Status of the LCLS-II Cryogenic Distribution System

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Abstract. The LINAC Coherent Light Source II (LCLS-II) located at SLAC National Accelerator Laboratory (SLAC) in Menlo Park, CA, is a U.S. Department of Energy project tasked to design and build a world-class x-ray free-electron laser facility for scientific research. The Linac has superconducting radio frequency cryomodules that are connected to the cryogenic plant by the Cryogenic Distribution System (CDS), which consists of distribution boxes with heat exchangers and reliefs, feed caps, end caps, and surface, vertical, and bypass transfer lines. The CDS components were designed and built to specification by industry. The components have been delivered and their installation at SLAC will be discussed. The as-built relief system design will be presented, showing minimization of relief inlet pressure drops while meeting capacity requirements. The relieving flow pressure drops along the lengths of the CDS to centrally located reliefs at the distribution box were analysed to satisfy Pressure Vessel and Process Piping Code criteria to ensure relief performance. The sub-atmospheric 2 K circuit relieving approach will be discussed, which includes a three-way diverter isolation valve suitable for sub-atmospheric service. The component anchoring load design approach and installation into concrete floor will be discussed. This addresses loading, including seismic loading, along the component’s load path to floor anchoring system.

1. Introduction
The Cryogenic Distribution System (CDS) consists of the components needed to feed and return the cryogens, via vacuum insulated pipelines to the Linac components needing these services, throughout the entire LCLS-II Linac. This includes Distribution Boxes (DB), cryogenic Transfer Lines (TL), Feed Caps (FC), and End Caps (EC). A simplified schematic of the Linac is shown in Figure 1. The LCLS-II Linac is located in the first 650 m of the existing tunnel at SLAC. The CDS supports two independent cryogenic Linac strings with fifteen 1.3 GHz Cryogenic Modules (CM) and two 3.9 GHz CMs on the upstream (US) and twenty 1.3 GHz CM on the downstream (DS). The US Linac string is 390 m long while the DS is 287 m. The US Linac has two cryogenic bypass TL, of approximately 73 m and 63 m, which provide tunnel space for room temperature bunch compressors and beam diagnostic equipment. Each Linac string connects to a dedicated DB through a dedicated vertical TL (VTL). There are six helium cryogenic process lines, as described in Table 1.

A thermodynamic analysis of the CDS reference design with Linac cryomodules [1] establishes design requirements; some results are summarized in Table 1. A description of the overall LCLS-II
cryogenic system, which includes two cryogenic plants each with equivalent refrigeration capacity of 18 kW at 4.5 K, is given elsewhere [2].

*Figure 1. LCLS-II Cryogenic System Overview.*

| Line | Purpose | CM cooling supply | CM subatm. gas return | Low temp. intercept supply | Low temp. intercept return | High temp. shield supply | High temp. shield return |
|------|---------|-------------------|-----------------------|---------------------------|----------------------------|--------------------------|--------------------------|
| Line A | Nominal Temp [K] | 4.5 to 2.5 | 2.0 to 3.5 | 5 | 8 | 35 | 55 |
| Line B | Nominal Pressure [kPa] | 320 | 3.1 to 2.7 | 320 | 280 | 370 | 270 |
| Line C | Nominal pipe size [DN] | 50 | 250 | 50 | 50 | 50 | 50 |
| Line D | Nominal mass flow [g/s] | 100 | 100 | 30 | 30 | 80 | 80 |
| Line E | Maximum mass flow [g/s] | 215 | 215 | 37 | 37 | 146 | 146 |
| Line F | Pressure drop budget [kPa] | 100 | 0.4 | 100 | 100 | 150 | 150 |
| | Heat load budget [W] | 290 | 280 | 4350 | 4350 | 4350 | 4350 |

2. Tunnel Components
The LCLS-II accelerator Linac is comprised of cryomodules made into contiguous sections utilizing CDS components, see Figure 2. Vertical and bypass Transfer Lines are connected to a Cryogenic Module set by a Feed Cap at each end. End Caps are located at the end of each Linac string and function as turnarounds for cryogenic process piping. The FC and EC also provide anchoring for thermal, pressure, and vacuum loading of process piping and vacuum vessels.
2.1. Vertical Transfer Line
The CDS enters the tunnel via two VTL segments through two 0.91 m diameter penetrations which extend 7.6 m from the surface to the tunnel, see Figure 3. The thermal compensation scheme for the vertical transfer lines utilizes braided flex hoses. An anchor module/vacuum break is located vertically at the FC which separates the cryomodule insulating vacuum from the CDS and also supports the weight of the circuits in the VTL. The VTL are fabricated by Demaco (Netherlands).

