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LCLS-II CRYOMODULE PRODUCTION AT JLab: SUMMARY AND LESSONS

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Abstract

Cryomodules (CMs) for the Linear Coherent Light Source II (LCLS-II) at SLAC National Accelerator Laboratory were jointly fabricated at Thomas Jefferson National Accelerator Facility (JLab) and Fermi National Accelerator Facility (FNAL). Procurements, cavity testing, cryomodule assembly, and cryomodule testing were carried out at the two labs. Twenty-one 1.3GHz cryomodules were fabricated at JLab. The LCLS-II cryomodules are based on the design used in the European X-Ray Free-Electron Laser (XFEL) but modified for continuous-wave operation. The higher performance requirements lead to challenges in cavity processing, microphonics, magnetic hygiene, and cryomodule transportation. This paper outlines the cryomodule production experience at JLab, as well as improvements to procedures and infrastructure to overcome the performance challenges of the LCLS-II design.

INTRODUCTION

The LCLS-II project involves the construction of a 4GeV continuous-wave superconducting linear acceleration at SLAC. The 35 new CMs were installed in a one-kilometer stretch of tunnel that formerly housed the normal-conducting LCLS. A total of 40 1.3GHz CMs were fabricated at JLab and FNAL.

The LCLS-II CM (Fig. 1) uses eight 9-cell TESLA-style cavities. The CMs are based on the design installed in the XFEL machine at DESY. The major difference between LCLS-II and XFEL is that the former is a CW machine and the latter is pulsed. Changes in design were implemented to allow for CW operation. Adapting the XFEL design was seen as a method for reducing risk. FNAL was chosen to be the design authority for the LCLS-II cryomodules due to their experience with TESLA-style CM design and assembly [1].

Cryomodule production for the LCLS-II project was carried out between 2015-2021. An extra five cryomodules were added to the initial count of 35, for redundancy. Twenty-one of these were fabricated at JLab and the remainder were fabricated at FNAL. Each lab built an initial prototype cryomodule (pCM) to test the new design and the two production lines. The pCMs were built using former ILC R&D cavities which were already fabricated. They also featured extra instrumentation to aid in qualification.

At the time of LCLS-II's conceptual start, JLab had completed four different cryomodule production runs in its history: the original CEBAF C20s, SNS high and medium beta CMs for ORNL, the JLab Free-Electron Laser (FEL), and the C100s for the recently completed CEBAF 12 GeV upgrade. Lessons and strategies from these projects were the basis for JLab's LCLS-II production strategies. The facilities and infrastructure used for producing these CMs would need to be modified for the very different ILC/XFEL-style CMs while remaining usable for future work on CEBAF-style CMs.

The evolution of the XFEL design to the CW LCLS-II cryomodules produced several unintended consequences during CM production. Work was stopped and restarted on several occasions to develop mitigations for these unforeseen issues.

Since the completion of the LCLS-II project, work has started on the LCLS-II High Energy Upgrade (LCLS-II-HE). JLab will assemble eleven HE cryomodules – which are the same as LCLS-II CMs apart from a different cavity processing recipe and tuner – utilizing the lessons learned from the original project.

Figure 1: An LCLS-II cryomodule being prepared for shipment to SLAC.

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CRYOMODULE TRANSPORTATION

CMs assembled at both labs would need to be transported over the road to SLAC for installation in the tunnel. This trip was ~3,000 miles from JLab and ~2,500 miles from FNAL [2].

The CMs were to be shipped via a flatbed trailer using a specially designed shipping frame that used helical isolator springs to attenuate shocks. The frame was loosely based on the system used by XFEL to ship over 100 CMs from Paris to Hamburg (500 miles).

The JLab pCM was used to test the shipping system. It first made an 800-mile trip that encompassed the start of the eventual route to SLAC. The pCM was RF tested in the cryomodule test facility (CMTF) before and after the trip; there was no degradation in CM performance. An additional trip from JLab to FNAL, and subsequent RF test, also showed no degradation. The shipping system was considered qualified for use for shipping production CMs to SLAC.

The first production CM (F1.3-06) to reach SLAC from FNAL did so with a vented beamline. The cause was initially thought to be screws that had come out of a flange on the beam position monitor feedthrough. While this would have been enough to cause the venting, a further examination found fatigue failure in the fundamental power coupler (FPC) bellows on several cavities. Minor changes were made to the shipping system and implemented on a test run using F1.3-05; the beamline was vented soon after starting the trip at FNAL.

