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LCLS-II COMMISSIONING RESULTS*

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Abstract

The Linac Coherent Light Source II (LCLS-II) is a new X-Ray FEL facility, extending the capabilities of the established LCLS hard X-ray FEL user facility. The main new feature is the superconducting electron accelerator serving two undulator beam lines, providing high repetition rate x-ray beams in the soft and hard x-ray spectral range.

The LCLS-II project is a collaboration of several United States National Laboratories, Universities and industrial partners. The cryomodules were constructed at Fermilab National Accelerator Laboratory (FNAL) and Thomas Jefferson National Accelerator Facility (JLab). The electron source was designed and build by colleagues at the Lawrence Berkeley National Laboratory (LBNL). LBNL also lend their expertise for variable gap undulator technology. The hard x-ray variable gap undulators were built at Argonne National Laboratory (ANL), there as the soft x-ray undulators were constructed by industrial partners: Keller Technology Corporation and Motion Solutions. Superconducting technology know-how was further provided by Cornell University and 'informally' by our colleagues from the European XFEL and DESY. Installation of the new facility took place at the SLAC National Accelerator Facility.

This paper will summarize the current status of the LCLS-II commissioning program and the outlook for the months ahead leading to the conclusion of the LCLS-II project.

Facility Overview

The LCLS-II accelerator is comprised of a normal conducting electron source, 33 cryomodules, each containing 8 9-cell superconducting cavities, operating at 1.3 GHz. Two additional cryomodules operate at 3.9 GHz and are used to control the energy profile of the electron bunches. The superconducting 4 GeV electron beams are sent to two undualtor beamlines, generating FEL beams in the soft (0.2-1 keV) and hard (1-5 keV) spectral ranges. The x-ray beams will be used in several high repetition rate enables instruments. In addition, several kilometres of beam transport lines have been installed. The established normal conducting accelerator will remain part of the LCLS-II facility and will provide high peak power performance.

The x-ray instrument systems have been extended to be able to use the high repetition rate beams. The formal project scope includes initially one high rep rate capable end-station. However, we expect future high repetition rate upgrades of additional end-stations.

Key performance parameters (KPPs) are summarized in Table 1. Threshold KPPs are the milestones for transitioning systems to normal facility operation, Objective KPPs are the final performance goals to be achieved over several years of user facility operation. Almost all KPPs based on the normal conducting accelerator have been achieved.

A full description of the facility can be found in the Final Design Report [1]. A schematic of the facility is illustrated in Figure 1.

Table 1: LCLS-II Key Performance Parameters

Parameter	Threshold	Objective
SUPER CONDUCTING BASED FEL		
Beam Energy (e-)	3.5 GeV	≥ 4 GeV
Repetition Rate	93 kHz	929 kHz
Bunch Charge	0.02 nC	0.1 nC
Beam Energy (γ)	0.25-3.8 keV	0.2-5.0 keV
Photon # (10^{-3} bandwith) per bunch	$5x10^8$@2.5 keV	> 10^{11}@3.8 keV
NORMAL CONDUCTING BASED FEL		
Beam Energy (e-)	13.6 GeV	15 GeV
Repetition Rate	120 Hz	120 Hz
Bunch Charge	0.1 nC	0.25 nC
Beam Energy (γ)	1-15 keV	1-25 keV
Photon # (10^{-3} bandwith) per bunch	10^{10}@15 keV	> 10^{12}@15 keV

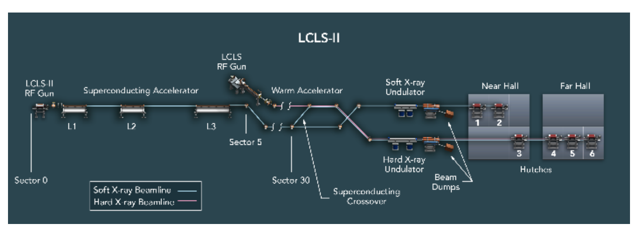

Figure 1: Schematic of the LCLS-II facility.

Cryogenics and SRF Commissioning

The construction and commissioning of the first 4 kW, 2K cryoplant and cryogenic distribution was accomplished in approximately 2.5 years and provided cryogens to the linac since January 2022. In addition, a second cryoplant with similar specifications was built and is now nearing completion. The second plant will serve a future expansion of the superconducting linac to achieve 8 GeV electron beams. Upon completion of the cryomodule installation, commissioning of the superconducting cavities was executed.

The cavity cooldown to 2 K is fully automated. Cooldown was completed in ~ 5 days at a rate of 2-3 K/hour. Cavities were fully stable 11 days later.

