ISBN: 978-3-95450-210-3 doi:10.18429/JACoW-FEL2019-FRA02

LCLS-II – STATUS AND UPGRADES*

Brachmann†, B. Dunham, J. Schmerge for the LCLS-II Collaboration,
SLAC National Accelerator Laboratory, Menlo Park, CA, USA

Abstract

LCLS-II is a major project to build and operate a 1 MHz, continuous-wave Free Electron Laser covering a wide photon energy range from ~ 200eV up to 25 keV. A superconducting accelerator, providing beams up to 4 GeV, drives two variable gap undulator systems, one providing soft energy X-rays (SXR) up to ~ 2keV, the other hard energy X-rays (HXR) up to 25 keV. In addition, the normal conducting accelerator used for LCLS-I will remain in operation, primarily driving the hard X-ray undulator beam line delivering photon energies up to 25 keV. We will summarize the project goals, current status of construction of the main sub-systems and future plans. The focus of this contribution will be the FEL itself. We will mention the X-ray instrumentation for context.

LCLS-II PROJECT OVERVIEW

A detailed overview of the LCLS-II facility is given in the Technical Design Report [1]. A schematic layout of the facility is shown in Figure 1. The project is supported by the United States Department of Energy and is a collaboration of several National Laboratories and Cornell University. The cryomodules are built by the Thomas Jefferson National Accelerator Facility (JLab) and Fermilab (FNAL). The undulator systems for the hard and soft X-ray energy ranges are provided by Argonne National Laboratory (ANL) and Keller Technology Corporation, New York, USA (KTC), respectively. The electron gun is a contribution of the Lawrence Berkeley National Laboratory (LBNL). This system is already fully installed, and commissioning activities are in progress. A key system is the cryo-plant. It is based on the 2K plant in operation at JLAB. The entire cryogenic system was designed and constructed collaboratively by SLAC, JLab, FNAL and several industrial partners. A ‘dual’ plant is installed to provide headroom for capacity and future extension of the cryogenic linac.

The goal of the project is to construct and operate an FEL user facility for advanced X-ray science that will be available to the international user community. Scientific motivation and opportunities have been summarized in [2]. The existing normal conducting (NC) accelerator will continue to operate and primarily provide beams in the HXR energy range but will also be used to assist commissioning of the new SXR beamlines and instrumentation.

The main construction activities will be completed in 2021. User operation based on the NC accelerator will commence in the spring of 2020. ‘First light’, generated by SC accelerator beams is anticipated in 2021, followed by a ramp-up period to full performance, over 3-4 years. A set of Design Parameters is given in table 1. Figure 2 shows the X-ray energy range and average beam brightness.

Table 1: Design Parameters

KPP	SC linac	NC linac
Linac Energy	4 GeV	15 GeV
Repetition Rate	1 MHz	120 Hz
Nominal Bunch Charge	0.1 nC	0.125 nC
Photon Energy Range	0.2-5 keV	0.2 - 25 keV
Photon Pulse Energy	0.5 mJ	~ 2 mJ

Approximately half of the cryomodules are now installed in the first kilometre of SLAC’s linac tunnel. The undulators both for SXR and HXR systems are in the process of magnetic measurement and calibration. Installation is imminent and we expect completion of commissioning in the early part of 2020, enabling the restart of the facility and user operation based on the NC linac. Many other systems are currently installed, for example the RF systems, cryogenic plant and cryogenic distribution system, beam transport and switching systems, beam dumps, controls and safety systems. In parallel, a major upgrade of the X-ray instrumentation is taking place: 3 new end stations will be added, high repetition rate capabilities will be implemented, and appropriate data processing technology is being developed and installed. A comprehensive description of photon and experimental system development is summarized in a strategic development plan [3].

LCLS-II Injector

The LCLS-II Injector uses a normal conducting VHF electron gun. The gun has been developed at LBNL and a prototype has been in operation for several years, also known as the ‘APEX gun.’ The injector design and gun are described in references [4, 5]. Beam is generated by a Cs_2Te cathode driven by a 257 nm laser system. The LCLS-II electron gun is installed in its final location. We succeeded to generate first beam, including a measurement of the electron beam energy, confirming specified performance (Figures 3 and 4).

