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OVERVIEW OF LCLS-II PROJECT STATUS AT FERMILAB*

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Abstract

The superconducting RF Continuous Wave (CW) Linac for LCLS-II consists of thirty-five 1.3 GHz and two 3.9 GHz cryomodules that Fermilab and Jefferson Lab are jointly producing in collaboration with SLAC. Fermilab's scope of work is to build, test, and deliver half the 1.3 GHz and all the 3.9 GHz cryomodules and to design and procure components for the cryogenic distribution system. Fermilab has the primary responsibility for delivering a working design. The cryomodule design basis was the European XFEL but some important elements evolved to meet CW operation requirements and specifics of the SLAC tunnel. There have been several challenges faced during the design, assembly, testing and transportation of the cryomodules which have required design updates. Success in overcoming these challenges is attributable to the strength of the LCLS-II SRF Collaboration (Fermilab, Jefferson Lab and SLAC with extensive help from DESY and CEA/Saclay). The cryogenic distribution system has progressed relatively well and there are also valuable lessons learned from that system. An overview of the status, accomplishments, problems encountered, solutions developed, and a summary of lessons learned will be presented.

INTRODUCTION

LCLS-II will be a world-class free-electron laser enhancement to the operational LCLS Facility located at Stanford Linear Accelerator Center (SLAC). The science objective is achieved using a continuous wave (CW) 4 GeV superconducting linac. The accelerator is being built with collaboration of SLAC and four other Department of Energy (DOE) labs; Lawrence Berkeley National Lab (LBNL), Argonne National Lab (ANL), Thomas Jefferson National Lab (JLab) and Fermi National Accelerator Lab (Fermilab) as well as Cornell University. The basis for the design is the European XFEL, and the success of the project is bolstered through a strong collaborative relationship with both DESY and CEA/Saclay. The scope of the SRF part of LCLS-II includes forty 1.3 GHz cryomodules (thirty-five of which will be installed, with five spares) and three 3.9GHz cryomodules (two installed with one spare).

Fermilab's scope of work includes supplying nineteen 1.3 GHz cryomodules, the three 3.9 GHz cryomodules, and the cryogenic distribution system (CDS) components. To date, Fermilab has built and tested eighteen 1.3 GHz cryomodules (three must still be rebuilt – two because of bellows damage during transport and one due to bellows damage during tunnel prep work at SLAC) and has delivered all the CDS components. The project has had its share of successes and challenges which resulted in valuable lessons learned. After initial transportation issues (including two cavity string vacuum failures) had been resolved, shipping resumed and Fermilab has delivered nine cryomodules to SLAC (total from both JLab and Fermilab delivered is sixteen).

KEY LESSONS LEARNED

Throughout the LCLS-II project at Fermilab, there have been valuable lessons learned. However, a few high-level lessons learned stand above others and may be most applicable to other SRF projects.

Project personnel are familiar with the project management (triple constraint) triangle of scope, cost, schedule with quality being a central parameter (Fig. 1). In many cases the legs of the triangle are thought to have equal weighting. Based on experience on LCLS-II within the SRF technology scope, it is possible to say that the one aspect that can be most impactful is schedule. This is due to the concept that when scope or cost are adjusted, these are typically overt actions which are well analysed for the potential changes to the quality or risk. In fact, there tends to be ways in which some of the change can be absorbed "off project". However, the danger with the schedule constraint is that the resulting change in risk or quality for an overly aggressive schedule is not so obvious. Paths taken, decisions made, and changes in personnel required to meet or accelerate the schedule can result in much higher levels of risk. This is compounded if a robust Work Planning & Control system is not in place. An aggressive schedule even when analysed for the high-level risk increases can drive lower level decisions that bring into play more technical or quality risk. This is particularly true if the schedule compression ignores the complexity of the SRF technology.

- Upper management, including funding agencies, should strive to analyse the consequences of their decisions and the effect they could have on risk or quality. This is most important for decisions that compress schedule which can initiate risk increases not currently captured.

Work Planning & Control (WPC) is a key part of production and project performance. It has a direct impact on quality and safety which will affect cost and schedule. WPC cannot be solely driven from the top. To be effective, the culture must be pervasive throughout the organization.

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Analysing the risk, especially if an off-normal path is being pursued, is essential to high quality and safe performance.

Figure 1: Triple constraint triangle.

