IOP Conf. Series: Materials Science and Engineering **1344** (2026) 012137 doi:10.1088/1757-899X/1344/1/012137

CRMF cryogenic system overview

B. Rama*, A. Apte, E. Fauve, M. Keenan, T. Ki, M. Martinello, T. Peterson, V. Ravindranath, J. Sevilla, S. Shrishrimal, and S. Vyawahare

SLAC National Accelerator Laboratory, 2575 Sand Hill Road, Menlo Park, CA-94025 United States

*E-mail: birenr@slac.stanford.edu

Abstract. The SLAC National Accelerator Laboratory is currently designing the Cryomodule Repair and Maintenance Facility (CRMF), a new facility scheduled for commissioning in 2028. The CRMF will contain a cryomodule assembly hall and test bench for repairing and testing cryomodules. Additionally, the CRMF will have provisions for single-cavity Vertical Test Stands (VTS) to be built in the future. The cryogenic infrastructure will provide 250 W of cooling capacity at 2.0 K enabling comprehensive performance testing of cryomodules. The system will include a 10,000 L dewar, low-pressure helium pumps, and a helium distribution and recovery system. This paper presents an overview of the CRMF cryogenic system design.

1. SLAC National Accelerator Laboratory

The SLAC National Accelerator Laboratory (SLAC) achieved first-light for the Super Conducting Linear Coherent Light Source (LCLS-II) in September 2023. The LCLS-II light source utilizes thirty-five 1.3 GHz cryomodules and two 3.9 GHz, split into four strings (L0-L3) as part of its electron beam accelerator. A new string (L4) of twenty-three 1.3 GHz cryomodules will be added to the existing system as part of the LCLS-II-HE (High Energy upgrade) project, which is scheduled to begin commissioning in 2027. Collectively, these five accelerator strings encompass the Superconducting Linac (SCL).

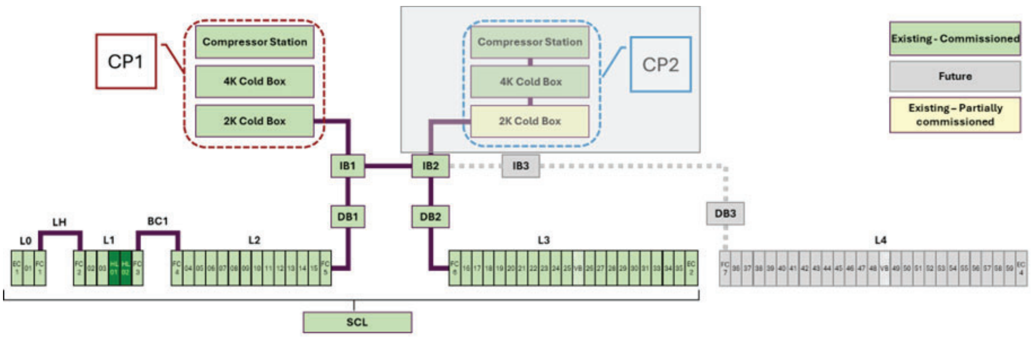

Figure 1. SLAC SCL cryogenic infrastructure

Cryogenic cooling for the SCL is achieved by two cryoplants, each with 4.0 kW at 2.0 K refrigeration capacity [1, 2].

Content from this work may be used under the terms of the Creative Commons Attribution 4.0 licence. Any further distribution of this work must maintain attribution to the author(s) and the title of the work, journal citation and DOI.
Published under licence by IOP Publishing Ltd

IOP Conf. Series: Materials Science and Engineering **1344** (2026) 012137 doi:10.1088/1757-899X/1344/1/012137

The required sixty cryomodules along with four 1.3 GHz spares and one 3.9 GHz spare, have been built at Thomas Jefferson National Accelerator Facility (TJNAF) and Fermi National Accelerator Laboratory (FNAL). After completion of the LCLS-II-HE partnership, relying on these labs for servicing SLAC's cryomodules will be impractical, as their test facilities will be re-purposed to focus on other projects. Therefore, SLAC would like the ability to maintain, repair, and re-qualify cryomodules in the event of performance degradation. To achieve this, SLAC is investing in a Cryomodule Repair and Maintenance Facility (CRMF) with the ability to disassemble, reassemble, and test 1.3 GHz cryomodules before re-installing them in the accelerator string.