* Work supported by the U.S. Department of Energy, Office of Basic Energy Sciences, Contract No. DE-AC02-76SF00515.
†brachman@slac.stanford.edu

ISBN: 978-3-95450-210-3 doi:10.18429/JACoW-FEL2019-FRA02

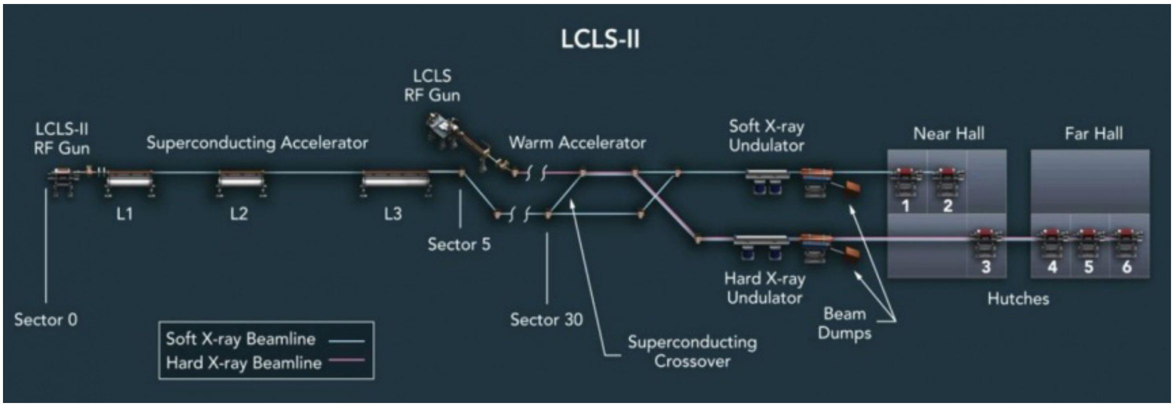

Figure 1: Schematic layout of the LCLS-II Facility.

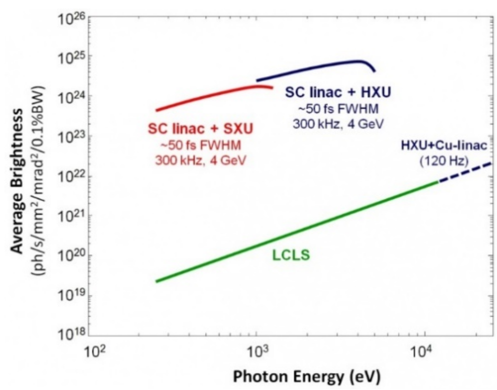

Figure 2: Photon energy and brightness of the LCLS FEL.

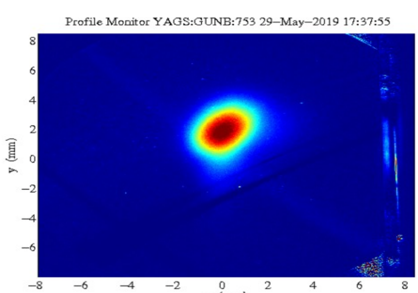

Figure 3: Profile of first LCLS-II electron beam.

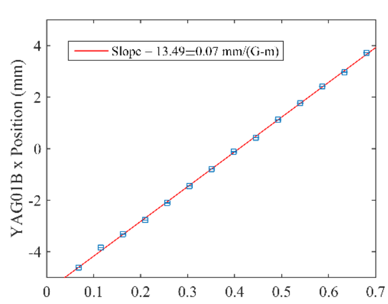

Figure 4: Gun electron beam kinetic energy 766 keV as determined from calibrated corrector scan.

