STATUS OF THE LCLS-II SUPERCONDUCTING RF LINAC

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Abstract

The Linac Coherent Light Source II (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. The assembly and testing of the 1.3 GHz cryomodules is well underway and the 3.9 GHz cryomodule work is entering into the pre-cryomodule testing and component validation phase. Both of these efforts will be reported on in this paper.

INTRODUCTION

The Linac Coherent Light Source II (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 in operation at SLAC since 2009. The original LCLS layout in the tunnel along with the LCLS-II accelerator is shown in figure 1. The LCLS-II upgrade will be complementary to LCLS as both accelerators will continue to operate and provide x-rays to the existing near and far experimental halls, 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, 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 [4-6].

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, adapted from XFEL, have also been modified for CW operation. This has focused on enlarging the helium exhaust chimney in order to handle the larger head load as well as installing 2 layers of magnetic shielding to ensure the cavity Q is not compromised by the large exhaust chimney.

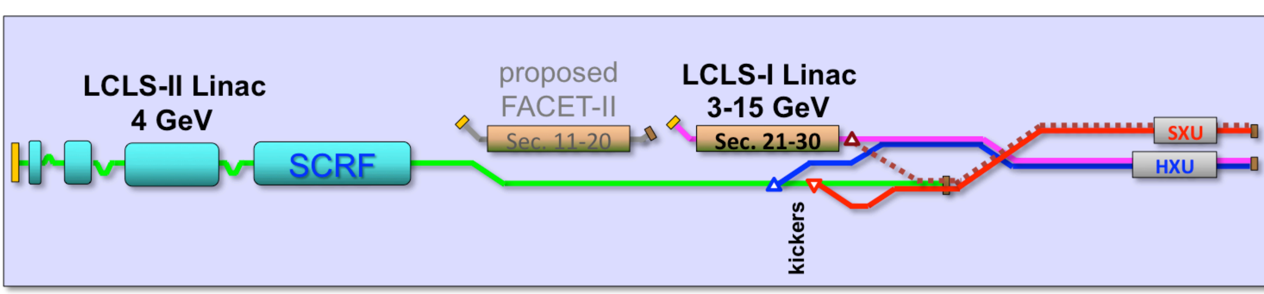

Figure 1: the LCLS-II Linac layout in the tunnel along with the existing LCLS accelerator.

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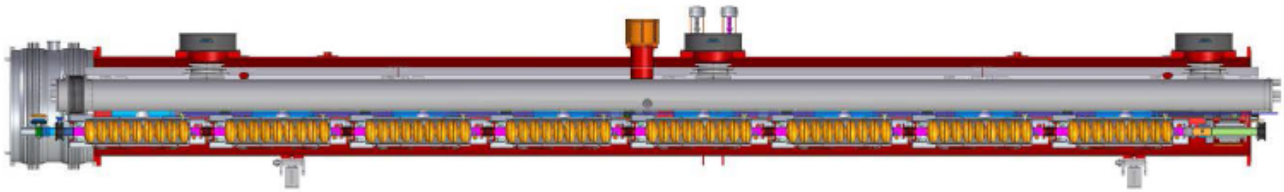

Figure 2: The LCLS-II 1.3 GHz Cryomodule.

1.3 GHz CAVITIES AND CRYOMODULE

Overview

The 35 1.3 GHz cryomodules for LCLS-II are being assembled and tested at Jefferson Lab and Fermilab prior to delivery to SLAC for installation. The cavities for the cryomodules have come from 3 sources. The 2 prototype cryomodules were built using cavities from the ILC project while the balance of the 33 CMs are being built with cavities produced by Research Instruments and Ettore Zanon. Cavity testing is split between JLab and FNAL with each lab primarily testing the cavities that will be installed in their own cryomodules. In addition to the cavities, there is also one beam position monitor (BPM), and a conduction cooled superconducting quadrupole magnet in each cryomodule. A model of these components can be seen in figure 3.

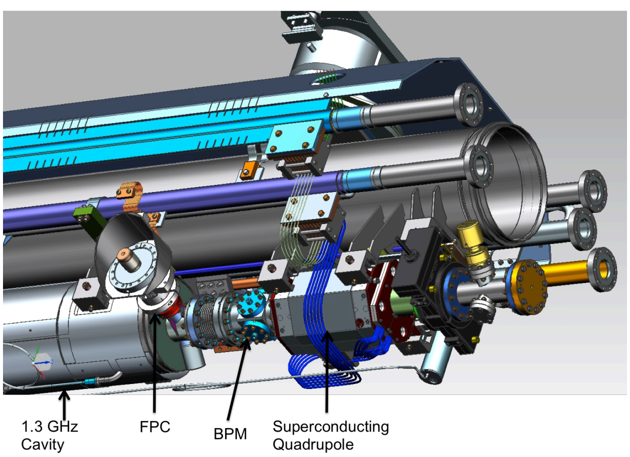

Figure 3: The end-view of the 1.3 GHz cryomodule.

