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LCLS-II CRYOMODULES PRODUCTION EXPERIENCE AND LESSONS LEARNED 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 their cryomodule production rate to meet the challenging LCLS-II project installation schedule requirements of approximately one cryomodule per month per laboratory. To date, Fermilab has completed the assembly and testing of eighteen 1.3GHz cryomodules. Fermilab has successfully shipped nine cryomodules to SLAC and will continue to ship approximately every two weeks. The first 3.9 GHz cryomodule assembly is scheduled to start in June 2019. Production readiness verifications are currently in process. This paper presents LCLS-II 1.3GHz cryomodule assembly and production experience, emphasizing the challenges, mitigations, and lessons learned.

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 [1]. Fermilab has completed the assembly of eighteen cryomodules (CM) and all eighteen cryomodules have been tested at the Cryomodule Test Stand (CMTS) at Fermilab. F1.3-1 is the prototype CM that was assembled with a 6-month duration at the 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 [2]. F1.3-2 through F1.3-4 were assembled in a pseudo-parallel assembly mode to ramp-up the production throughput. During the ramp-up phase, we hired and trained additional manpower, refined assembly travelers, and developed manufacturing bill of material (MBOM aka parts kits). Starting from F1.3-5, peak production throughput of 1 CM per 4 weeks is reached [3]. As we are nearing the completion of the 1.3GHz cryomodule assembly, we were able to maintain a relatively stable hands-on technician workforce since the halfway point of the production despite some expected and unexpected turnovers. Production and quality culture are embedded well to the team using the established and proven cryomodule assembly facilities infrastructure and QA/QC systems in the laboratory. We had experienced several challenges during the production and all these challenges are mitigated. Challenges that we experienced are product and/or process related. Process related challenges were minimized during natural improvement of production and quality culture as the production progressed. Product related challenges were also mitigated but they became major cost and schedule drivers for the project. The aggressive schedule for the LCLS-II project caused us to follow a nonstandard very fast product life cycle process. Production of the cryomodules started before the prototype cryomodule was tested in CMTS and transported. The XFEL cryomodules were tested at DESY where they are installed in the linac tunnel. The LCLS-II cryomodules are first to be cold tested and then shipped to another laboratory for installation to the linac tunnel.

CHALLENGES & MITIGATIONS

Field Emission

During testing of the F1.3-1 through F1.3-3 at CMTS [4], we experienced excessive field emission (FE). The FE specification requires the onset of measurable field to be above a gradient (Eacc) of 14 MV/m for all cavities. Starting from F1.3-5, we started to increase quality oversight during cavity string assembly in the 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 string assembly, an external expert audit was conducted by Stephane Berry from CEA/Saclay. Audit recommendations (infrastructure and assembly processes improvements) are mostly implemented to achieve consistent FE performance [5]. F1.3-17 is the latest cryomodule tested at CMTS. Figure 1 shows the FE performance of the tested cryomodules at CMTS [6,7].

Microphonics

During F1.3-1 testing, microphonics detuning exceeded the specification [8]. 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 the cavity at string position #1 still did not meet the requirements of the

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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 in Figs. 2-4. Most of these modifications were later retrofit to earlier cryomodules F1.3-1 through F1.3-6.

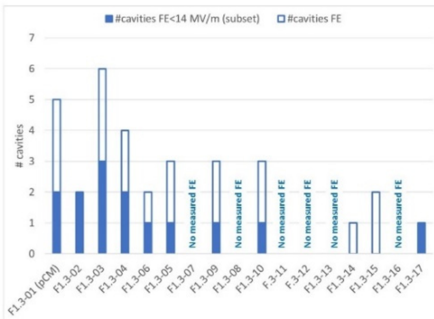

Figure 1: Field Emission Performance.

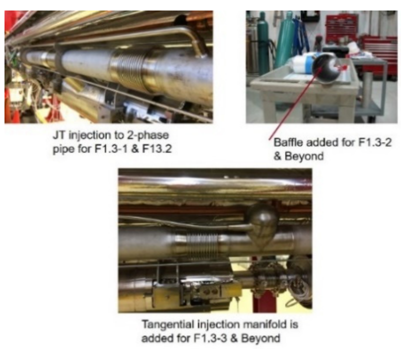

Figure 2: Better Liquid Management and Microphonics Optimization.

