LCLS-II LINAC Cooldown and Fast Cooldown

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Abstract. The upgrade of the SLAC National Accelerator Laboratory's Linac Coherent Light Source (LCLS) to LCLS-II marks a significant advancement in accelerator technology, incorporating a superconducting linear accelerator enhanced by 37 cryomodules segmented into two LINAC sections. This configuration, with 17 cryomodules upstream and 20 downstream, is uniquely supported by one of two helium refrigeration systems. A pivotal aspect of this upgrade is achieving an average cryomodule cavity quality-factor Q_0 of 2.7×10^{10}, essential for the operational efficiency of LCLS-II. A critical strategy employed to meet this requirement involves cooling the cavities slowly from room temperature and special cooling at a rapid rate through the niobium superconducting transition temperature of 9.2 K, aimed at minimizing the remnant magnetic field. This paper presents a detailed account of the first-ever implementation of a fast-cooldown process in a string of cryomodules. It elaborates on the automated functions, sequences, control logic, and machine protections that have been integrated into the system. Furthermore, it provides insights into the design decisions and valuable experiences garnered throughout the process of integration and commissioning, offering a comprehensive overview of this achievement in accelerator science.

1. Introduction

The LCLS-II project at SLAC signifies a major advancement in accelerator technology. It features a superconducting accelerator that occupies about one-third of SLAC's original 2-mile linear accelerator tunnel. This setup produces a nearly continuous X-ray laser beam, achieving an unprecedented repetition rate of one million pulses per second at 4 GeV. This performance is made possible by a powerful cryogenic system that maintains operational temperatures at 2.0 K [1].

1.1 Cryogenic System

The cryogenic system consists of two cryoplants (CP) with a capacity of 18 kW at 4.5 K paired with a 2.0 K cold box. The cryogenic distribution system (CDS) includes transfer lines, Interface boxes and distribution boxes (DB) where DB1 connects to the upstream section (L0 – L2) with fifteen 1.3 GHz cryomodules and two 3.9 GHz cryomodules, while DB2 connects to the downstream section (L3) with twenty 1.3 GHz cryomodules.

During the LCLS-II project, it was determined that one cryoplant (CP1) could handle the heat load for all 37 cryomodules. CP2 will support an upgrade project, adding 23 more 1.3 GHz cryomodules to the LINAC, along with a new IB3 and DB3.

1.2 Cryomodule Overview

The cryomodule designs leverage significant advancements from the XFEL project, incorporating TESLA-style superconducting radiofrequency (SRF) cavities tailored for continuous wave (CW) operation. These designs are optimized to meet the specific beam parameters of LCLS-II [2]. The cryomodules feature three circuits divided into seven cryogenic lines, operating at various pressures and temperatures, named alphabetically from A to F and interconnected with adjacent cryomodules as shown in the figure 1 while line G is specific to each individual cryomodule.

- Line A operates at 4.5 K and 3.0 bar, supplying helium to the cavities.
  Each cryomodule has two valves connected to line A: the JT and CD valves. The JT valve is used in nominal 2.0 K operation, feeding the two-phase line G, while the CD valve feeds the bottom of the cavities and is used during cooldown or warm-up.
- Line B is a 12-inch pipe connected to the cavities via two-phase line G, operating at 2.0 K and 31 mbar.
- Line C supplies 5.5 K, 3.0 bar helium through a low-temperature thermal intercept (LTTI) and returns 8.0 K, 2.6 bar through line D.
- Line E supplies a high-temperature thermal shield (HTTS) with 35 K, 3.0 bar helium and returns 55 K, 1.3 bar through line F.

The state-of-the-art cryomodule (CM) design was achieved through the collaborative efforts of SLAC, Fermilab, and the Thomas Jefferson National Accelerator Facility which require specialized fast cooldown protocols from 50 K to 4.5 K and a slow cooldown from 300 K to 4.5 K.

