

LCLS-SC OPERATIONS STATUS AND THE LCLS-II-HE UPGRADE*

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Abstract

In August 2023, the Linear Coherent Light Source-II (LCLS-II) Project achieved first light from its superconducting beamline (LCLS-SC). In 2026, the LCLS-II High Energy (LCLS-II-HE) project will add 23 additional 1.3 GHz cryomodules, bringing the LCLS-SC maximum electron beam energy from 4 GeV to 8 GeV. Here we will provide an overview of operational experiences, challenges, and performance analysis of the SRF cavities and associated systems during the first few years of LCLS-SC operation, performance improvements in preparation for LCLS-II-HE, as well as the LCLS-II-HE cryomodule performance test results.

INTRODUCTION

In 2016, construction began on the first superconducting beamline at SLAC as part of the Linear Coherent Light Source II (LCLS-II) Project. This installation included 35 TESLA-style 1.3 GHz cryomodules and two 3.9 GHz harmonic linearizer cryomodules (CMs), each containing 8 cavities [1, 2]. The LCLS-II Project elected to use the newly developed high Q_0 nitrogen-doping Nb technique for the 1.3 GHz cavities, representing the first application of the technology in an operational accelerator.

Every cavity has individual LLRF controls, with a 4 kW solid state amplifier (SSAs) for every 1.3 GHz cavity and a 1 kW SSA for every 3.9 GHz cavity. 1.3 GHz cavities run with a standard administrative gradient limit of 16.6 MV.

In addition to the superconducting accelerator, the LCLS-II project included a new normal conducting (NC) gun and buncher system, new hard and soft x-ray undulators, and the ability to feed both undulators from either the NC or SC accelerators, as shown in Fig. 1.

The LCLS-SC accelerator will be further upgraded and expanded as part of the LCLS-II High Energy (LCLS-II-HE) Project, as described below.

LCLS-SC PERFORMANCE

At present, LCLS superconducting (LCLS-SC) accelerator operates at 3.8 GeV with sections of off-crest RF operation (L1B and L2B) to produce bunch compression. Details of the design performance are shown in Fig. 2. The maximum beam rate is 93 kHz CW due to an administrative limit. This spring, simultaneous delivery to the hard and soft x-ray beamlines from the LCLS-SC accelerator was achieved.

LCLS-SC is presently delivering to the user community. For the upcoming fall user run, 70% of time is planned to be user delivery, 18% is planned as machine studies, and 12% is planned maintenance.

Q_0

Using a novel technique, Q_0 was measured cryogenically on the installed accelerator as part of commissioning [3]. Across the linac, the 1.3 GHz cavities averaged 2.8×10^{10} , exceeding the specification of 2.7×10^{10} , with full results in Fig. 3.

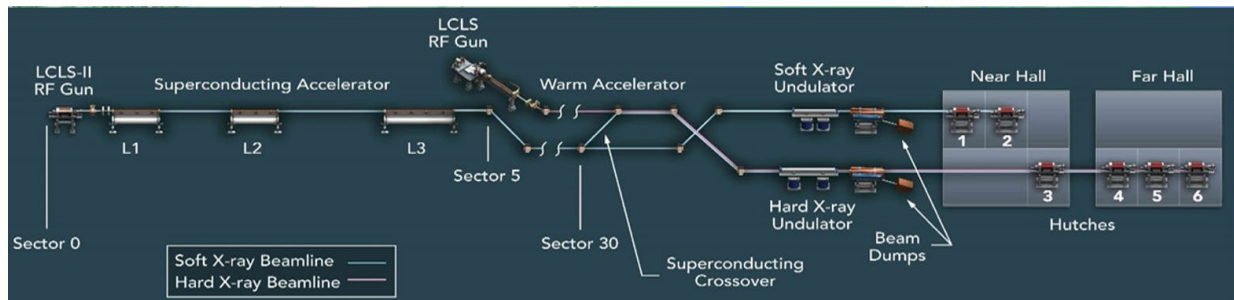


Figure 1: Diagram of the LCLS-II Project, showing the new accelerating sections and crossovers between the NC and SC beamlines.

