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STATUS OF THE LCLS-II-HE PROJECT AT JEFFERSON LAB*

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Abstract

The Linac Coherent Light Source II High Energy (LCLS-II-HE) upgrade at the SLAC National Accelerator Laboratory is being constructed in partnership with the Thomas Jefferson National Accelerator Facility (JLab) and the Fermi National Accelerator Laboratory (FNAL). The cryomodule production scope consists of the design, procurement, construction, and acceptance testing of 24 eight-cavity, 1.3 GHz cryomodules, as well as R&D activities necessary to develop the required technology. To achieve this, JLab and FNAL are also contributing to SLAC's effort to develop the cavity recipe and production processes necessary to meet the LCLS-II-HE goal of 20.8 MV/m and average Q_0 of 2.7x10^{10}. This paper details the JLab scope, focusing on the project initiation phase, in particular technology development and prototyping, project development and planning, and implementation of lessons learned from LCLS-II.

BACKGROUND

In the mid-2010s, SLAC began a major upgrade to its LCLS accelerator, called LCLS-II. Several Department of Energy national laboratories, including JLab, participated in this project. JLab, along with FNAL, was responsible for the construction of a total of 40 SRF cryomodules. SLAC is now beginning the upgrade to that project, LCLS-II-HE, which will increase the power of the linac from 4 GeV to 8 GeV. To achieve this, the requirements for cavity performance have increased to 20.8 MV/m and Q_0 of 2.7e10.

The LCLS-II cryomodule design was based on the XFEL design to reduce schedule risk and cost. Some modifications were added for LCLS-II to support the different requirements of the accelerator, particularly continuous wave operation. For LCLS-II-HE, the same design will be used except for a new cavity processing protocol and redesigned tuners. Otherwise, the hardware designs will, with some minor corrections, be identical to LCLS-II.

Jefferson Lab has many years of experience with design, construction and testing of SRF cryomodules, beginning with the design and construction of the CEBAF cryomodules in 1987. Since then, JLab has vertical tested more than 5500 cavities and built 42 cryomodules for CEBAF, 23 for SNS, 3 for JLab's FEL, 21 for LCLS-II, and is on track to build 8 for SNS PPU.

SCOPE OF WORK

The HE baseline project consisted of twenty 1.3 GHz cryomodules, each containing eight elliptical cavities. The project has since added four more cryomodules, three for the accelerator and one for the injector. JLab will be responsible for producing eleven of the cryomodules.

In the three-lab partnership for the cryogenics scope, SLAC is responsible for management of the overall project, FNAL is responsible for cryomodule design, all three labs will share the procurements, and JLab and FNAL will construct and test the cryomodules. As shown in Fig. 1, JLab and FNAL will follow generally parallel production paths.

This collaboration obviously requires significant interaction and communication between the partner laboratories to ensure smooth coordination of work. From the beginning, there have been frequent regular meetings and other paths of communication set up to insure the large and geographically distributed team works together cohesively.

PROJECT PLAN AT JLab

JLab developed a schedule which begins with pre-production activities such as developing procurement documents and evaluating lessons learned from LCLS-II. The schedule moves through all phases of production, from procurements to cavity testing to cryomodule assembly, testing, and shipping. There are separate activities for cavity research and development, which focus on developing the cavity treatment process necessary to produce the cutting-edge cavity performance required for this project (Fig. 2).

Schedule development was greatly facilitated by the recent work on LCLS-II, which was used as a basis of estimate to develop cost and labor estimates for HE [1]. A small learning curve at the beginning of HE production was planned, to allow for training of new staff or implementing process improvements.

The production rate is somewhat slower than on LCLS-II to allow other projects to be intermeshed with HE. While LCLS-II used two assembly rails in parallel, HE will use only one to allow other construction projects in the Test Lab to proceed simultaneously, including cryomodules for JLab's own CEBAF accelerator and SNS PPU.

The HE project is staffed by JLab employees drawn from several departments. Many of the HE team are veterans of LCLS-II, and therefore familiar with the work and lessons learned. The production staff from the SRF Institute, many of whom worked on LCLS-II, are supporting other projects in the interim between LCLS-II and HE, but will be available to transition to HE production as needed later this year. The project has worked with line managers to develop a staffing plan to integrate the needs of HE and other projects at JLab.