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97% of all installed cavities are fully operational (vs. a planned 94%). The majority of testing was done up to the administrative limit of 18 MV/m. A total commissioned cavity voltage of 4.9 MV was achieved, exceeding the design by > 20%. The cavity gradients achieved at SLAC are very close to results measured at the partner labs (JLab and FNAL), no degradation was observed as a result of installation. Following a fast cool-down sequence, an average Q_0 of $2.6x10^{10}$ was achieved.

Injector Commissioning

The LCLS-II injector is comprised primarily of the electron gun, buncher system, the first cryomodule and appropriate diagnostics. It includes a dedicated 100 MeV diagnostics beamline that can be used during normal operation by selecting a subset of beam pulses. Commissioning of the electron gun and buncher system began in 2018. During a ~ 6 week period in the summer of 2022, beams were established using the first cryomodule. A beam energy of 100 MeV was achieved. We operated 929 kHz beams in a burst mode (1ms bunch trains at 10 Hz) to facilitate radiological surveys, however, the demonstration of the full cw repetition rate of 93 kHz (threshold KPP) is still outstanding. Beam commissioning of the laser heater will be executed during undulator commissioning when x-ray beams are available and can serve as a diagnostic tool.

A key performance metric of the 100 MeV injector is the beam emittance. During the commissioning period at the end of 2022, we demonstrated beam emittance performance of ~ 0.5 µm in both dimensions, which is in line with the design and expectations.

The poster TUPA026 [2] will further discuss the details and results of the injector commissioning.

SC Linac Beam Commissioning

The first period of electron beam commissioning of the superconducting accelerator was conducted from October of 2022 until the end of December 2022. The focus of this initial period was to establish beam transmission through the SC linac, bunch compressors and beam transport lines to the electron beam dump in the 'Beam Switch Yard'). We established cavity phasing for appropriate beam compression and began calibration of beam diagnostics and devices used by the beam containment systems. Many beam diagnostics and control system were established and commissioned:

- RF Abstraction Layer to control energy and chirp for entire linac sub-sections,
- Longitudinal feedbacks to maintain beam energy and chirp,
- Heat Load Optimization systems to calculate cavity amplitudes for individual cavities and minimize the overall cryoplant heat load,
- Linac Energy Management system to scale magnet settings according to the desired energy profile,
- Beam based optics measurements (Oscillation data and quad alignment) and
- Beam based hardware and controls checkout.

Most of the linac commissioning was carried out at 100 MHz repetition rate. For short periods of time we achieved a cw beam rate of 10 kHz. This will be the starting point to continue the commissioning in the near future.

Remaining Commissioning Scope

The first performance goal is the demonstration of the 93 kHz continuous wave beam rate and complete the associated radiological surveys. This also includes the measurement of the beam emittance at the end of the linac, minimization of beam losses and confirmation of beam quality necessary for undulator operation. This will be followed by commissioning of the pulsed RF system that transports the electron from the main linac to the two undulator beam lines. A short but complex beam transport system must be commissioned to transport beams to both undulators, including confirmation of beam quality. The commissioning of the undulators will start with single shots and commence up to a 1 kHz beam rate. Verification of the x-ray performance parameters will be conducted using diagnostics systems in the x-ray transport beam line leading the x-ray instrument section. The main parameters to be measured are the x-ray pulse and photon energy. The techniques applied for these measurements are gas ionization measurement and absorption edge spectroscopy.

We expect a duration of 2-3 months for the remaining commissioning program and plan to complete this scope in the summer of 2023.

SUMMARY

Commissioning of the LCLS-II Accelerator is currently ongoing after completion of installation of all required systems. The cryoplant is fully operational, including the cryogenics distribution system. Cool-down of the linac was completed very successful without problems using mostly automated procedures. Cavity performance is excellent and exceeds design specification. Electron beam commissioning of the 100 MeV injector is complete and a high-quality beam was established. The commissioning of SC linac has begun and electrons of 3.5 GeV energy were transported to the first main electron beam dump at up to a 10 kHz repetition rate. The remaining linac commissioning scope is the ramp-up of the repetition rate to 93 kHz. The next and final phase of the commissioning program is to establish lasing with SC linac beams and the final verification of the x-ray FEL pulse parameters. We expect commissioning will be complete with 2-3 months.

REFERENCES

[1] LCLS-II Final Design Report, LCLSII-1.1-DR-0251-R0, Nov. 2015.

[2] F. Zhou *et al.*, "Commissioning Results of LCLS-II Injector," presented at the 14th International Particle Accelerator Conference (IPAC'23), Venice, Italy, May 2023, paper TUPA026, this conference.