The additional instrumentation on F1.3-05 lead to the discovery that the FPC bellows were being excited by resonant frequencies from the road. The subsequent motion lead to early fatigue failure. Investigation into the previous success of the JLab pCM shipments found a difference in the FPC designs. The pCM used ILC-style FPCs, which had a sleeve designed to protect the bellows convolutions from accidental damage; this sleeve was also acting to stop the motion of the bellows and hence stopping the fatigue failure. The modified LCLS-II style FPCs used in the production CMs did not have this sleeve. A successful test run using J1.3-07 was also carried out over 800 miles using the same system as the pCM; the reasons behind the success were not investigated. Other studies looking to find whether the bellows had been weakened during the CM testing process were inconclusive and incomplete.

Comparisons of the shipping frame with that used by XFEL found a large difference in the stiffness of the spring system. Parameter studies done at JLab with differing numbers of springs found that reducing the number from the original 32 to 8 removed the resonant frequency vibrations which were exciting the bellows.

A support device – the M-Mount (Fig. 2) – was developed to physically stop the movement of the bellows. Testing on a shaker table found that the restraint reduced the movement of the bellows by a factor of three. The restraints and new spring configuration were tested on a previously vented cryomodule shipped between JLab and SLAC; the beamline vacuum and FPC bellows remained intact after the trip. The cyclic motion of the bellows was found to be a maximum of ±0.85 mm, which was far lower than the ±2.0mm desired spec and the ±3.0 mm motion that would be theoretically required for the bellows to fail [2].

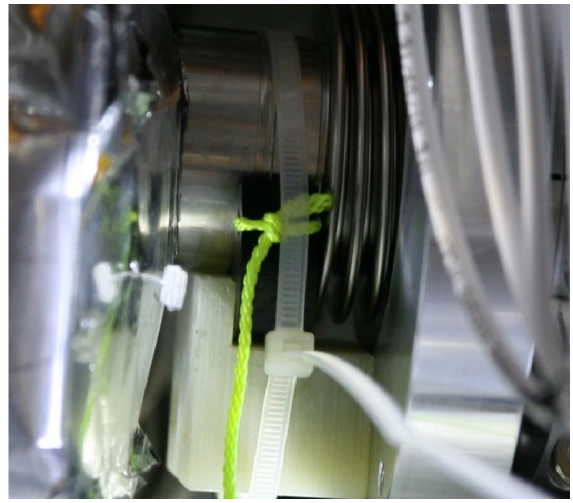

Figure 2: An M-Mount installed on an FPC.

The successful test run cleared J1.3-04 for shipment to SLAC. It arrived with no degradation of the beamline vacuum. Production CM shipments were also cleared to resume. By the end of the project, 38 LCLS-II CMs were successfully delivered to SLAC from the two labs (the other two CMs were turned over to the LCLS-II-HE project for rework).

At JLab, the major lessons from the LCLS-II shipping issues will be implemented in three upcoming CM production projects, the SNS Proton Power Upgrade (shipping from JLab to Oak Ridge, TN), LCLS-II-HE (shipping from JLab to Menlo Park, CA) and the Electron-Ion Collider (shipping from JLab to Upton, NY).

- Individual components (e.g. FPCs) are individually analyzed to ensure no resonant frequencies are excited by road travel.
- Changes in CM design after successful tests/shipments are analyzed to determine the overall effect on shipping. For example, despite CMs being successfully shipped for the SNS project, a change in end-can design necessitated new shipping tests for SNS-PPU.

CRYOGENIC IMPROVEMENTS FOR CRYOMODULE TESTING

CMTF

The Cryomodule Test Facility (CMTF) at JLab was commissioned in 1988 to test the original CEBAF C20 CMs. Liquid helium is supplied by the 650 W Cryogenic Test Facility (CTF). It was later also used to test CEBAF C100 CMs and SNS high-β and medium-β CMs [3]. In addition to the CMTF, the CTF also supplies cryogens to the Vertical Test Area (VTA) which is used for testing cavities; this leads to CM testing having to compete with cavity testing for cryogens, as the CTF could not fully supply both simultaneously.

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LCLS-II CMs have a 5 K circuit in addition to just the 2 K and 40 K circuits in CEBAF CMs for which the CMTF was designed. A 4 K-2 K heat exchanger was installed to provide the additional circuit in the CM [4].

