ISBN: 978-3-95450-233-2 ISSN: 2673-5504 doi:10.18429/JACoW-SRF2021-THPTEV003

LCLS-II CRYOMODULES PRODUCTION EXPERIENCE AND LESSONS LEARNED TOWARDS LCLS-II-HE PROJECT*

T. T. Arkan†, D. Bice, J. Blowers, C. Grimm, B. Hartsell, J. Kaluzny, M. Martinello, T. Nicol, Y. Orlov, S. Posen, K. Premo, R. Stanek, Fermilab, Batavia, USA

Abstract

LCLS-II is an 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 (SRF) continuous wave (CW) cryomodules with high quality factor cavities. Cryomodules are produced at Fermilab and at Jefferson Lab (JLab) in collaboration with SLAC. Fermilab has successfully completed the assembly, testing and delivery of seventeen 1.3 GHz and three 3.9 GHz cryomodules. LCLS-II “High Energy” (LCLS-II-HE) is a planned upgrade project to the LCLS-II. The LCLS-II-HE linac will consists of twenty-three 1.3 GHz cryomodules with high gradient and high quality factor cavities. This paper presents LCLS-II-HE cryomodule production plans, emphasizing the improvements done based on the challenges, mitigations, and lessons learned from LCLS-II.

INTRODUCTION

Fermilab delivered the last LCLS-II cryomodule (CM) to SLAC in March 2021. LCLS-II-HE cryomodule production started at Fermilab with the assembly and testing of the verification cryomodule (vCM). With the goal of preserving the momentum for the experienced teams and for the proven functional facilities/infrastructure from LCLS-II, vCM assembly was done without a duration gap right after the last LCLS-II CM.

For LCLS-II-HE, as it was for LCLS-II, Fermilab is the engineer of record and is responsible for the cryomodule design. The vCM design is the same as the LCLS-II cryomodule except for two major differences: i) superconducting radio frequency (SRF) cavities are processed with a new processing protocol for the required performance specifications, ii) cavity end level tuner has an extended range which might be used for the dual frequency operations of the accelerator.

With the contributions from Fermilab, Jefferson Lab and SLAC, an R&D effort has been successfully completed to develop the new processing protocol and transfer the technology to industry. Ten fully dressed cavities were fabricated and processed with the newly developed treatment in industry, and successfully tested at Fermilab; performance exceeded the specification with average Q0=3.6e10 and Eacc=25.6 MV/m (specifications are Q0=2.7e10, Eacc=21MV/m) [1, 2]. The best 8 cavities were used for the string assembly of the vCM which is currently being cold tested at Fermilab with a 5-month test program. At Fermilab, production of series cryomodules will start in the Fall of 2021. Fermilab will assemble, test, and deliver 13 cryomodules to SLAC.

LESSONS LEARNED & CONTINUITY FROM LCLS-II

Cryomodule (CM) Design & Change/Configuration Control

LCLS-II CM design which started with the reference European XFEL pulsed CM design has evolved and significant changes were done first for the continuous wave design and then consecutively to mitigate the technical challenges throughout the lifecycle of CM production [3]. LCLS-II-HE CM design is practically identical to LCLS-II. There is an explicit effort and goal to not change the proven and working design of the cryomodule unless it is absolutely necessary for the performance requirements of the project. A specific lesson learned from LCLS-II is that substitution of parts thought to be equivalent must be reviewed and approved with the help of engineering reviews (peer and independent), small changes matter, and both can have ripple effects and make a big difference on the performance of the cryomodule [4]. Another important lesson learned from LCLS-II is that focusing CM design through a single individual is an organizational weakness since that places undue burden on that person. For the only major design change, which is the extended range tuner, LCLS-II-HE adopted a team approach with a lead design engineer supported by additional designers (as needed) and focused by an overall lead engineer/subject matter expert. Another improvement done for the LCLS-II-HE is to augment the change/configuration control. LCLS-II has a change control board (mostly to review/approve the scope and budget changes) and a records of decision process to document the significant changes. For LCLS-II-HE, a technical change control board and systems engineering structure are introduced early in the project. All proposed changes, even a simple redline drawing change from LCLS-II to LCLS-II-HE, are managed with this new scheme. Initially, this new scheme might seem to be additional and unnecessary paperwork/bureaucracy, but it will pay dividends on the long term.

Facilities/Infrastructure

Proven and successfully used Fermilab facilities/infrastructure for LCLS-II are fully functional and dedicated to LCLS-II-HE CM production. Throughout the LCLS-II CM production, based on audit/review recommendations,

* Work supported by 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)
† arkan@fnal.gov

ISBN: 978-3-95450-233-2 ISSN: 2673-5504 doi:10.18429/JACoW-SRF2021-THPTEV003

some infrastructure upgrades were implemented. These upgrades helped to improve the functional performance of the cryomodules. For LCLS-II-HE before the assembly and testing of the vCM, in order to increase the reliability of the high gradient cavity performance specification (21 MV/m for LCLS-II-HE vs. 16 MV/m for LCLS-II), some additional upgrades were completed for the cryomodule assembly and testing infrastructure.

