LCLS-II 1.3 GHz CRYOMODULE DESIGN – MODIFIED TESLA-STYLE CRYOMODULE FOR CW OPERATION*

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Abstract

We will present the design of the 1.3 GHz cryomodule for the Linear Coherent Light Source upgrade (LCLS-II) at SLAC. Fermilab is responsible for the design of this cryomodule, a modified TESLA-style cryomodule to accommodate continuous wave (CW) mode operation and LCLS-II beam parameters, consisting of eight 1.3 GHz superconducting RF cavities, a quadrupole-corrector magnet package, and instrumentation. Thirty-five of these cryomodules, approximately half built at Fermilab and half at Jefferson Lab, will become the main accelerating elements of the 4 GeV linac. The modifications and special features of the cryomodule include: thermal and cryogenic design to handle high heat loads in CW operation, magnetic shielding and cool-down configurations to enable high quality factor (Q0) performance of the cavities, liquid helium management to address the different liquid levels in the 2-phase pipe with a 0.5% SLAC tunnel longitudinal slope, a support structure design to meet California seismic design requirements, and with the overall design consistent with space constraints in the existing SLAC tunnel. The prototype cryomodule assembly will begin in September 2015 and is to be completed in March 2016.

INTRODUCTION

The LCLS-II main linac cryomodule is based on the XFEL design, including TESLA-style superconducting accelerating cavities, with modifications to accommodate CW operation and LCLS-II beam parameters [1]. 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, shown in Fig. 1.

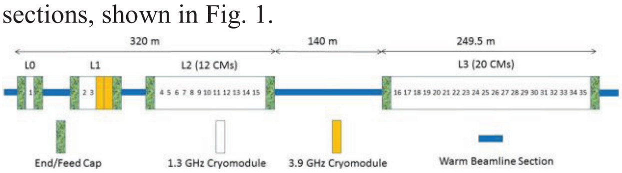

Figure 1: LCLS-II Linac with cryomodules in sections.

The cryomodule houses eight superconducting cavities which are operated at 2 K, and it provides mechanical support and thermal insulation to the RF cavities. These 9-cell, 1.3 GHz cavities with an envisaged Q0 of $2.7\text{x}10^{10}$ will provide an energy gain of 16 MV/m. The cryomodule installed "slot length" is 12.222 m.

The general layout of the module is shown in Fig. 2.

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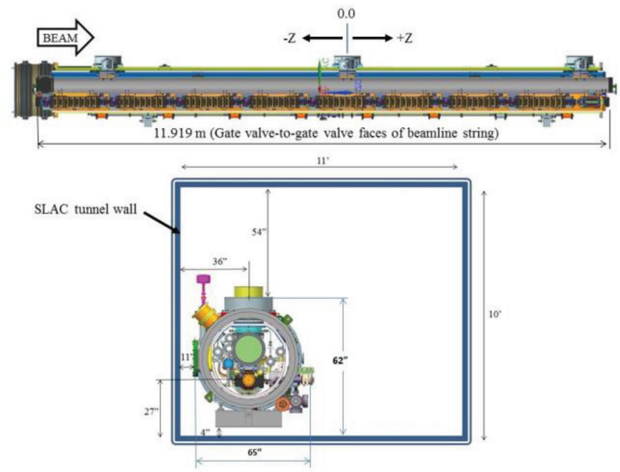

Figure 2: LCLS-II 1.3 GHz cryomodule.

The high Q0 requirement and CW operation drive some modifications for the LCLS-II module with regard to the TESLA-style module. The major features of the LCLS-II cryomodules are listed in Table 1.