Figure 2. LCLS-II CDS Component Block Diagram.

Figure 3. Reference Design of Vertical Transfer Line, tunnel end (left) and surface end (right)
2.2. **Horizontal and Bypass Transfer Lines**

The TL carry process lines A-F as described above, see Figure 4 for a TL cross section. The design allows cool-down and warm-up of each circuit and shield independently. Each TL section will be supported from the tunnel ceiling by sliding supports mounted to the ceiling, which compensate for movements of the outer vacuum jacket in the event of a rupture of a cryogenic circuit. The TL are fabricated by Demaco (Netherlands).

![Figure 4. Cross-section of Transfer Line interface.](image)

2.3. **Feed Caps and End Caps**

There are six FC as shown in Figure 2 providing interfaces between the cryomodules and the TL. FC also act as rigid supports to transfer all pressure, vacuum, and seismic loads from the CM outer vacuum shell to the floor of the tunnel via external structural supports bolted and grouted to the floor, see Figure 5 for usage. The FC are fabricated by Demaco (Netherlands).

Each EC provides a turn-around flow path for the various CD circuits. Line A has a pneumatic valve to control helium flow returning to the Cryoplant through Line B. The furthest upstream EC-FC-1 has an additional small DN8 cryogenic process line with a surface mounted heater which is used to aid cooldowns at the end of the US string. The EC are fabricated by Cryotherm (Germany).

![Figure 5. Feed Caps interfacing cryomodules with horizontal transfer line.](image)

3. **Surface components**

The surface portion of the cryogenic distribution consists of Transfer Lines connecting to the Cryoplant and Distribution Boxes as seen in Figure 6.
3.1. Distribution Box

The DB connects the tunnel with the surface portion of the cryogenic distribution system. The DB is 2.4 m in diameter and 5.1 m tall. CDS process line relieving is performed at the DB. In addition the DB has a subcooling 2 K heat exchanger as well as electrical heaters at the returns for both high temperature shield (Line F) and low temperature intercept (Line D) circuits for dynamic load trimming. A solid model of a DB is given in Figure 7 and its flow schematic is shown in Figure 8. The DB were fabricated by Linde Engineering North America (USA).

3.2. Surface Transfer Line

There are two Surface Transfer Lines (STL) in the CDS and both are fundamentally similar in design to the tunnel TL and also were fabricated by Demaco. Each STL connects to a dedicated Cryoplant Interface Box and serves as a mechanical interface between CDS and Cryogenic Plant. The US STL is 72 m long and DS STL is 26 m long. There are three types of external supports that are sized for seismic conditions. The supports include: anchor supports located at each end of the STL, sliding supports between the anchor supports, and one lateral support that limits the movement of the upstream STL during a seismic event, thus limiting the bending stress. Thermal contraction is made up by a combination of guided inline bellows at the straight sections and lateral offset flexhoses at the elbow.
4. Heat Exchanger
The CDS has a centrally located heat exchanger for each Linac string within each DB. The heat exchanger sub-cools the Line A CM supply flow with the Line B return flow.

The DB uses an existing aluminum plate-fin design with a proven performance history at Thomas Jefferson National Laboratory [3]. The heat exchanger was built by Chart Energy and Chemicals Inc. (USA). The performance of this 4 K to 2 K heat exchanger is presented in prior literature [4]. The design performance requirement is a minimum effectiveness of 90%. Heat exchanger process specification parameters are given in Table 2. The DB is designed so that the heat exchanger is removable. Valving is included to allow for warming up of the heat exchanger for de-contamination of heat transfer surfaces.

| Description                                      | High pressure side | Low pressure side |
|--------------------------------------------------|--------------------|-------------------|
| Helium mass flow [g/s]                           | 215                | 215               |
| Inlet temperature [K]                            | 4.6                | 2.4               |
| Inlet Pressure [kPa]                             | 310                | 3                 |
| Maximum allowable pressure drop [kPa]            | 10                 | 0.2               |
| Maximum allowable working pressure[kPa]          | 2000               | ≥ 500             |

5. Relieving approach
The CDS process line reliefs are all centrally located at the DB. The CDS design provides pressure safety to all Cryomodules and CDS process circuits for all credible failure scenarios in compliance with CGA S-1.3 and ASME BPVC Section VIII, including non-mandatory Appendix M. This Appendix requires safety valve inlet pressure drop to be ≤ 3% of set pressure at the safety valve nameplate capacity along the lengths of the CDS (or alternatively use a non-reclosable relief device). The reliefs are provided with three-way valves at their inlet to facilitate maintenance and testing. The Line B sub-atmospheric 2 K circuit employs a three-way diverter isolation valve suitable for sub-atmospheric service made by SchuF (Germany), which employs a guard volume around the sub-atmospheric seals. This three-way valve model is typically used for containment in hazardous gas service.