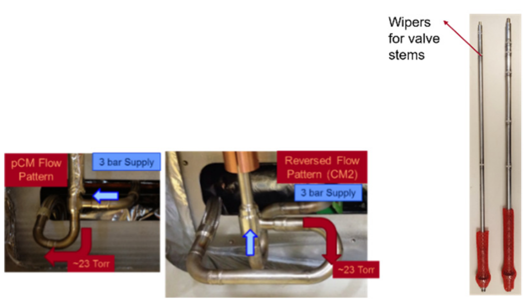

Figure 3: Wipers added to valve stem and reverse configuration welding of the valves to reduce TAO.

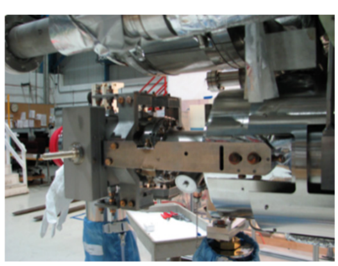

Figure 4: Added bellows between gate valve-Cav#1 and decoupled gate valve support from HGRP to reduce Cav#1 microphonics.

Fasteners Improvement

During the testing for F1.3-3, the cavity at string position 3 experienced end group heating [4]. 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 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 for repairing 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 in a specified sequence, but a bad thread on the fastener caused a false torque reading and resulted in 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 and sink and giving more attention to the torqued fasteners by peers, lead techs and the responsible engineer.

Figure 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.

During the assembly of F1.3-5, the RF group found that Cav#2 HOM feedthrough center pin in broken. This was found during the final HOM notch frequency tuning before the lower heat shields were welded. After the RF cable was removed, the broken pin was diagnosed. A tent cleanroom was built. A nitrogen fogger was used to optimize the location and rotation speed of the fan filter unit. Particle-free UHV disassembly and assembly procedures were developed and tested on the bench with a spare cavity. A HOM feedthrough with a broken pin was replaced and leak checked successfully. This was a one-time incident, and an official root cause analysis was not done. The mitigation strategy to eliminate re-occurrence is to ensure that protective caps are installed throughout the cold mass assembly. The RF group also changed the procedure for HOM notch frequency tuning by keeping the RF cable connected during tuning. See Figure 6.

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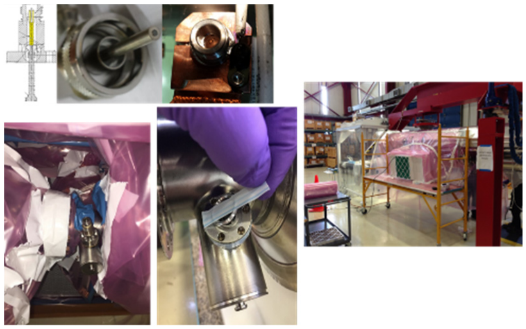

Figure 6: Broken HOM feedthrough replacement.

After the testing of F1.3-3, during warm-up, a beamline leak developed. This cryomodule was disassembled at CAF for further diagnosis and to pinpoint the leak location. The leak was located at the beam position monitor (BPM). Three 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. The remaining 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 were revised to specify the torque values and torque wrench use. Due to the size of the leak observed, F1.3-3 beamline was deemed to be contaminated and no longer particle free, so this cryomodule was fully disassembled.

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. These small beamline leaks experienced at CMTS could not be found later during further diagnosis at CAF on these 2 modules and they remain not well understood.

Transportation Improvement

F1.3-6 is the first cryomodule that Fermilab shipped to SLAC for LCLS-II. F1.3-6 was tested successfully at CMTS, and no vacuum leak during was 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 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 at SLAC, it was found that the beamline vacuum was at atmospheric pressure. Further investigation at SLAC 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 only by a thread. See Figure 7. 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.

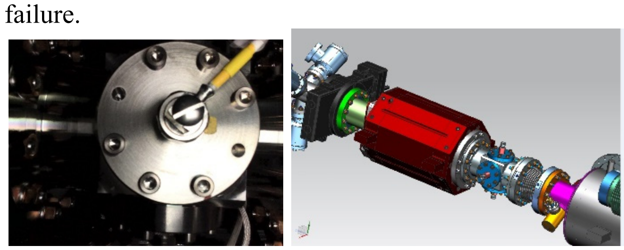

Figure 7: BPM.