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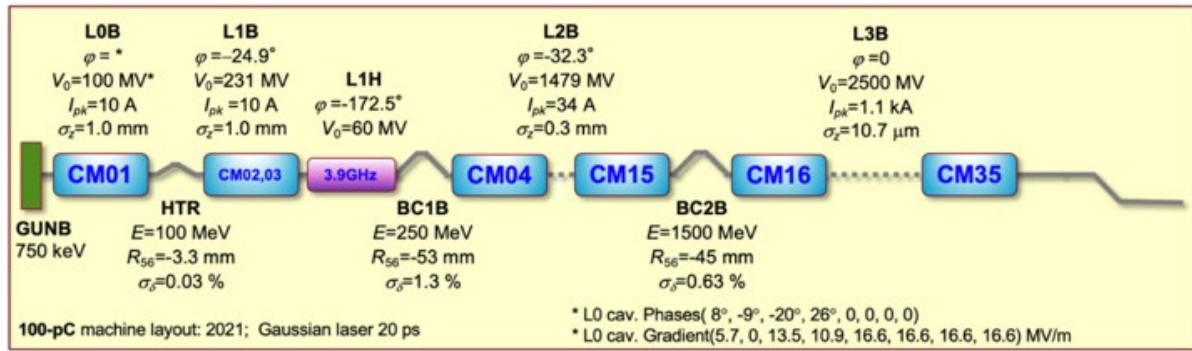
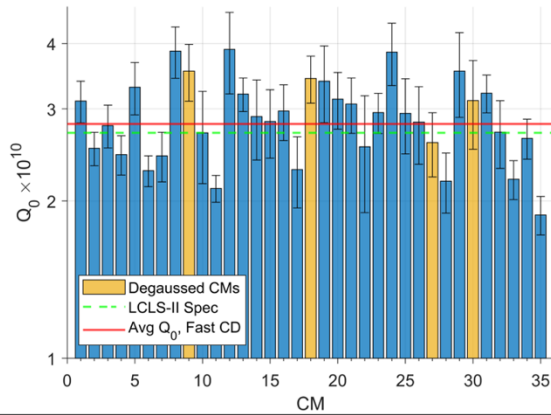


Figure 2: LCLS-SC design parameters.

Figure 3: Q_0 measured during LCLS-II commissioning, with degaussed cryomodules in gold [4].

Four low-performing cryomodules were degaussed and had their Q_0 s remeasured, as shown above. The degaussing brought the previously underperforming cavities above the mean. Due to the positive results, the SRF team would like to include degaussing cryomodules as a standard for future commissioning plans.

Apart from a multipacting processing study discussed below, no degradation of Q_0 has been observed during the past 3 years of operations. Following the multipacting processing study, a fast cooldown was performed and heat loads returned to normal.

Reliability

During the 2024-2025 user run, SRF cavities accounted for 0.58% of unplanned downtime, or 0.09% of the total run. The cryogenic system accounted for 0.20% of unplanned downtime, or 0.03% of the total run.

Automation has been very helpful for maintaining high machine availability. Single-button turn on has been implemented as part of the AutoSetup system, allowing Accelerator Operations staff to recover all SRF cavities in ~30 minutes. During this recovery, cryoplant automation and reasonably accurate Q_0 measurements have allowed single-button SRF turn-on for the full accelerator without calling the cryoplant [5].

Field Emission

The most upstream cryomodule in LCLS-SC, CM01, was selected for particularly high performance and had no field emission upon installation. A significant degradation of onset gradient for field emission was observed in 4 of the 8 CM01 cavities, instigating a field emission re-characterization campaign over the past two years.

Measurements are taken with a set of two moveable “decarads”: 10 Geiger-Müller detectors mounted on Unistrut, designed to measure radiation at the fundamental power coupler of each cavity in a cryomodule, with the final two radiation monitors placed at the upstream and downstream bellows. These radiation monitors were re-positioned in front of targeted cryomodules during planned machine maintenance access days, allowing two cryomodules to be measured approximately every two weeks.