SC Linac and Cryomodule Installation

The LCLS-II linac consists of 37 cryomodules, each containing eight 9 cell niobium cavities. The SC linac is arranged into 3 sections, L1, L2 and L3. The spaces between L1 / L2 and L2 / L3 provide room for bunch compressors (BC1 and BC2). Otherwise the linac forms a continuous cryogenic system with welded connections between the cryomodules. Approximately half of the cryomodules arrived from JLab and FNAL and are installed in SLAC's linac tunnel. At this time, the cryomodule connections are being welded, using automated orbital welding technology.

Early in the CM shipping phase, we experienced a technical issue with excessive vibrations during transport, leading to a failure of bellows, which caused the venting of the vacuum system. This problem was mitigated by temporary constraints implemented for the road journey of the CM's across the American continent. A related problem occurred during installation, leading to damage of the fragile bellow convolutions. An appropriate investigation and failure analysis lead to improved processes, techniques and procedures. Installation continues at approximately one unit per week in a routine manner. We expect to have the full compliment of CM's installed and connected by early summer of 2020 and plan to begin the cooldown process in the summer of 2020.

Cryoplant

The cryoplant for LCLS-II will provide the liquid Helium required to operate the cryogenic linac at temperatures of 2K. A dual interconnected plant provides capacity and room for future expansion. A complex distribution system transfers cryogens to the modules installed in the linac tunnel. Plant construction is currently underway with completion of commissioning of plant #1 in mid-2020 and about a year later for plant #2. Operation of the SC linac will begin with only one operational plant.

ISBN: 978-3-95450-210-3 doi:10.18429/JACoW-FEL2019-FRA02

Undulator System

Two new undulator beamlines will replace the predecessor, fixed-gap LCLS-I undulator system. Each LCLS-II undulator beam line is dedicated to one photon energy range and are therefore called SXR and HXR undulators, respectively. Both are variable gap designs but distinguished by their orientation, horizontal gap for HXR and vertical gap for SXR. All SXR and most of the HXR undulators have been delivered to SLAC and are in the process of magnetic measurement and calibration. The installation is currently being prepared and will be completed in the spring of 2020. A drawing of the arrangement in the FEL tunnel is shown in Figure 5.

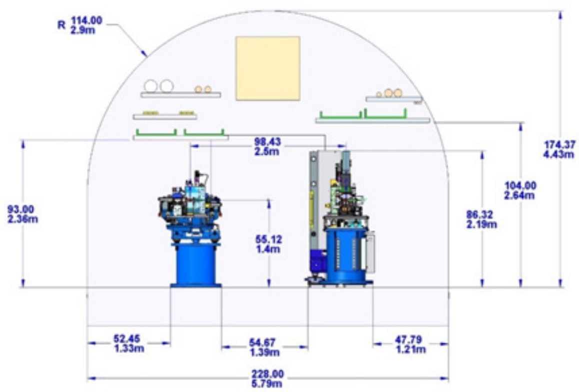

Figure 5: Arrangement of HXR (left) and SXR (right) undulators in the FEL tunnel.

Operational efficiency and flexibility will be achieved by fully switchable accelerator beam destinations using kicker magnets. Both the SC and the NC linac can provide electron beams to both undulator beamlines. Even though the SC linac beam will not be available until 2021, commissioning of both undulators beamlines and new LCLS-II X-ray instrumentation and beamlines can proceed upon NC linac restart in early 2020, including execution of a scientific user program.

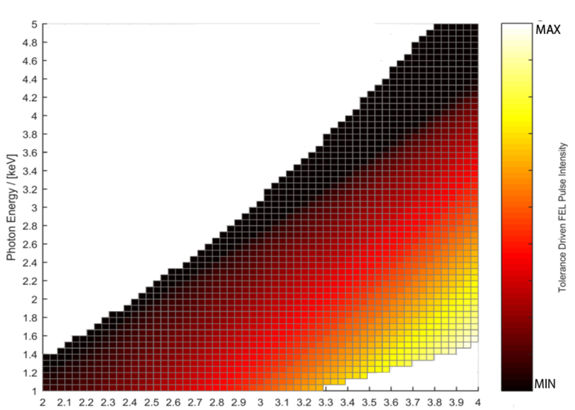

Figure 6: SXR undulator energy range.

