THE NEW LCLS-II PROJECT: STATUS AND CHALLENGES*

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Abstract

The LCLS-II was an upgrade of the LCLS which essentially replicated the LCLS in another tunnel using the middle 1/3 of the SLAC S-band linac. In August 2013, the project was doubled in scope and redirected towards providing MHz-rate x-ray pulses from 0.2 to 5.0 keV while still supporting the ongoing program at the LCLS. The new accelerator is now based on a 4.0 GeV SCRF linac installed in the front of the SLAC linac tunnel. Key features of the LCLS-II linear accelerator are described, so that LCLS-II can be responsive to the July 2013 recommendation of DOE BESAC for a fully coherent, CW FEL with photon energies up to ~5 keV.

INTRODUCTION

The Linac Coherent Light Source (LCLS) [1,2] started as a 1992 proposal to employ the third kilometer of the 3 km SLAC linac to create an x-ray free-electron laser. This proposal was followed by a comprehensive design study and numerous workshops on the scientific potential of an x-ray free-electron laser. In 2000, the US Department of Energy (DOE) Office of Science officially recognized the need to build such a facility. Groundbreaking took place in 2006 and the LCLS produced first x-rays in April 2009. Since then, LCLS has become a major scientific user facility hosting thousands of experimenters per year at one of the six x-ray experiment stations that share the single x-ray source. The high energy of the LCLS copper linac has enabled LCLS to produce very intense x-ray pulses with >2 mJ concentrated in a few 10's of femtoseconds. SLAC began planning an expansion of the facility very soon after operations began. LCLS was designed to support several options for expansion which have been developed in various degrees since 2010 [3,4,5]; some of these options have been developed into mature concepts. By July 2013, SLAC had prepared a complete design for adding two x-ray sources in a new tunnel. The second kilometer of the SLAC linac was to be dedicated to these two sources, while the original LCLS linac would continue to serve the LCLS undulator. In July 2013, the DOE Basic Energy Sciences Advisory Committee concluded [6] that duplicating the 120Hz repetition rate of the SLAC linac in LCLS-II would limit the scientific reach of the facility; a pulse repetition rate in the kHz to MHz range would be necessary to meet future needs. This advice prompted SLAC to propose a sweeping change to the LCLS-II project.

During August and September of 2013, the project was re-planned [7]. Rather than use another portion of the SLAC linac, LCLS-II will construct a new 4 GeV CW superconducting linac in the first kilometer of the SLAC linac tunnel. Two new undulator x-ray sources will be installed in the existing LCLS undulator hall. A soft x-ray (SXR) source (200-1,300 eV) will occupy an area reserved for a future undulator during construction of LCLS, and the original fixed-gap LCLS undulator will be replaced by a new variable-gap hard x-ray (HXR) source. Both undulators will be configured to receive electrons simultaneously from the new superconducting linac. In addition, the HXR source will be configured so that it may be switched to receive >14 GeV electrons from the LCLS "copper" (Cu) linac at 120 Hz. In this configuration, the HXR source can produce a beam of coherent x-rays, extending the spectral coverage of the facility to 25 keV.