During the LCLS-II project, it was found that the high cavity Q_0s achieved through nitrogen doping (and required to meet the specification) were severely impacted by trapped magnetic flux present during testing (and operation). Cooling down the cavities at a rapid rate is required to expel the flux; specifically, the cavities needed to go through the transition temperature of niobium (9.25 K) as fast as possible.

The CTF in its normal operating form could not cool down cavities fast enough to allow them to meet their Q_0 spec (2.70×10^{10}). The cavities could only be cooled at a rate of 1.5-2.5 K/min, which achieved Q_0s of ~2.0×10^{10} [4]. The higher cooling capacity of the equivalent facility at FNAL proved that faster-cooled cavities lead to higher Q_0s. The following steps were implemented to increase the measured Q_0s in the CMs through fast cooldowns (FCDs):

- Cold Box 3 in the CTF was upgraded to increase its liquefaction capacity from 5 g/s to 9.3 g/s [3].
- Bypass lines were added to the 4 K-2 K heat exchanger to reduce the pressure drop on the return side of the flow.
- A u-tube procedure was devised where flex u-tubes were temporarily used to bypass the dewar and recovery system in the CTF to allow the compressors to flow directly into the cold box.

After being cooled down to 2K and completing gradient limit testing, a warm helium line was used to bump the cavity temperatures to 40 K. They were then kept stable at 40 K while the u-tube operation was carried out and the heat exchanger bypassed. The cavities were then cooled rapidly. Q_0 measurements were carried out after the system was pumped back down to 2 K.

The improvements to the cryogen supply systems allowed the cavity cooling rates to increase to 21 K/min (through 9.25 K). The increased cooling rate leads to greater flux expulsion and higher CM Q_0 values (Fig. 3). Each point in Fig. 3 represents the average Q_0 of all eight cavities compared to the average rate of cooling of the cavities. It should be noted that Q_0 values depend on numerous factors such as Field Emission (FE) and the original Q_0 of the cavity before assembly onto a string.

The LERF as a CM Testing Facility

The CMTF was predicted to be the bottleneck for CM production at JLab. A solution was to test CMs in the Low Energy Recirculation Facility (LERF) – formerly the JLab Free Electron Laster – which was then under light usage.

The CMs in the LERF received cryogens from CEBAF's main Central Helium Liquefier (CHL). The 9.2 kW capacity of the CHL was a major upgrade from the supply available from CTF. A caveat was that the CHL also supplies CEBAF, and any CM testing in the LERF would need to not affect the main accelerator operations.

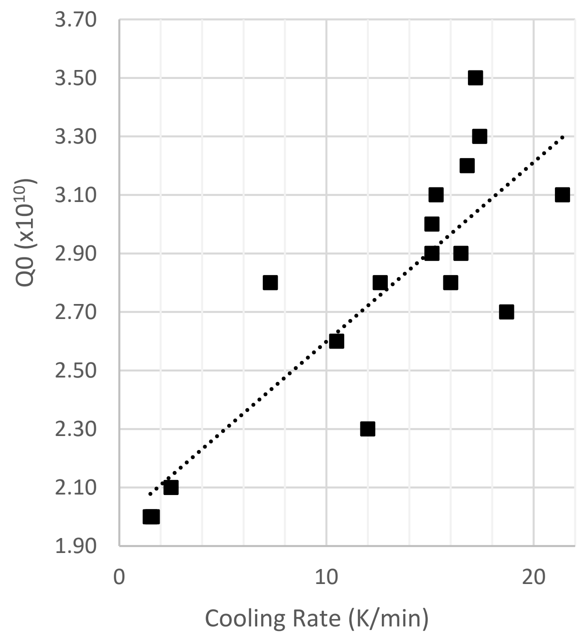

Figure 3: Relation between cooldown rate and CM average Q_0.

The LERF allowed two CMs to be connected and tested in series similar to how they would be installed in the SLAC tunnel. This allowed for unique RF measurements to be done on a 'vertical slice' of the full linac. The Solid State Amplifiers (SSAs) and other RF control systems were identical to those used at SLAC.

Cryogenic supply from the CHL provided a far more stable RF testing environment. Though the cryogen supply was greatly increased, the rate of cavity cooling remained comparable to that achieved in the CMTF. This was due to administrative rules put in place to protect the CHL from trips during CEBAF operation. The four CMs tested in the LERF achieved cooling rates between 12.6 – 16.8 K/min.

The successful operation of the LERF as a testing facility has earmarked it for testing all LCLS-II-HE cryomodules.

