CHALLENGES IN REALIZING THE LCLS-II CRYOMODULE PRODUCTION

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Abstract

The LCLS-II project requires the assembly and installation of 37 cryomodules in order to deliver a 4 GeV electron beam to the undulators to produce both soft and hard x-ray pulses at a repetition rate up to 1 MHz. All of the cryomodules will operate in continuous wave mode, with 35 operating at 1.3 GHz for acceleration and 2 operating at 3.9 GHz to linearize the longitudinal beam profile. One of the challenges of this project, and the topic of this paper, is coordinating the effort of three DOE labs in order to realize this machine in just a few years time. This coordination is necessary due to the fact that the cryomodules will be assembled at both Jefferson Lab and Fermi Lab, tested, and then shipped to SLAC for installation, commissioning and operation. This paper will report on our experiences to date, issues that have been identified and planned mitigation going forward.

INTRODUCTION

The LCLS-II is a 4 GeV CW X-ray free electron laser (FEL) driven by a superconducting RF linac [1, 2]. It is being built to upgrade the capabilities of the current LCLS, a normal conducting FEL that has been operational at SLAC since 2009. Figure 1 shows the original LCLS layout in the tunnel along with the LCLS-II accelerator. The LCLS-II upgrade will be complementary to LCLS as both accelerators will continue to operate and provide x-rays to the existing user end-stations, albeit not at the same time (in the current operational plan). The upgrade to LCLS-II will expand the operational range of the FEL complex by providing X-ray pulses at up to 1 MHz repetition rate, an increase from the 120 Hz of LCLS, and covering the spectral range from 0.2-1.2 keV and 1-5 keV through two new undulator systems.

The LCLS-II project has a very tight schedule, only 6 years from design through delivery of first beam. In order to accomplish everything that is required to design, build, install and commission a new accelerator in such a short period of time a collaboration between 6 Institutions in the United States has been established. Five Department of Energy (DOE) Laboratories, SLAC, LBNL, Argonne, FNAL and JLab, are each lending their expertise in their respective fields along with Cornell University providing their knowledge of superconducting RF as well as development of an alternative injector for LCLS-II. In the context of this paper the primary contributors are JLab, FNAL and SLAC providing the superconducting RF accelerator components necessary to drive LCLS-II.

THE ACCELERATOR

The superconducting RF (SRF) linac that will drive LCLS-II is made up of 35 – 1.3 GHz cryomodules and 2 - 3.9 GHz cryomodules. Each cryomodule contains 8 superconducting RF cavities. The 1.3 GHZ cavities are based on the TESLA design, most recently used for XFEL, and have been modified for CW operation[3]. The preparation of the cavities has also been modified to incorporate the "High-Q_0 recipe" that utilizes nitrogen doping that can improve the Q_0 of the cavities by roughly a factor of 3 at the operating gradient of 16 MV/m[4].

The modification for CW operation have included modifying the XFEL/TTF-III input coupler, enlarging the exhaust chimney of the helium vessel to handle the larger dynamic heat load, installing 2 cryogenic fill lines to improve the cooldown process and installing 2 layers of magnetic shielding to better achieve the stringent magnetic hygiene requirements that result from using the high Q_0 recipe. The 3.9 GHz cavities, also adapted from XFEL, have also been modified for CW operation, but do not require the additional magnetic hygiene program of the 1.3 GHz cavities.

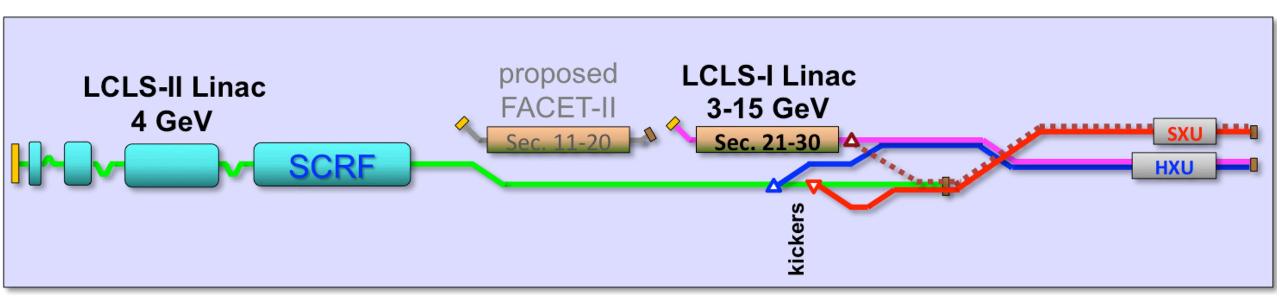

Figure 1: the LCLS-II Linac layout in the tunnel along with the existing LCLS accelerator.

