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Revision History

Revision	Date Released	Description of Change
R0	1/23/2017	Original Release.

Table of Contents

1 Scope

This document describes the technical requirements and design for the 3.9 GHz cryomodules for LCLS-II.

2 Introduction

The LCLS-II main linac cryomodule is based on the existing XFEL design, including TESLA-style superconducting accelerating cavities, with modifications to accommodate CW operation and LCLS-II beam parameters. Thirty-five 1.3 GHz cryomodules and two 3.9 GHz cryomodules will be connected to form four linac segments (L0, L1, L2, and L3) which are separated by three warm beamline sections (LH, BC1, and BC2) for the laser heater and bunch compressors as shown in Figure 2.1.

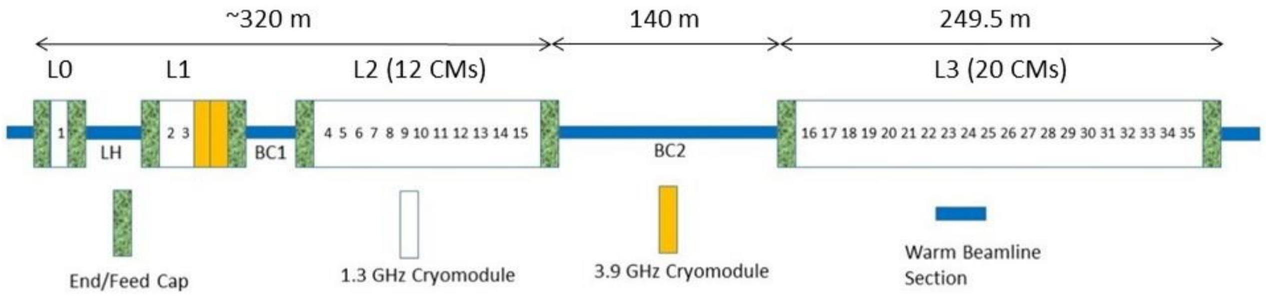


Figure 2.1: Linac with cryomodules in sections

For reference and comparison, the 1.3 GHz Cryomodule Technical Description can be found in this controlled document: LCLSII-4.5-ES-0356.

The two 3.9 GHz Cryomodules containing superconducting cavities, together with cryogenic distribution lines and thermal shielding, are assembled back to back. Each cryomodule has two gate valves at both ends of the beam line. Compared to 1.3 GHz cryomodules, there is no focusing and steering magnets. However there is a beam position monitor at the downstream end within the cryomodule. The beam position monitor is identical to the ones installed in 1.3 GHz cryomodule. Beam line higher-order-mode (HOM) absorbers are located in the cold beamline interconnects between cryomodules. The cavity tuners, HOM couplers, and fundamental power couplers attach to each cavity, and are also developed from existing designs.

The 3.9 GHz cryomodules contain eight RF cavities each. Active control of the cavity resonant frequency is provided by a blade tuner that is stacked with a pair of piezo tuners. Access to the tuner mechanism is NOT provided by cryomodule ports as those in 1.3 GHz cryomodules. Each RF cavity is independently powered through a fundamental power coupler which is connected via air-filled waveguide to a solid-state amplifier at 3.9 GHz. Each coupler antenna is fixed with NO capability to adjust the external Q.

Cryogenic circuits provide 2 K liquid helium to the cavities with a valve for liquid supply in each cryomodule. The cryostat includes a second valve and piping for cool-down of cavities in an individual cryomodule, a nominally 5 K thermal intercept circuit, and a nominally 45 K thermal radiation shield and thermal intercept circuit. The 2 K cryogenic heat load is dominated by dynamic RF heating of approximately 14.3 W per cavity. Figure 2.2 illustrates the cryomodule cross-section and cryogenic circuit labels. Figure 2.3 shows the cryomodule flow scheme. Figure 2.4 illustrates the cryomodule mechanical assembly.

