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LCLS-II COMMISSIONING AND OPERATION WITH HIGH-REPETITION-RATE CW FELS*

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Abstract

LCLS-II first stage commissioning is completed in the summer of 2023, with demonstration of 93 kHz electron beam and 1 kHz FELs using the superconducting CW linac. Operation-based electron beam and FEL commissioning has been continued with the goal of ramping up beam rate, improving the FEL performance, and developing advanced FEL operation modes. We started 33 kHz x-ray FELs to user experiments from 2025. The latest machine performance, commissioning challenges, and next-step plan will be discussed in this paper.

INTRODUCTION

The LCLS-II facility is upgraded from the LCLS, which was the first hard x-ray FEL facility that started user experiments in 2009 [1]. The LCLS-II upgrade [2] includes the addition of a high-repetition-rate CW FELs with a new CW gun and superconducting (SC) linac, two undulator lines with adjustable gaps, new experimental stations and other related elements. The upgrade design also includes the capability of delivering Copper-linac and SC-linac beam to either HXR undulator or SXR undulator line. The layout of the LCLS facility is illustrated in Fig. 1. In this report we will focus on the SC-linac based FEL commissioning and operation progress.

The LCLS-II CW FEL facility started with an electron beam injector, which includes a laser sysem, a continous wave (CW) RF gun, a buncher, and the first cryomodule (CM01). It also has a laser heater for energy spread modulation. The electron beam energy out of the injector is designed at 100 MeV. Out of the injector, the electron beam is further accelerated by three linac sections, L1B, L2B, and L3B. Two bunch compressors (BC1B and BC2B) are located in between. The designed final beam energy is 4000 MeV, and the bunch is compressed to be about a few tens of micron-meters. In the current operation (May 2025), the energy is slightly lower than the design, as we listed the main beam parameters in Table 1.

Table 1: LCLS-II SC Linac Beam Parameters

item	Design	current Operation
Injector E	100 MeV	75 -90 MeV
Final E	4000 MeV	3800 MeV
Charge	20 -300 pC	20 -100 pC
FEL Rate	930 kHz	33 KHz

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COMMISSIONING PROGRESS

The LCLS-II commissioning has two major stages, the first stage is to achieve the threshold Key Performance Parameters (KPP), after that the system is transitioned to operation. The second stage, operation-based commissioning, is continuing with performance improvement and also delivering FELs for experimental stations commissioning and early science user program. Previous status reports can be found in 2023 IPAC [3] and 2024 Linac Conference proceedings [4].

During Stage-1 commissioning, we performed the work in four major phases: injector commissioning, SC linac commissioning, spreader and FEL commissioning, and photon beamline commissioning. Machine Protection System (MPS) and Beam Containment System (BCS) are critical parts during the initial commissioning process which helped minimize the risk and control the maximum operating beam power. All KPP thresholds were achieved in the summer of 2023, and after that, the bean and FEL was further commissioned using machine development time. The beam power and rate were ramped up in the past two years from 1 kHz in 2023 to now 33 kHz in 2025. Below we summarize the current subsystem operating status and performance.

Injector

The injector system commissioning has been reported in the past publication [5] and conference [6]. We list the status of the main components here:

- A VHF gun, operating in CW mode at 185.7 MHz. The current operating RF amplitude is about 700 kV.
- A buncher with two cavities, operating in CW mode at 1.3 GHz. The current total RF amplitude is about 220 kV.
- A Cs2Te Cathode has been used, with UV laser at 257.5 nm. A load-lock system supports cathode swap from a suitcase to the gun.
- One standard 1.3 GHz cryomodule (CM01) with 8 cavities is used to accelerator the beam energy to up to 90 MeV.
- A laser heater system including a chicane, an undulator, a 1030 nm laser, and diagnostics for energy spread modulation.
- Two solenoids are used for emittance compensation, and one collimator with four fixed apertures (12 mm, 16 mm, 20 mm, and 24 mm diameter) to stop the dark current before CM01.
- There are various diagnostic devices, such as YAG screens, wire scanners, transverse cavities, toroid, etc.

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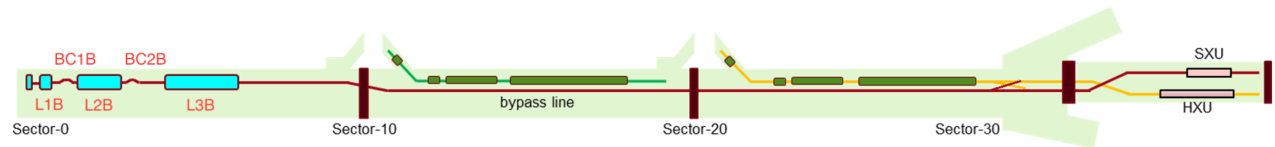

Figure 1: Layout of the LCLS facility

The cathode plug design has been modified recently, with 1-mm longer over-inserted into the gun wall, which helped reduce the dark current and also the emittance. This similar scheme with cathode over-insertion scheme has been recently reported by the SHINE group [7]. The measured dark current at LCLS-II gun is reduced by 3 orders, from a few uA level to now nA level, at the collimator station. This lower dark current also allows us to increase the gun voltage, which further helps improve the beam emittance.