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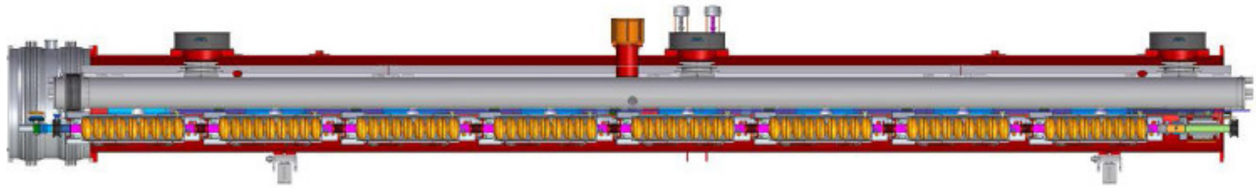

Figure 2: The LCLS-II 1.3 GHz Cryomodule.

THE CRYOMODULE PRODUCTION

Jefferson Lab and Fermilab are the lead laboratories responsible for the majority of the engineering, assembly, testing and delivery of the cryomodules to SLAC. SLAC is providing the fundamental power couplers and will be responsible for receiving the cryomodules, installing them in the tunnel and making the connections to adjacent cryomodules and cryogenic distribution end- and feed-caps. A cross section of the cryomodule is shown in Fig. 2, with a model of the internal cryogenic plumbing, the cavity, beam position monitoring package and the conduction cooled quadrupole magnet package shown in Fig. 3.

The cryomodule assembly process at both labs takes place over approximately a 2-year period during which all 37 CMs must be assembled, tested and shipped to SLAC. In order to accomplish this both labs have set up production lines that will allow them to work on multiple cryomodules at once in different work-centers. In the end each module has approximately 1 month for testing. Based on these facts it should be easy to see many of the challenges that arise during this portion of the project.

CRYOMODULE CHALLENGES

Magnetic Hygiene

The specification for the LCLS-II cavities is a Q_0 >$2.7x10^{10}$ at an accelerating gradient of 16 MV/m. In order to meet this goal the nitrogen doping recipe was developed that provides this high Q_0, but with two trade-offs. The first is the maximum accelerating gradient of the cavity is lowered compared to an un-doped cavity. However for the LCLS-II recipe the average gradient still well exceeds the required 16 MV/m gradient by at least 50% as demonstrated during the prototype phase of the project[5]. The second is that the cavity's susceptibility to trapping magnetic flux as the cavity becomes superconducting is approximately 3.6 times higher than for an un-doped cavity[6]. This is a significant concern as cooling down the cavity in too high of a remnant magnetic field would quickly negate the benefits of the nitrogen doping.

Based on these facts the maximum magnetic field adjacent to the cavity was set at 5 mG for the LCLS-II 1.3 GHz cryomodules. As this level of low magnetic field had never been sought before in a large-scale SRF cryomodule production, detailed flux-expulsion studies were carried out to better understand the impact of remnant field adjacent to the cavity[7]. Then a 3-prong approach magnetic hygiene program was developed. First, shield the cavities as well as possible from remnant magnetic fields. This is accomplished by using 2 layers of magnetic shielding as well as met-glass adjacent to the helium vessel exhaust chimney. Second, specify non-magnetic materials whenever possible, and measure and degauss all

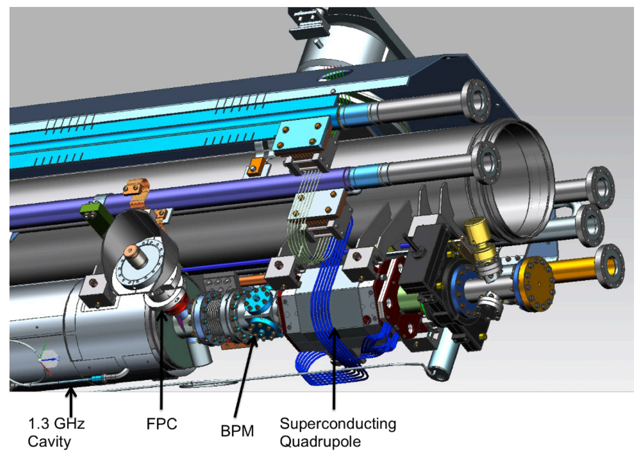

Figure 3: The end-view of the 1.3 GHz cryomodule.

components that go adjacent to the cavity. This required using materials such as 316LN stainless steel whenever possible, and significant effort to measure and degauss other components. Third, develop a method to measuring the field inside the cryomodules and degauss the vacuum vessel, as well as all components inside the vacuum vessel once fully assembled.

This demagnetization project was undertaken by FNAL and reported on in reference 9 at this conference[8, 9]. Figure 4 shows a photo of the demagnetization coil wound around the cryomodule.