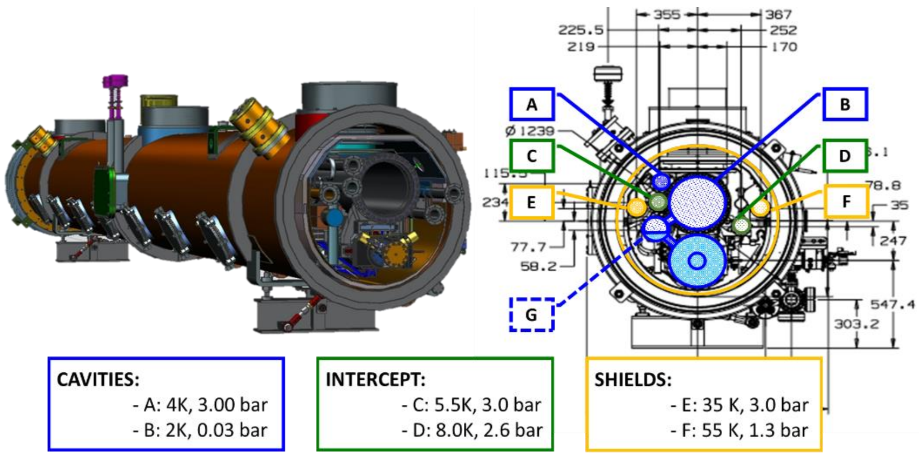

Figure 1. SLAC Cryomodule Overview

2. Slow Cooldown 300 K – 4.5 K

The cryogenic system (CP + CDS + CM) was meticulously planned to allow simultaneous cooldown while ensuring uniformity across all three circuits (HTTS, LTTI, and cavities). The cooldown of the SLAC cryogenic system was analyzed, establishing a specific cooldown rate (~3 K/hr) based on the cryoplant's capacity. The entire cooldown process was automated from 300 K to 4.5 K and operation was completed over a period of one week, as shown in figure. 2.

Automation was key, ensuring uniform cooldown across all circuits and cavities. Each cryomodule's CD valve, controlled by a PID controller, maintained a 0 K ΔT between the average

LINAC CM cavity temperature and individual CM cavity temperatures. The cooldown rate was managed by gradually reducing turbine outlet temperatures, with system protections in place. If any constraints from table 1 or deviations in the turbine discharge temperature control setpoints occurred, the cooldown would pause, allowing the system to thermalize before resuming.

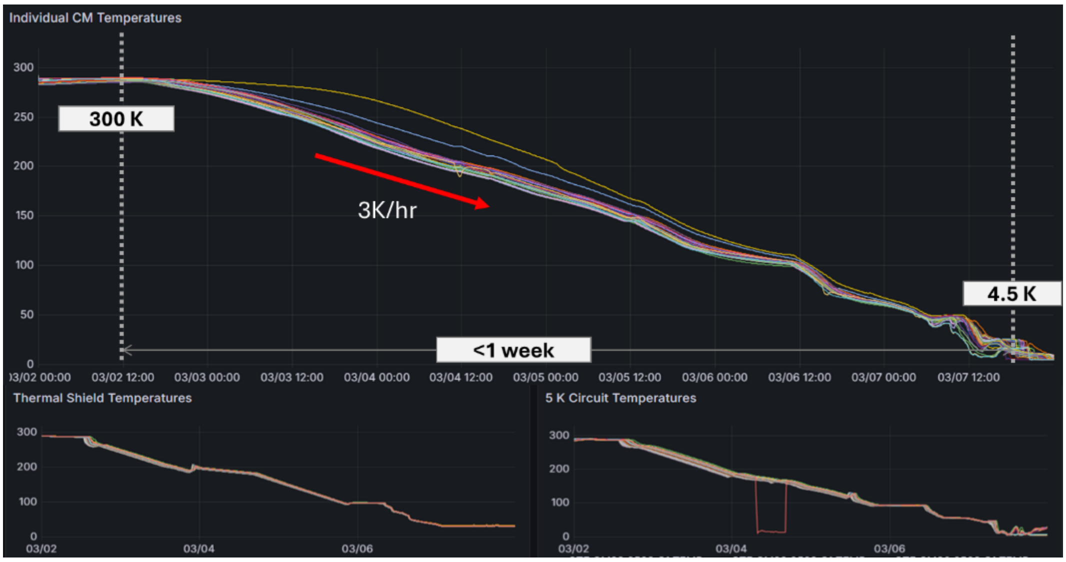

Figure 2. Cooldown trends of LCLS-II LINAC where the system reached 4.5K in less than a week while achieving homogenous cooldown of all the three circuits and cryomodules with cryoplant.

Throughout the cooldown, the return valves within the helium refrigerator returned cryogenic helium at various temperature levels as the cooldown progressed, enabling the recovery of refrigeration. The only manual operation was adding room temperature helium to account for density changes. At around 8 K, control switched from CD valves to JT valves, also PID-controlled, to maintain a 90% liquid level. The floating pressure cycle adjusted system pressures to control CP capacity, accommodating varying heat loads from LINAC.

The table 1. presents the cooldown constraints established to prevent equipment damage resulting from thermal stress.