CAVITY R&D

The project focused initial efforts on research to develop the cavity recipe and production requirements necessary to reliably produce even higher performance cavities; JLab

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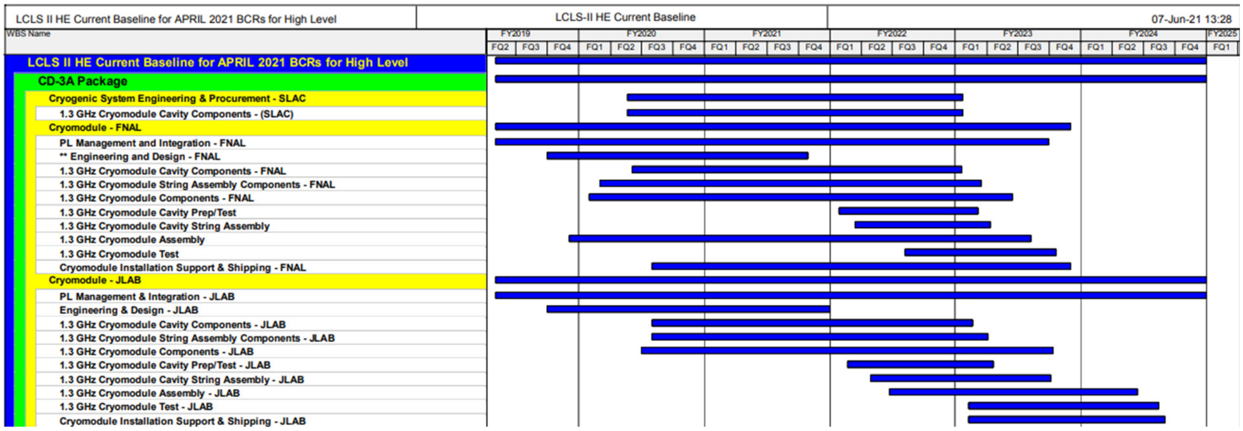

Figure 1: High-level HE cryomodule schedule.

has been integrally involved in this work, including advising SLAC regarding cavity process refinements and cavity vendor interaction.

Figure 2: An LCLS-II-HE-style cavity.

Cavity experts from the three labs formed a Cavity Technical Board. As part of its remit, the CTB looked for ways to improve the cavity recipe to increase performance to meet HE specifications, and several research paths were followed during the efforts to optimize the cavity recipe.

One process change that was adopted was the use of a cold electropolish (lower temperature than on LCLS-II) for more uniform removal of material and to reduce interior surface roughness through slowing down the polishing phase of the active chemistry. Initial testing has shown this to improve cavity performance by 3-5 MV/m on average.

The CTB also decided to split the bulk electropolish in two. This was in reaction to the concerns about furnace contamination that persisted throughout LCLS-II. As part of the cavity preparation recipe, cavities undergo a high-temperature anneal to reduce the magnetic field flux trapping. There were concerns that contamination in the furnace might be vaporized during the annealing process and form lossy compounds on the interior surface of the cavity, degrading performance. Therefore, instead of a single bulk EP before the furnace treatment, for HE there are EP steps both before and after the anneal to remove such surface contamination.

JLab has investigated another option for remediating furnace contamination. Due to concerns that the furnaces are outgassing unknown materials that are not removed by the electropolishing (one of the leading candidates being carbon, which may produce an unknown phase of niobium carbide) JLab has developed a process for treating cavities with a soak in nitric acid, which will preferentially remove contaminants not removed by electropolishing. (See talk in this conference by A. Palczewski for more detail.) In preliminary tests, this method has been successful at improving performance of cavities exposed to furnace contamination in terms of both Q_0 and gradient, and may be adopted by the project for use during production.

On LCLS-II, it was observed that cavity performance varied depending on the lot of niobium the cavity was made from. This was found to correlate with sheet material grain size, and could therefore be mitigated by annealing some lots at higher temperatures than others. In order to verify this problem was addressed prior to cavity construction, a single-cell cavity was made from each lot of niobium and tested for flux expulsion, a practice that was incorporated into HE. JLab attempted to develop a process to use a rolled tube to measure flux expulsion instead to save on the fabrication cost of a single cell cavity. Although the process offers promise, due to manufacturing differences between the tubes and single cell cavities, the method did not converge quickly enough to be incorporated into the project scope.

