. 6. Tuner access ports were used to determine that some fasteners from the cavity string position 1 tuner and cold mass upper assembly got loose and fell during cryomodule shipping. The LCLS-II project halted cryomodule production immediately to start a formal investigation for the root cause of this catastrophic failure.

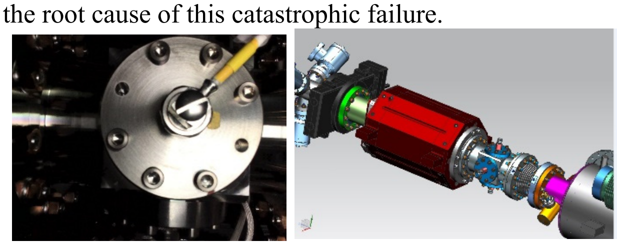

Figure 6: BPM

Two external audit teams were created focusing on design differences between European XFEL CM versus LCLS-II CM and quality assurance/control practices followed during LCLS-II cryomodule production. At Fermilab, we have started three investigations in parallel to understand the root cause of the unsuccessful F1.3-6 shipping. The first investigation was done to understand the BPM failure. We reviewed the product life cycle for this button BPM. Design is referenced to XFEL button BPM. Closer look revealed that XFEL drawings used to design LCLS-II BPM were not the latest version drawings used for the actual XFEL CMs. The fasteners that were specified to be used on the LCLS-II BPM were not the same as specified for the XFEL BPM. Bench tests were performed with various configurations of BPM sub-assemblies. Test steps were: Assemble per specification, leak check, check torque post leak check, adjust torque as needed, thermal test, check torque, leak check, disassemble, inspect seal. See Fig. 7 for one test setup after thermal test.

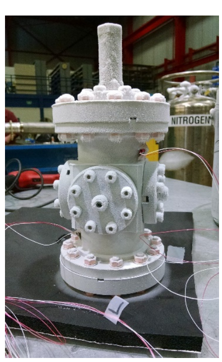

Figure 7: BPM cold shocked tested

Few tests partially reproduced the failures (both caused beamline vacuum leaks) experienced with F1.3-6 and F1.3-3. We have concluded from these tests that fastener type, material and specified torque used for the LCLS-II BPM provide vacuum leak tight assemblies in the cleanroom but do not provide a long-term reliability for cavity string beamline vacuum integrity.

The second investigation was made to improve cold mass assembly fasteners reliability. Starting with F1.3-1, a fasteners spreadsheet was created by the CM design group. This spreadsheet specifies critical (structural, thermal connections) fasteners installation procedures. The upper cold mass assembly (UCM) is fabricated at an outside vendor. The fasteners installation specifications are shown in the drawings and fabrication specification document. When the first UCM arrived from vendor, some loose hardware was observed during incoming QC. The vendor was contacted to correct this problem for future deliveries. We did not experience any loose hardware for future deliveries. Based on the recommendations from quality assurance/control practice audit, we have revised the fasteners spreadsheet to include all (not only critical) fasteners. The goal is to ensure at least two means of locking to a fastener (such as Loctite and torque). We also contacted the UCM vendor to increase QA/QC procedures and documentation during fasteners installation for the UCM assembly.

A third investigation is currently being done to understand the long-distance CM shipping fixture. Shipping vibrations are under study to see if they might also be a cause of fastener loosening.

CONCLUSION

With the corrective actions in place and lessons learned, CM production is being resumed gradually. F1.3-11 cavity string assembly is completed. F1.3-8 is the first module for which a retrofit BPM repair will be done. Fasteners QA/QC/repair is currently done for F1.3-8

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