

First-Year Operation Overview of the SLAC LCLS-II Cryoplant

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Abstract. The LCLS-II, an advanced X-ray light source operated by Stanford University at SLAC for the US Department of Energy (DOE), features 37 cryomodules and a 700-meter linear accelerator (LINAC) connected to two Cryoplants, each capable of generating over 4.0 kW at 2.0 K. Commissioned in 2023, the LCLS-II Cryoplants are managed by the SLAC Cryogenic Division. This paper provides a comprehensive review of the Cryoplant's first year of operation, covering staffing dynamics, budgetary considerations, and availability metrics. The insights gained from this initial year highlight critical areas for optimization and offer valuable lessons for similar cryogenic systems.

1. Introduction

SLAC National Accelerator Laboratory, located in Menlo Park, California, is operated by Stanford University and is one of the 17 Department of Energy (DOE) laboratories. SLAC is home to the LCLS-II, a prominent light source facility. The LCLS-II is a 4 GeV continuous-wave (CW) superconducting linear accelerator (LINAC) capable of providing pulses of electrons at rates of up to 1 MHz. The LINAC consists of 37 cryomodules.

The LCLS-II is supported by two Cryoplants, each capable of delivering 18 kW at 4.5 K or 4.0 kW at 2.0 K. The first Cryoplant was commissioned in 2021, the LINAC was cooled down in 2022, and the second Cryoplant was commissioned in 2023. The LCLS-II project was completed in October 2023.

Currently, Cryoplant #1 is in operation and connected to the LINAC. Cryoplant #2 is off and will only return to operation in 2026 to support an additional 23 cryomodules, which will be added to support the LCLS-II High Energy (HE) upgrade, increasing the total beam energy from 4 to 8 GeV.

This paper focuses on the early operational life of Cryoplant #1 at LCLS-II. It provides information regarding staffing, budget, and availability to assist other projects in planning for early operations. Additionally, it outlines future plans for improvements aimed at increasing availability and reducing operating costs.

2 Cryoplant System Overview

The LCLS-II Cryogenic System comprises two Cryoplants, a Cryogenic Distribution System, and the LINAC. Currently, only Cryoplant #1 is operational to support LCLS-II. Cryoplant #2 is scheduled to resume operations in 2026 for the LCLS-II High Energy Commissioning. For more details, refer to [1].



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2.1 Cryoplant: Main Equipment

The Two LCLS-II Cryoplants share the same auxiliaries.

Table 1. LCLS-II Cryoplants, Auxiliaries

| AUXILIARIES | | | | |
|--|-----------------------------|---------------|--------------|--------------|
| Recovery System | 40 g/s in nominal operation | | | |
| Recovery Compressors | 2 x | 20 g/s | | |
| Purifier (Dual Beds) | 1 x | 40 g/s | | |
| Storages | | | | |
| Nitrogen | 2 x 80 m3 Liquid | | | |
| Helium | 2 x 10 m3 Liquid | 6x 110 m3 Gas | | |
| Note: The overall helium inventory of 4 tons, exceeds the storage capacity. | | | | |
| CRYOPLANT | | | | |
| Compressor Station | 4.0 MW in nominal operation | | | |
| Cycle Compressors | 3 x LP | 1 x MP | 1 x HP | 1 x HS* |
| Power | 550 kW ea. | 750 kW ea. | 1,850 kW ea. | 1,850 kW ea. |
| Note*: HS 'hot spare' is ready for use and can be configured to operate as a LP, MP or HP. | | | | |
| 4.5 K Cold Box | Equivalent 18 kW @ 4.5 K | | | |
| LN2 Pre-cooling | 5,000 kg/day | | | |
| Turbines | 4 x | 3 to 30 kW | | |
| 2.0 K Cold Box | Equivalent 4.0 kW @ 2.0 K | | | |
| Cold Compressors | 5x | 230 g/s | | |

Note: The LCLS-II Cryogenic System comprises two Cryoplants. The equipment listed above pertains to a single Cryoplant.

2.2 Cryoplant Lay-Out

The 3 km LINAC is composed of 30 segments of 100 m each. Segment 0 to 10 are dedicated to LCLS-II. The Cryoplant is located at sector 04, 2.6 km from the SLAC Campus. Given the access road and the speed limit a round trip from the campus to the Cryoplant takes about 30 minutes. As a result, the Cryo-Team is stationed at the Cryoplant. The 1,900 m² Cryoplant Building includes a control room but does not include office space. Two office trailers with 12 workstation each have been installed to accommodate staff. Additionally, Engineers also have office space on SLAC Campus to support on-going projects.