Table 1. SLAC Cryogenic System cooldown constraints

System	Parameters	Threshold
CM	Line B Radial ΔT *(between top and bottom temperatures)*	< 25 K
	Line B Longitudinal ΔT *(between adjacent cryomodules)*	< 70 K
	Line F Longitudinal ΔT *(between adjacent cryomodules)*	< 70 K
CDS	2K – 4K Heat exchanger ΔT	< 50 K
CP	Brazed Aluminium Heat exchanger ΔT	< 50 K

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3. Fast Cooldown

3.1 Overview

Trapped flux degrades the quality factor (Q_0) of LCLS-II SRF cavities, which impacts cryogenic efficiency. A higher Q_0 reduces the cryogenic heat load at the same accelerating gradient. The average Q_0 requirement for LCLS-II is 2.7×10^{10}. To achieve this, cavities are rapidly cooled through the niobium superconducting transition temperature of 9.2 K, creating a temperature gradient that expels the remnant magnetic field.

A slow cool-down to 4.5 K followed by thermalization for 24-48 hours precedes the fast cool-down. The fast cooldown involves:

1. Warm-up of cavities to 50 K.
2. Fast Cooldown to 4.5 K.

During this process, the other two circuits, HTTS and LTTI, are maintained at their nominal operating conditions. The fast cooldown in the LCLS-II LINAC can only be performed in either the upstream (L0 – L2) section or the downstream (L4) section. The other section maintains the liquid helium (LHe) level at 4.5 K using the JT valves.

3.2 Warm-up to 50 K

Line A, which supplies helium at 4.5 K and 3 bar to the cavities from the helium refrigerator, is mixed with 300 K, 3 bar helium from the compressor station's high-pressure line within the interface box (IB) Line A seen in figure 3. During warm-up, JT valves are closed, and control shifts to CD valves to ensure uniform warming to 50 K. The temperature is gradually increased to supply 70 K helium, preventing sub-cooling. This process, taking about 20 hours, transfers about 1000 kg of helium to the CP, half liquefied and stored in dewar while other half stored as gas in buffer.

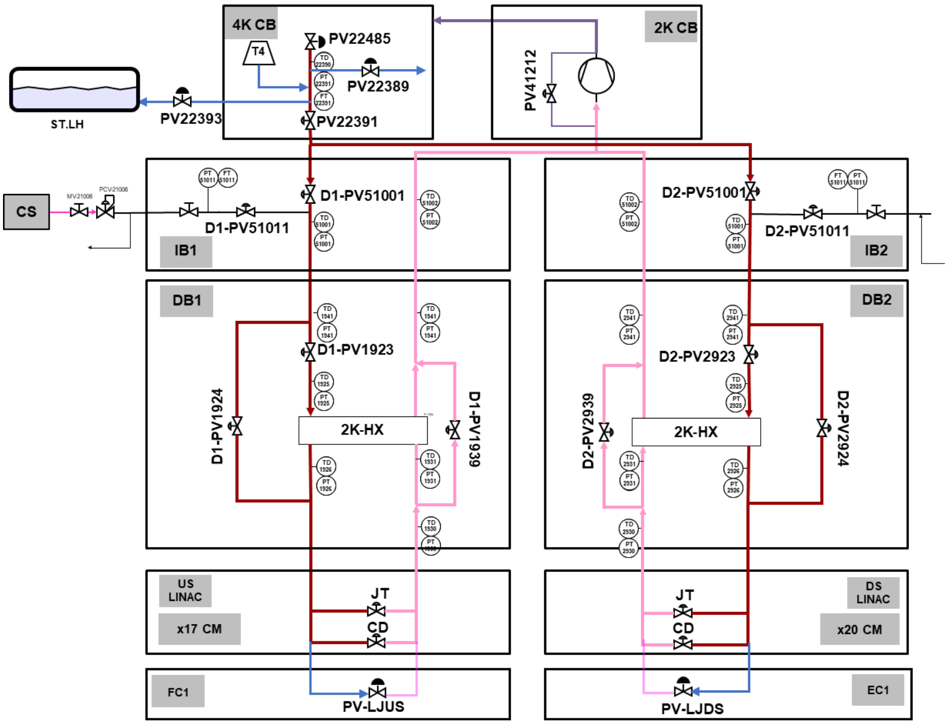

Figure 3. Simplified process flow diagram for fast-cooldown operation.