Table 1: Major Features of the LCLS-II Cryomodules

Key Requirement	**Major Features**
Series configuration	Continuous insulating vacuum; no external parallel transfer line; cold beam pipe through the interconnect
0.5% longitudinal tunnel slope	One 2 K supply valve in each module for individual steady-state management of helium liquid level
Retention of high Q0 cavity performance	Active external magnetic field cancellation coils provide magnetic shielding and residual field of ≤5 mG at the cavities; a cool-down/warm-up cryogenic valve in the closed-ended cool-down circuit in each module provide high thermal gradient during cool-down through 9.2 K transition temperature to minimize flux trapping; using non-magnetic materials in the module
Seismic safety	Comply with SLAC seismic loading requirements under various accelerations and oscillatory modes
Removal of high heat loads in CW operation	Increased size and closed-ended 2-phase pipe allows sufficient conduction of the heat from the cavities through the superfluid helium; copper plating on beamline components; improved thermal intercepts at 5 K and 45 K

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MECHANICAL DESIGN

The overall structural design of the LCLS-II cryomodule is similar to that of the TESLA-style module, shown in Fig. 3. The 5 K radiation shield is omitted not only for cost saving, but also due to the large dynamic heat at 2 K making such a thermal shield of a marginal value.

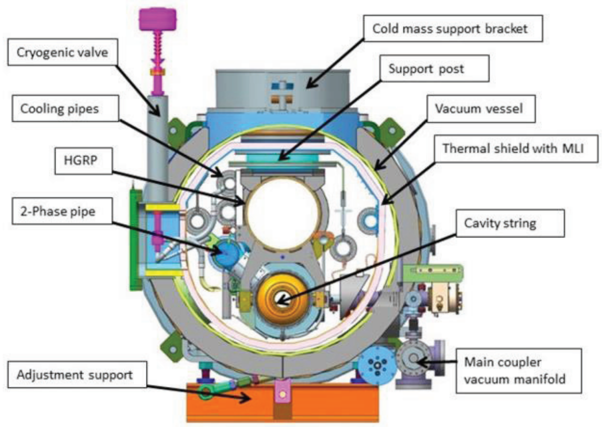

Figure 3: Cross-section of the cryomodule showing its major sub-assemblies.

Cavity Beamline String

The beamline string in each cryomodule consists of eight RF cavities. At the downstream end are combined focusing and steering magnets and a beam position monitor (BPM). The beamline terminates at each end with an all-metal gate valve. Between these two gate valves is a Beam line higher-order-mode (HOM) absorber. Active control of the cavity resonant frequency is provided by an end-lever tuner with motor and piezo-driven components. Each RF cavity is independently powered through a fundamental power coupler. The beamline components are shown in Fig. 4. Table 2 gives the descriptions of these components.

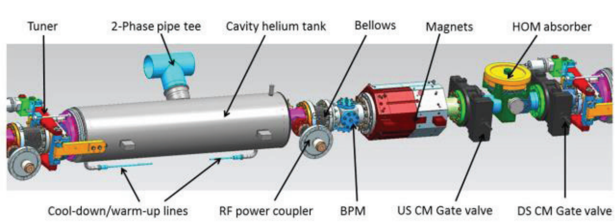

Figure 4: Components in dressed RF cavity and beamline string.

Table 2: Beamline String Components

Component	Description
RF cavity	9-cell XFEL 1.3 GHz cavity
Helium vessel	Large chimney nozzle for CW heat removal, which also provides the material transition from the titanium helium vessel to the stainless steel piping [2]; two symmetrically located cool-down / warm-up supply ports
Tuner	End-lever tuner designed for stiffness, precise tuning, piezo integration, and accessibility; tuner can be accessible through tuner ports on the vacuum vessel
RF power input coupler	Copper plating and improved thermal intercepts at 45 K and at 5 K for CW operation [3]
Magnet package	Split magnet (consisting of quadrupole and two dipole correctors) for assembly onto the beam pipe after cavity string assembly, outside of the clean room
BPM	DESY button-style with modified feedthrough
HOM absorber	XFEL-style, propagating microwaves are absorbed by ceramic ring hanging on the brazed copper stub

Cold Mass Support and Alignment System

The beam-line string is suspended under the helium gas return pipe (HGRP), which acts as the beamline backbone and is supported by three support posts to the vacuum vessel, shown in Fig. 5.