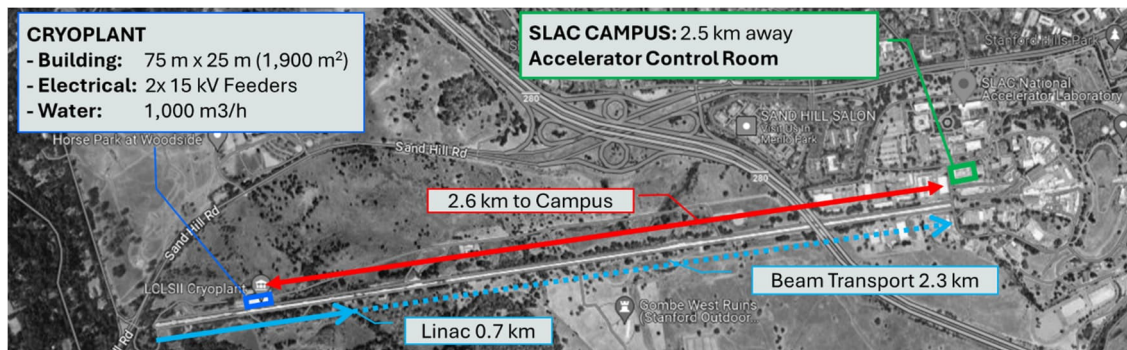


Figure 1. Cryogenic System Layout.

3. Staffing

The Cryoplant is located 2.6 km from the main campus, making remote operation less than ideal. Tasks such as walkdowns (oil levels, vibration measurements, visual inspections), maintenance, and manual operations require onsite staffing. Additionally, being near the machine provides invaluable information, as hearing the machine (compressors, turbines, valves opening/closing, flow through the system) can be crucial. For these reasons, the Cryo staff is located onsite at the Cryoplant.

3.1 Staffing: 24/7

The LCLS-II Cryoplant operates 24/7 with continuous staffing to prevent the loss of the LINAC liquid helium inventory, which could be depleted within 5 to 10 hours during a failure. Such a loss could lead to a LINAC warm-up, significantly impacting LCLS-II availability. While this round-the-clock operation incurs costs, it is justified by the savings from preventing helium loss, beamtime loss, and LINAC warm-up. Since the LINAC's initial cool-down in 2022, this strategy has proven effective. The Cryogenics Division plans to further enhance automation, including advanced alarm systems and automated recovery, to reduce the need for constant staffing.

3.2 Staffing: Team Structure:

The Cryogenics Division, established in 2016 for the LCLS-II project, has grown from 4 to 24 members by 2023, with ongoing efforts to refine staff classification and training. The Division is divided into two departments: Engineering and Operation. The Operation Group includes 11 technicians and 1 leader, working 24/7 in three 8-hour shifts with a focus on balancing skill sets in mechanical, instrumentation, electrical, vacuum systems, and gases. The Engineering Department supports operations with expertise in Process, Instrumentation & Controls, and Mechanical, providing continuous 24/7 on-call coverage and managing both operations and new projects like the LCLS-II HE upgrade. External support from SLAC Facilities includes maintenance for HVAC, safety systems, and utilities, while vendors and contractors provide crucial support for cryogenic equipment (Turbines, Cold Compressors) and specialized analyses (Water, Oil, Vibrations). These external services, though vital, represent a small portion of the overall operating costs.

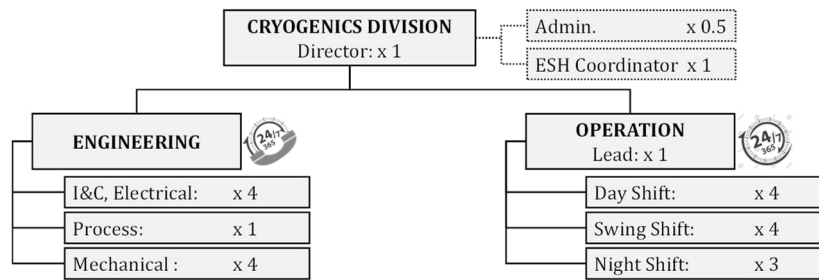


Figure 2. Cryogenic Division Structure.