A project cannot "police" Work Planning & Control, it must be built with WPC in everyone's mind. Throughout the layers of management and supervision, it is important to maintain a focus on how the work will get done, the risks involved in performing the work and how those risks can be controlled and minimized. Upper management does not typically have the insight into the details of the processes to be fully effective in dictating proper WPC measures. If the culture of the project is one that believes WPC leads to better performance, one can get buy in from all levels, from the shop floor to the engineering and design group. Building this environment takes time and budget.

- Develop the culture of Work Planning and Control early in the project and establish commitment at all levels.
- Monitor all off-normal work and assure risks are properly analysed. Procedures, tooling and infrastructure changes which need to be instituted prior to commencing the work should all be evaluated with respect to adding risk to the normal workflow.

Another important lesson learned from the LCLS-II project is the simple concept that singular points of failure should be avoided whenever possible. Whether this be related to a single person doing a critical design in semi-isolation, a single piece of infrastructure needed in the workflow, or a sole vendor for critical parts. Each of these scenarios have touched the LCLS-II project and influenced cost and schedule performance. Redundancy helps maintain schedule even if there is an increase in cost for that item. Keeping on schedule controls overall project cost especially for the Level of Effort labor.

- Set up small teams of people to work on designs, assuring that there is always back up and cross checking. If a challenging problem needs a quick and immediate solution, consider forming a working group containing individuals from various related disciplines to offer a broad perspective and look at a range of possible solutions.
- The sole vendor issue is harder to solve for it may be the only vendor available or it may be too costly to bring in another source. Here the only option is to monitor the vendor's progress, quickly feeding back critical information, and work to provide solutions when problems are encountered.

Building a successful collaboration is an essential part of many modern day large SRF-based accelerator projects. Some lessons learned from the LCLS-II project collaboration include:

- Define the type of relationship desired upfront and develop a management and evaluation scheme that reflects the core principals. For instance, partners should have equal voices otherwise it becomes a customer/vendor relationship. Also, in a collaborative model there is a shared responsibility to deliver the scope and solve problems.
- Building a strong collaborative relationship with other similar SRF projects will help assure that valuable lessons learned are shared and minimize repeating the same mistakes.
- Respect the boundaries of each institution by setting priorities on requests which tap valuable staff resources. Otherwise, every person with some level of responsibility, will think that their request is most important and will continue to push for immediate action, taking away from other high priority activities.
- Where possible, set the organizational structure so that people in positions of management responsibility understand the essential technology of the machine including risks that might increase because of their decisions. This can also be addressed by assuring the work is assigned correctly to the various organizational units.
- In the end, the host lab is responsible for building the machine. It is imperative that they be comfortable and skilled with the SRF technology and they take responsibility for solving problems and making things work. Everyone needs to have a stake in the game.

Large high energy physics experiments are great examples of how collaborations can work, particularly if that model is coupled correctly to the increased documentation and proper WPC needed for production of SRF cryomodules.

For SRF-based production projects, quality assurance and control, data traceability and record management are essential. Most projects will be set up with a common set of acceptance criteria that is invoked at the cavity test, cryomodule test and cryomodule receipt check points. Acceptance criteria should be set not at the level of what might be possible to achieve but rather at what is required. Otherwise, there will be many additional Non-Conformance Reports. Also, projects are not funded at the "what might be possible to achieve" level.

- It is important to agree on how to handle the components that do not meet the acceptance criteria.
- Early in the project, define the amount of documentation that will be provided, where it will be stored, and on what timescale it is needed. Documentation is very important in large projects, but it is not preventative of problems. In fact, documentation in the hands of people that are not experienced with SRF technology, can lead to a false sense of knowledge.
- Be careful not to change the technical or documentation requirements during the project as it will lead to subsequent cost increase or schedule delay.

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- When producing SRF components at multiple locations, it is important to look for nonconformance or differences at the assembly stage (not just the test stage). This is where small changes in how a cryomodule is assembled and handled can make a difference in performance. Having a clearly defined nonconformance resolution path is essential to keeping on the production schedule.
- Per the LCLS-II experience, identifying and addressing vendor delivery issues early, whether they be quality or schedule related, is crucial. If the problem is there, it is most likely not going to go away on its own and even if it does, it might return if the root cause is not addressed.