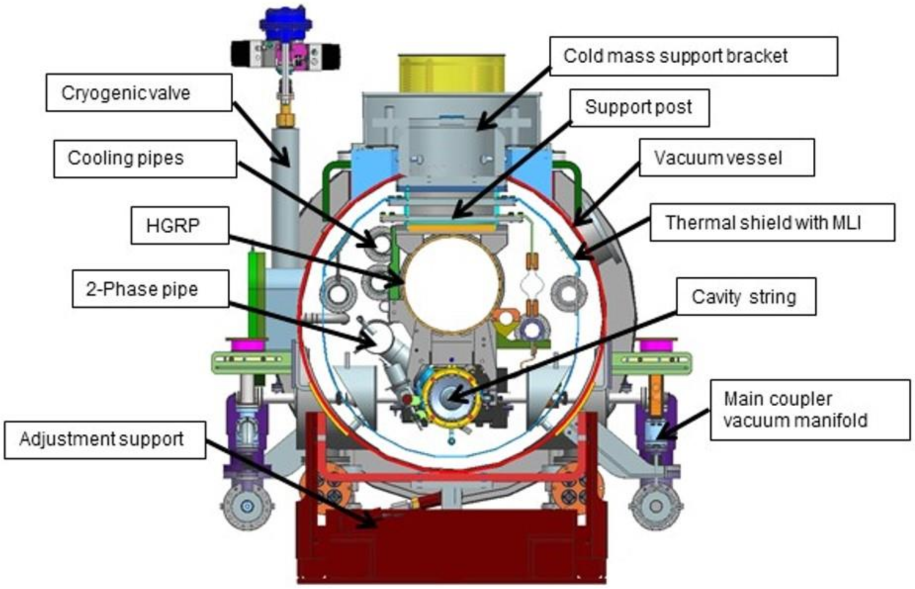


Figure 2.2. LCLS-II 3.9 GHz cryomodule assembly cross-section

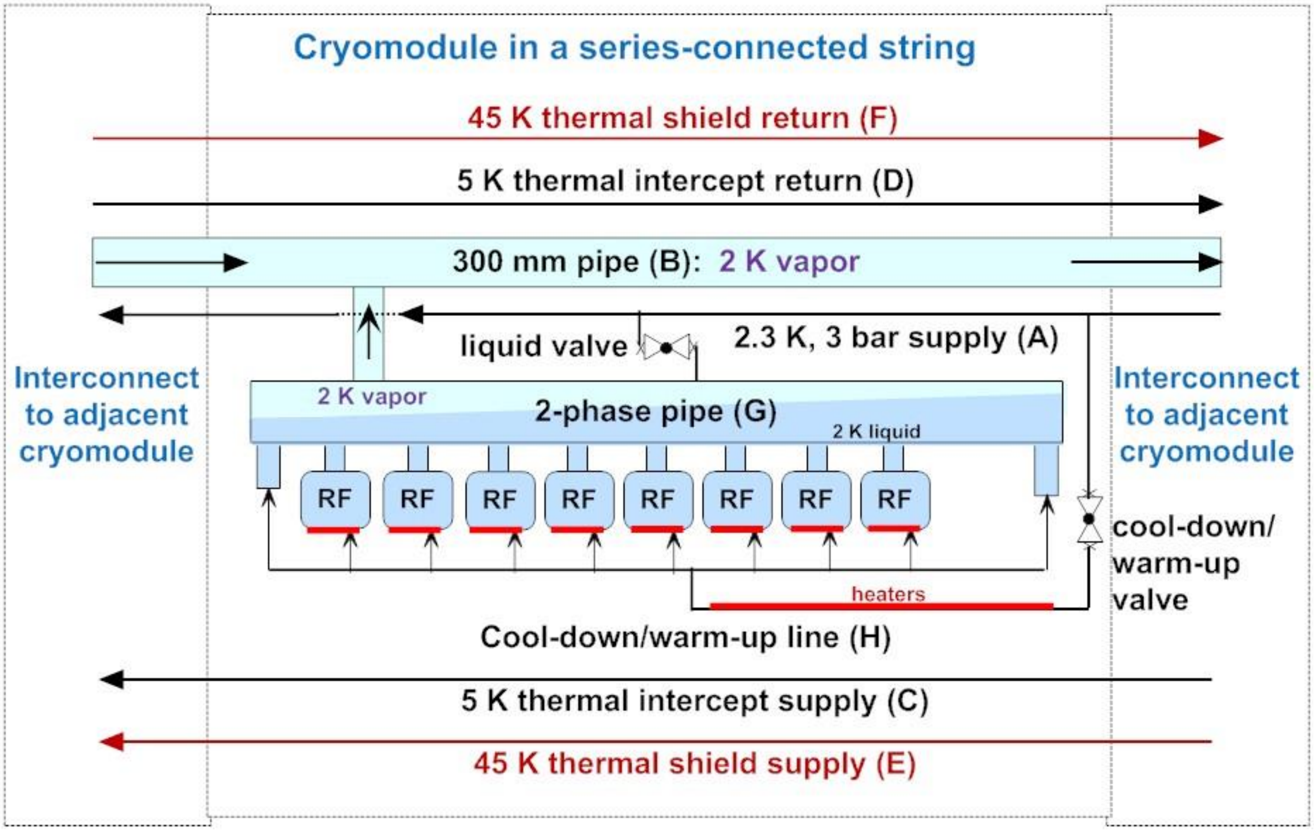


Figure 2.3. LCLS-II 3.9 GHz cryomodule schematic

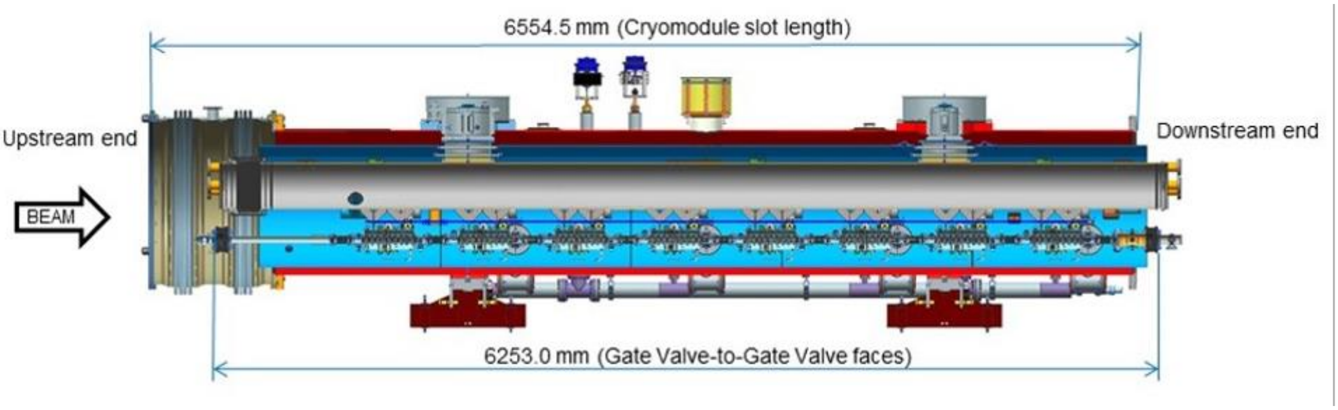


Figure 2.4. LCLS-II 3.9 GHz cryomodule assembly

3 Definitions

Table 1. Definitions

Term	Definition
SLAC	SLAC National Accelerator Laboratory
FNAL	Fermi National Accelerator Laboratory
LCLS-II	Linac Coherent Light Source upgrade
SRF	Superconducting Radio Frequency
CW	Continuous Wave operating mode
TESLA	TeV Energy Superconducting Linear Accelerator – the predecessor to the ILC concept, developed collaboratively by DESY, Saclay, INFN, Fermilab, Jefferson Lab and Cornell as well as other labs and universities under the leadership of DESY.The LCLS-II cryomodule configuration (RF cavities in close-fitting helium vessels suspended from a large helium return pipe, cryogenic piping all within the cryostat) comes from the TESLA collaboration. Hence it is referred to here as TESLA-style.
XFEL	X-ray Free Electron Laser, an SRF linac under construction at DESY which includes TESLA-style cryomodules
2 K	Nominally 2 Kelvin temperature level, 2.0 K
5 K	Nominally 5 Kelvin temperature level, which ranges approximately from 5.5 K to 7.5 K
45 K	Nominally 45 Kelvin temperature level, which ranges from approximately 35 K to 55 K. (Note that this cryogenic circuit and thermal shield will be ~80 K in test facilities with LN2.)
MAWP	Maximum Allowable Working Pressure, a term that is used to define the safe pressure rating of a component or test system
Cold mass	Those portions of the cryomodule within the vacuum vessel ~~which~~ are cooler than room-temperature – RF cavities, piping, thermal shield, etc.
HGRP	Helium Gas Return Pipe, the 300 mm diameter helium pipe which also serves as the structural backbone of the cold mass
MLI	Multi-Layer Insulation, or “superinsulation”, aluminized mylar wrapped in layers alternately with a conductively insulating material in the insulating vacuum space to block thermal radiation

4 References

Table 2. References

Document Reference Number	Document Title
	Physics requirements
LCLSII-1.1-PR-0133	LCLS-II Parameters
LCLSII-4.1-PR-0146	1.3 GHz Cryomodule
LCLSII-2.4-PR-0136	Beam Position Monitor
LCLSII-4.1-PR-0097	SCRF 3.9 GHz Cryomodule
LCLSII-1.1-IC-0657	MAD Model for LCLS-II Cryomodules
	General cryomodule requirements
LCLSII-4.1-FR-0096	Functional Requirements Specification, "3.9 GHz Superconducting RF Cryomodule"
LCLSII-4.5-ES-0356	Engineering Specifications Document, “1.3 GHz Cryomodule Technical Description”
LCLSII-4.5-EN-0179	Engineering Note, “Cryomodule Heat Load”
LCLS-II-4.5-EN-0186	Engineering Note, “Cryogenic System – Cryomodule Design Methodology”, (Same as 1.3 GHz Cryomodule)
LCLSII-2.5-IC-0056	Interface Control Document, “Accelerator Systems to Cryogenic Systems”, (Same as 1.3 GHz Cryomodule)
LCLSII-4.5-IC-0661	1.3 GHz Cryomodule Physical Interfaces
SLAC-I-720-0A24E-001	Seismic Design Specification for Buildings, Structures, Equipment and Systems: 2014, (Same as 1.3 GHz Cryomodule)
LCLSII-4.5-EN-0226	Engineering Note, “Cryomodule Seismic Design Criteria”, (Same as 1.3 GHz Cryomodule)