In comparison with commissioning data, we have observed lowered field emission onset gradients in 25 cavities, representing 8.5% of all cavities. Radiation produced by field emission is administratively limited to 50 mR/hr as measured by the decarad system, and maximum allowable amplitudes are lowered in our LLRF software to comply with these limits. The cavities with changed amplitude

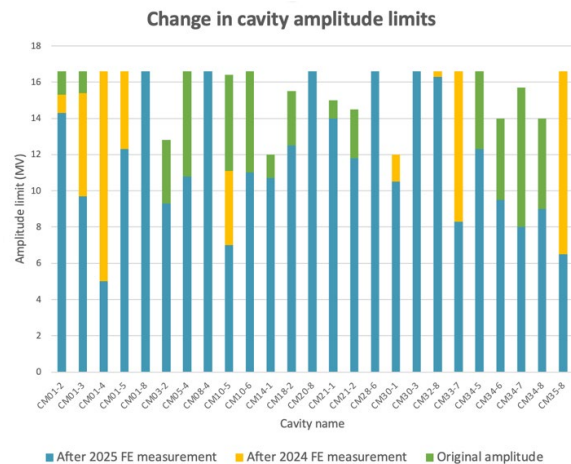


Figure 4: Cavity amplitude limit changes resulting from 2024 and 2025 field emission measurements.

limits are shown in Fig. 4. Due to these limits, we have lost a total of 99.1 MV of available accelerating amplitude.

To date, no clear pattern has emerged regarding conditions producing worsened field emission. We have not been able to establish a causal link to vacuum valve actuation, distance from the end of a cryo-string, etc.

Microphonics

Analysis of the microphonics across the LCLS-SC accelerator has shown that 94% of cavities are within their specification, as shown in Fig. 5. The cavities with the worst performance have microphonics that are driven by leaking cooldown valves [6].

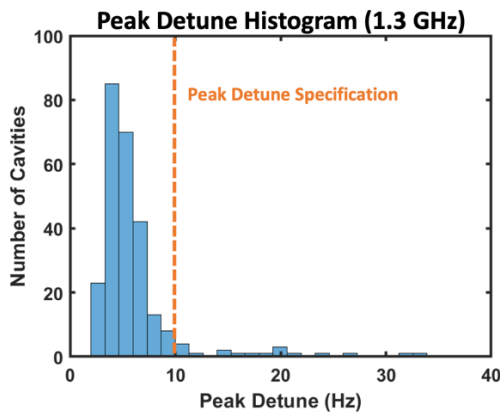


Figure 5: Peak detune as measured over a typical 3-hour operational run [6].

During the last LCLS-SC summer downtime, schedule pressure drove an attempt to deliver to LCLS-SC users while excavating a new tunnel directly next to our injector. Although we did observe microphonics excitations on CM01 that were disruptive to users for ~10 minute windows, the operations team has been pleasantly surprised that user delivery has been able to continue concurrent with this work.

Offline Cavities

During accelerator operations, high uptime requirements incentivize running with sufficient RF overhead to be able to turn off problematic cavities without programmatic impact. Often, cavities can be recovered by Accelerator Operations staff at a convenient time using our AutoSetup program, or with guidance from the SRF team.

Problems requiring hardware interventions can either be performed parasitically during beam operations or during planned maintenance windows. These cavities are placed in “Offline” status until a repair can be performed. Typically, around half of cavities offline are awaiting repairs during a bi-weekly maintenance period. Beam physics simulations have suggested better performance with an L0B cavity offline, adding to the offline cavity total when this mode is in use. The percentage of offline cavities over the past few operational runs is shown in Fig. 6.

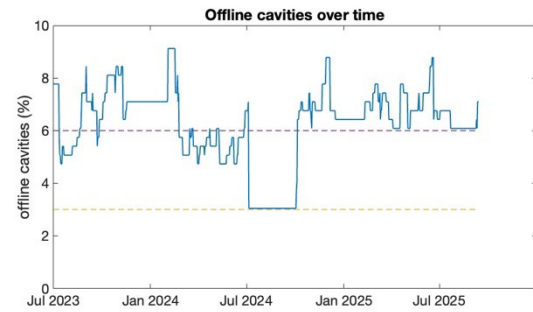


Figure 6: Percentage of cavities offline over the past 2.5 years of operation, with lines indicating the specifications for LCLS-II and LCLS-II-HE.