2. Facility details

The CRMF will be a greenfield project, purpose-built for servicing and testing cryomodules. The site is located 1 km east of the existing SCL cryoplant site. Construction activities are scheduled to begin in January 2026, with commissioning of the cryogenic system expected to start in mid-2028.

The 2,000 m² facility will have an assembly hall area with five assembly workstations (WS1 – WS5) necessary for disassembling and reassembling cryomodules and one workstation for staging (WS0). Each workstation is tooled to perform a different step of the cryomodule assembly process. Workstation 1 is contained in an ISO-4 clean room with a high-pressure rinse (HPR) system for maintaining the cleanliness of the beamline cavities.

There are two Vertical Test Stand (VTS) areas for testing cavities outside of a cryomodule, as well as a 130 m² shielded enclosure for performing cryomodule testing.

The east end of the facility is dedicated to cryogenic equipment (288 m²) with some auxiliary cryogenic systems (bulk LN_2 tank and ambient heaters) external to the building.

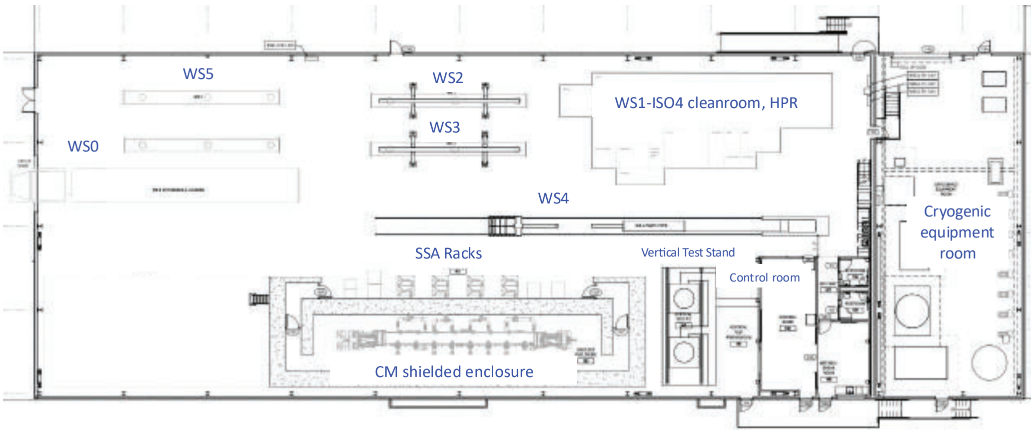

Figure 2. CRMF layout overview

3. Cryogenic requirements

The SCL cryomodule design has three helium cryogenic circuits: a high-temperature thermal shield circuit (HTTS), a low-temperature thermal intercept (LTTI) circuit, and a 2-phase cavity circuit, with nominal operating temperatures of 50 K, 8 K, and 2.0 K respectively [3].

IOP Conf. Series: Materials Science and Engineering **1344** (2026) 012137 doi:10.1088/1757-899X/1344/1/012137