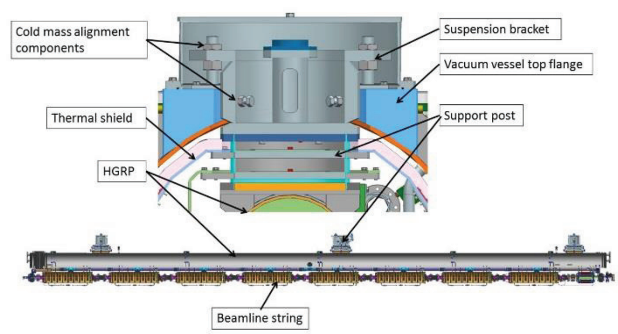

Figure 5: Cold mass support and alignment system.

The support and alignment system provides precision alignment of cavity, quadrupole, and BPM (<0.5 mm RMS). The alignment and push screws on the suspension brackets provide the positional adjustment of the beamline to the vacuum vessel at room temperature. The adjustment mechanism is enclosed in the insulating vacuum space; the beamline alignment is set relative to the survey fiducials on the vacuum vessel during module assembling process and will be maintained during the module thermal and pressure cycling.

On the vacuum vessel there are ports for instrumentation, RF power couplers, vacuum pump-out, cryogenic valves, tuner access and safety relief.

Differential Thermal Contractions and Expansions

To accommodate the HGRP thermal contraction at cold relative to the vacuum vessel, the two side post brackets are slide-able over the top flanges while the central post bracket is locked in position. The needle bearing structure on the side post brackets provides frictionless movement of the cold mass in the module axial direction during thermal cycling.

RF cavities are supported through four lugs on the helium vessel to the HGRP bottom hangers with C-shaped needle clamps, shown in Fig. 6. The cavities are anchored in position longitudinally via a clamp to an invar rod. The C-shaped needle clamps with bearing structure for the cavity, magnet package and gate valve mounts allow beamline frictionless movement with respect to the HGRP during thermal cycling.

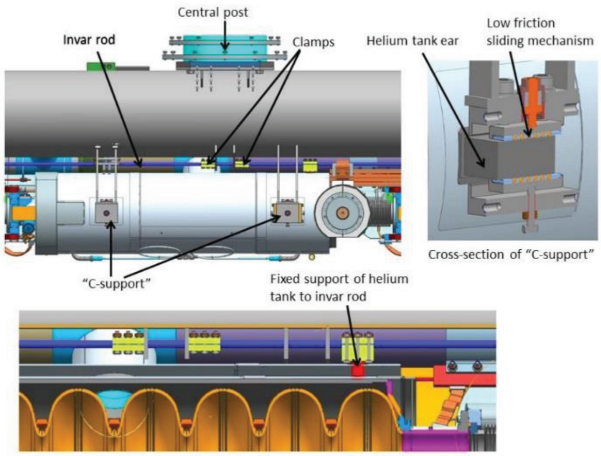

Figure 6: Support system of cavity helium tank to the HGRP and invar rod.

Support system stiffness is analyzed and verified to minimize cavity vibration and coupling of external sources to cavities.

CRYOGENIC AND THERMAL DESIGN

The cryomodule provides cryogenic fluid or gas to the superconducting RF cavities and also provides thermal insulation to the cold mass.

Cryogenic Design

Heat from the outside surface of the 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. Evaporation from the surface of the saturated helium liquid results in vapor flow within the 2-phase pipe over the liquid surface to an exit port connecting to the HGRP.

The cryogenic system of the module consists in principle of four different circuits, listed in Table 3.

The scheme of cryogenic flow is shown in Fig. 7.

Figure 8 illustrates the cryogenic pipe positions and labels.