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 started investigations 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. The design is referenced to the XFEL button BPM. A 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 those 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 Figure 8 for one test setup after thermal test.

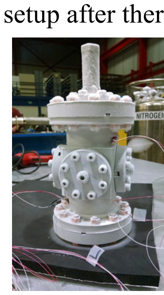

Figure 8: BPM cold shocked tested.

A 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 long-term reliability for cavity string beamline vacuum integrity.

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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 industrial 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.

F1.3-6 is then returned to Fermilab for disassembly and further investigation of the beamline failure. Cryomodule is partially disassembled for thorough beamline leak check mostly to better understand the BPM leak and assess if there are any other leaks in the beamline. During leak check, we were able to pump down to a marginal vacuum level, first attempt was done to tighten the BPM fasteners to fix the big leak so we can pump down to a good vacuum level and conduct planned leak checks. To our surprise, the marginal vacuum level did not get better, further investigation with an audio amplifier scope, we found a leak on Cav#4 cold end couplers bellows. We removed this cold end coupler and replaced it with a blank flange. The marginal vacuum level did not improve. We then found another leak on Cav#5 cold end coupler bellows. After removing this leaky coupler, we were able to pump down and conduct the leak check. No other leak was found including the BPM, though because we had to tighten the BPM fasteners at the beginning of the leak check, we probably fixed the small leak therefore after cold end couplers bellows big leaks were eliminated, BPM leak was not present.
The disassembled cold end couplers showed that the convolutions of the bellows were damaged for both couplers and caused the catastrophic beamline failure for F1.3-6. See Figure 9.

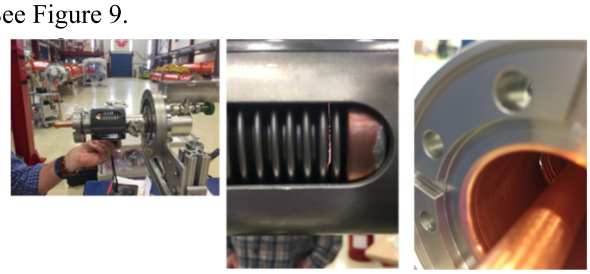


Figure 9: First convolution of the bellows is broken.

A new investigation was started to understand the root cause of these bellows convolutions failures. Looking at the fundamental power coupler design [9] and performing an autopsy on the F1.3-6 couplers, we found that the G10 coupler support parts experienced some scoring and G10 dust was found on all the supports. See Figure 10.

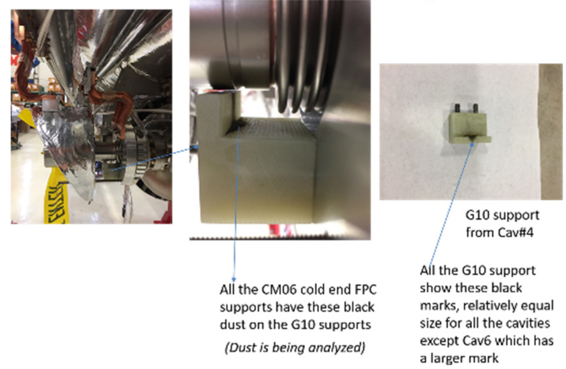
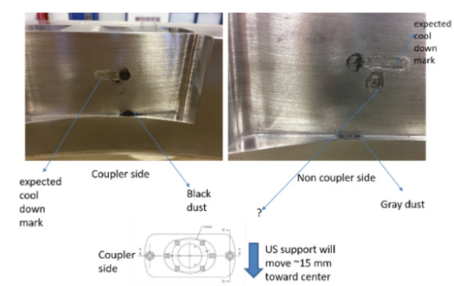
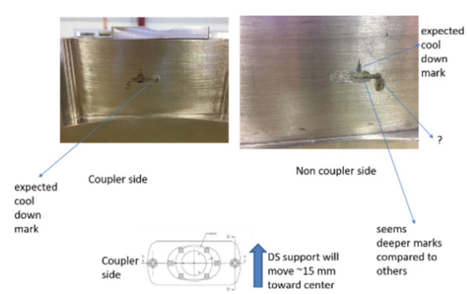


Figure 10: G10 coupler supports friction dust and scoring points to excessive motion during cryomodule shipping.