In order to minimize the pump and purge cycles of the cavity string beamline and to minimize the multipacting of the SRF cavities, a combination NEG/ion pump is installed at the end of the cavity string assembly in the cleanroom and the beamline vacuum is actively pumped and monitored throughout CM assembly outside of the cleanroom. In order to further minimize field emission potential, inert gas backfill and purge lines which were optimized for LCLS-II are expanded for higher flow in LCLS-II-HE. For the vacuum pumping setup, rather than using a manually controlled slow pumping scheme, mass flow controllers are installed for LCLS-II-HE as shown in Fig. 1. All these upgrades for the cleanroom infrastructure are validated with a qualified 9-cell cavity pump/purge cycle and re-test/qualification method.

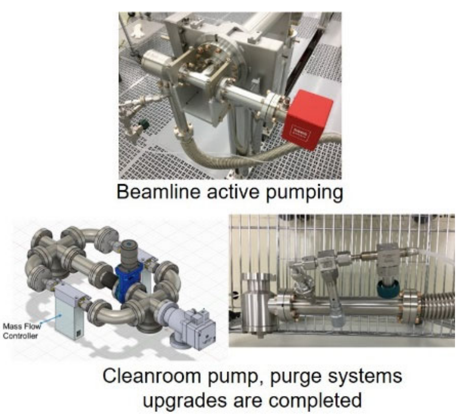

Figure 1: Cleanroom upgrades.

R&D/Prototyping

One of the key lessons learned from LCLS-II is not to cut off R&D too early. This is especially true when state-of-the-art performance is required. For this reason, LCLS-II-HE started with an aggressive R&D phase that was crucial for the development of the new cavity processing protocol that improved significantly performance compared to the previous state-of-the-art, allowing to meet the new challenging specifications. It is important to assure tests are conducted in as close to final CM configuration as possible. The prototype cryomodule (there should always be one) should be as close as possible to the production cryomodule in design, component procurement, and cryomodule assembly. Another major take away from LCLS-II is the need to provide adequate time (after the prototype is tested) to feedback desired changes into production. Even though CM design changes that were done for LCLS-II-HE are minimal, 5 months of cold test time is planned for the vCM in order to adequately address cavity performance, multipacting processing optimization, Q-factor degradation during quenches, plasma processing, unit test and extended range tuner test. Cavity performance results from the vCM gate the start of the processing of the production cavities at the industrial vendor. For LCLS-II-HE, considering that the design changes were minimal, we believe that adequate time and importance are given to vCM before we transition to the production of the series cryomodules.

Quality Assurance & Process Controls

LCLS-II-HE is building on the LCLS-II quality program, by implementing improvements based on our successes as well as our unwanted outcomes. The two primary areas that we are making improvements in are Design Change management and Work Planning & Control (WPC). Examples are the addition of systems engineering, technical change control board; increased utilization of the formal Records of Decision (implemented towards the end of LCLS-II); writing more Failure Modes & Effects Analysis (FMEA); more extensive Readiness Reviews prior to the start of each cryomodule assembly workstation; and more rigorous management of the discrepancy reports to gate the next assembly work station phase etc.

Quality culture, especially during production, is heavily embedded in the Fermilab team thanks to LCLS-II. One of the important factors to keep the momentum from LCLS-II to LCLS-II-HE is to retain the experienced personnel and the quality culture.

Personnel

For LCLS-II, we had to augment the experienced core technician workforce with hiring new temporary contract technicians. The training period for new hands-on personnel is long for the SRF CM production (~1 year). For these contract technicians, high turnover rate was experienced at the early stages of the project. Throughout the LCLS-II CM production, all the trained contract technicians were hired with permanent and/or 3~5 years fixed term positions. We currently have a stable, qualified, and experienced technician workforce who possess production and quality culture that is learned and proven during LCLS-II production. The Fermilab CM production team consists of scientists, engineering physicists, various discipline engineers, designers/drafters, technicians, procurement department, process engineering, quality control department, and machinists/welders all of whom learned a lot from LCLS-II CM production. Another important motivation for keeping the momentum from LCLS-II to LCLS-II-HE for the CM production is that this trained and experienced workforce is retained and will work on LCLS-II-HE CM production.