One of the main advantages of variable gap undulators is the capability to tune the photon energy wavelength while maintaining a constant electron beam energy. As an example, the photon energy tuning range of the SXR undulators as a function of electron beam energy is depicted in Figure 6.

For a given energy range, the electron beam energy can still be used to optimize the photon pulse energy. We expect pulse energies of several hundreds of μJ up to a mJ will be initially available for user operation. Currently, we are planning to develop tuning procedures to allow automated continuous photon energy scanning capabilities.

Commissioning Plans and Ramp Up

Our plan is to begin commissioning of the SC linac based FEL systems in the spring of 2021. The FEL electron beam power is planned to incrementally ramp up to a target of ~ 120 kW at the dump downstream of the undulators, in order to prevent damage to the permanent magnets in the undulators. Beam repetition rate and electron bunch charge are the principal parameters to control beam power. We anticipate this process to continue for several years, approximately until the end of calendar year 2024, when we reach full performance. Figure 7 illustrates the projected ramp-up of beam power. User operation will take place during this period. Machine performance will be coordinated with user operation and the LCLS-II science program.

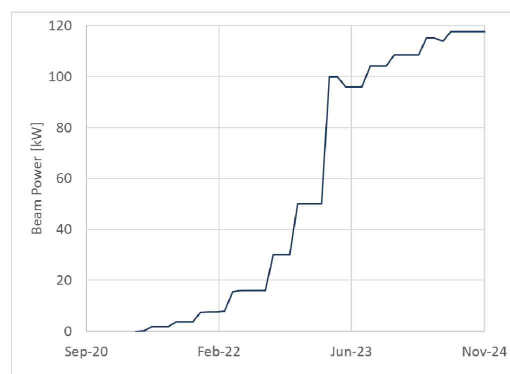

Figure 7: Ramp up of beam power during machine start and early years of operation.

Plans for Advanced Capabilities

In addition to the project baseline, we plan to implement self-seeding capabilities for the SXR and HXR beamlines. The seeding systems are based on established LCLS designs [6, 7], adapted for high repetition rate operation.

We are adapting the existing XLEAP system [8] for LCLS-II operation, providing sub-femtosecond X-ray pulses in the SXR energy range [8]. The technique is based on self-energy modulation of the electron bunch up to ~ 50 MeV. Modulation will be induced by four 10-period wigglers, which have been built by modifying 4

ISBN: 978-3-95450-210-3 doi:10.18429/JACoW-FEL2019-FRA02

now unused LCLS fixed gap undulators. Availability of sub-femtosecond pulses in the HXR range will remain by continued use of non-linear compression techniques developed with the LCLS NC linac [9].

X-ray beams with up to 99% circularly polarization have been available for the LCLS (DELTA undulator [10]). A new design appropriate for high repetition rate beams is currently in the engineering phase [11] and will be installed shortly after the initial commissioning phase of the LCLS-II. It is anticipated to be operational in 2022.

LCLS-II-HE

The LCLS-II-HE project will continue to extend the energy reach of the LCLS facility up to 12 keV at a 1 Mhz repetition rate [12]. This will be achieved by addition of 19 cryomodules, using improved cavities, doubling the electron beam energy of the superconducting accelerator up to 8 GeV. It is necessary to install a new cryogenic distribution box and transfer line between the cryoplant and new L4 linac. A system of beam switching devices and bypass lines will allow to run multiple CW beams at different energies, further extending the flexibility of the LCLS facility. The full range of energy reach is illustrated in Figure 8.

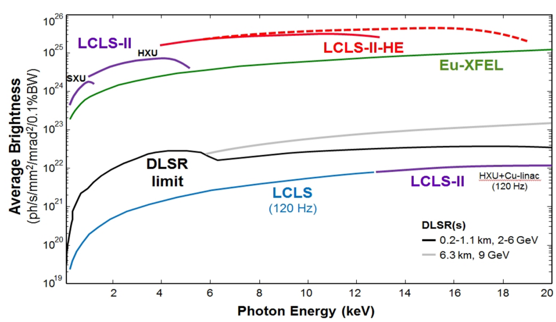

Figure 8: Energy reach and brightness of the LCLS FEL complex.