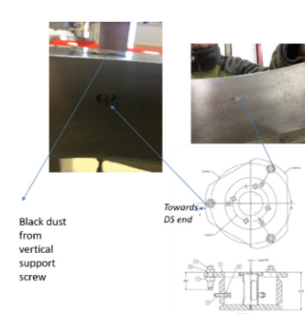
The vacuum vessel removed from F1.3-6 was inspected for damage and some unusual wear marks were found inside the vacuum vessel (Figure 11). These wear marks indicated that the cold mass moved and shifted inside the vacuum vessel during cryomodule shipping.



Upstream sliding support



Downstream sliding support



Center fixed support
Figure 11: Wear Marks on F1.3-6 Vacuum Vessel.

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These findings triggered a review of the cryomodule assembly travelers; we changed the procedures and added torque and multiple check-and-verify requirements to ensure that the cold mass is properly secured inside the vacuum vessel. An extensive investigation was also done by several multi-laboratory teams to better understand the root cause of the coupler bellows failures. These investigations concluded that the bellows used on the couplers is properly manufactured and properly handled during cryomodule assembly. There were no indications that anything done by coupler vendor nor the cryomodule assembly group which could have caused these bellows to fail during cryomodule shipping. As part of this extensive investigation, cryomodule shipping procedures and fixtures were also investigated to further understand the root cause of the cold end coupler bellows failure. [10] Simulations, shaker table tests using actual coupler components, road tests using the concrete dummy cryomodule with extensive and sophisticated instrumentation (such as shock logs, accelerometers, laser displacement sensors etc.) indicated that performance of the LCLS-II shipping end caps and shipping frame fixture are very different from those for XFEL (the design basis for the LCLS-II fixture). The shipping caps as designed did not provide reliable support of the cold mass inside the vacuum. The shipping frame fixture isolation system was very stiff; the isolation springs were not properly sized to dampen unwanted shocks and to restrict the undesired motion. After improvements were done and approved by the project team, F1.3-5 was used for local transport tests with the improved fixtures and procedures. To our surprise, F1.3-5 experienced a beamline failure during local transport tests. In further investigation of the beamline failure, we found the same cold end bellows failure on Cav#1 cold end coupler bellows. An in-depth analysis of the data showed that the fundamental power couplers as assembled in the cryomodule experience motion which results in failure of the cold end coupler bellows. This was not experienced for the 100 XFEL cryomodules shipped from CEA/Saclay France to DESY, Germany. The reason for this is currently being investigated by DESY team with some shaker table bench tests.

For LCLS-II cryomodules shipping, it was decided that we need to reduce / eliminate this unwanted coupler motion. One alternative is to remove and ship the cryomodule without warm end couplers. The beamline is under vacuum during cryomodule shipping. In order to support the vacuum forces on cold end coupler bellows, restraint rods also called "Berry Bolts" are used. These are shipping restraints and need to be removed during warm end coupler assembly after shipping. Fermilab shipped the F1.3-4 cryomodule with this configuration to SLAC and it arrived with beamline vacuum intact. Although it was expected to be the most technically safe solution for the cold coupler bellows, the logistics and cost of warm end coupler installation at the SLAC linac area were deemed difficult to overcome and this scheme of cryomodule shipping was dropped. The JLab team developed a scheme to install temporary supports called M-mounts to the coupler. (See Figure 12). This scheme does not require warm end coupler disassembly and provides the needed support to minimize the motion of the coupler which causes cold end bellows failure.

To date, Fermilab has successfully shipped seven cryomodules using the M-mounts. F1.3-12 recently suffered a beamline loss incident at SLAC during incoming QC and preparation for moving to the linac tunnel. During M-mount removal, accidentally, the cold end coupler bellows convolution was cut/damaged with the diagonal cutter that is used to cut the plastic zip tie that holds the M-mount in place. This incident halted cryomodule shipping for a short period. A review of the work control and planning documents, hands-on personnel training, adherence to work control and planning documents, and generation of off-normal work control and planning documents, as needed, were revisited at SLAC and partner labs (Fermilab and Jefferson Lab). This prompt action resulted in resuming cryomodule shipping to SLAC. Unfortunately, F1.3-12 is a damaged cryomodule and has been returned to Fermilab for full disassembly.