THE LCLS-II PROJECT COLLABORATION

A collaboration of six institutions has been formed to design and construct LCLS-II. Thomas Jefferson National Accelerator Facility (JLAB) will design and acquire the cryogenic refrigeration system and assemble half of the 1.3 GHz cryomodules. Fermi National Accelerator Laboratory (FNAL) will design and acquire the helium distribution system and 3.9 GHz modules. FNAL will also make the necessary design changes to 1.3 GHz modules and assemble ½ of the cryomodules. Lawrence Berkeley National Laboratory (LBNL) is responsible for design/performance optimization and fabrication of the 187 MHz photocathode electron gun as well as the 53 undulator magnets required for the two x-ray sources. Argonne National Laboratory (ANL) will support the FNAL cryomodule effort and provide aluminium vacuum chambers for the undulators. Cornell University is a collaborator in the effort to achieve major improvements in performance of the superconducting cavities. Cornell is also conducting theoretical and experimental studies of the capabilities of its DC gun design, an alternative choice for the LCLS-II injector. SLAC, the host laboratory for the project, is responsible for overall design and integration of the facility, including the installation of the linac. SLAC will also design and construct the electron beam transport systems, controls, and x-ray optics. This collaboration, an extraordinary concentration of US accelerator expertise, has made it possible to transform the LCLS-II project in a matter of months. The collaboration has a goal of producing first x-rays using the superconducting linac by September 2019.
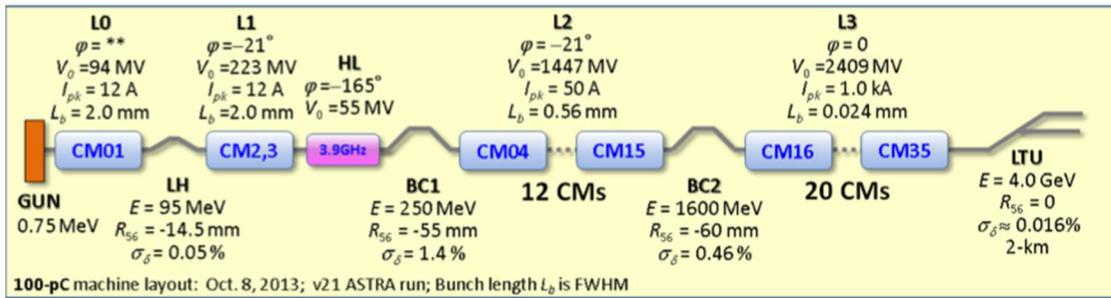
Figure 1. Schematic Layout of the LCLS-II SC Linac

SUPERCONDUCTING LINEAR ACCELERATOR

The LCLS-II linac design will be based on technology developed for the International Linear Collider and the European X-ray Free-Electron Laser (XFEL). Engineering designs will be adapted from the XFEL cryomodule design, with a number of modifications to support continuous-wave operation. The linac will include 35 cryomodules, each containing eight 1.3 GHz 9-cell accelerating structures identical in geometry to XFEL and fabricated of fine-grain niobium. The target accelerating gradient for the LCLS-II cavities is 16 MV/m; this gradient is generally considered to be near the economic optimum, taking into account the cost of cryomodules and associated refrigeration. The linac will include two additional cryomodules, each containing eight 3.9 GHz cavities. These modules are required to correct any quadratic dependence of electron energy on longitudinal position, which would produce undesirable "spikes" in the bunch current during the compression process. A schematic of the accelerator is shown in Figure 1. The operating temperature of the cavities will be $2^{o}K$.

CONSIDERATIONS FOR CW OPERATION

For CW operation, the dominant demand on refrigeration (about 2.7kW at $2^{o}K$) is the "dynamic" heat load deposited in the cavities by RF. The required refrigeration capacity is a very close match to the Central Helium Liquefier 2 (CHL2) refrigeration plant designed by JLAB for its 12 GeV Upgrade project. JLAB is presently designing and acquiring a somewhat updated version of this plant design for the Facility for Radioactive Ion Beams (FRIB) at Michigan State University [8]. LCLS-II is planning to use the same design with minimum modification. Choice of a well-characterized, operation-proven design ought to reduce the time to acquire the plant by at least one year; this is very attractive from the point of view of project schedule.

IMPROVEMENT IN QUALITY FACTOR OF CAVITIES

LCLS-II is planning to take advantage of a remarkable breakthrough in cavity performance, studied at FNAL over the past few years. Grassellino, et al. [9,10] have demonstrated that Q_o, the unloaded quality factor of an XFEL cavity, can be elevated to $\sim 3 \times 10^{10}$ as a result of exposing the cavities to a controlled introduction of nitrogen gas during the high temperature bake sequence routinely used to drive out sub-surface hydrogen. The bake sequence is then followed by etching/removal of cavity material to a prescribed depth. Over the past six months, members of the LCLS-II collaboration (FNAL, JLAB & Cornell) been investigating this process intensively [11,12] to define the recipe for the bake, nitrogen exposure and etch steps to be used by manufacturers of LCLS-II cavities. The performance goals for LCLS-II cavities and cryomodules are:

- average unloaded Q_o exceeding 2.7×10^{10} measured at a gradient of 16 MV/m
- capability to operate CW up to at least 18 MV/m
- field emission current <25 pA at 16 MV/m

Tests of single cells and cavities in vertical and horizontal orientation over the past months have demonstrated that Q_o targets can be exceeded regularly; additional study will hopefully reduce the variation in quench field. Studies have established the recipe which produces results that meet the above criteria and are least sensitive to the parameters of the process [13]. It is known, however, that achievement of high Q in operation requires that cells or cavities be cooled through superconducting transition in the presence of very low ($\leq$ 5 milligauss) ambient magnetic field. Recently it was observed that Q_o can be increased by a considerable margin (e.g. from 2.5×10^{10} to 3.2×10^{10}) if the cavity is cooled very rapidly from $\sim 100^{o}K$ to below transition. It is believed that fast cool-down results in a higher spatial gradient of temperature, reducing or eliminating the trapped ambient magnetic flux in the form of persistent currents trapped the superconducting niobium.
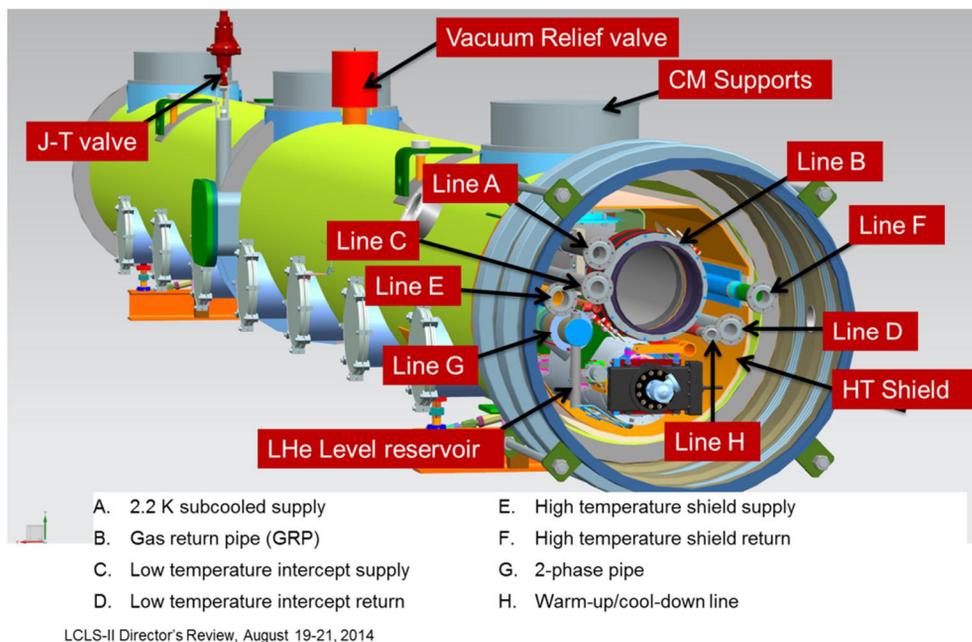
Figure 2. End View of LCLS-II Cryomodule

CRYOMODULE DESIGN

The LCLS-II cryomodule (see figure 2.) will incorporate a number of changes to the XFEL cryomodule design. The coupler [14] will likely be based on the TTF3 design, modified slightly to match the RF source to the cavity with 100-300 µA electron beam current. A modification of the higher mode damper feedthrough will be required to provide more cooling.

With a bunch frequency up to 1 MHz and average beam current as high as 300 µA, higher mode dampers must cope with the resultant HOM power [15]. Some modification of the HOM coupler arrangement is under consideration for the first cryomodule in the linac to eliminate deflecting wake fields [16] and thus minimize emittance degradation of the low-energy electron beam. An electromechanical/piezoelectric double-lever actuated tuner is being developed at FNAL.

A simplification of the cryomodule design is achieved by eliminating the 5°K thermal shield. This is permissible because there is little to be gained by a reduction in static cooling load, which is only 12% of the total. Cooling of the input power coupler at 5°K will be retained. Accommodations for the dynamic load include an increase in diameter of the two-phase pipe to about 100mm and larger diameter "chimney" pipes connecting the cavity vessels to the two-phase pipe.