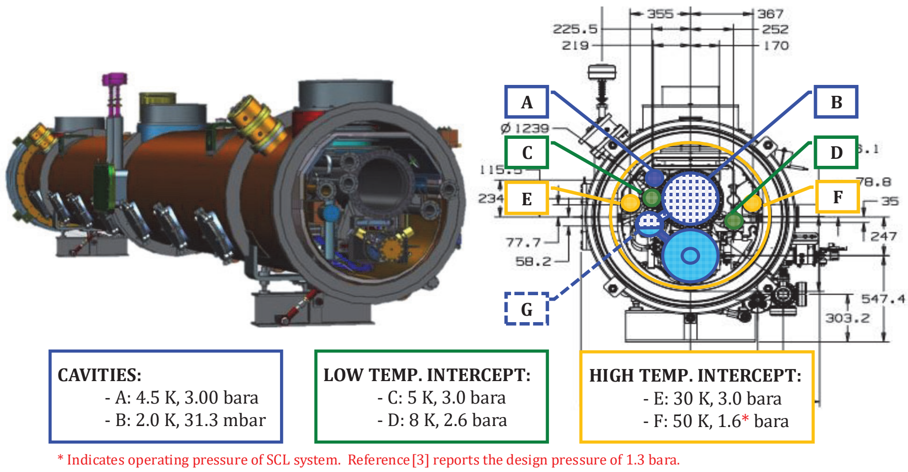

Figure 3. SLAC cryomodule overview

Table 1. Cryogenic circuit heat load requirements

Circuit	Cryomodule (Dynamic)	Cryomodule (Static)*	Distribution Sys. (Static)*	Total
Cavity	190 W	13 W	48 W	250 W
LTTI	10 W	22 W	41 W	75 W
HTTS	121 W	163 W	943 W	1,230 W

*Including 30 % margin.

During cryomodule testing, the heat load requirement at 2.0 K is 250 W. The expected duration of a full 8-cavity cryomodule test is 8 hours.

Additional “single-cavity” tests will be performed requiring 100 W at 2.0 K. Each cryomodule has eight cavities and requires 8 hours per single cavity test. The facility must also be able to perform a fast-cooldown for rapid transition through the RF cavities’ niobium critical temperature. This requires 30 g/s of 4.5 liquid K helium to be supplied to the cavity circuit for approximately 5 to 10 minutes [4].

The facility will be used intermittently, at most three times per year. Each test run may take up to one month, including installation and leak-testing of the cryomodule in the shielded enclosure.

4. Trade study

The CRMF project has significant cost constraints. To develop a cryogenic solution which meets all technical requirements, but minimizes overall cost, three cryogenic solutions were considered.

Option 1 would use a refrigerator designed to fully support the loads outlined in **Table 1**. Option 2 and option 3 would rely on the excess capacity of the SCL cryoplant system. The excess liquefaction capacity of the SCL cryoplant system was tested and determined to be 15 g/s [2] for each SCL cryoplant. Note, due to the configuration of the SCL cryogenic distribution system, we can only take advantage of one of the SCL cryoplant's excess liquefaction capacity for the CRMF.

In option 2, cryogens are filled into a 5,000 L portable dewar, mounted on a flat-bed trailer, and transported 1 km to the CRMF facility for decanting into a 10,000 L dewar. 4.5 K liquid helium will be supplied directly from the 10,000 L dewar to the cavity circuits. When the 10,000 L dewar is depleted, the test will be paused while the dewar is refilled.

In option 3, a new 1 km nitrogen cooled transfer-line would be built from the SCL cryoplant site to the CRMF.

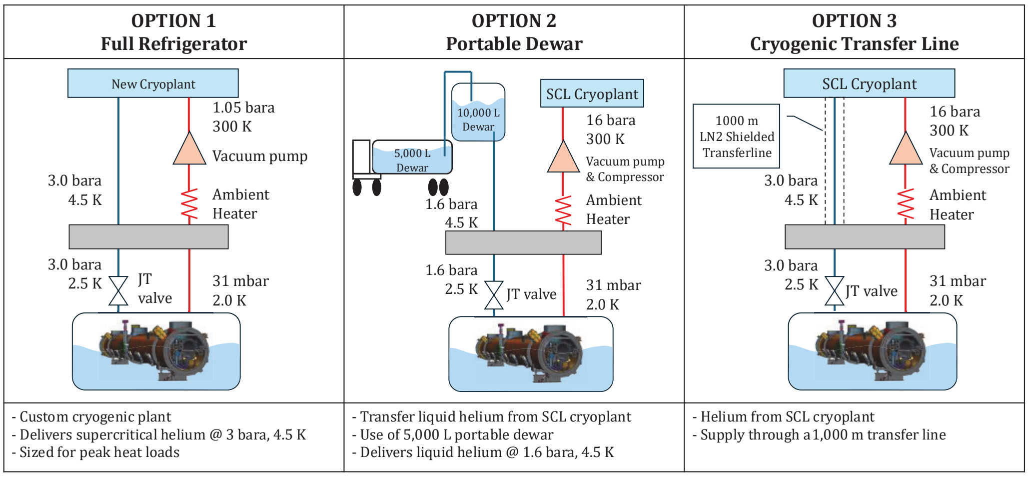

Figure 4. Comparison of cryogenic supply options considered

Table 2. Comparison table for CRMF cryogenic supply options.