We show in Fig. 2 an exmaple of the measured injector emittance at 75 MeV with 75-pC bunch charge. The injector performance is pretty reproducible during daily operation, which is critical for producing a stable FEL for user experiments.

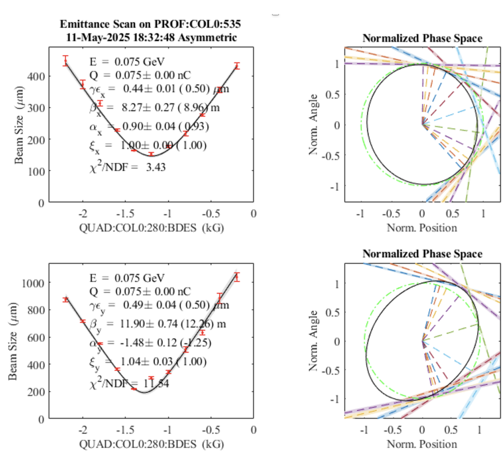

Figure 2: The measured injector emittance with 75 pC bunch charge. The bunch length measured with an S-band transverse cavity at this condition is about 0.9 mm rms.

The laser later heater system is fully commissioned in 2025 and helps improve FEL power when it is optimized. Currently, the laser heater is operating at the 3rd harmonic mode, i.e., the e-beam energy at 75 MeV, with fundamental resonance at 3 um, but the optical laser wavelength we used is 1 um.

SC Linac

The LCLS-II has 35 1.3-GHz crymodules and 2 3.9-GHz crymodules. SC linac is another critical element for supporting CW mode operation. The commissioning of the SC linac includes pre-beam SRF characterization at 2 K, and beam based phasing, alignment, feedback, and beam loss control etc. Detailed report especially on the SRF topic can be found in previous conferences [8].

The designed final energy is 4 GeV, with two bunch compressors located at 250 MeV (BC1B) and 1.5 GeV (BC2B) locations. With recent laser heater operation at the 3rd harmonic and injector at 75 MeV, we lowered the BC1B energy to 235 MeV. Overall the SRF linac shows very stable operation, and the final energy jitter is measured a factor 2 better than that in the design requirement, as reported in [4] and will also be discussed in later sections.

Spreader and FEL

One advantage of the high-repetition-rate beam is to support various undulator beamlines, by steering and distributing the bunches through a timing system. The current LCLS-II uses magnetic kicker systems up to 500 kHz to kick the beam into either or both of the two undulator lines. The spreader system can be expanded in the future to support more beamlines. The fast kicker details can be found in NAPAC 2019 proceedings [9].

The undulator lines are upgraded from the original LCLS single fixed gap undulator line to two variable gap undulator lines, dedicated for hard X-ray (HXR) FEL and soft X-ray (SXR) FEL, respectively. The HXR undulator line used the existing LCLS girder, but modified to have horizontal gap, generating light with vertical polarization, while the SXR undulator line has the traditional vertical gap design generating horizontally polarized FELs.

During the commissioning, we parked the beam at the tuning dump right before the undulator, then we tuned the machine and measured beam at various diagnostic stations. The wire scanners in the linac area were not ready at the early commissioning stage though, and we just measured the linac optics response versus model without measuring the beta matching parameters. Nevertheless, the first lasing test was very successful which was achieved in the summer of 2023 for both SXR and HXR undulators.

There are a few X-ray diagnostics being used to support the FEL commissioning. The popular ones are Gas Monitor Detectors (GMD), imagers, spectrometer, and later the X-band Transverse cavities (XTCAV) which measure the lasing effect on the e-beam longitudinal phase space.

Figure 3 shows a measured longitudinal phase space with the XTCAV for 850 eV FEL. The bunch charge is 70 pC in this case, and a clear lasing effect causing beam energy loss can be seen in this measurement. By analyzing the lasing-on and lasing-off images, we can reconstruct the X-ray temporal profile [10]. This measurement also helps us optimize the compression settings from the two bunch compressors, or study the laser heater effect and microbunching instability.

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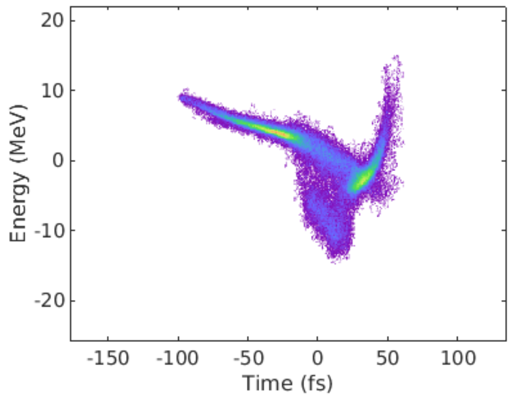

Figure 3: The measured e-beam longitudinal phase space downstream of the undulator with lasing condition. The FEL lasing caused energy loss in the core part of the beam can be used to reconstruct the X-ray temporal profile. This example is with 70 pC for 850 eV FEL, at 3.8 GeV.