3.3 Fast Cooldown to 4.5K

After warming one section to 50 K and keeping the other at 4.5 K, fully automated sequences managed the fast cooldown. The master sequence controls the initial cooldown of Line A to 4.5 K, manages valve operations, cryoplant capacity, and helium boil-off. It then calls individual cryomodule sequences to perform the fast cooldown. These individual sequences were developed using ladder logic and user-defined data types (UDT), reducing the need to program 37 separate sequences. Smart logic within the master sequence tracks active cryomodules and automatically switches to the next one upon completion of fast cooldown. Analysis based on the helium refrigerator capacity identified that a maximum of three cryomodules can be fast-cooled simultaneously. Additionally, a study by Dr. Hans Quack at Technische University of Dresden identified ways to minimize spillover and cooldown in adjacent cryomodules. Since the SLAC accelerator tunnel is sloped, the fast cooldown is performed in descending order, from cryomodule 35 through 16 in the downstream LINAC and from the two 3.9 GHz cryomodules followed by 15 through 1 in the upstream LINAC section.

When the master sequence initiates the fast cooldown for an individual cryomodule, the CD valves open instantly to 100%, allowing 4.5 K helium to flow through the bottom of the cavities at high flow rates. This creates a radial temperature difference (ΔT) across the cavities which are at 50 K, expelling the trapped magnetic flux. Temperature sensors on cavity 1 and cavity 5 measure the top and bottom temperatures. The average of these four temperatures is used, and once it falls below 8 K, the CD valve gradually closes to 10% to maintain some flow through the cryomodule. The master sequence then switches to the next cryomodule.

After the last cryomodule completes the fast cooldown, the master sequence initiates liquid helium filling in all cryomodules simultaneously. At this point, the CD valve closes completely, and the JT valves open to 50% using a slow ramp to avoid overwhelming the helium refrigerator. Once the liquid level in the cryomodule reaches 90%, the JT valve mode changes to auto to control the liquid level. When all cryomodules are in nominal operation with JT valves controlling the liquid level, the fast-cooldown sequence is complete.

4. Cavity Performance

After the fast cooldown, the cavity Q_0 is measured by calculating the dynamic heat load of a cavity and then deriving Q_0 from this heat load and the operating gradient. Given that a single cavity's heat load at operating gradient is approximately 10 W, it can be challenging to measure accurately. Therefore, the dynamic heat load for an entire cryomodule is measured to extract an effective Q_0. Figure 4 shows the effective Q_0 for each of the cryomodules in the LINAC following a fast cooldown. An average Q_0 of 2.8×10^{10} was observed across the LINAC, with a significant spread. This measurement represents the first time such a high Q_0 has been achieved in an installed SRF

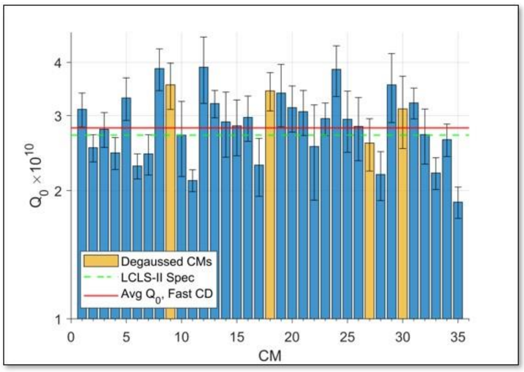

Figure 4. Effective Q_0 for each of the 1.3 GHz cryomodules exceeds average LCLS-II Q_0 of 2.7×10^{10}.

accelerator, marking a remarkable achievement. The spread in cryomodule Q_0 performance can be attributed to differences in the flux-expelling characteristics of the niobium used in the cavities. This large variation in material performance has been explored during cryomodule and cavity testing and presented elsewhere [3]. The achieved Q_0 is sufficient to run at the required operating beam energies for LCLS-II with a single cryoplant.

5. Conclusion

The SLAC cryogenic system, with its extensive automation, facilitated the successful and homogeneous cooldown of 37 cryomodules, the cryogenic plant, and the cryogenic distribution system. This automation was crucial for the LINAC cooldown process, providing precise temperature control and ensuring safe, efficient operation. The 300 K – 4.5 K cooldown achieved homogeneous temperatures across all components in less than one week, with continuous temperature control and the ability to adjust the cooldown rate as needed, ensuring homogenous CM temperature through control loops. The 50 K – 4.5 K fast cooldown marked the first-ever automated implementation in a string of cryomodules, exceeding LCLS-II Q_0 requirements. Fast cooldown results matched those at test facilities with a single CM, and automation allowed for the fast cooldown of 20 CMs within 90 minutes, along with automated inventory management between different modes of operation. An average Q_0 of 2.8×10^{10} was observed across the LINAC, representing the first time such a high Q_0 has been achieved in an installed SRF accelerator, marking a significant advancement in accelerator technology.

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