Option	Pros	Cons
Option 1 Full Refrigerator	- Efficient and technically consummate - Operability / flexibility - Stable cavity supply at 3 bara, 4.5 K	- Price - Procurement and commissioning duration
Option 2 Portable Dewar	- Price - Upgradable to liquefier - Meets technical needs	- Operationally intensive - Dewar requires periodic refills, resulting in limited test durations - Potential for helium losses and contamination - Reliant on SCL cryoplant
Option 3 Transfer Line	- Price	- Risk of instabilities from transfer line - Heat load on transfer line may limit testing capability - Reliant on SCL cryoplant

5. Cryogenic supply design

Option 2 is the currently selected cryogenic system design. This provides the lowest project cost, while meeting all system requirements. Additionally, this design can be upgraded in the future by installing a liquefier at the CRMF to fill the 10,000 L dewar in place of the portable dewar. To reduce costs, such a liquefier could be undersized for the cryomodule load requirements listed in **Table 1** and could operate on a duty cycle with intermittent stoppages to recharge the dewar.

Table 3. Total dewar fill operations required per operation.

Operation	Heat Load (Static + Dyanamic)	Duration	Transport Operations
Dewar and cryomodule cooldown	N/A	72 hr	3
Inventory to fill system (9,000 L)	50 W	24 hr	3
Single cavity tests (8 total)	100 W	64 hr	4
Full (8-cavity) cryomodule test	250 W	8 hr	1

One transport operation includes filling the portable dewar at the SCL cryoplant, transporting to the CRMF, and decanting into the CRMF 10,000 L dewar.

An 8 hour full cryomodule test requires 3,000 L of 4.5 K liquid helium, assuming a 80 % yield from the 2.0 K JT expansion. Full cryomodule re-qualification, requires 11 fill operations from the 5,000 L portable dewar to the 10,000 L dewar. This includes the inventory required to cool and fill the system, perform a cryomodule fast-cooldown, perform single-cavity tests on all eight cavities, and peform the full 8-cavity test. The estimation assumes a portable dewar operating band of 20 % to 85 % (3,250 L per transfer), and a 10 % loss due to boil-off and flash associated with the transfer process.