CRYOMODULE PERFORMANCE SUMMARY

The required performance characteristics of LCLS-II cryomodules are defined by the SLAC acceptance criteria document. A summary is shown in Table 1. The average Q_0 criteria was a new requirement, added after very favorable results from prototype testing at FNAL.

Table 1: Summary of CM Acceptance Criteria

Criteria	Value
CM Gradient	128 MV
Average CM Q_0	2.7×10^{10}
Min Cavity Gradient	12 MV/m
Min Cavity FE Onset	14 MV/m

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Figure 4 shows the maximum and usable gradients of all the CMs produced for LCLS-II at JLab. CMs with low maximum and usable gradients are generally signs of early-onset field emission. The usable gradient is the gradient at which the cavity could run for one hour without exceeding field emission limits, quenching, or being halted by another factor such as FPC temperatures or vacuum.

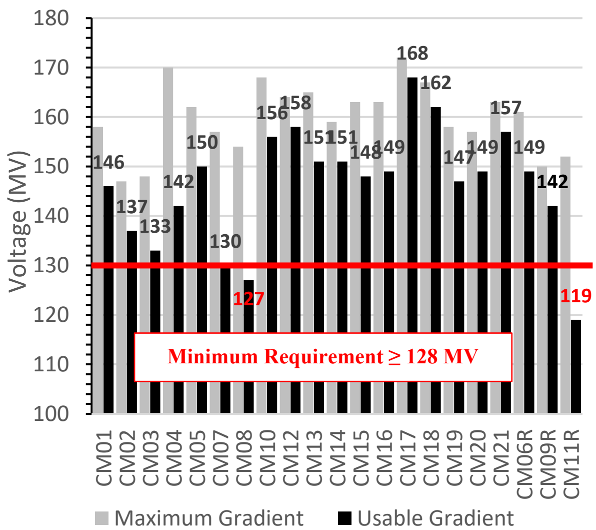

Figure 4: Max and usable gradients of LCLS-II CMs.

Out of the 168 cavities that were installed in CMs, 47 were found to field emit. Of these, 35 had onsets below the minimum spec of 14 MV/m, and 28 had usable gradients below the minimum spec of 12 MV/m [5].

Reductions in FE and gradients after CM08 were the result of a cleanroom process audit and changes to procedures. The admin limit of 24 MV/m was removed from VTA testing; this addressed the theory that FE which would be detected in the VTA at high gradients may ‘settle’ at lower onsets during the cavity string assembly process.

Figure 5 shows the average Q_0s for all the production CMs. The red line represents the point during production when FCDs were instituted in the CMTF. CMs before that point illustrate the difference between the VTA tests with a faster cooldown through transition (and hence more flux expulsion) and the corresponding CMTF tests with a much slower cooldown (and hence more trapped flux). After the FCDs were implemented, the average Q_0 went from 2.0×10^{10} to 3.0×10^{10}.

LESSONS LEARNED

Parts in Circulation

A number of the CM components procured from outside vendors included parts that were only used for shipping and/or processing. These parts were not required for installation on CMs. The project decided to reduce the number of these components that were bought, choosing instead to return used ones to the vendors for reuse on future shipments.

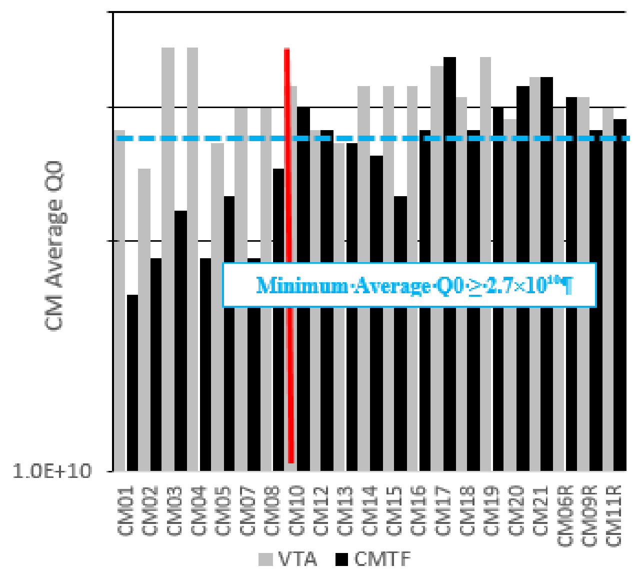

Figure 5: Average Q_0s of LCLS-II CMs.