Ten cavities are offline due to long-term issues requiring warm up. Eight of these cavities have problems with their tuner systems. The remaining two have contact problems with their fundamental power couplers.

Multipacting Processing

To study the feasibility of improving available gradient on the LCLS-SC machine, we multipacting processed 7 of our L3B cryomodules that showed the most promise for gain.

Cavities were monitored throughout processing by our decarad systems. Each cavity was run up in CW to the gradient where it began to quench, then stayed at said gradient until quenching stopped or no radiation was noted on the decarads, indicating a hard quench. If no quenching was observed, processing was also discontinued. As we successfully processed past the quenching at a particular gradient, we moved to a higher gradient. The process was continued until we reached 21.8 MV or a stopping condition.

26 out of the 48 processed cavities successfully reached 21.8 MV. The final processed amplitudes for all 48 cavities is shown in Fig. 7. Cavities that underwent multipacting processing were raised to a new administrative amplitude limit of 18.68 MV and have stayed there for the past year.

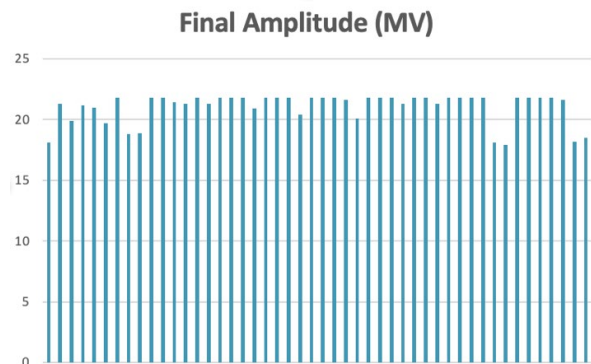


Figure 7: Final processed amplitudes for cavities in multipacting processing machine development study.

After multipacting processing, we observed a higher heat load until we were able to perform a fast cooldown during an accelerator maintenance period.

Risks from Power Outages

In the past 3 years of LCLS-SC operation, SLAC has experienced 4 power outages leading to helium venting. Each uncontrolled power outage carries the risk of an uncontrolled warm up where cavities could be permanently inelastically deformed if they are not “detuned” to a safe “cold landing” position.

Due to a helium leak into the insulating vacuum system, experts only have a few hours to recover cavities to a safe position during an uncontrolled warm up. They must manually connect to each cavity and move stepper motors a set amount according to a checklist. The ambient working conditions during a power outage – dark with flashing and audible alarms – is far from ideal.

SLAC has developed a 3-tiered strategy to mitigate future cavity risks from power outages:

- *6 MW generator*: will be installed to maintain LCLS-SC cavities in a safe state. This will feed the cryoplant, the superconducting linac, and the site air system which actuates vacuum valves.
- *Uninterruptible power supplies*: will be installed on the isolation vacuum pump and cryomodule controls to provide a more comfortable window for cavity detuning if a warmup becomes inevitable.
- *Permanently installed emergency detuning chassis*: will provide faster connections and detuning, if necessary.

Preparing LCLS-SC for LCLS-II-HE

To improve the performance of the present LCLS-SC cavities for LCLS-II-HE upgrade, we will implement lessons learned during our commissioning and operations periods. Every cryomodule will be degaussed prior to cooldown to improve Q_0 . We will also process our cavities for multipacting to raise available gradient, followed by a fast cooldown to restore Q_0 .

Two steps are needed to raise our repetition rate for LCLS-II-HE operations. The most crucial of the two is a

roll-out of a chassis redesign for a fiber beam loss monitor system critical to the LCLS-SC beam containment system. Until this redesign is implemented, we are administratively limited from going above 93 kHz. Our LLRF team is also working on a feed-forward to improve performance at higher beam rates.

LCLS-II-HE UPGRADE

In conjunction with other upgrades, LCLS-II-HE will add 23 LCLS-II 1.3 GHz CMs to the end of current LCLS-SC linac as L4 and will be fed by a new cryogenic distribution box (Fig. 8). The new cryomodules will have an increased available gradient and will be driven by 7 kW SSAs. Excepting any cavities used for a beam-based energy feedback, all cavities will be run on crest.