LCLSII-4.9-IC-0058	Interface Control Document, "Cryogenic Distribution System", (Same as 1.3 GHz Cryomodule)
LCLSII-4.5-EN-0214	Cryomodule Design Heat Flux for Vacuum Failures, (Same as 1.3 GHz Cryomodule)
	Cryomodule engineering details, analyses, and compliance documents
F10014857	Assembly, 3.9 GHz cryomodule drawing
LCLSII-4.5-EN-0711 (ED0004081)	LCLS-II 3.9 GHz cryomodule mechanical design
LCLSII-4.5-EN-0566 (ED0004361)	LCLS-II 1.3 GHz cryomodule mechanical design
LCLSII-4.5-ES-0414	Engineering Specifications Document, “CM Coaxial Cable and Connectors Specification" (Same as 1.3 GHz Cryomodule)
LCLSII-4.5-ES-0415	Engineering Specifications Document, “Cryomodule Instrumentation

Document Reference Number	Document Title
	Specification", (1.3 GHz Cryomodule)
LCLSII-4.5-ES-0416	Engineering Specifications Document, "Cryomodule Multi-pin Connectors Specification" (Same as 1.3 GHz Cryomodule)
LCLSII-4.5-ES-0417	Engineering Specifications Document, "Cryomodule Wire Specification" (Same as 1.3 GHz Cryomodule)
LCLSII-4.5-ES-0419	LCLS-II 1.3 GHz Cryomodule Transport System (Same as 1.3 GHz Cryomodule)
LCLSII-4.5-EN-0418	LCLS-II Cryomodule Stand Analysis
LCLSII-4.5-ES-0403	Cold Button Beam Position Monitor (Same as 1.3 GHz Cryomodule)
F10023160	LCLS-II Cold BPM Assembly Drawing (Same as 1.3 GHz Cryomodule)
ED0001995	LCLS-II CDS Relief System Analysis
ED0002396	Cryomodule vacuum vessel venting calculation
ED0004908	Structural analysis of 3.9 GHz cryomodule vacuum vessel
ED0002638	A subset of 1.3 GHz P&ID (instrumentation) tag name list
LCLSII-4.5-EN-0710 (ED0002593)	Cryomodule interconnect design and installation (Same as 1.3 GHz Cryomodule)
Fermilab Document Draft	JT valve sizing and flow calculation (Similar to 1.3 GHz Cryomodule ED0002453)
Fermilab Document Draft	Cool-down valve sizing and flow calculation (Similar to 1.3 GHz Cryomodule ED0002406)
Fermilab Document Draft	Cryomodule two phase pipe pressure, vapor velocity, and venting calculation (Similar to 1.3 GHz Cryomodule ED0002405)
Fermilab Document Draft	Cryomodule cooldown line pressure, flow, and venting calculation (Similar to 1.3 GHz Cryomodule ED0002404)
LCLSII-4.9-EN-0253	CDS/Cryomodule What-If Analysis, (Same as 1.3 GHz Cryomodule)
LCLSII-4.9-EN-0255	CDS/Cryomodule Failure Mode and Effects Analysis (Same as 1.3 GHz Cryomodule)
ED0005767	Engineering Specification Document, 3.9 GHz Fundamental Power Coupler
Fermilab Document Draft	Engineering Specification Document, 3.9 GHz Cryomodule Coaxial Cable and Connectors Specification
LCLSII-4.5-EN-0918-R0	LCLS-II 3.9GHz CM Instrumentation List
	Other reference documents and publications
TESLA report #94-18 (June, 1994).	"Notes about the Limits of Heat Transport from a TESLA Helium Vessel with a Nearly Closed Saturated Bath of Helium II", by Tom Peterson, Fermilab
REVIEW OF SCIENTIFIC INSTRUMENTS 81, 074701 (2010).	O. Kugeler, A. Neumann, W. Anders, and J. Knobloch, Helmholtz-Zentrum-Berlin (HZB), 12489 Berlin, Germany, "Adapting TESLA technology for future cw light sources using HoBiCaT"
Advances in Cryogenic	"Latest Developments on He II Co-current Two-phase Flow Studies,"