The Parts in Circulation (PICs) as they were known proved to be problematic throughout the project. The major difficulties were with the shipping stands for FPCs and flanges/hardware for cavities. The intent was that these PICs would be taken off the parts after the latter had been inspected and/or installed on CMs. Delays in inspections and CM production meant PICs could not be returned to vendors quickly.

In the worst cases, the vendors’ lack of PICs delayed shipment of components to partner labs, further jeopardizing the schedule. Efforts to track and coordinate the PICs getting returned to vendors spent was a further drain on personnel.

Plans for LCLS-II-HE involve buying 100% of the required transition parts so that no circulation is required.

Cryomodule Rework

During CM production, damaged helium vessel bellows were found on CM09 and CM11. This was attributed to accidents by a technician unfamiliar with the presence of these bellows under multi-layer insulation. The two CMs were fully disassembled and the damaged cavities were removed, instead of only trying to remove the affected cavities; the CMs were to be completed after the end of the production run with the designations CM09R and CM11R.

While CM11R was being rebuilt, a leak was found in another helium vessel bellows (unrelated to the first incident). This leak was much smaller this time around and could only be located after pressurizing the helium space to 14 psig. The defect is a latent one and not caused by any particular operation.

The risk of a repaired weld opening up again when cold was deemed to be too great. The other option was to take the string apart and replace the cavity. Due to the late point in the project and the schedule concerns (delaying would set back first light), the project decided to replace the single cavity without disassembling the string and reprocessing the other cavities.

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This meant that the string would need to be taken back into the cleanroom and a single cavity would need to be removed and another one added in its place. This presented a risk not only for the cleanliness of the CM11R string but also that of the cleanroom itself. To minimize risks to both, the entire string was bagged and wiped down before entering the cleanroom for the swap.

CM11R's CMTF test showed five cavities having FE onset lower than spec and three of those cavities having usable gradients lower than spec. The entire CM managed a total voltage of 118.9 MV, which was lower than the minimum spec of 128 MV and the worst of any LCLS-II CM.

The operation to replace a single cavity without disassembling the string – and reprocessing the cavities – is considered a failure and is not recommended for any projects in the future.

Cold Coupler Ceramic Leak

CM02 was the second CM built at JLab. The niobium used in the cavities produced low Q_0 values (even with FCD) and so these CMs from both labs were slated to be kept as spares instead of being used in the linac. After CMTF testing, the CM was stored at JLab for three years.

A small (10^{-6} torr L/s range) was found in a cold FPC ceramic. This leak was not present during the initial cold testing in the CMTF, which raised the possibility that it may have been caused by the cooldown.

The small size of the leak meant that there was little risk of harming the cleanliness of the string itself. The coupler was changed under a flowhood using regular cleanroom protocols. The CM was not tested in the CMTF after this operation, so it is unknown whether or not the string remained clean (only one cavity had FE in the initial CMTF test).

The leak was only found when the main coupler line was bled up, which is not a regular operation for CMs after cold testing. This step should be added to future CMs during the LCLS-II-HE project

Quality Assurance and Quality Control

Most of the components that were used in LCLS-II cryomodules had some degree of inspection at either JLab or FNAL. At JLab, the data is recorded in travelers in the JLab Pansophy system. Other travelers recorded quality assurance data from assembly steps. A Non-Conformance Report (NCR) is issued whenever a measured quantity is outside the defined specification.

At the end of the LCLS-II project, more than half of the NCRs generated involved the inspection and rework of sealing surfaces on components such as beamline bellows and beamline absorbers [6].

The SRF Quality Group made the following recommendations for future projects:

- For components requiring almost certain rework (e.g. polishing of flange sealing surfaces), repairs should be made standardized preparation steps and completed before their inspection.
- A large number of dimensional NCRs were repeatedly generated and dispositioned "use-as-is". This process could be avoided if the relevant specifications on the traveler are relaxed to reflect realistic requirements

CONCLUSION

The LCLS-II project was completed at JLab with the delivery of the 21st and last CM to SLAC. Initial performance issues were tackled by auditing cleanroom processes and improving cryogenic testing capabilities. Methods for protecting the FPC bellows from failure during shipping were tested and implemented, which lead to no further issues with CM shipments.

The project faced several unique issues arising from both unfortunate events and latent defects. The lessons from these and other events will be implemented (where needed) for LCLS-II-HE and other upcoming CM production projects at JLab.

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