For the sudden loss of insulating vacuum (SLIV), the worst-case credible failure is identified as a rupture of an ISO80 pumping flange located on the warm insulating vacuum of either the CM or TL section. The heat load to cold surfaces and fluids as a result of in-rushing air condensation is calculated elsewhere [5]. The air condensation heat flux to the various process line fluids is calculated with the limitation of choked air flow with longitudinal effects and pipe surface geometry and mass considered. When air intake area is not the limiting factor, i.e. when the air intake orifice is not in choked regime, a lumped system heat flux is alternatively applied to determine heat flux. The Line B circuit also must consider sudden loss of beam tube vacuum. This follows a similar process, except now the surface is not insulated with MLI. Here, longitudinal effects with the build-up of frozen air on the surface are considered in the calculated heat flux, which results in lower heat flux for Line B than the SLIV case. An additional check is made for an overfill or blocked flow condition where the worst-case flow equals the maximum available flow from the Cryoplant. The relief system design is summarized in Table 3 [6].
6. Mechanical design of anchors and supports

The component anchoring load design addresses loading along the component’s load path to floor anchoring system. For anchor loads, forces include dead weight, seismic effects, and external pressure or vacuum loading. Here the external structural support with a focus on seismic loading will be discussed since this equipment is in a high seismic region. Inner process piping was designed per standard piping code [7], with additional load cases for thermal contraction, testing, and shipping and will not be further discussed.

Civil engineering structural code [8] is used to create load combinations and calculate the seismic effect for piping or vessels. Similar analyses for the LCLS-II Cryoplant are given elsewhere [9]. The resulting anchor forces are then used to size the anchors and component support structure.

CDS components are attached to concrete floor surface using commercial post-installed concrete anchors, except for Bypass TL which are anchored to the tunnel ceiling and walls. The nominal seismic load is applied to the supplied anchor system and commercial, proprietary software determines the design for the concrete and epoxy-embedded steel anchor rods. The calculations have a design criteria which increases the likelihood that upon seismic overload any yielding of the concrete-embedded anchoring system occurs first in the anchor rods, which are chosen for their ductility and ability to absorb energy through large plastic deformations. That is, the floor anchor system tailors the steel anchor rod’s strength in tension or shear such that rod plastic deformation occurs before undergoing a sudden brittle failure of the concrete. Furthermore, the seismic force-resisting elements of the structure transmitting the load path from the vessel to the anchor plates are designed for seismic loading with an overstrength factor ($\Omega = 2$ for DB and 2.5 FC/EC) on the horizontal seismic component to also increase the likelihood that the anchor rods would first plastically yield, before any structural support member. Support structures for the components were analysed with ANSYS for stress and deflection applying the overstrength load. Some of the floor supports are illustrated in Figure 9 as examples.

In the tunnel, all FC and EC supports are designed to handle the large vacuum load (~25,000 lbs) imparted from the vacuum bellows on the FC, EC, and Cryogenic Modules. These supports are designed to minimize the deflection of the upper point of the FC/EC end plate to $\leq 1$ mm to not affect the alignment of the beam line. The DB anchors allowed for adjustment to align with the previously installed VTL.

![Figure 9. Floor supports illustrations: FC/EC (left), Surface TL anchor (middle), and DB (right).](image-url)
7. Summary
The LCLS-II Cryogenic Distribution System components have been described. These were designed to specification and fabricated by industry. All the CDS components have been delivered to SLAC and satisfy all acceptance, test, and design specifications. The EC, FC, Bypass and Vertical TL are installed in the Tunnel with Cryogenic Module installation in progress. The DB are mounted in place in the Linac gallery. The Surface TL installation is pending. The downstream DB is positioned to facilitate future addition of another Cryogenic Module string.

The CDS uses centralized heat exchangers for subcooling the cavity supply helium flow to each Cryomodule Linac to provide 2 K refrigeration to each CM as required for LCLS-II to achieve target gradient and beam operation. CDS required relief flow calculations applied experimental, analytical, and numerical work across several laboratories to satisfy LCLS-II partner lab and industry accepted pressure safety standards.

8. References
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