Supply Chain

LCLS-II-HE FNAL scope for production CM parts procurements is the same as what was done for LCLS-II. Lessons learned documents were written for the LCLS-II major procurements and these are being applied to LCLS-II-HE. Approximately 90% of the LCLS-II-HE procurements were awarded to the same, experienced vendors from

ISBN: 978-3-95450-233-2 ISSN: 2673-5504 doi:10.18429/JACoW-SRF2021-THPTEV003

LCLS-II. All the redlined 2D drawings and engineering specification documents from LCLS-II were reviewed, revised and approved for LCLS-II-HE in preparation for the procurements. Established acceptance criteria and incoming QC procedures from LCLS-II are revised as needed with the lessons learned. These procedures will be used for LCLS-II-HE. Identifying and addressing vendor delivery issues early, whether they are quality or schedule related, is crucial for LCLS-II-HE, and due to using experienced suppliers from LCLS-II we expect to prevent major quality issues. Schedule related concerns, especially during COVID-19, are valid since the global supply chain was negatively impacted during the pandemic. LCLS-II-HE CMs will be produced and shipped well ahead of the tunnel installation schedule. CMs will be stored (with beamline under active vacuum pumping) at SLAC for up to ~1 year. Keeping the momentum for CM production from LCLS-II to LCLS-II-HE helps in both respects in this case, working with the experienced vendors and because the CMs are not needed to be installed upon delivery to SLAC, there is comfortable float for the procurement schedules.

VERIFICATION CM ASSEMBLY & TEST

vCM is assembled using 8 out of the 10 best performing cavities fabricated with the new processing protocol. R&D to develop the new processing protocol, transfer the technology to industry, test and qualify the cavities processed with the new protocol is the first part of the equation to declare success. Phase-II is to assemble these cavities into the cryomodule and prove that the performance of the cavities can be preserved. vCM is assembled very soon after completing the last LCLS-II CM (keeping the momentum). CM assembly team completed the last LCLS-II CM assembly at a specific workstation then started to work on vCM. As explained above, some infrastructure upgrades are done and validated. These upgrades necessitated revisions to the CM assembly travelers. WP&C and supporting FMEAs are developed and integrated to the production workflow. We plan for the benefits of using the experienced team from LCLS-II, but we also had to make sure that there is no complacency, especially for the revised procedures needed for the high-performance requirements for the LCLS-II-HE CMs.

Figure 2: vCM cavity string assembly final leak check.

vCM cavity string was assembled (Fig. 2) in two months which is twice the duration of the LCLS-II production CM string assembly. We had to ensure that the new procedures, tooling and infrastructure upgrades are fully understood and utilized by the team.

Summary of the changes done to the cavity string assembly:

- Beamline slow vacuum pumping & nitrogen gas backfill / purge systems upgrades
- Leave beamline under active vacuum pumping with NEG/ion pump
- Eliminate fundamental power cold coupler (FPC) assembly workstation in the cleanroom and combine the cavity interconnect bellows and cold end FPC assembly into one workstation. This is mainly done to eliminate additional handling of the cavity with vented beamline and to reduce the opening and closing cycles for the cavity beamline isolation right angle valve.
- To tighten the specification for the magnetic hygiene, 316 L stainless steel fasteners used to assemble interconnect bellows & cold end FPC to the cavities are replaced with 316 LN stainless steel.

After the string assembly is completed and rolled out of the cleanroom, cold mass and cryomodule assembly are assembled in 4 months (1.5 times longer than LCLS-II Production CM assembly out of the cleanroom). We again had to ensure that the new procedures, tooling and infrastructure upgrades are fully understood and utilized by the team. One of the biggest concerns is the beamline under vacuum assembly. Fermilab CM assembly team visited LCLS-II JLab CM assembly to learn and transfer the knowledge for the beamline under vacuum assembly. We introduced new tooling and procedures to eliminate any risk to the cavity string bellows and unintentional collapse due to beamline vacuum forces. An FMEA was written to complement the travelers. See Fig. 3 for during vCM cold mass and CM assembly photos.

Figure 3: vCM cold mass & CM assembly.

The assembly of vCM was completed at the end of March 2021 and it was transported to the Fermilab CM Test Stand (CMTS). We used the proven, established on site CM transport procedures and experienced team to transport the CM from the assembly floor to CMTS as seen in Fig. 4.

ISBN: 978-3-95450-233-2 ISSN: 2673-5504 doi:10.18429/JACoW-SRF2021-THPTEV003

Figure 4: CM transport to CMTS.

For LCLS-II, 3.9 GHz CMs were assembled and tested before the last 1.3 GHz CM. To be able to test the last 1.3 GHz CM, CMTS had to be reconfigured after the completion of LCLS-II 3.9 GHz CM tests. CMTS upgrades needed for the LCLS-II-HE CM test were installed and commissioned during this LCLS-II CMTS changeover. Thanks to the LCLS-II project leadership for agreeing to add this additional scope and allowing this opportunity to install and commission LCLS-II-HE specific infrastructure to CMTS. This scheme saved several months for LCLS-II-HE vCM test readiness at CMTS.