DESIGN

For LCLS-II, the Cryogenic System Manager is the Design Authority and Fermilab is the Designer of Record. In this role, Fermilab has primary responsibility for delivering a working design that meets requirements. LCLS-II used a system of requirement documents that flow down to set the specifics of the cryomodule design. The cryomodule design basis was the European XFEL but several elements evolved to meet CW operation requirements and the specifics of the tunnel, as shown in Fig. 2 and described in [1] and [2]. Requirements that drove design changes were:

CW operation

- Higher cavity heat load associated with CW operation, drove the requirement for high Q0 which led to N-doping, changing the pipe sizes, and minimal environmental magnetic flux.
- Minimized magnetic flux led to a change of materials, two magnetic shields, and use of demagnetization coils.
- N-doping led to the fast cooldown requirement.
- Fast cooldown requirement led to adding cooldown valves on each cryomodule, dual cooldown cavity inlets, and larger helium vessel chimney.
- Tighter constraint on cavity frequency led to design changes on tuner, use of piezos and techniques for reduction of microphonics.
- Tuner concerns led to inclusion of access ports (a very useful and positive step).
- Reduction of microphonics drove reversal of cryogenic valves to eliminate thermal acoustic oscillations, inclusion of a baffle on the 2K helium line to reduce the effects of high velocity injection, the addition of a beamline bellows between cavity one and the upstream gate valve, and various tube tie downs to eliminate rattling as detailed in [3,4].

Tunnel specifics

- 0.5% slope in tunnel drove closing off pipes at the end of the cryomodule and use of individual JT valves on each cryomodule.

Regarding the cryomodule design effort, LCLS-II found that it is not reasonable to focus cryomodule design through a single individual since that places undue burden on that person. Rather, a team approach with a lead design engineer supported by additional designers and focused by an overall lead engineer works much better. A specific lesson learned was that substitution of parts thought to be equivalent must be reviewed and approved by an independent member of the design team.

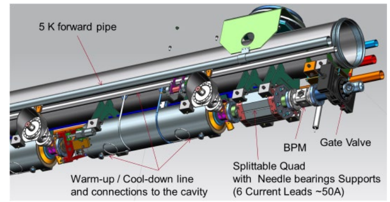

Figure 2: Solid model of cold mass.

Typically, the intention of a project is to complete all the R&D work and lock down the design prior to baselining. For LCLS-II, changes to the design were made as R&D continued at the beginning of the project and after the testing of the first prototype cryomodule.

- One of the key lessons learned is to not cut off R&D too early. The issue with the differences in magnetic flux expulsion properties of the material could have been detected much sooner had R&D been allowed to continue.
- Push to make the prototype cryomodule (there should be one) as close as possible to the production cryomodule in design, component procurement, and cryomodule assembly. LCLS-II let schedule dictate the use of components in the prototype that were not the same and not from the production vendors and unfortunately the production was started before the prototype was tested, see details in [3,5].

TESTING

Fermilab has fully tested seventeen cryomodules, the results for which are shown in Fig. 3 and Fig. 4. To date, for the Fermilab tested cryomodules, the average usable energy gain per cryomodule is 159 MV compared to the specification of 128 MV. The average Q0 for all cavities in the Fermilab cryomodules is ~3 E10 compared to the specification of 2.7 E10, see additional details in [6]. JLab has had similar results. Lessons learned from the LCLS-II experience include:

- Plan additional time for the first few cryomodule tests so that interesting as well as possibly negative responses can be investigated, and a retest can occur, if warranted.
- There will be a learning curve on most tasks including mechanical installation and removal from the test stand.
- A dedicated test facility, with adequate redundancy, improves testing efficiency and make the schedule more achievable.
- Develop a detailed test plan even if it is assumed it will change.
- If possible, establish testing shift coverage early so that extended testing will not be interrupted.

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- To the extent possible, match the cryogenic parameters of the accelerator with regards to inlet conditions and cooldown rate.

In general, the cryomodule testing has progressed extremely well.

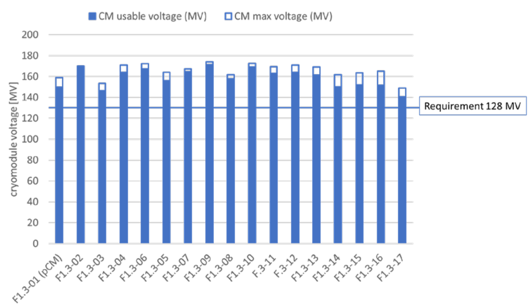

Figure 3: Cryomodule Voltage Gain.