Pressure drops within and through the module have been analyzed in combination with the helium distribution system. Pipes are sized for the worst case among steady-state, peak flow rates, upset, cool-down, warm-up, and venting conditions. Table 4 lists the parameters of the cryogenic pipes in the module.

Table 3: Cryogenic Circuits in the Cryomodule

Circuit	Description
2K	Provides 2K liquid helium to the cavities with a valve for liquid supply in each module. The RF cavities are maintained within 1.8 K to 2.1 K range by means of a stagnant bath of saturated liquid helium
Cool-down /warm-up	A cool-down/warm-up valve and closed-ended piping for cool-down /warm-up of individual module, to provide high thermal gradient during cool-down through 9.2 K transition temperature to minimize flux trapping
5 K	A helium circuit 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, and instrumentation wires
45 K	A helium circuit in the temperature range of 35 K to 55 K, provides conductive thermal intercepts to the thermal radiation shield, and to tuner piezo actuator wires and housing, RF power coupler, HOM absorbers, cryogenic valves, and instrumentation wires

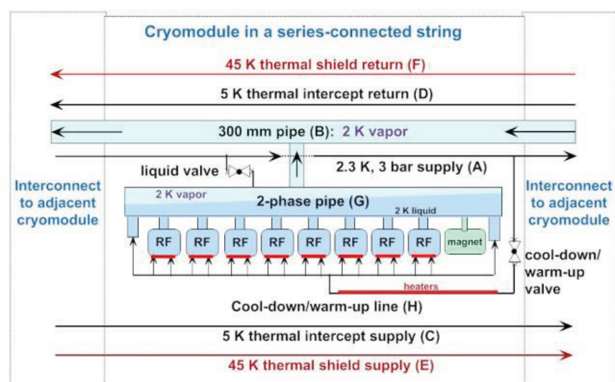

Figure 7: Scheme of cryogenic flow in the module.

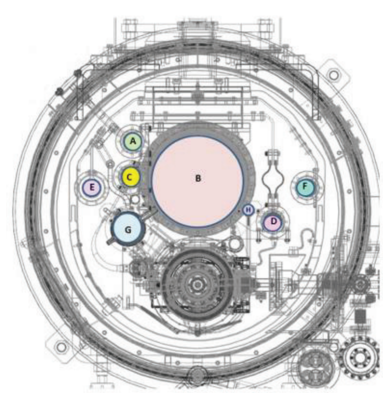

Figure 8: Cryogenic pipe positions and labels.

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Table 4: Cryogenic Pipes in the Cryomodule

Line	Size ID (mm)	Description	Working Pressure (bar)	Design Pressure (bar)
A	54.8	2 K supply	3	20
B	300	HGRP	0.031	2.05 warm 4.10 cold
C	54.8	4.5 K supply	3	20
D	50.8	8 K return	2.8	20
E	54.8	35 K supply	3.7	20
F	52.5	55 K return	2.7	20
G	97.4	2 K-2 phase	0.031	2.05 warm 4.10 cold
H	38.9	Cool-down /warm-up	3	20

In order to accommodate the relatively large per-cryomodule heat load of 80 W or more at 2 K and the 0.5% SLAC tunnel slope, a large diameter of the 2-phase pipe (Line G in Fig. 8) is selected. With the pipe closed at each end and a 2 K supply valve for each cryomodule, it is possible to adequately control helium mass flow and helium inventory in each cryomodule. The influence of the slope of the SLAC tunnel on liquid helium level in this larger 2-phase line is illustrated in Fig. 9.