The testing of vCM is currently in progress at CMTS (See Fig. 5).

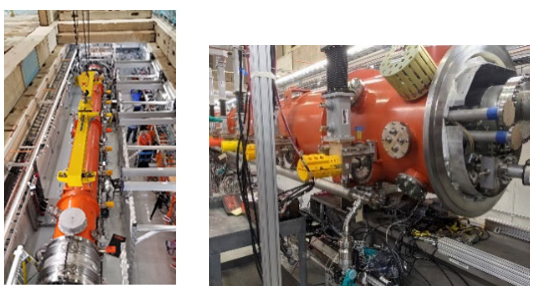

Figure 5: vCM installation to CMTS.

Cavity performance results look excellent. This is a world record CW CM. Gradient and Q0 in all eight cavities exceed LCLS-II-HE specification (see Fig. 6 and Fig. 7) and are well above average compared to LCLS-II production. The CM is also almost field emission free: only a very minimal level of x-rays (~1 mR/hr) were detected while powering one cavity at the operating gradient (see Fig. 8); this proves that all the work done to prepare for LCLS-II-HE CM assembly, i.e. keeping the momentum from LCLS-II and applying the lessons learned, was an effective strategy. vCM is an excellent start to LCLS-II-HE.

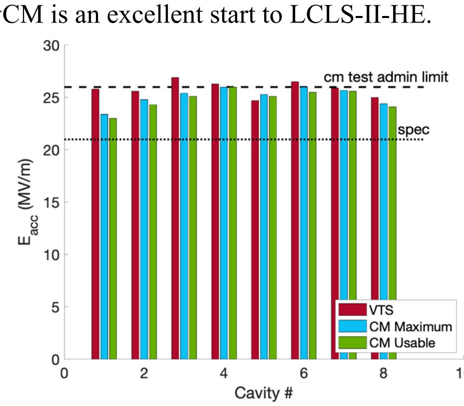

Figure 6: vCM gradient.

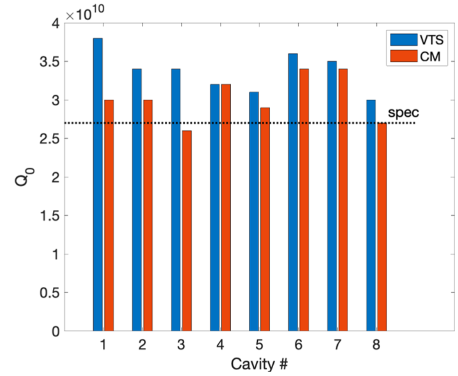

Figure 7: vCM Quality Factor.

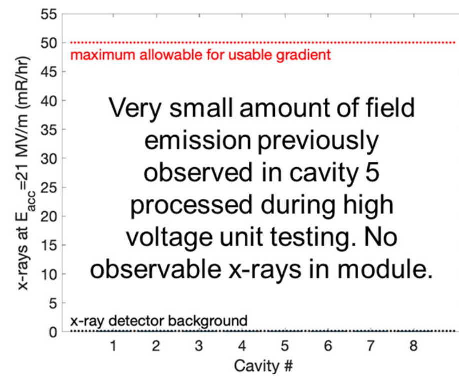

Figure 8: vCM Field Emission.

CONCLUSION

LCLS-II CM production at Fermilab has brought technical readiness and important lessons learned for LCLS-II-HE. We have developed a strong team. We have proven that our team of people worked well together internally and externally and produced excellent results. The Fermilab team has demonstrated the capability of producing world record performance cryomodules on schedule and on budget. The push for even higher performance for LCLS-II-HE is progressing well with the vCM successful assembly and excellent test results. Fermilab infrastructure and team are ready and fully committed to deliver its scope for the LCLS-II-HE.

REFERENCES

[1] M. Martinello, "LCLS-II-HE R&D collaboration overview", presented at the *20th Int. Conf. on RF Superconductivity (SRF'21)*, Lansing, MI, USA, virtual conference, June 2021, paper THOTEV08, this conference.

[2] J. Maniscalco *et al.*, "Statistical modeling of peak accelerating gradients in LCLS-II and LCLS-II-HE", presented at the *20th Int. Conf. on RF Superconductivity (SRF'21)*, Lansing, MI, USA, virtual conference, June 2021, paper THPCAV009, this conference.

[3] T. T. Arkan *et al.*, "LCLS-II Cryomodules Production Experience and Lessons Learned at Fermilab", in *Proc. SRF'19*, Dresden, Germany, June-July 2019, pp. 709-714. doi:10.18429/JACoW-SRF2019-TUP101

[4] R. Stanek, "LCLS-II Lessons Learned from STL perspective", LCLS-II-HE Second Partnering Workshop, January 2021.