Document Reference Number	Document Title
Engineering, Vol 43B, pp. 1441 - 1448	by B. Rousset, A. Gauthier, L. Grimaud, and R. van Weelderen, in Advances in Cryogenic Engineering, Vol 43B (1997 Cryogenic Engineering Conference).

5 Responsibilities

Table 3. Responsibilities

Fermilab	Cryomodule Design

6 Functional requirements summary

The cryomodule functional requirements are defined in "3.9 GHz Superconducting RF Cryomodule," [LCLSII-4.1-FR-0096-R0]. The following table provides a summary of the key functional requirements which drive the design.

Table 4. Key functional requirements for the cryomodules

Key requirement	Description
Series configuration	The baseline design concept includes TESLA-style cryomodules with insulating vacuum openings at each end, whereby connecting end to end, in addition to a cold beam pipe through the interconnect.
No external parallel transfer line	TESLA-style cryomodules include all cryogenic piping within the cryostat, as opposed to having a parallel external cryogenic transfer line to supply cooling to cryomodules
0.5% longitudinal tunnel slope	The SLAC tunnel enclosure, in which the cryomodules will be installed, has a 0.5% longitudinal floor slope, which dictates careful attention to liquid helium management
Microphonics	Minimize cavity vibration and coupling of external sources to cavities. This is addressed by means of providing a stiff support system and stiffening of elements such as the thermal shield.
Alignment	Provide good cavity and BPM alignment (<0.5 mm RMS). Tests of TESLA-style cryomodules with a support system identical to this for LCLS-II, have verified that this support system satisfies this requirement.
Seismic	Follow SLAC seismic loading requirements
Thermal efficiency	Intercept significant heat loads at intermediate temperatures above 2.0 K to the extent possible in full CW operation
Pressure safety	Cryomodules and components comply with 10CFR851 – equivalence to pressure code safety level. Protect the helium and vacuum spaces including the RF cavity from exceeding maximum allowable pressures (MAWP).
Magnetic shielding	Provide excellent magnetic shielding and average residual field of ≤15 mG at the cavities

Key requirement	Description
Other requirements	**A few additional requirements not explicitly in the FRS**
Thermal performance	Allow removal of up to 28.6 W per cavity and/or 150 W at 2 K per cryomodule. (For thermal design within the cryomodule, we apply a larger uncertainty factor than globally for cryoplant sizing.)
Cool-down	Provide~~,~~ to the extent possible given the cryomodule string configuration, cool-down conditions which retain high cavity Q0. Recent recognition of the role of thermal gradient on the niobium cavity to “sweep out” magnetic flux as the Nb passes through the superconducting transition during cool-down created new design goals for management of cool-down, including the addition of a cool-down valve in each cryomodule.

7 Cryomodule mechanical design

7.1 Cryomodule major components and features

LCLS-II 3.9 GHz cryomodules consist of various complex subassemblies, some of which are taken from previous TESLA-style cryomodule designs and some of which are new developments for LCLS-II and CW operation. The table below lists major cryomodule features or components and notes about each.

Table 5. Major cryomodule features or components

Feature	Notes
RF cavity	XFEL and FLASH cavity shape with slight reduction in beampipe aperture
Helium vessel	Dramatically enlarged “chimney nozzle for CW heat removal and one cool-down / warm-up supply port
Tuner	Blade tuners integrated with Piezo tuners for precision resonance control. The overall tuner envelope must not interfere with other features like piping. Tuners will not be accessible as those in 1.3 GHz cryomodule. Cables are thermally intercepted at the 45 K level.
RF power input coupler	Modified for CW operation by means of additional copper plating, fewer bellows convolutions, and improved thermal intercepts. The cryomodule includes features to accommodate the input coupler assembly including input coupler flange on the vacuum vessel and features to support any associated assembly tooling. Input coupler thermal intercepts are provided at 45 K and at 5 K.
Magnet assembly	There is no magnet in 3.9 GHz cryomodule.
Beam Position Monitor	The XFEL button BPM has been selected (Same as 1.3 GHz Cryomodule).
45 K thermal shield	Serves both as a thermal radiation shield and as a conductive manifold for thermal intercepts.
Magnetic shielding	Magnetic shielding goal is to limit imposed magnetic field on the dressed cavity to no more than 15 milligauss on average. A hybrid helium vessel internal and external magnetic shield design is adopted. One must watch also for internal sources of magnetic fields. No component of the cryomodule shall impose a magnetic field of more than 5 milligauss on the dressed RF cavity. The