CONCLUSION

The LCLS-II project is well underway, approximately >85% complete. User operation will commence in 2020 driven by the NC linac, followed in 2021 by first SC beam operation. Undulator performance will be initially established using the NC linac followed in 2021 by first SC beam operation. Many advanced capabilities such as self-seeding, sub-femtosecond pulses and polarized beams will be available for early user operation. A major extension, doubling the SC linac energy is planned for the near future, further extending the reach of the LCLS FEL facility.

ACKNOWLEDGEMENTS

We wish to thank the staff of SLAC and our partner labs in the US that contribute to the LCLS-II project (JLab, FNAL, ANL, LBNL and Cornell University). The team's dedication is tremendous and sustained over many years. A multi-laboratory collaboration is crucial to have access to a large amount of expertise, talent and resources. We also thank our funding agency, the US Department of Energy, Office of Science, Office of Basic Energy Science for their guidance and trust with this large project. Finally, we must acknowledge and thank our colleagues internationally, especially the accelerator physics and technical teams of DESY and the European XFEL for their advice, collaboration, sharing of knowledge and expertise with many aspects of superconducting accelerator technology.

REFERENCES

[1] LCLS-II Final Design Report, SLAC, Menlo Park, CA, USA, LCLSII-1.1-DR-0251-R0, Nov. 2015

[2] New Science Opportunities Enabled by LCLS-II X-Ray Lasers, SLAC, Menlo Park, CA, USA, SLAC-R-1053, June 2015.

[3] LCLS Strategic Facility Development Plan, 2018. 2. Published by: SLAC National Accelerator Laboratory. 2575 Sand Hill Road. Menlo Park, CA 94025.

[4] J. F. Schmerge *et al.*, "The LCLS-II Injector Design", in *Proc. 36th Int. Free Electron Laser Conf. (FEL'14)*, Basel, Switzerland, Aug. 2014, paper THP042, pp. 815-819.

[5] F. Sannibale *et al.*, "Status of the APEX Project at LBNL", in *Proc. 3rd Int. Particle Accelerator Conf. (IPAC'12)*, New Orleans, LA, USA, May 2012, paper WEEPPB004, pp. 2173-2175.

[6] J. Amann *et al.*, "Demonstration of self-seeding in a hard-X-ray free-electron laser", *Nature Photonics*, vol. 6, 2012, pp. 693–698. doi:10.1038/nphoton.2012.180

[7] D. Ratner *et al.*, "Experimental Demonstration of a Soft X-Ray Self-Seeded Free-Electron Laser", *Phys. Rev. Lett.*, vol. 114, 2015, p. 054801. doi:10.1103/PhysRevLett.114.054801

[8] A. Marinelli *et al.*, "Experimental demonstration of a single-spike hard-X-ray free-electron laser starting from noise". *Appl. Phys. Lett.*, vol. 111, 2017, p. 151101. doi:10.1063/1.4990716

[9] Huang S *et al.*, "Generating single-spike hard X-ray pulses with nonlinear bunch compression in free-electron lasers" *Phys. Rev. Lett.*, vol. 119, 2017, p. 154801. doi:10.1103/PhysRevLett.119.154801

[10] A. Lutman *et al*, "Polarization control in an X-ray free-electron laser", *Nature Photonics*, vol. 10, 468–472 (2016). doi:10.1038/nphoton.2016.79

[11] K. Tian and H.-D. Nuhn, "Numerical Study of the Delta II Polarizing Undulator for LCLS II", in *Proc. 10th Int. Particle Accelerator Conf. (IPAC'19)*, Melbourne, Australia, May 2019, pp. 1899-1902. doi:10.18429/JACoW-IPAC2019-TUPRB102

[12] T.O. Raubenheimer, "The LCLS-II-HE, A High Energy Upgrade of the LCLS-II", in *Proc. FLS2018* Shanghai, China, 2018. doi:10.18429/JACoW-FLS2018-MOP1WA0