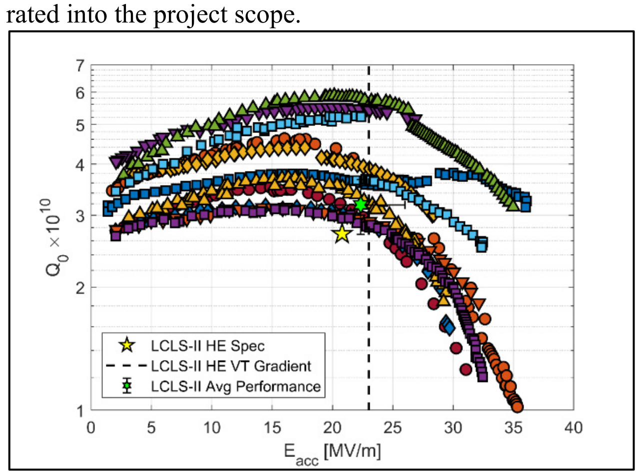

Figure 3: Cavity test results from proposed JLab recipe.

FNAL and JLab both suggested new "doping" (technically, interstitial alloying) recipes in an effort to improve cavity performance over LCLS-II. (See Fig. 3.) The LCLS-II nitrogen "doping" recipe has been extensively documented (for example, [2]). Both of the recipes suggested for HE were successful in early testing [3]. Because of the larger number of early testing results, and the fact that the recipe produced cavities that met the project's requirements, the recipe developed by FNAL was selected by the project for use on 10 nine-cell cavities to be used in a

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verification cryomodule which will be tested to confirm the performance of the new recipe. An adequate process has been identified and frozen for the production. The relative weights of the various process refinements in obtaining improved performance remains a bit ambiguous.

INFRASTRUCTURE UPGRADES

The project is supporting two upgrades to the JLab infrastructure to improve production. The first is a nitrogen purge system (Fig. 4) for use during cavity string assembly. The design of the purge system is based on one already in use at FNAL. During LCLS-II, FNAL used the purge system during cavity string assembly, but JLab did not, instead following its traditional string assembly process. One of the goals of HE is to better align the assembly procedures at the two labs, and implementing a purge system at JLab is a significant step in that direction. A nitrogen purge provides a number of advantages. It provides flexibility in string assembly, thus reducing overall downtime. It allows the replacement of parts, if necessary, without full string disassembly. It reduces moisture and oxidation of copper parts in the string. (During LCLS-II, copper-plated beamline bellows were found to have significant oxidation after string assembly due to residual moisture.) The purge system is also expected to reduce field emission due to particulate generation during assembly, thus improving cryomodule performance.

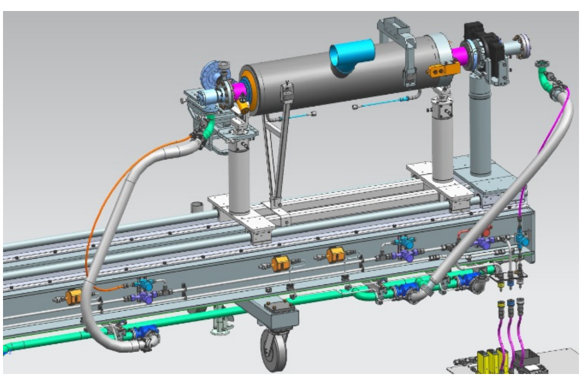

Figure 4: Purge system concept.

In addition, the project will be adding magnetic shielding (Fig. 5) to the largest of the vertical test dewars, capable of testing three HE cavities at once. The magnetic shielding is designed to reduce the fields at the cavity from around 20 mG to 5 mG, in order to meet the requirements for HE. Experience with LCLS-II has shown that these nitrogen-doped cavities are particularly sensitive to magnetic fields, and thus maintaining low magnetic fields in the dewars is essential to achieving high Q_0 in vertical test.

QUALITY

Process Improvements During LCLS-II

LCLS-II operated on a continual improvement basis; staff looked for opportunities to improve the processes, and these were implemented over the course of the project. Some examples of these include the development of a magnetic hygiene procedure for measuring magnetic fields and

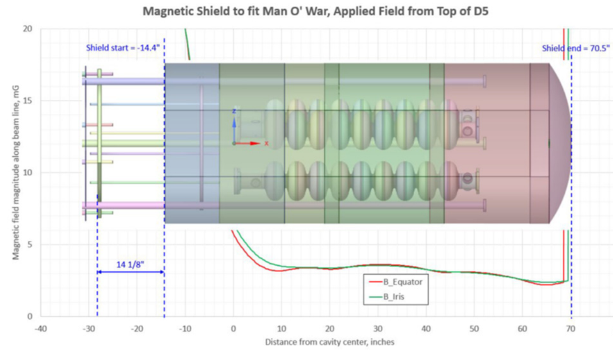

Figure 5: Dewar magnetic field simulation (G. Cheng).