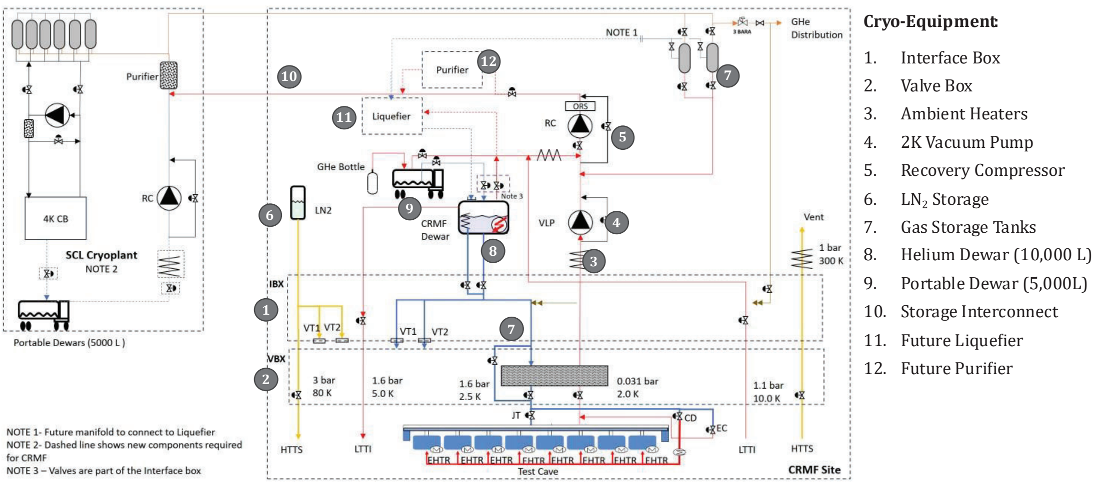

Figure 5. CRMF selected design option (portable dewar) process flow diagram

IOP Conf. Series: Materials Science and Engineering **1344** (2026) 012137 doi:10.1088/1757-899X/1344/1/012137

The LTTI circuit will be fed by 4.5 K boiloff gas from the dewar (~2 g/s required to maintain a return < 10 K). The HTTS circuit will be fed by LN_2, which will be bulk delivered to the facility. This is a difference from the SCL operation which has a helium-supplied 50 K HTTS circuit. Experimental correlations [5] show the use of 80 K thermal shields will increase the static heat to the cavity circuit by 60 %. This is accounted for in the distribution system heat leak estimation. Additionally, increased conduction to thermally intercepted elements of the cryomodule beamline is expected to increase the cavity static heat from 13W to 20W.

6. Additional design details

To achieve 2.0 K temperatures, the system will use an array of warm low pressure process pumps (roots blowers, screw pumps and/or vane pumps). There will be a heat exchanger between the supply and return of the cavity circuit to pre-cool the 4.5 K liquid supply closer to 2.0 K. However, the remainder of the return stream cooling capacity will be lost and warmed via ambient heaters before being recompressed.

The gas will be compressed, purified and returned to the SCL system inventory and storage tanks. Inventory management is one of the major challenges associated with this design. The SCL system inventory must be large enough to absorb swings of up to 12,750 L of liquid helium (assuming the 10,000 L and 5,000 L dewars are filled to 85 %). To augment SLAC's onsite storage capacity, the CRMF will have two 113 m^3 gas tanks interconnected with the six 113 m^3 existing tanks supporting the SCL system. The combined eight storage tanks have a cumulative volume of 904 m^3 and operate between 3 bara and 16 bara. The storage system can therefore absorb 1,850 kg of helium, equivalent to 16,000 liquid liters at 4.5 K.

7. Portable dewar design

Another significant design challenge associated with this project is performing the dewar fill operations in a way that minimizes helium and refrigeration capacity losses and mitigates the risk of contamination. Two fill stations are required for the project: one to fill the portable dewar from the SCL cryoplant, and one to fill the 10,000 L dewar at the CRMF.

The portable dewar will be equipped with three flex-hose connections, each with a globe valve for isolation and a male bayonet on the end. Additionally, a gas-bottle and electric heater will boost the pressure in the portable dewar to increase the decant rate.

Table 4. Portable Dewar Connections

Name	Function	Process Condition	Size	Location
SCL Fill Line	Fill the portable dewar at the SCL cryoplant	4.5 K gas, 3.25 bara	DN20	Above dewar liquid level (top-fill)
CRMF Fill Line	Withdraw liquid from the portable dewar	4.5 K liquid, 1.6 bara	DN15	Below dewar liquid level (dip-tube)
Boil-off Recovery Line	Maintain dewar pressure	4.5 K gas, 1.6 bara	DN25	Above dewar liquid level
Gas-bottle	Boost dewar pressure / withdrawal rate	Warm gas, 1.6 bara	DN6	Above dewar liquid level

Keeping the flex-hoses connected to the portable dewar ensures that we will never insert warm bayonets into a cold liquid volume. This minimizes helium boil-off when connecting the dewar. At the SCL cryoplant, all flash and boil-off gas will be captured and sent to a recovery compressor and purifier through the boil-off recovery line. Recovering the refrigeration capacity of this gas would increase the efficiency of the operation, however, the infrastructure required to return the gas to the SCL cryoplant would be significant and would increase the risk of introducing contaminants to the SCL system. The recovery system as currently designed does not include any gas-bags or gasometers to stabilize the suction pressure of our recovery system. During the initial cooldown of the CRMF dewar, boil-off gas can be sent through the distribution system to simultaneously cool down the distribution piping, before being recovered via the recovery compressors.