LCLS-II-HE cavities were treated with a slightly different recipe than LCLS-II [7], leading to improved performance.

Vertical Test Performance

Of 192 cavities ordered for LCLS-II-HE, 181 (93.8%) have qualified for use in the project. Of these, 125 passed qualification on the first test (65%). 7 cavities have been completely disqualified: 3 with low E_{acc} , 1 with low Q_0 , 2 with persistent field emission, and 1 with an HOM scratch. 4 cavities are awaiting re-test after a high pressure rinse.

Two cavity reprocessing methods have been effective to restore/improve gradient. A HF acid rinse improved 7/9 (78%) of treated cavities. Supplier re-doping improved all 6 treated cavities.

There has been an effort to recover pre-existing cavities from the LCLS-II and “verification” cryomodule (vCM) orders [8]. 9 remediated LCLS-II cavities and 2 vCM cavities will be used for LCLS-II-HE.

Vertical tests show strong performance: there is a mean quench gradient of 27.7 MV/m and a mean Q_0 of 3.25×10^{10} . All vertical tests for cryomodule production are complete (Fig. 9).

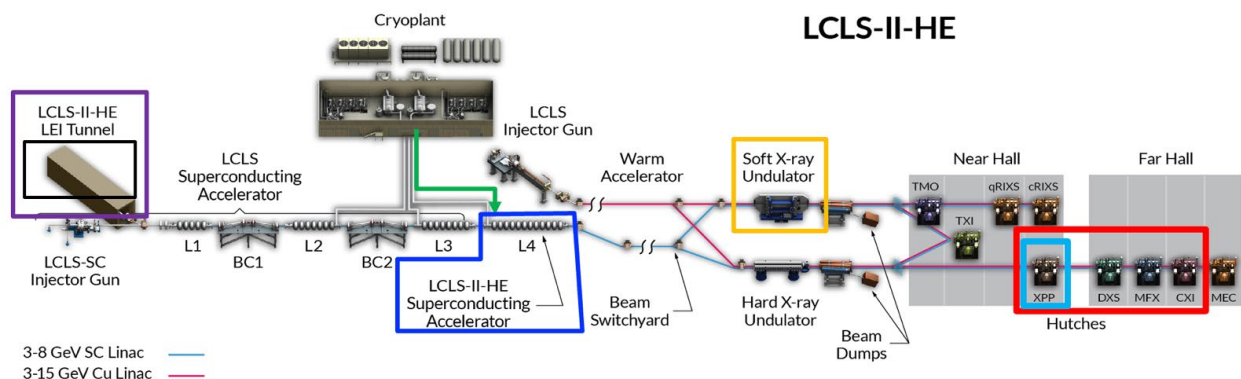


Figure 8: Diagram of the LCLS-II-HE project.

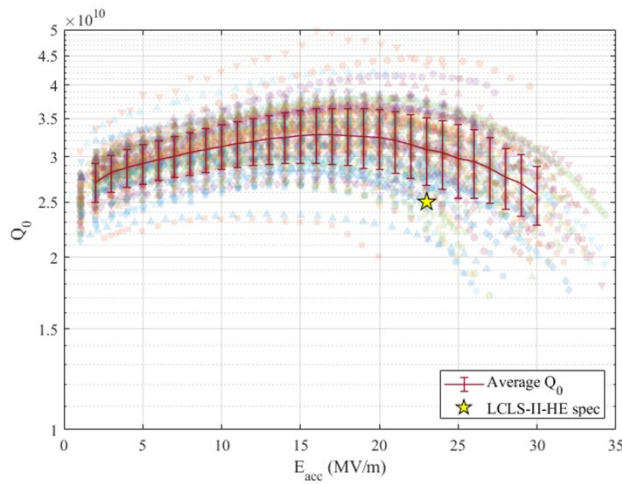


Figure 9: Vertical test performance results for all LCLS-II-HE cavities.