degaussing parts on the cryomodule, intended to improve cavity performance by ensuring low magnetic fields throughout the cryomodule. Also, a new HOM tuning procedure was developed because the HOMs were more sensitive to detuning than expected; after realizing the issue, JLab implemented a new procedure which consistently gave good HOM *Qext's*. In addition, JLab learned to integrate radiography into the welding workstation flow, a new process which required coordinating an outside NDT firm's work at JLab and determining how to manage the radiation safely.

JLab also worked to improve its work planning by completing risk assessments of production processes to identify all the vulnerabilities of a given part or operation, implementing engineered and administrative controls, and training technical staff to perform each task prior to starting work. The lab followed this detailed procedure for work planning to minimize the risk of damage during production.

These improvements made over the course of LCLS-II will all be carried forward to HE.

Lessons Learned

In addition, lessons learned from LCLS-II and other recent projects were incorporated into the planning for HE. They touch on all facets of the project. At the start of the project, a series of discussions was held with the technical representatives from LCLS-II and other subject matter experts to evaluate changes to the design. Variations between the original drawings and as-built parts, as well as suggestions for improvement were evaluated. The project followed a policy of updating drawings to reflect as-builts but only making limited changes for the sake of improvement to avoid causing new, unforeseen issues. Design updates include primarily things such as updating drawings to reflect field fits that had been made at the labs, correcting interferences and tolerance errors, and clarifications of material type, rather than any attempt to redesign parts.

Procurement processes were also improved. On LCLS-II, in-person vendor visits had been found to be extremely valuable, resulting in improved production methods, speedier problem resolution, and cost savings. They also allowed the technical representatives to develop relationships with their counterparts at the vendors in order to facilitate communication throughout the procurement. HE therefore planned for regular and frequent visits to vendors

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to monitor the status of the procurements. (Despite the plan, this was unfortunately hindered by COVID-19, which has prevented travel for the past year. JLab has been monitoring procurements remotely, using methods such as videoconferencing for meetings and witnessing vendor inspections over video, but these methods have their limitations.) JLab also asked for longer warranty periods (18 months) as the extended production schedule on LCLS-II did not allow all parts to be inspected or tested within the warranty period. Also, additional oversight of vendor packaging and shipping was required due to shipping damage that occurred on several parts during LCLS-II.

JLab is now beginning an exercise to review all production travelers and collect lessons learned to improve our processes. A particular focus will be on any areas where problems occurred during LCLS-II, for example, handling bellows, which are delicate and prone to damage.

PROCUREMENTS

Procurements of cryomodule components are split between the three labs, as shown in Fig. 6, with SLAC responsible for cavities and cryomodule interconnect parts; JLab responsible for fundamental power couplers, gate valves, copper-plated beamline bellows and spools, and end lever tuners; and FNAL responsible for remaining components. The JLab scope is the same as on LCLS-II, except that JLab took on FPCs instead of cavities and beamline absorbers for HE. Each lab is responsible for procurement of the total required quantity of their components, with deliveries then split between the labs.

Component	JLab	FNAL	SLAC
Dressed Cavities			■
HOM/FP Feedthroughs			■
Cavity Flanges/Hardware			■
FPCs	■		
Cavity String Bellows	■		
Cavity String Hardware		■	
SC Magnet Assembly		■	
Beam Position Monitor (BPM)		■	
HOM Absorber		■	
Gate Valves	■		
Two-phase Pipe Bellows		■	
End Lever Tuners	■		
Magnetic Shielding		■	
Cold Mass		■	
Vacuum Vessel		■	
Instrumentation		■	
Cryogenic Valves		■	
Vacuum Equipment		■	
Beamline Interconnect Parts			■

Figure 6: HE procurements.

Procurements at JLab are typically managed by a technical representative working in partnership with a procurement officer. The TR is assigned to interface with the subcontractor on technical matters after subcontract award and authorized to provide technical direction within the scope of the subcontract. (However, only the JLab procurement officer may make changes to an ongoing contract.) For all HE procurements, each lab assigned its own TR to work together as a team to collaborate on technical oversight. Any significant technical decisions are agreed to by the whole team, to ensure that all labs are informed and in agreement with decisions. However, the TR for the lab that owns the procurement will be the lead and will act as point of contact with the vendor.