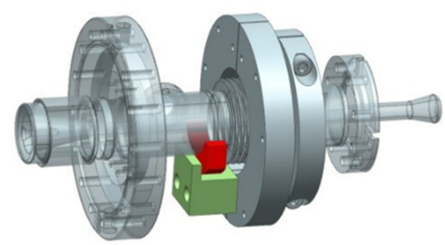

Figure 12: M-mount installed on an LCLS-II coupler.

CONCLUSION

With the corrective actions in place and lessons learned applied, 1.3GHz cryomodule production is nearing completion, with 18 of 19 cryomodules assembled and tested. Fermilab has shipped 9 cryomodules to SLAC. 8 out 9 cryomodules were shipped with M-mounts and arrived to SLAC with beamline intact. Unfortunately, one cryomodule was damaged after safe transport.

Fermilab will start LCLS-II 3.9GHz cryomodule production in July 2019. Lessons learned from 1.3GHz cryomodules production will be directly applied to 3.9GHz cryomodules production.

REFERENCES

[1] T. J. Peterson et *al.*, "LCLS-II 1.3 GHz Cryomodule Design – Modified TESLA-Style Cryomodule for CW Operation", in Proc. 17th Int. Conf. RF Superconductivity (SRF'15), Whistler, Canada, Sep. 2015, paper THPB119, pp. 1417-1421.

[2] T. T. Arkan *et al.*, "LCLS-II 1.3 GHz Design Integration for Assembly and Cryomodule Assembly Facility Readiness at Fermilab", in *Proc. 17th Int. Conf. RF Superconductivity (SRF'15)*, Whistler, Canada, Sep. 2015, paper TUPB110, pp. 893-897.

ISBN: 978-3-95450-211-0 doi:10.18429/JACoW-SRF2019-TUP101

[3] T. T. Arkan *et al*., "LCLS-II Cryomodules Production at Fermilab", in *Proc. 9th Int. Particle Accelerator Conf. (IPAC'18)*, Vancouver, Canada, Apr.-May 2018, pp. 2652-2655. doi:10.18429/JACoW-IPAC2018-WEPMK010

[4] E. R. Harms *et al*., "Commissioning and First Results from the Fermilab Cryomodule Test Stand", in *Proc. 28th Linear Accelerator Conf. (LINAC'16)*, East Lansing, MI, USA, Sep. 2016, pp. 185-188. doi:10.18429/JACoW-LINAC2016-MOPLR022

[5] G. Wu *et al.*, "Optimization of Clean Room Infrastructure and Procedure During LCLS-II Cryomodule Production at Fermilab", presented at the 19th Int. Conf. RF Superconductivity (SRF'19), Dresden, Germany, Jun.-Jul. 2019, paper TUP096.

[6] E. R. Harms *et al.*, "Experience With LCLS-II Cryomodule Testing at Fermilab", presented at the 19th Int. Conf. RF Superconductivity (SRF'19), Dresden, Germany, Jun.-Jul. 2019, paper THP060.

[7] N. Solyak *et al.*, "Performance of the First LCLS-II Cryomodules: Issues and Solutions", in *Proc. 9th Int. Particle Accelerator Conf. (IPAC'18)*, Vancouver, Canada, Apr.-May 2018, pp. 34-37. doi:10.18429/JACoW-IPAC2018-MOZGBD3

[8] J. P. Holzbauer *et al.*, "Passive Microphonics Mitigation during LCLS-II Cryomodule Testing at Fermilab", in *Proc. IPAC'18*, Vancouver, Canada, Apr.-May 2018, pp. 2668-2670. doi:10.18429/JACoW-IPAC2018-WEPML001

[9] K. S. Premo *et al.*, "LCLS-II Fundamental Power Coupler Mechanical Integration", in *Proc. 17th Int. Conf. RF Super conductivity (SRF'15)*, Whistler, Canada, Sep. 2015, paper THPB086, pp.1340-1342.

[10] P. Holzbauer *et al.*, "LCLS-II Cryomodule Transportation: Failures, Successes, and Lessons Learned", presented at the 19th Int. Conf. RF Superconductivity (SRF'19), Dresden, Germany, Jun.-Jul. 2019, paper MOP090.