Assembled Cryomodule Performance

As of writing, 21 cryomodules have been assembled and tested. The mean usable gradient across all cavities is 24.0 MV/m (Fig. 10) with a mean Q_0 of 3.0×10^{10} (Fig. 11). All cryomodule testing is expected to be complete in Fall 2025.

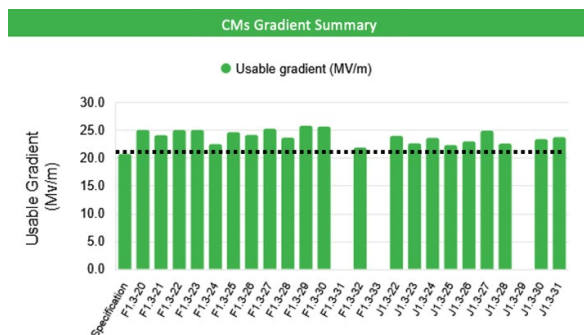


Figure 10: Measured usable gradients for assembled LCLS-II-HE cryomodules with the specification indicated in black.

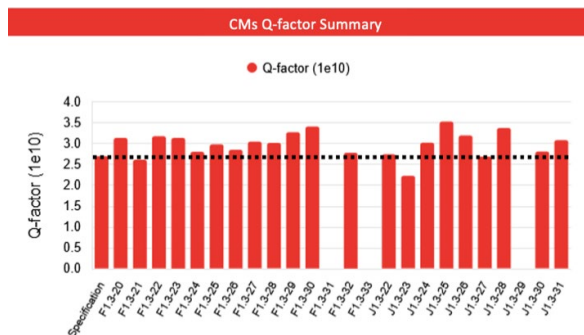


Figure 11: Measured Q_0 results for assembled LCLS-II-HE cryomodules with the specification indicated in black.

Three cryomodules required rebuilds after full assembly. After several rounds of successful cooldowns in the course of testing, the first of these cryomodules developed a leak in its pickup probe during a cooldown, venting the beamline. The next was found to have a chipped ceramic on the warm side of the fundamental power coupler. The final cryomodule requiring rebuild was found to have excessive field emission during testing. Root cause analysis points to a contaminated nitrogen purge system. The filters on this system have since been replaced and the N_2 flow rate has been increased. We are awaiting test results from the revamped system.



Figure 12: LCLS-II-HE cryomodule storage pictured with installation team. Photo courtesy of SLAC National Accelerator Laboratory.

Pre-installation Cryomodule Storage

During the period of cryomodule assembly and shipping, the LCLS-SC accelerator will still be online and delivering to users. This requires a period of storage of up to three years for LCLS-II-HE cryomodules upon receipt.

After analysis, the installation team elected to store cryomodules onsite across several buildings, with an example storage location in Fig. 12. The varied spaces required extra lift practice with a dummy “concrete cryomodule.” Cryomodules required additional planning for earthquake anchorage for their storage locations [9].

Following LCLS-II experiences, LCLS-II-HE determined that the small amount of pumping from gauges monitoring beamline pressure was adequate to maintain vacuum during storage. However, due to the long storage window, pressure has risen on most of the cryomodules with the earliest delivered ones requiring active pumping. We believe this is due to the gauges losing pumping or function over time. No leaks have been found on cryomodule beamlines so far.

Outlook for LCLS-II-HE and Beyond

In January 2026, the LCLS-SC beamline will shut down for LCLS-II-HE cryomodule installation and bypass line reconfiguration. The normal conducting part of the LCLS

complex will remain operational and available to users during this period.

Installation for the cryogenic distribution system and the 23 new cryomodules into L4 is expected to be complete in summer 2026. Cooldown, commissioning, and multipacting processing of L4 will take place from late winter through the spring of 2027. The existing linac will under go cool down and multipacting processing during the same window.

CONCLUSION

The LCLS-SC SRF has been a high-reliability system and a solid demonstration of nitrogen-doping application. LCLS-II-HE will add 23 cavities with even higher available gradients. Degaussing, multipacting processing, and fast cooldowns have been shown to be powerful techniques for improving cavity performance of the LCLS-SC accelerator. We will apply these techniques to improve the performance of the existing accelerator cavities and include them in the commissioning strategy LCLS-II-HE.

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