When connecting to either fill station, the flex-hoses can be fully isolated for pumping and purging to minimize contamination. When disconnecting, the flex-hoses can be warmed by isolating each line and flowing gas helium to the recovery compressor.

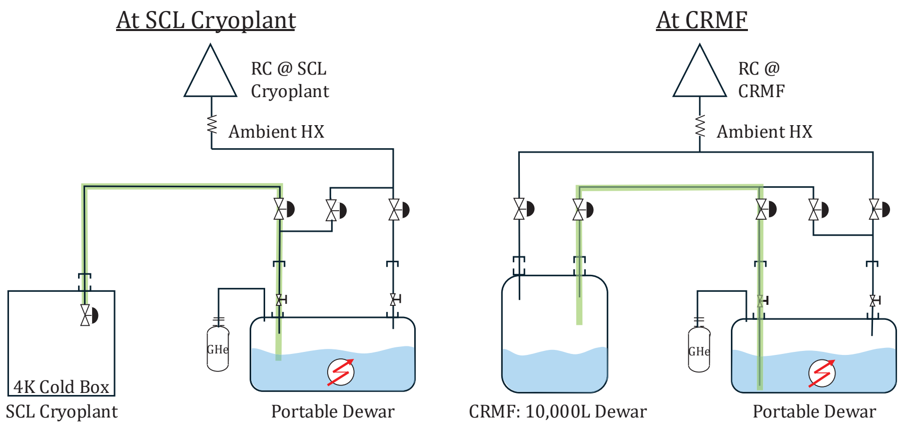

Figure 6. Liquid transfer at SCL cryoplant and CRMF sites

By utilizing bypass lines at the fill stations, each flex-hose can be pre-cooled with 4.5 K gas helium while remaining isolated from the dewar. Pre-cooling the lines reduces the risk of sudden boil-off events caused by pushing warm gas into a partially full dewar.

8. Conclusion

The SLAC CRMF project will rely on the existing SCL cryoplant's excess liquefaction capacity as a lower cost alternative to building its own stand-alone helium refrigeration system. This solution comes with additional technical challenges, inefficiencies, and drawbacks including the necessity for intermittent testing, difficulties with inventory management and the risk of contaminating or venting large quantities of helium. Operation of the system will be more labor intensive and less flexible than a stand-alone refrigerator solution. The CRMF design team has addressed these challenges to provide a functional solution which meets the system requirements, as well as the restrictive project budget.

Acknowledgements

This work was supported by Department of Energy contract DE-AC02-76F00515.

References

[1] E. Fauve et al, "LCLS-II Helium Refrigeration System: A comprehensive overview of the project" 2024 *IOP Conf. Ser.: Mater. Sci. Eng.* **1301** 012117 [https://doi.org/10.1088/1757-899X/1301/1/012117]

[2] A. Apte et al, "LCLS-II Helium Refrigeration System Commissioning Results" *2024 IOP Conf. Ser.: Mater. Sci. Eng.* **1301** 012112 [https://doi.org/10.1088/1757-899X/1301/1/012112]

[3] S. Shrishrimal et al, "LCLS-II LINAC Cooldown and Fast Cooldown" *2024 IOP Conf. Ser.: Mater. Sci. Eng* **1327** 012004 [https://doi.org/10.1088/1757-899X/1327/1/012004]

[4] R. Wang et al, "Operational experience from LCLS-II cryomodule testing" *2017 IOP Conf. Ser.: Mater. Sci. Eng* **278** 012187 [https://doi.org/10.1088/1757-899X/278/1/012187]

[5] J.E. Fesmire, W.L. Johnson, "Cylindrical cryogenic calorimeter testing of six types of multilayer insulation systems" 2018 *Cryogenics.* **89**, Pages 58-75, ISSN 0011-2275 [https://doi.org/10.1016/j.cryogenics.2017.11.004]