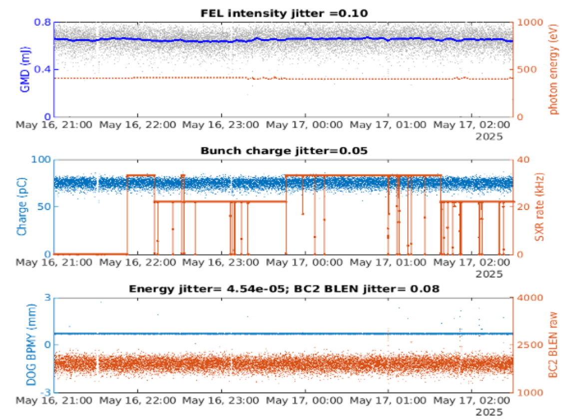

Figure 4: The measured e-beam and FEL jitter over 4 hours. The e-beam energy is 3.8 GeV with 75pC bunch charge. FEL photon energy in this example is 400 eV.

High Power Operation

After demonstrating the FEL operation at 1 kHz in 2023, we started to ramp up the beam rate for higher power operation and FEL delivery to users. The MPS and BCS system are interlocked for machine protection and beam power control. Two Average Current Monitors (ACM) are used to limit the maximum allowed operating current. So far we had two phases of beam rate ramping up. The first one is operating with up to 8 kHz, started from the spring of 2024. The second phase is operating at up to 33 kHz, started from early 2025. The 33 kHz rate is aligned with the current hutch optical laser rate. The bunch charge is typically at 75 pC. Since the ACM limit is the average beam current, in principle we can also run higher rate with lower charge at the current ACM limit.

For power ramp-up commissioning, we have checked all the diagnostics response, the spreader kicker performance, and the beam loss along the beamline. Part of the fiber-based long beam loss monitors (LBLM) and all diamond-based point beam loss monitors (PBLM) are used to monitor the beam loss. In general the beam loss is well mitigated with beam and collimator optimization.

We show in Fig. 4 a short-term beam stability measurement. During this 5-hour period there was no tuning effort and we can calculate the machine jitters. As we can see, the FEL at 400 eV has an average pulse intensity of 600 uJ with jitter about 10%. This intensity jitter comes from the bunch charge jitter about 5%, the energy jitter of 0.005%, and the final bunch length (beam current) jitter about 8%. Comparing to the design requirement, the measured current jitter is a factor 2 worse, but the measured energy jitter is a factor 2 better.

COMMISSIONING CHALLENGES

The commissioning of the LCLS-II from the injector, linac, FEL, and photon beamlines has been very successful in general. We have a few challenges as well during the process. We focus on discussing the technical challenges here. One challenge is the delayed readiness of diagnostic devices. These include wire scanners for beam profile and emittance measurement; transverse deflector for injector and final bunch length and longitudinal phase space measurement; bunch length monitor downstream the compressors; and some missing BPM electronics. These missing diagnostic devices slowed down the commissioning progress. After transitioning to operation, we added back most of the missing diagnostic devices. Some of the wire scanners and one bunch length monitor are still to be completed.

Another challenge is the dark current mitigation in the gun area. The dark current is suppressed by setting solenoid strength higher. This is to over-focus the dark current electrons so that they can get lost at the first colliamtor, which is measured typically about 3 uA. However, the emittance is sacrificed and the higher solenoid strength sometime causes a two-beam distribution in transverse dimensions. This non-Gaussian beam distribution typically leads to beam loss issues in the downstream beamline when operating at higher beam rate. This dark current issue was finally resolved in 2025 after we upgrade the cathode plug with 1-mm over-insertion into the gun wall, as discussed earlier.

The laser heater commissioning is also another interesting challenge. It took longer than expected to see the laser heater effect, which was found later due to transverse misalignment. There are other technical challenges as discussed in other papers [4], such as the long beam loss monitors, cavity field emission growth, the cathode uniformity and lifetime, etc.

SUMMARY AND OUTLOOK

Since the Project complishment with initial goal achieved in the summer of 2023, we have been continuing with operation-based commissioning of the LCLS-II, and have made great progress on FEL performance, machine stability and user delivery. The user hutches, TMO and RIXS, have

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been performing experiments with high-repetition-rate FELs up to 32 kHz. Some special modes like attosecond pulses have also been developed for TMO users.

In the next step, completion of leftover diagnostics (wire scanners, bunch length monitors, long beam loss monitors etc.) will be one top priority, with which we expect to improve the FEL performance and tuning efficiency. There are also various machine development programs ongoing, including advanced FEL schemes such as self-seeding, machine stability improvement, cathode studies, modeling benchmark, etc. The power ramp-up will also be planned after approval from the safety system certification.

The current operation of LCLS-II with SC-linac will pause at the end of 2025, giving time for installation of the required additional 23 cryomodules in the tunnel for LCLS-II-HE, an upgrade of the LCLS-II from 4 GeV to 8 GeV [11].

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