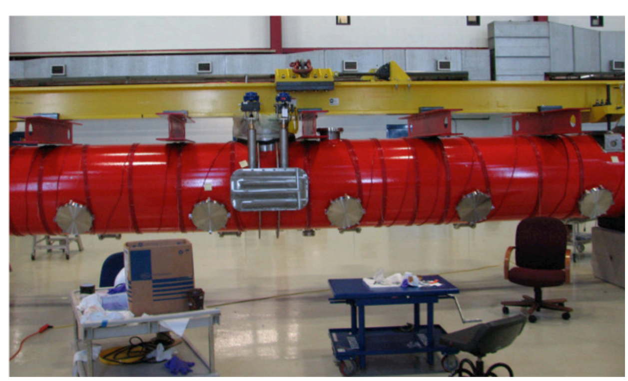

Figure 4: This is a picture of the cryomodules at FNAL that is ready to be demagnetized. The solenoid coil is wound around the CM for the demagnetization process.

The results of all three of these efforts have been measured at FNAL and resulted in a cryomodules that measured less than 2 mG remnant field during cooldown for testing. The key challenge will be maintaining this performance during the production cryomodule assembly campaign as well as through installation in the SLAC tunnel.

High Q_0 Cavity Fabrication

In order to achieve the aforementioned necessary high Q_0 for the LCLS-II project the recipe that was developed at FNAL needed to be reproduced at two commercial cavity fabricators. This required both vendors to modify their heat treatment furnaces with the additional control system and plumbing in order to introduce nitrogen to the furnace during the heat treatment cycle. Both vendors were able to perform the modification, and then successfully dope two 9-cell cavities that were provided by JLab and FNAL. These validation tests were carried out before the vendors were released to begin doping the cavities they had fabricated.

Due to the project's tight schedule the vendor immediately moved to producing cavities dressed in the helium vessel and ready for testing at JLab and FNAL. There was known risk in doing this, but since both vendors had previously built the TESLA style cavity for the XFEL project the risk was considered low.

At the time of this paper submission only one cavity vendor has delivered production cavities to the project and the nitrogen doping of these cavities is excellent. However two new challenges have been identified. The first is that the cavities residual resistance is 2-3 nanoOhms higher than it was for the prototype cavities (that were built from different material and processed at JLab and FNAL). The second item is that the flux trapping of the production material is worse than that of the prototype cavities when utilizing the same recipe. This means that the remnant field in which the cavity is cooled down can have a much greater impact on the cavity performance, as discussed above.

Based on the test results of the first 4 production cavities, as well as ongoing single cell cavity testing, a new recipe was developed to help remedy both of these items. These recipe modifications have been passed along to the vendors and are being implemented for all future cavity production.

Cryomodule Assembly and Testing Schedule

As previously mentioned, all of the cryomodules for the project must be assembled, tested and shipped to SLAC in roughly a 2-year period. As the 1.3 GHz cryomodules are the bulk of this effort the following comments are only related to their assembly and testing.

The schedule that has been developed for these activities at both JLab and FNAL was developed based on past experience building this style of CM at FNAL, as well as thank to the generous support from XFEL, in particular the staff at CEA-Saclay and DESY. Since the 1.3 GHz CM is very similar to the XFEL cryomodule the practices used for the XFEL assembly, as well as their lessons learned have been invaluable to LCLS-II. While this guidance and advice has saved the project many man-years of development, the execution of these plans still needs to be carried out at both JLab and FNAL. To accomplish this both labs have developed detailed schedules, travelers and assembly procedures that have been validated during the prototype cryomodule assembly. It should be noted that these are not the same procedures, but equivalent processes to yield equivalent results. The reason for this is that the infrastructure and general practices are different for the two labs, but yield the same results. In order to deliver all of the cryomodules on time the labs have implemented multiple workstations that can each be populated during the CM assembly campaign. This means that up to 4 CMs can be in different stages of assembly, with a 5^{th} being tested in each labs cryomodules test cave. The duration for CM testing at each lab is roughly one month, and this duration cannot be prolonged as CM testing runs back to back at each facility beginning in early 2016 through the end of 2018. If a problem is found that will delay other cryomodules from testing then the cryomodules in question will need to be put to the side to be addressed while not impeding the workflow and other module testing.

Cryomodule Installation

Once the cryomodules are delivered to SLAC they must be unloaded, inspected and installed it in the tunnel at a rate of 1 every 3 weeks. Once installed onto pre-installed stands the CM must be aligned and connected to the adjacent CM or cryogenic supply or recovery cap. For the interconnects 6 cryogenic lines must be welded together and a higher order mode beamline absorber must be installed in an ISO 4 cleanroom environment. Following a leak check and weld inspection on these components the thermal shields and multi-layer insulation must be installed and a large bellows must be positioned over the previously mentioned section. This must all be accomplished while a great deal of other work is taking place in the tunnel. This includes installation of conventional facilities, wiring, piping, RF waveguide and much more. In addition the space in the tunnel adjacent to the cryomodules must remain clear so that new cryomodules can be brought down the 3 x 3 m cross-section tunnel past already installed cryomodules.

CONCLUSION

While there are many challenges for the LCLS-II project the teams at JLab and FNAL are in an excellent position to produce all of the cryomodules required thank in large part to the generous knowledge transfer from XFEL.

ACKNOWLEDGMENT

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