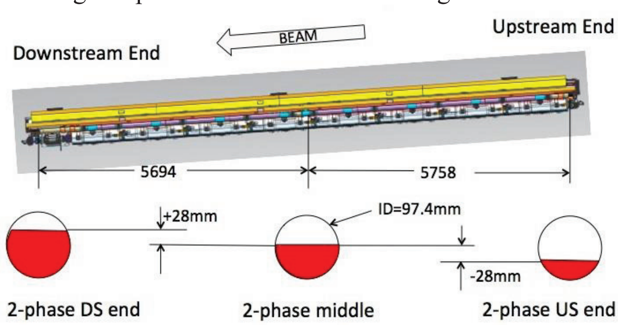

Figure 9: Liquid helium levels in the 2-phase pipe with 0.5% SLAC tunnel slope, with pipe sized to accommodate liquid levels both downstream and upstream.

Stresses in piping, piping stability with respect to pressure loads, taking into account forces resulting from the use of bellows are analyzed and verified. The design and fabrication of piping comply with pressure vessel code. Each helium vessel includes an electric heater to compensate for heat load changes so as to control subsequent flow and pressure changes.

Thermal Insulation

The module thermal insulation is provided to minimize the thermal conduction, convection and radiation from the room temperature environment to the cold components, shown in Fig. 10. Table 5 describes the thermal insulation in the module design.

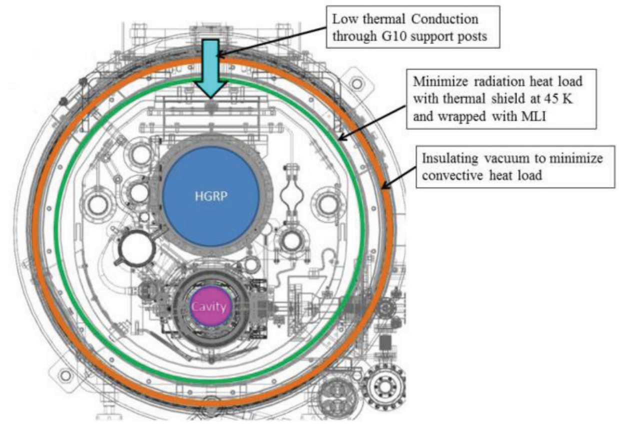

Figure 10: Cryomodule thermal insulation.

Table 5: Module Thermal Insulation Design

Sub-system	Description
Insulating vacuum	Vacuum vessel provides an insulating vacuum in the range of 1.0 x 10^{-4} Pa to minimize convective heat loads to the cold mass
Thermal shield and MLI	The radiation heat loads are reduced by operating the shield at 45 K and wrapping it with 30 layer multilayer insulation (MLI) blankets; 10 layers of MLI are used on colder piping and helium vessels
Support with low thermal conduction	Thermal conduction is minimized by employing a low thermal conduction composite material G10 tube in the support posts

Thermal intercepts are used for various components to intercept significant heat loads at intermediate temperatures above 2.0 K to the extent possible in full CW operation.

Each support post is an assembly of a low thermal conduction composite material tube and four stages of shrink-fit aluminum or stainless steel discs and rings for thermal interception at room temperature, 45 K, 4.5 K and 2 K, respectively.

In summary, Table 6 lists the materials and sizes of major components of the module.

Table 6: Material and Size of Module Major Components

Components	Material
Vacuum vessel	Carbon steel A516 GR. 60 Φ965.2 mm, 9.5 mm wall
HGRP	Stainless steel 316L Φ312 mm, 6 mm wall
Support post	G10 fiberglass tube Φ300 mm, 2.2 mm wall
Thermal shield	Aluminium 1100-H14 6.35 mm/3.175 mm sheets
Cryogenic manifolds	Stainless steel 316L

MODULE TUNNEL INSTALLATION

The cryomodule will be installed in the SLAC tunnel in series to make the linac sections. With the exception of the single module in L0, all other 1.3 GHz cryomodules are identical with standard interconnects. Seismic analyses were performed to ensure that the module will be able to survive the design level earthquake, without causing any structure safety hazard.

Module Interconnects

An inter-module unit is to be installed between adjacent modules, shown in Fig. 11.