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 up to 6 cryomodules simultaneously in different work-centers. In the end each cryomodule has approximately 1 month for testing in the laboratories cryomodule test caves. [7]

Cavities

The 1.3 GHz cavities have been prepared using the aforementioned nitrogen doping process. This recipe was developed at FNAL and JLab and then successfully transfer to the cavity vendors for production. [8] The nitrogen doping process produces 1.3 GHz cavities that are capable of reaching Q_0 >3.5e10 at 16 MV/m, but come with the trade off that they are up more susceptible to trapping remnant magnetic flux during cooldown through the lambda point. This susceptibility is up to 3.6 times higher than for an un-doped cavity.[9] The 16 cavities that make up the prototype cryomodules were prepared and doped at FNAL and all exhibited very good flux expulsion during testing. These cavities were treated with the original heat treatment recipe, the 800/140 process, which refers to heat treatment at 800°C and 140 μm of electropolishing.

As the production cavity campaign began the cavities exhibited lower than anticipated Q_0 values during testing. This reduction in Q_0 was attributed to both larger residual resistance as well as an increase in flux trapping. Based on these findings the recipe was changed to the 900/200 process, whereby the heat treatment was done at 900°C and 200 μm of electropolishing was performed. This change in recipe resulted in cavity performance on par with the 16 prototype cavities. Since this change in recipe 70 cavities from Vendor B have been successfully tested in the vertical testing dewars at JLab and FNAL and are ready for installation in the cryomodule. More details about the cavity effort can be found in references 5, 6, 8 and 10. [5, 6, 8, 10] An example of the overall performance of the cavities is shown in figure 4, the plot of the maximum gradient achieved vs Q_0 for both the prototype cavities as well as from Vendor B. It is clear from this plot that the cavities are well exceeding our specification of $Q \geq 2.7e10$ at 16 MV/m.

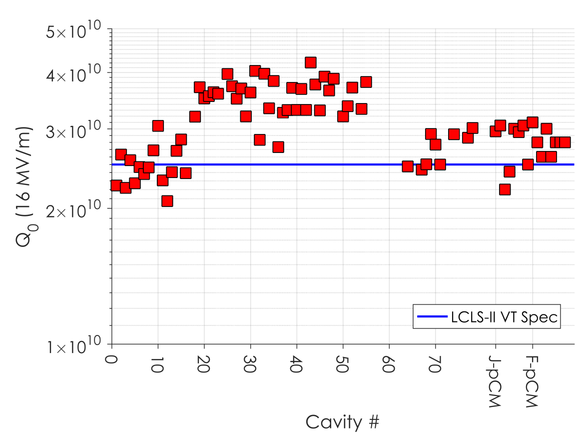

Figure 4: The Q value for the 16 cavities in the prototype cryomodules along with the Q for the cavities from vendor B for both the 800/140 and 900/200 recipe. The increase in Q from the change in temperature is clear after cavity 16.

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Prototype Cryomodule

Two prototype cryomodules (pCM) have been assembled and tested, one each at JLab and FNAL. These were built with the ILC cavities in order to demonstrate the proof of design of the LCLS-II 1.3 GHz cryomodules. The cryomodule design is based on that of XFEL, but modified for CW operation as mentioned in the introduction. These cryomodules are actually first articles as they will be installed in the linac and required for operation, thus making their assembly and testing success all the more critical.

While the pCM assembly at each lab was a learning experience, the exchange of information and ideas went very smoothly and has resulted in 2 cryomodules that exceed the requirements for LCLS-II. At a high level the cryomodules need to be able to deliver the criteria listed in table 1. The pCM at FNAL has been tested and found to be capable of meeting all of these goals, while the JLab pCM is finishing it's second round of testing as of the writing of this paper.

Table 1: A List of the Cryomodule Acceptance Criteria

	Criteria
1	Cryomodule capable of 128 MV acceleration
2	Cavity beamline vacuum cold < $1x10^{-10}$ Torr
3	Center Frequency 1.300000 GHz ±20 kHz
4	Each cavity reaches 16 MV/m
5	Field emission onset ≥ 14 MV/m
6	Average CM $Q_0 \geq 2.5x10^{10}$ at 16 MV/m
7	HOM Qext ≥ $5x10^{11}$
8	Tuner range slow 450 kHZ, fast 0-500 Hz
9	Magnet operates to 20 Amps
10	FPC Qext = $4x10^7$ with range from $1x10^7$ to $6x10^7$
11	Static heat load for CM within specification

Production Cryomodule Assembly and Testing

The production cryomodule campaign began in the fall of 2016 and as of the writing of this paper 9 cryomodules are in various stages of assembly and testing with both JLab and FNAL ramping up to their full production rate. 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 5 CMs can be in different stages of assembly, with a 6th being tested in each labs cryomodules test cave. If a problem is found that will delay other cryomodules from progressing to the next workstation 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. Both labs have provisions for doing this should the need arise.

The production CM testing at each lab is scheduled for 6 weeks, which includes the installation and removal of the CM from the test cave, cool-down, testing and warm-up. This means that the actual testing time for a CM is only 14 days with 2 shifts of operation planned. The third shift at each lab is available for additional testing as needed and is the planned opportunity for testing of the LCLS-II LLRF system.

Currently the first FNAL production cryomodule is being tested at FNAL, marking the beginning of ~ 2 years of CM testing that will result in the 35 CM being processed and ready for delivery to SLAC for installation.

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 (1 from FNAL and JLab every 6 weeks). Once mounted to pre-installed stands the CM must be aligned and connected to the adjacent CM or cryogenic supply or recovery cap. For the cryomodule 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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