Feature	Notes
	specification follows that of 1.3 GHz cryomodule for production consistency.
Cryogenic valves	A major difference from XFEL is the addition of two cryogenic valves to each cryomodule; one for cool-down of each cryomodule individually and one for steady-state management of helium liquid levels in each cryomodule individually.
Cryogenic piping	Stresses in piping and support structures include those due to pressure loads and shall not exceed allowable stresses. Piping stability with respect to loads, taking into account forces resulting from the use of bellows, piping area changes, etc., is analyzed and verified.
Cold mass supports	Epoxy-fiberglass cylinders of the TESLA design support the cryomodule cold mass
Cavity support system	Like for TESLA and XFEL, RF cavities are anchored in position longitudinally via a clamp to an invar rod. Vertical and lateral support is provided by the 300 mm HGRP which in turn hangs from the vacuum vessel via two support posts.
Vacuum vessel	LCLS-II Cryomodule Vacuum Vessels satisfy Fermilab ES&H Manual requirements in Chapter 5033, Vacuum Vessel Safety
Instrumentation	Instrumentation is detailed in LCLS-II 3.9GHz CM Instrumentation List and also in the P&I Diagram F10068916.
Cryomodule linac lattice dimensions	Cryomodule linac lattice dimensions and inter-cavity spacing including both warm and cold dimensions, are defined and shown in LCLSII-4.5-EN-0711 (ED0004081). Two key dimensions are: main coupler cavity-to-cavity distance is 634.2 mm, which is 8+1/4 lambda (at 3.9 GHz) at cold, and cryomodule slot length is 6,253 mm. Having a cavity spacing equal to an integer number of half-wavelengths plus a quarter-wavelength was suggested in the 3.9 GHz Cryomodule Physics Requirements Document to suppress dark current from propagating upstream.

7.2 Cavity

A cavity pair is illustrated in Figure 7.1 showing cavity length and opposite placement of fundamental power couplers.

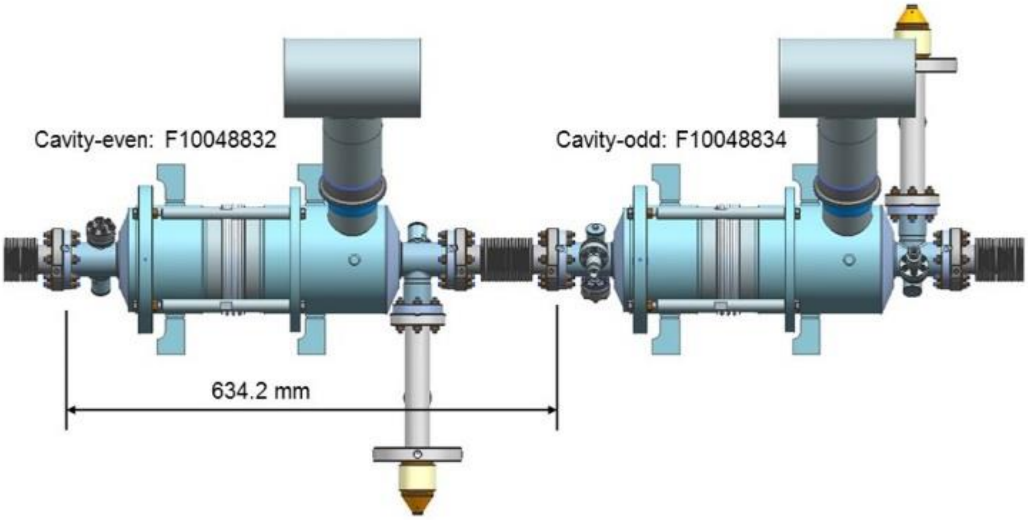


Figure 7.1: 3.9 GHz cryomodule cavity pair

7.3 Cryomodule weight

Table 6, below, lists cryomodule component and total weights.

Table 6. Cryomodule mass (kg)

Sub-assembly	**Weight (kg)**
Vacuum vessel	2400
Cold mass	1800
Module stand	500
Other	550
Total	5750

7.4 Major interfaces

Major interfaces from the cryomodule to other linac components are similar to LCLSII-4.5-IC-0661 "1.3 GHz Cryomodule Physical Interfaces”. Figure 7.1 illustrates the cryomodule external features.