All JLab procurements have been awarded, most to the same vendor as on LCLS-II. TRs are closely involved in the production process at the vendors, monitoring the status remotely (due to COVID) via phone calls, emails, and video meetings.

Inspections

Parts are currently arriving at JLab and beginning to undergo receiving inspections using travelers written by the JLab TRs. For HE, the traveler format was revised to have clear divisions between work stations, which provides increased ownership of each process and enhanced tracking of parts locations, as well as increasing traveler compliance with ISO standards. Separate inspection travelers are therefore written for different work stations, such as visual inspection, dimensional/CMM inspection, leak check, pressure test, and cold shock. Skilled technicians at JLab carry out the inspections and enter the resulting data into the travelers. Non-conformance reports (NCRs) are generated where appropriate, and the technical representatives disposition them, based on whether the parts should be accepted or reworked or rejected. Revisions were made to the formats of NCRs & D3s (discrepancy reports) to increase relevance and utility of generated data.

FABRICATION

The assembly of LCLS-II-HE cryomodules will be strongly based on the assembly process used for the LCLS-II cryomodules, with the application of lessons learned and some modifications to improve processes.

Although construction facilities at the two labs differ, efforts will be made to use identical or equivalent tooling, equipment, and processes to ensure the final products are interchangeable and compatible.

Infrastructure

JLab's Test Lab, which is used for cryomodule production, allows all stages of production, from cavity testing through assembly, to be completed under one roof (Fig. 7). The Test Lab contains a cryomodule testing facility which was used for LCLS-II until the development of a second testing facility, the LERF, which will be used for HE.

The tooling used on LCLS-II is still in place in JLab's Test Lab. (See Fig. 8.) Cavity strings will be assembled in JLab's ISO class 4 cleanroom using the rails and lollipops from LCLS-II. In the high bay area of the test lab, large tooling including four-posters, a cantilever, spreader bar, vacuum vessel stands will be used for cryomodule assembly.

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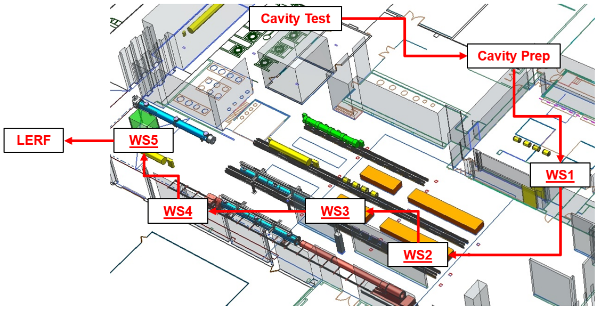

Figure 7: Layout of the Test Lab.

Figure 8: Test Lab with LCLS-II/HE tooling.

Work Stations

The cryomodule will move through five work stations during assembly [4]. The first is the cavity string assembly in the clean room, during which cavities, beamline bellows, gate valves, and cold FPCs are assembled. The cavity string, under vacuum, is then rolled out of the clean room into the high bay. At work stations 2 and 3 – cold mass assembly – the two-phase pipe is welded on, magnetic shielding and tuners are installed, and leak checks, electrical checks and alignment occur. At work station 4 – vacuum vessel assembly – the thermal shields and MLI are installed before the cold mass is installed inside the vacuum vessel using the large cantilever tooling. At work station 5– final assembly – warm FPCs and waveguides are installed, and vacuum and instrumentation are verified.

Cryomodule Testing

For HE, cryomodule testing will take place in the LERF, a facility which was converted to support testing of LCLS-II cryomodules and to provide a vertical slice of the power and control systems used at SLAC. LERF has supported successful testing of 4 LCLS-II cryomodules over 3 test cycles. For HE, the SSAs were upgraded from 4 kW to 7 kW, and a single cryomodule will be tested at a time as opposed to two at a time for LCLS-II.

CONCLUSIONS

The experience and infrastructure provided by LCLS-II allow for a smooth transition into HE, which builds on this background. JLab has contributed to technical cavity developments and implemented infrastructure improvements to help the project achieve the higher technical requirements for HE. A detailed schedule and project plan have been developed for the work ahead. With experience and lessons learned from LCLS-II, JLab is well positioned to successfully complete its scope on LCLS-II-HE.

ACKNOWLEDGMENTS

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