The SLAC linac tunnel was given a 0.5% slope over its entire length to minimize earthmoving during construction over 50 years ago. Because of this slope, the liquid level changes by 60 mm from one end of a cryomodule to the other. For this reason the two-phase pipe cannot run continuously between cryomodules, and must be capped at both ends within each cryomodule. A

quadrupole magnet, steering magnet and "button" capacitive beam position monitor will be placed at the downstream end of each cryomodule.

In order to reduce ambient magnetic fields to a minimum, additional shielding in the cryomodule and possible compensation with correction windings will be necessary.

PROTOTYPE CRYOMODULES

JLAB and FNAL will each build a prototype 1.3 GHz cryomodule for testing by December 2015. If test results are favorable, production of cryomodules can be completed by the end of 2018.

RF SYSTEM

LCLS-II will employ solid-state amplifiers for each cavity in five cryomodules (numbers 1-3 and 34-35) where precise control of phase and amplitude is essential for control of bunch compression and time-of-arrival of the x-ray pulse at the x-ray experiment station. The initial concept calls for the remaining 30 cryomodules to be powered by five 300 kW klystrons, with one klystron powering six cryomodules; however, there is strong reason to consider the use of solid-state amplifiers for all cavities. This higher-cost alternative would provide optimal control over phase and amplitude and reduce the risk of phase/amplitude instabilities that might arise due to the combined effect of microphonics and Lorentz force detuning.

PERFORMANCE GOALS

No changes to the LCLS copper linac will be made by the LCLS-II project; the expansion of the tuning range of

the HXR source comes from the new HXR undulator source. Overall performance goals for the superconducting linac are listed in table 1. It is anticipated that, as is the case with LCLS, experimenters using the x-ray beam will request a wide variety of operating configurations in terms of electron bunch charge, pulse duration, etc. This broad range of operating modes poses a formidable challenge for the accelerator designer [17] and, in the future, for the operating staff.

PRESENT AND FUTURE ACTIVITIES

The project is preparing to purchase niobium immediately. Solicitations for major refrigeration subsystems are presently in preparation. The project plans to place these orders in spring 2015.

Table 1. Target Performance Parameters for the LCLS-II SC Linac

Electron Beam Parameters	symbol	nominal	range	GeV
Final electron energy (operational)	E_f	**4.0**	2.0-4.14	GeV
Electron bunch charge (limited by beam power)	Q_b	**0.10**	0.01-0.3	nC
Max. bunch repetition rate <u>in linac</u> (CW)	f_b	**0.62**	0-0.93 (9.3)	MHz
Average electron current <u>in linac</u>	I_{av}	**0.062**	0.001-0.3	mA
Average electron beam power at <u>linac end</u> (limit)	P_{av}	**0.25**	0-1.2 *	MW
Norm. rms transverse slice emittance at undulator	$\gamma\varepsilon_{\perp\text{-s}}$	**0.45**	0.2-0.7 #	μm
Final peak current (at undulator)	I_{pk}	**1000**	500-1500	A
Final rms bunch length (at undulator)	σ_{zf}	**8.3**	0.6-52	μm
Final estimated useable bunch duration (FWHM)	$\Delta\tau_f/\tau_f$	**50**	-	%
Total magnetic compression (cathode to undulator)	C_T	**85**	25-150	-
Final slice energy spread (rms, with heater)	σ_{Es}	**500**	125-1500	keV
Estimated RMS Beam Stability Goals:				
Relative rms electron energy stability (at und.)	$(\Delta E/E_f)_{rms}$	**< 0.01**	-	%
Relative rms peak current stability (at und.)	$(\Delta I/I_{pk})_{rms}$	**< 5**	-	%
Bunch arrival time stability (rms, at und.)	$(\Delta t_b)_{rms}$	**< 20**	-	fs
Transverse centroid stability (rms, at und., 100 pC)	$\Delta x_{rms}/\sigma_x$	**< 10** †	-	%

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*The linac is designed to 1.2 MW of beam power although more FEL lines are needed to operate there

The transverse emittance varies with approximately the square-root of the bunch charge.

† Defined as the rms variation of the position or angle centroid normalized to its rms size.

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