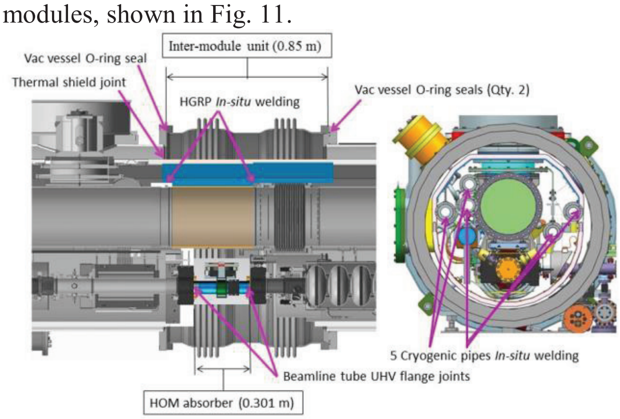

Figure 11: Cross-sectional views showing inter-module connections.

The connections of each subsystem need to be made *in-situ* and each has its distinct requirement, listed in Table 7.

Table 7: Requirements of each Sub-system Inter-connect

Sub-system	Type of Joint
HGRP	Welding, pressure piping code compliance
Cryogenic pipes (5 lines)	Welding, pressure piping code compliance
Beamline tube	Particle free ultrahigh vacuum flange joints
Thermal shield	Connection with fasteners, good thermal conduction
Vacuum vessel	O-ring flange joints, vacuum seal

The outer shell of the inter-module unit can slide over the vacuum vessel to allow space for making the internal joints. Bellows are used to mechanically decouple the modules and allow for thermal contraction or expansion during thermal cycling.

Module Support Stands and Seismic Safety

The module support and stands are designed to provide a complete load path from the cold mass to vacuum vessel, and to the tunnel floor. The embedded stainless steel plate in the adjustable module support will be surveyed and anchored with Hilti anchors to the tunnel floor at a fixed elevation offset to the beamline center line. A pair of seismic restraints are used to secure each stand. The mechanism of the module positional adjustment and the support attachment to the floor are shown in Fig. 12.

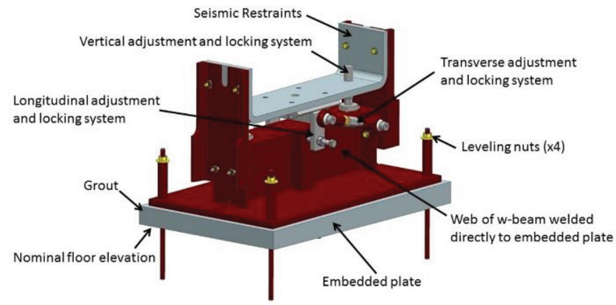

Figure 12: Cryomodule adjustable support stand and its attachment to the tunnel floor.

The cryogenic pipes are securely supported to minimize the possibility of rupture during an earthquake.

Insulating vacuum is protected from over pressurization by means of a spring-loaded lift plate. Provisions are provided to allow free passage of the helium out past thermal shield and MLI to the lift plate.

STATUS

Towards the construction of the prototype cryomodule, major components have been fabricated. The prototype assembly process is starting in September 2015, and is to be finished and ready for test in March 2016 [4].

ACKNOWLEDGMENTS

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REFERENCES

[1] M. Ross, “SRF Linac for LCLS-II: Design Approaches, R&D and First Test Results”, MOBA01, these proceedings, SRF2015, Whistler, Canada (2015).
[2] J. Kaluzny, et al., “Stainless Steel to Titanium Bimetallic Transitions”, presented at the 2015 Cryogenic Engineering Conference, June, 2015.
[3] K. Premo, et al., “LCLS-II Foundamental Power Coupler Mechanical Integration”, THPB086, these proceedings, SRF2015, Whistler, Canada (2015).
[4] T. Arkan, et al., “LCLS-II cryomodule design integration and assembly at Fermilab”, TUPB110, these proceedings, SRF2015, Whistler, Canada (2015).

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