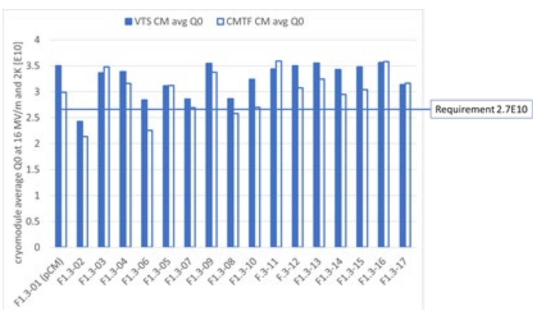

Figure 4: Cryomodule Average Q0.

TRANSPORTATION

Since the resumption of shipping, Fermilab has successfully transported nine cryomodules to SLAC. However, the project had a tough time early with cryomodule transportation. There were two beamline vacuum failures attributable to damage to the cold coupler bellows caused by excessive vibration during transportation. This meant that two cryomodules must be rebuilt. The first failure occurred on the very first cryomodule shipped to SLAC. The second failure on a short road test run (second test of that cryomodule) from Fermilab and intended to gather vibration data for analysis.

- The lesson learned is that if the root cause of the problem is not addressed, the failure will reoccur even if other mitigations are put in place. Initial success, namely being able to successfully complete the first test run, was not conclusive that the problem was solved.

Again, the simple lesson learned is that little things matter. Small differences between the XFEL design and the LCLS-II design at the failed coupler region coupled with changes in the spring configuration of the transport frame and the initial differences in the transport caps, may hold the key to why the XFEL Project experienced no failures while LCLS-II had two. In addition, the LCLS-II initial road tests were performed on the JLab prototype cryomodule which again had a slightly different cold coupler design. Additional lessons learned include:

- Require independent review of transport analysis, data, and equipment designs.
- Plan adequate test time for transport hardware which whenever possible uses non-critical components (dummy cryostats) as the test apparatus.
- As part of WPC, perform a Failure Mode & Effects Analysis to analyse risks associated with transport.
- Accumulated motions could matter. and a short road test is not equivalent to a long transport.
- Collect accurate and reliable data which focuses on possible areas of weakness. For LCLS-II, this was essential to the process of identifying the problem and qualifying a transport scheme.

In the end, the strength of the LCLS-II collaboration helped develop solutions that solved the transport failures. Two solutions were developed. JLab designed the m-mount which helps minimize movement of the cold coupler bellows and is what has been used for essentially all transports. Fermilab optimized the approach which removed the warm coupler and locked the cold coupler in place using threaded bolts (Berry bolts). This was used on the first transport after resumption of shipping. Transportation is now proceeding on a regular basis, see details in [7].

CRYOGENIC DISTRIBUTION

The cryogenic distribution system (CDS) consists of six feed caps, two end caps, two bypass sections, two distribution boxes and approximately ninety meters of surface transfer line. All components were procured from industry using design and build contracts and all have been delivered to SLAC. Installation for all tunnel components is complete. The success of the CDS effort is attributable to a combination of:

- Following a system engineering process throughout the project.
- Providing a reference design and detailed specifications so that the vendor knew what was being requested.
- Performing formal reviews with issue tracking, that gated the ability to move to the next step and covered both technical and documentation aspects of the work.
- Close vendor oversight, including weekly meetings, multiple vendor site visits to witness progress and assistance with technical problems resolution.
- Conducting factory acceptance testing at the vendor before allowing shipment to proceed, and site acceptance testing at SLAC.

The thoroughness and level of commitment to the engineering and review process, from both sides of the procurement, resulted in high quality components that met specifications. The cost and schedule performance of the procurements was quite good.

- Transportation was once again an issue on the first shipment of components as the third-party shipping

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firm (contracted by the vendor) did not ship the components as originally specified. This led to increased oversight and specificity on the terms and conditions of the transport contract. There were no other occurrences of this issue.

CONCLUSION

The 1.3 GHz cryomodule LCLS-II work at Fermilab is nearing completion. Despite initial challenges associated with cavity material properties, microphonics, and transportation, the project has made good progress. Cryomodule performance exceeds specification. There are many lessons learned from this effort that can be applied to other SRF projects and as a community we should learn from our shared experiences.

The transition is being made to start the 3.9 GHz assembly work and it can be assumed that a new list of lessons learned will be developed.

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