4. Budget

4.1 Budget: Warning

This chapter details the operating costs for a typical year, excluding major maintenance, which involves separate intervals, duration, and costs. Operating costs mainly encompass labour, electricity, liquid nitrogen, helium, and parts. These costs can vary greatly depending on the plant’s location, with notable differences in energy costs and labour rates. In the USA, the labour-to-utility cost ratio is generally higher than in other locations.

4.2 Budget overview: for 1 Cryoplant

The overall annual cost for operating Cryoplant #1 is approximately \$15 million. Labor costs, which make up 50% of the budget, are influenced by the decision to operate 24/7. Energy costs, accounting for 38% of the budget, include electricity and liquid nitrogen, and are primarily determined by the cryogenic system’s performance. Despite SLAC’s efforts to optimize processes and negotiate utility costs, achieving significant reductions is challenging. Helium-related costs make up 7% of the budget, driven by substantial losses during Cryoplant outages, with rapid helium boiling rates potentially leading to the loss of up to 4 tons of inventory. Spare parts and tools costs are 5%, which is about 1% of the total equipment cost per year for regular maintenance, excluding capital spares and major maintenance.

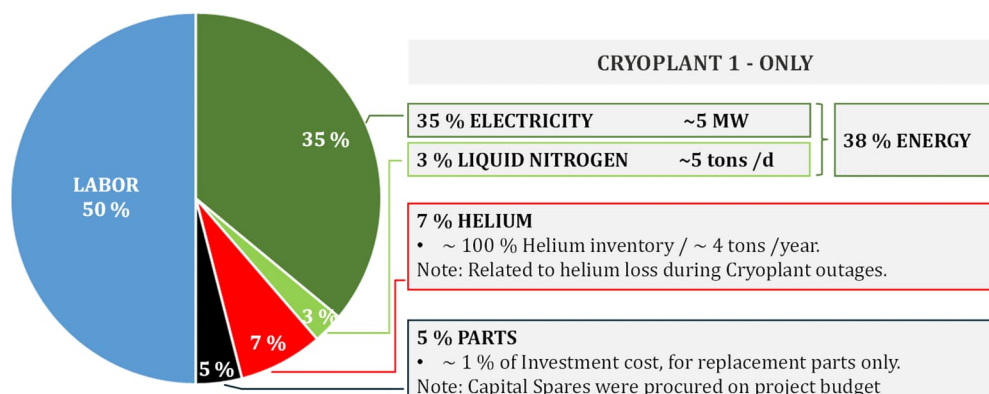


Figure 3. Cryogenic Division Annual Budget [Typical year, does not include major maintenance]

4.3 Budget future: for 2 Cryoplant

Transitioning from one to two Cryoplants operations in 2026 will significantly impact the budget and its distribution. The budget is expected to increase to approximately \$24 million, with 35 %

allocated for labour, 45 % for electricity, 5 % for liquid nitrogen, 10 % for helium, and 5 % for spares.

5 Availability

5.1 Availability: Target

The target availability for the Cryoplant was set at 98.62%. This figure was primarily an assumption based on observations from other laboratories, without a substantial Reliability & Availability analysis being performed.

5.2 Availability: Critical Decision

Three essential decisions were made to maximize availability: (1) cycle compressor redundancy, (2) availability of capital spares, and (3) 24/7 manned operations. The compressor station includes a hot spare compressor that can be used in place of any other machine. Critical capital spare parts, including turbines and cold compressors, were procured during the project. Finally, the Cryoplant is staffed 24/7, 365 days a year.

5.3 Cryoplant Availability: Overview

Information related to the availability of the Cryogenic System was collected from March 2022, during the first LINAC cool-down, to June 2024, covering over 860 days of continuous operation. During this period, the Cryoplant availability was 88%. Of the 12% unavailability, 5% was inherent to the Cryoplant, while 7% was due to external factors, essentially utilities.