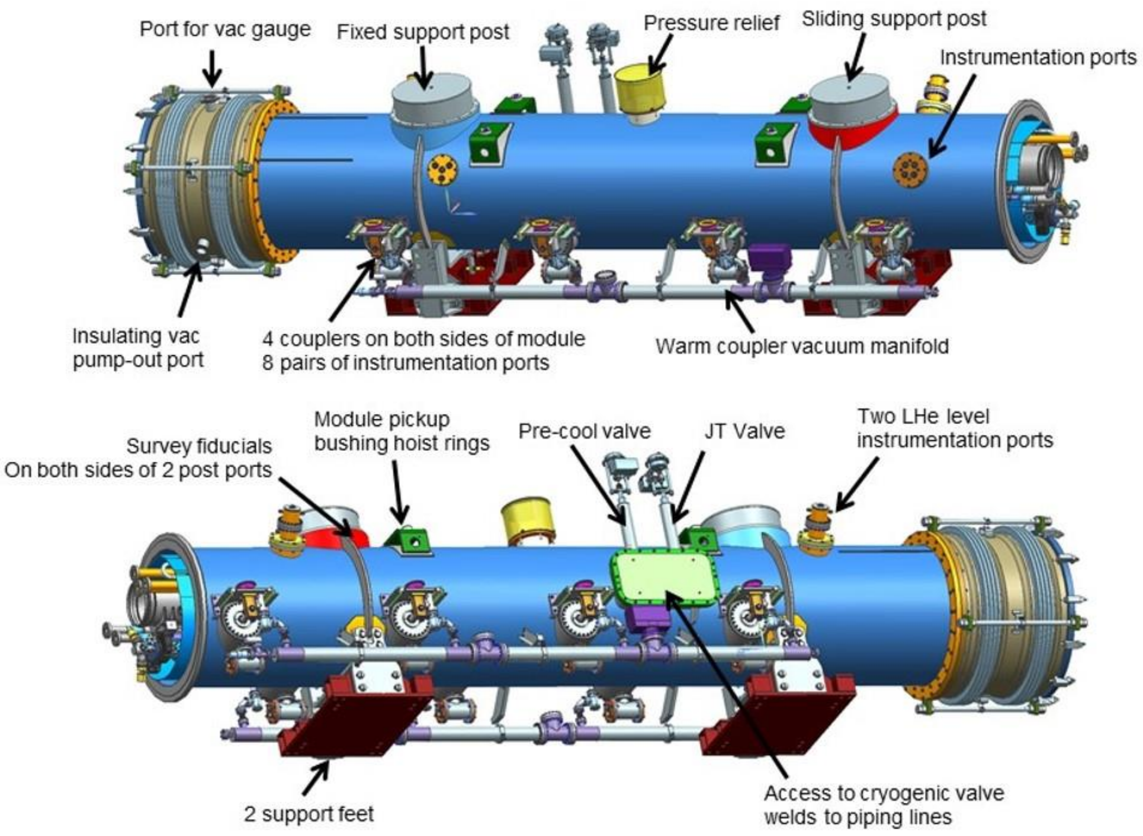


Figure 7.1. LCLS-II 3.9 GHz cryomodule external features

Table 7. Major interfaces

Interface	Notes
Vacuum vessel support structure	The support of the vacuum vessel in the SLAC tunnel is described in detail in LCLSII-2.5-IC-0056, “Interface Control Document, Accelerator Systems to Cryogenic Systems”
Connections at the cryomodule string ends to the distribution system	Cryomodule ends at the string ends which are standard interconnects.
RF waveguide to input couplers	RF power input waveguide connections are described in detail in LCLSII-4.5-EN-0711 (ED0004081), “LCLS-II 3.9GHz Cryomodule Mechanical Design”
Instrumentation connectors on the vacuum shell	Electrical connectors are located on various round covered plates mounted on the vacuum shell. The connector plates are sealed with O-ring seals. A pair of instrumentation flanges is also associated with each input coupler to reduce wire lengths and risks associated with long runs of wires inside the cryomodule.
Alignment fiducials on the vacuum shell with reference to cavity	Alignment fiducials on the vacuum shell are described in detail in LCLSII-4.5-EN-0711 (ED0004081), “LCLS-II 3.9GHz Cryomodule Mechanical Design”

Interface	Notes
positions.	
Pneumatic actuators for cryogenic valves	Compressed air supply
Guard helium for sub atmospheric instrumentation	Low pressure, room temperature helium supply in the tunnel ~~for helium supply~~ to ~~the~~ guard helium space on the sub atmospheric connectors.

7.5 Cavity alignment requirements relative to external reference

Cavity lateral and vertical alignment requirements are 0.5 mm (RMS). Cavity positions relative to fiducials on the vacuum vessel are set during assembly with no requirement for later internal adjustment of cavity position within the cryomodule after assembly. Alignment needs to be maintained with thermal and pressure cycling. (Return to position within 0.5 mm RMS tolerance.) The final alignment for the vacuum vessel assembly by means of the external fiducials, are in reference to the cavity string. The table below summarizes approximate allocation of alignment tolerances, illustrating that for each source of misalignment, due to their additive nature, tolerances must be tighter than the overall requirement.

Table 8. Alignment tolerances

	Subassembly	**Tolerances (RMS)**	**Total envelope**
Cryomodule assembly	Cavity and helium vessel	+/- 0.1 mm	Positioning of the cavity with respect to external reference +/- 0.5 mm
	Supporting system	+/- 0.2 mm	
	Vacuum vessel construction	+/- 0.2 mm	
	Action		
Transport, testing, and operation	Transport and handling (+/- 0.5 g in any direction)	+/- 0.2 mm	Reproducibility and stability of the cavity position with respect to external reference +/- 0.5 mm
	Vacuum pumping	+/- 0.3 mm	
	Cool-down		
	RF tests		
	Warm-up		
	Thermal cycles		

8 Cryomodule vacuum design and vacuum vessel

Vacuum vessel design is described in detail in "LCLSII-4.5-EN-0711 (ED0004081), “LCLS-II 3.9GHz Cryomodule Mechanical Design". No tuner access port will be available, as those in 1.3 GHz cryomodule, due to the limited space available in the vacuum vessel. The risk of tuner failure is mitigated by high margin of the cavity total voltage and a readily available spare cryomodule.

The insulating vacuum is protected from over pressurization by means of a spring-loaded lift plate. A single worst case piping rupture internal to the insulating vacuum was analyzed to determine lift plate size (ED0002396, “Cryomodule vacuum vessel venting calculation”). Provisions are provided to allow free passage of the helium out past thermal shield and MLI to the lift plate.

Insulating vacuum shares the common vacuum system in linac section L1.

Beamline vacuum valves are all metal manual gate valves. Upon delivery, the downstream gate valve will remain open and connected to a vacuum manifold which provides pressure monitoring during ~~the~~ shipping. The gate valves shall be closed before interconnect installation.

Table 8.1 lists the vacuum pressure requirement as in functional requirement document.

Vacuum	Engineering Specification
Beam line vacuum (room temperature)	1e-8 torr
Beam line vacuum (cold)	1e-10 torr
Insulating vacuum (room temperature)	1e-4 torr
Insulating vacuum (cold)	1e-6 torr
Coupler vacuum (warm)	1e-8 torr

9 Cryomodule RF Design

The RF subsystem describes the RF parameters related to the test and operation of the cryomodule including the cavities and the power couplers.

Table 9.1 lists the engineering specification which expands the 3.9 GHz RF parameters in 3.9 GHz cryomodule functional requirement document.

Table 9. Cavity and coupler RF Parameters

Parameters	Notes
RF frequency	Cavity frequency is 3,900,000,000 Hz at 2.0 K.
Cavity accelerating gradient	Cavity vertical test gradient Eacc_VTS >18 MV/m Cavity horizontal test gradient Eacc_HTS > 18 MV/m Cavity cryomodule test gradient Eacc_CM > 16 MV/m Cavity cryomodule nominal gradient Eacc = 13.4 MV/m Cavity cryomodule maximum gradient Eacc = 14.9 MV/m
Cavity Q0	Cavity vertical test Q0_VTS >2.0e9 @14 MV/m, >1.5e9@14.9 MV/m Cavity horizontal test Q0_HTS >2.0e9@14 MV/m, >1.5e9@14.9 MV/m Cavity cryomodule average Q0_CM > 2.0e9@14 MV/m, >1.5e9@14.9 MV/m
Qext_FP	5.7e10, 0.5 W power at nominal gradient 13.4 MV/m
Qext_HOM	>3.8e10, 1W maximum power leakage at 14.9 MV/m
Lorentz detuning	<=1.2 Hz/(MV/m)^2
Coupler Qext (fixed)	2.7e7 (nominal), acceptable range 2.5e7 - 2.9e7. Maximum forward + reflected power with beam = 1.6 kW. Maximum coupler temperature is to be < 450 K.
RF power	Total 0.9 kW: (for the coupler qualification in CMTF) 0.8kW coupler power (Engineering note by N. Solyak). 10% transmission loss
Tuner	750 kHz (coarse range) 1 kHz (fine range) better than 1Hz piezo tuner resolution

Size of waveguide mating to the 3.9 GHz power coupler is WR284. No adjustment capability is provided for power coupler inner antenna.

For reference, the detailed engineering specification for the 3.9 GHz power coupler can be found in LCLSII-4.5-ES-0925, Engineering Specifications Document, “3.9 GHz Fundamental Power Coupler.“

10 Cryomodule thermal design and helium flow design

10.1 Major thermal design features

Table 10. Major thermal design features

Feature	Notes
2 K temperature level	The RF cavities are maintained at nominally 2 K by means of a bath of saturated liquid helium. 1.8 K to 2.1 K are possible temperatures, and the RF cavity helium vessel and piping design accommodate any temperature within this range. The design baseline is 2.0 Kelvin.
5 K temperature level	A helium circuit with pressures above the helium critical pressure (2.27 bar) so as to avoid 2-phase flow, and in the temperature range of 5 K to 8 K, provides a low temperature thermal intercept for the support posts, magnet current leads, RF power coupler, HOM absorbers, and instrumentation wires. Unlike XFEL, LCLS-II cryomodules have no thermal radiation shield at this temperature level.
45 K temperature level	The highest temperature level will be helium in the range 35 K to 55 K. This temperature level provides not only conductive thermal intercepts but also cools a thermal radiation shield. There will be no liquid nitrogen in the LCLS-II tunnel. However, for test purposes in various test cryostats and facilities, the "45 K" thermal shield may be cooled with liquid nitrogen at approximately 80 K. This higher temperature within the test facilities will have some impact on thermal measurements relative to the 45 K tunnel condition, which will be assessed.
45 K thermal shield	The thermal shield is designed such that introduction of cold (process temperature) helium into the thermal shield piping when the thermal shield is warm, resulting in a very fast cool-down, does not damage the thermal shield or other parts of the cryomodule. (The issues are warping and associated forces, thermal stresses, etc.) Thermal shield trace piping is arranged such that counterflow heat transfer does not inhibit cool-down of the thermal shield.
Cryomodule heat loads	Heat loads are summarized in "Cryomodule Heat Load" [ref 5], which also in turn lists the many sources of information for heat loads and thermal analyses. Special considerations for the high heat loads at 2 K with CW operation are described in section 8.2 of this document.
MLI	Evacuated multi-layer insulation (MLI) is used within the cryomodule on the thermal radiation shield, piping, and helium vessels. MLI on colder piping and vessels under the thermal radiation shield, while not very effective in terms of reducing overall heat load, greatly reduces boiloff rates from loss of vacuum incidents, in turn reducing emergency venting pipe and valve size requirements.
Electric heaters	Eight electric heaters for 2 K flow and pressure control are installed. Four are on cavity helium vessels and four on 2-phase pipe chimney connections. In order to avoid cold feed-throughs from superfluid helium to insulating vacuum, these heaters are installed on the outsides of the helium vessels. The presence of a steady-state pressure drop results in a pressure change at the cryomodule with a change in flow rate (e.g. due to heat load change or liquid level control valve position change), even with constant cold compressor inlet pressure (perfect cryoplant pressure regulation). Heaters

Feature	Notes
	distributed within the cryomodules are required to compensate for heat load changes so as to control subsequent flow and pressure changes.
Tuner	Cables are thermally intercepted at the 45 K level. Special attention is given to thermal intercepting of the piezo actuator wires and housing so as to assure piezo temperatures remain below 80 K, to improve lifetime and performance.
RF power input coupler	Input coupler thermal intercepts are provided at 5 K and at 45 K. Estimated input coupler heat loads (per coupler) are 0.09 W at 2 K, 0.41 W at 5 K, and 14.00 W at 45 K. (to be verified)
Cryogenic valves	Valves appropriate for low temperature helium cryogenic service with thermal intercepts at the 45 K level and bellows stem seals are used. Valves are sized and have control characteristics based on the anticipated operating flow rates with allowance for worst-case conditions such as cool-down, warm-up, or recovery from some other upset condition.