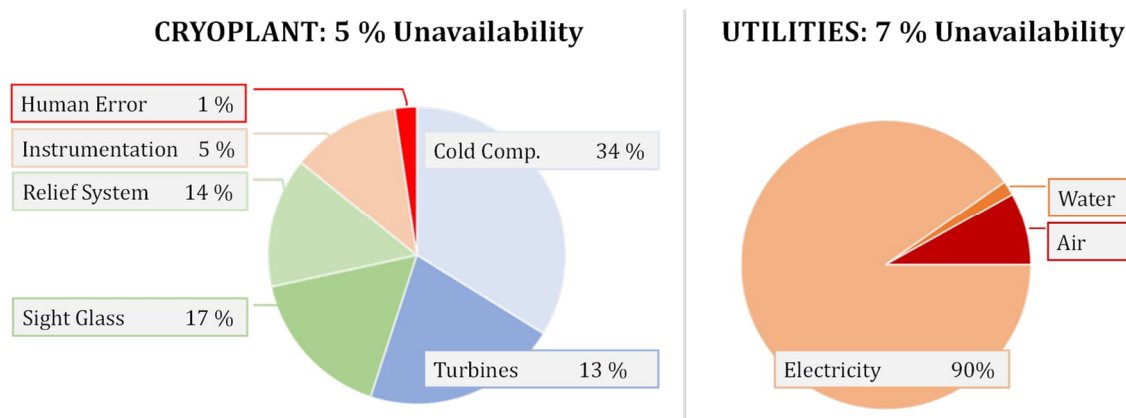


Figure 4. LCLS-II Cryoplant Availability Mar. 2022 – Jun 2024 [860 days of continued operation].

5.4 Cryoplant unavailability

Out of 860 days of operation, 42 days of unavailability stemmed from inherent issues (internal to Cryoplant). With an observed MTBF (Mean Time Between Failure) of 25,000 hours, the electronics related to the VFD (Variable Frequency Drive) and AMB (Active Magnetic Bearing) of the 2K.CC (2K Cold Compressors) have been the leading cause of Cryoplant unavailability. While never dramatic, 2K.CC electronic failures are difficult to investigate. Despite a measured MTBF of 80,000 hours, turbines have been the second leading cause of unavailability. Other causes include leaks to the atmosphere due to sight glass failures and issues with the relief system failing to reseal properly. Surprisingly, instrumentation has so far caused only a minor fraction of the Cryoplant's unavailability.

5.5 Utilities unavailability

Out of 860 days of operation, 82 days of unavailability were caused by external factors: 76 days due to electrical power issues, 5 days due to instrument air failures, and 1 day due to cooling water problems. California has experienced a period of unreliable electrical power. Multiple storms have downed power lines, significantly impacting Cryoplant availability. Instrument air systems, which are air-cooled, have failed on hot days, affecting site air for the LINAC. Although cooling water had a more modest impact on availability, it remains a major concern. The cooling system, consisting of 4+1 cooling water cells and 2+1 water pumps, appears to have built-in redundancy. However, issues with water chemistry, corrosion, and rapid filtration clogging have persisted, necessitating frequent maintenance and causing pump stoppages multiple times a month. SLAC Facilities is exploring solutions to improve utilities availability, particularly options for back-up power.

5.6 MTBF and MTBM

The MTBF (Mean Time Between Failures) has been approximately 34 days, with an MTTR (Mean Time To Recover) of 5 days for the Cryoplant (6 days including the LINAC). This frequency necessitates significant mobilization of the engineering team, requiring about one week per month for Cryoplant and LINAC recovery, which is considerably more than initially anticipated.

6. Conclusion

Transitioning from project to operation presents significant challenges, particularly in establishing an appropriate budget and staffing levels for the initial years. These factors are influenced by internal elements such as equipment reliability and external factors like utility availability.

For the SLAC LCLS-II Cryoplant, an annual budget of approximately \$15 million is required. This budget is primarily allocated to Human Resources (50%), Energy (38%), Helium (7%), and Parts (5%).

The Cryogenic Division is divided into two main groups: Engineering (9 staff) and Operation (12 staff). Staffing levels are determined by the required expertise and the need for 24/7, 365-day operation.

The Cryoplant's availability of 88% did not meet the expected 98.62% in the early stages of operation, largely due to the unreliability of electrical power, which significantly impacted overall availability. Improving availability will be a key focus for SLAC Cryo in the coming years.

Another critical area for development will be planning major maintenance activities, including determining maintenance intervals and specific tasks. Effective planning will be essential for ensuring the long-term reliability and efficiency of the Cryoplant.

References

- [1] E. Fauve, 2023 "LCLS-II Helium Refrigeration System: A comprehensive overview of the project", CEC-2023 Hawaii.

Acknowledgments

This work was supported by Department of Energy contract DE-AC02-76SF00515.