10.2 Design for large 2 K heat transport and helium flow

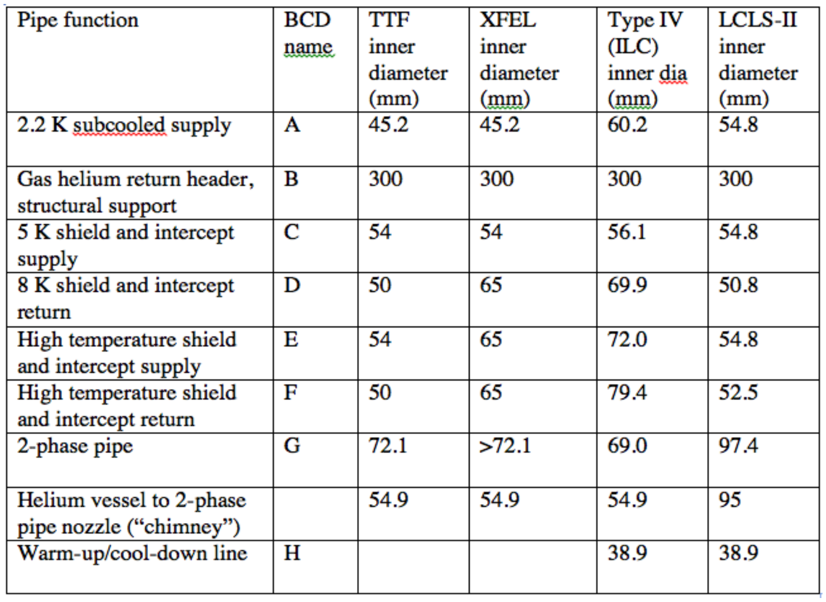
Heat from the outside surface of the niobium RF cavity, and heat entering via conduction from the beam pipe at the RF cavity ends, is carried through stagnant saturated Helium II to the liquid helium surface in the 2-phase pipe via superfluid heat transport. For heat transport through saturated superfluid helium around 2.0 K, 1 W/cm^2 is a conservative rule for a vertical pipe. The critical heat flux for a non-vertical pipe connection from the helium vessel to the 2-phase pipe may be considerably less than 1 W/cm^2. Configurations other than vertical require analysis to verify that the anticipated heat flux is less than the critical heat flux. Also, temperatures above 2.0 K result in a lower critical heat flux due to reduced superfluid heat transport. For LCLS-II, these considerations have resulted in our increasing the inner diameter of the nozzle (or “chimney”) as described in LCLSII-4.5-EN-0851, Helium II Heat Flow from 3.9 GHz Helium Vessel.

Maximum allowable pressure for emergency venting, combined with distances to relief devices influence line sizes. Helium piping and vessels vent into the adjacent cryomodules and out to the distribution system, allowing placement of all process relief valves in the distribution system.

Loss of vacuum venting: pressure in the helium vessel of the dressed cavity less than the cold maximum allowable working pressure (MAWP) of the helium vessel and dressed cavity. Venting path includes nozzle from helium vessel, 2-phase pipe, may include gas return pipe, and also includes any external vent lines. Worst-case heat flux to liquid helium temperature metal surfaces with loss of vacuum to air is assumed to be 4.0 W/cm^2. Worst-case heat flux to liquid helium temperature surfaces covered by at least 10 layers of multi-layer insulation (MLI) is assumed to be 0.6 W/cm^2.

Finally, we match cryomodule and cryogenic distribution system design to the cryogenic plant in terms of providing flow rates, temperatures, and pressures consistent with cryogenic plant requirements. Pipe sizes with comparison to similar cryomodule designs are summarized in Table 11.

Table 11. Cryomodule pipe size comparison



Pipe function	BCD name	TTF inner diameter (mm)	XFEL inner diameter (mm)	Type IV (ILC) inner dia (mm)	LCLS-II inner diameter (mm)
2.2 K subcooled supply	A	45.2	45.2	60.2	54.8
Gas helium return header, structural support	B	300	300	300	300
5 K shield and intercept supply	C	54	54	56.1	54.8
8 K shield and intercept return	D	50	65	69.9	50.8
High temperature shield and intercept supply	E	54	65	72.0	54.8
High temperature shield and intercept return	F	50	65	79.4	52.5
2-phase pipe	G	72.1	>72.1	69.0	97.4
Helium vessel to 2-phase pipe nozzle (“chimney”)		54.9	54.9	54.9	95
Warm-up/cool-down line	H			38.9	38.9

10.3 Maximum allowable working pressures (from Cryomodule FRS, LCLSII-2.5-FR-0053-R1)

Table 12. Maximum allowable working pressures

Region	**Warm MAWP (bar)**	**Cold MAWP (bar)**
2 K, low pressure space	2.05	4.10
2 K, positive pressure piping (separated by valves from low P space)	20.0	20.0
5 K piping	20.0	20.0
45 K piping	20.0	20.0
Insulating vacuum space	1 atm external with full vacuum inside 0.5 positive differential internal	
Cavity vacuum	2.05 bar external with full vacuum inside 0.5 positive differential internal	4.1 bar external with full vacuum inside 0.5 positive differential internal
Beam pipe vacuum outside of cavities	1 atm external with full vacuum inside 0.5 positive differential internal	1 atm external with full vacuum inside 0.5 positive differential internal

10.4 Instrumentation

The cryomodule must be instrumented with liquid level probe (or probes) for the 2-phase helium II system, thermometry for cool-down and monitoring of critical input coupler, HOM coupler, and other instrumentation as listed in "LCLS-II 3.9GHz CM Instrumentation List”.

10.5 Cryomodule test requirements. The cryomodule will be tested before installation in the linac. Tests will check the following:

- Leak and pressure tests for quality assurance and FESHM compliance.
- Temperature profiles
- Approximate heat loads
- RF cavity performance
- Tuner performance
- Instrumentation

10.6 Pressure stability at the 2 K level

It is possible to generate pressure pulses within a cryomodule, for example via heat input from the warm end of a closed pipe. Hence we have a requirement to avoid “dead-headed” lines which can warm up, for example, the line terminating at the closed cool-down valve after it is closed. To avoid a warm valve providing such a warm termination on the closed pipe, one solution is to locate the valve lower than the supply pipe such that cold helium sits on the valve. This is implemented for the LCLS-II cryomodule valves.