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# Introduction

Fermilab and Jefferson Lab are collaborating with SLAC on their LCLS-II upgrade project by supplying SRF design and fabrication expertise [[1](#_References)]. The accelerating structures will utilize superconducting RF cavities packaged in cryomodules based on the design developed for the European XFEL and the ILC. The cryomodule design will be modified to allow operation in the CW mode.

The cryomodule design incorporates internal cryogenic distribution piping and therefore will not require an external cryogenic transfer line. This accelerator will be housed in an existing tunnel the size of which does not allow for an external transfer line. As a result, the linac will be divided into two long strings of cryomodules by centrally locating the cryogenic refrigeration system.

This document provides the functional requirements to be used for the design, fabrication, testing, installation and commissioning of the superconducting RF cryomodules in support of the SLAC National Accelerator Laboratory LCLS-II project.

# Definitions

|  |  |
| --- | --- |
| CW | Continuous wave operating mode |
| FNAL | Fermi National Accelerator Laboratory |
| ILC | International Linear Collider |
| ISO | International Organization for Standardization |
| JLab | Thomas Jefferson National Accelerator Facility |
| JT | Joule-Thomson effect, fluid temperature change due to a throttling process |
| LCLS-II | Linac Coherent Light Source upgrade |
| MAWP | Maximum Allowable Working Pressure, a term that is used to define the safe pressure rating of a component or system |
| SLAC | SLAC National Accelerator Laboratory |
| SRF | Superconducting Radio Frequency |
| XFEL | X-ray Free Electron Laser |

# Scope of Work

## Inclusions

Design, fabrication, testing, installation and commissioning procedures for SRF cryomodules required for a 4 GeV CW electron linac.

Interconnect components required for field installation.

## Exclusions

Non-cryogenic related equipment is excluded from this FRS, e.g. civil structures, RF power sources, controls, shielding, etc.

Cryogenic distribution system including transfer lines to/from the refrigeration system, low temperature heat exchangers, cryogenic feed caps, cryogenic bypasses around warm beamline and cryogenic end caps.

Component(s) required to segment the cryostat or beam vacuum system.

Insulating vacuum pumping system and vacuum instrumentation are outside the scope of the cryomodule supply.

Beam tube vacuum system (pumping and instrumentation) is provided outside of the cryomodule and not part of cryomodule scope.

Beam loss monitoring.

# Key Assumptions, Interfaces and Constraints

1. Necessary enclosures, support structures and utilities are available prior to the installation of the cryomodules
2. Total electron acceleration of 4 GeV with 6% built-in redundancy
3. Temperature levels. There will be three temperature levels of helium cooling in the cryomodules. Designs will allow for any temperatures within the ranges given here.
4. RF cavity: 1.8 K to 2.1 K are possible temperatures, the precise design temperature is to be determined. This level is referred to as “2 K” in this document.
5. A next temperature level will be in the range 4.4 K to 8.0 K. This level is referred to as “5 K” in this document.
6. The highest temperature level will be helium in the range 30 K to 80 K, the precise range yet to be determined. This level is referred to as “70 K” in this document.
7. There will be no liquid nitrogen in the LCLS-II tunnel. However, for test purposes in various test cryostats and facilities, the “70 K” thermal shield may be cooled with liquid nitrogen at approximately 80 K.
8. The following cryomodule goal has been set for the 35 1.3 GHz cryomodules with an accelerating gradient = 16 MV/m.

Q0 ≥ 2.7 x 1010 at an operating temperature = 2 K

This results in the following cryomodule nominal heat load.

Nominal

2 K Static 6 [W]

2 K Dynamic 80 [W]

Cold intercept (5 K) circuit 22 [W]

Warm shield (70 K) circuit 184 [W]

Then we apply the following factors:

Static heat load uncertainty factor = 1.30

Dynamic heat load uncertainty factor = 1.10

This results in the following weighted cryomodule heat load budget.

Maximum (with uncertainty factor)

2 K Static 7.8 [W]

2 K Dynamic 86 [W]

Cold intercept (5 K) circuit 26 [W]

Warm shield (70 K) circuit 222 [W]

The value of Q0 ≥ 3 x 1010 represents the current state of the art for single cell cavities at 16 MV/m at 2K. If this average value is determined to be unachievable in completed and installed cryomodules, the following options, or combination of options, are available to the project:

1. Operate within the cryoplant overcapacity factor
2. Operate with less installed accelerating gradient redundancy
3. Operate at reduced gradient and more cryomodules
4. Operate at lower temperature
5. Install more refrigeration capacity
6. Indoor storage of cryomodules is available on-site prior to installation
7. Controls system is provided elsewhere
8. Electrical grounding is determined and provided elsewhere
9. Cryomodule magnet’s power leads are conductively cooled
10. Cryomodule cool down and warm up limitations

Applies to warm shield and cavity circuits

* 1. Rate limit < 10K/hour
	2. ΔT limit <50K longitudinally
	3. ΔT limit <15K radially in 300 mm gas return pipe
1. The cryomodules will be housed in a tunnel enclosure which has a 0.5% longitudinal floor slope (lower toward the east) and 0.6° transverse floor slope (lower toward the south).
2. The JT heat exchanger will be supplied externally as a part of the cryogenic distribution system
3. Each cryomodule will have its own JT valve supplying LHe to its cavities
4. Distribution of cryogenic circuits is internal to the cryomodule
5. SLAC will install two surveyed plates into the tunnel floor for each cryomodule to a precision relative to the beam line that will allow final alignment using the stand range specified under Requirements. The plate will accommodate a means for locking down the cryomodule stand consistent with the seismic requirements.

# Requirements

## General

1. The system is expected to operate for 20 years
2. The cryomodules are subject to comply with Fermilab ES&H Manual (FESHM), in particular, FESHM chapters 5031, 5031.1, 5031.6, 5032, 5033
3. System will be manufactured using industry accepted QA procedures and standards
4. ISO accepted testing procedures and standards shall be used for system and component tests
5. An external lug will be supplied for connection of an electrical grounding cable.

## Operating

1. 1.3 GHz accelerating structures
2. Operating Parameters (nominal and tolerances)

Operating pressures

Cavity bath – P ≥ 1600 ± 20 [Pa]

Cold intercept circuit – 0.3 ≤ P ≤ 1.8 [MPa]

Warm shield circuit – 0.3 ≤ P ≤ 1.8 [MPa]

Operating temperatures

Cavity bath – at saturation [1.8 K ≤ T ≤ 2.1 K]

Cold shield circuit – (5.0 ± 0.5) ≤ T ≤ (8 ± 0.5) [K]

Warm shield circuit – (30 ± 5) ≤ T ≤ (80 ± 5) [K]

## Mechanical

1. Seismic

Seismic loading requirements are per SLAC-I-720-0A24E-001 Seismic Design Specification for Buildings, Structures, Equipment and Systems: 2014 and the 2013 California Building Code based on a Category II.

1. Stand requirements
	1. The fully assembled cryo-module supports should be powder coated to protect against corrosion due to tunnel leakage.
	2. Care should be taken to protect powder coating during transportation, lifting and rigging.
	3. The stand will be nominally installed in its neutral position and have the following adjustability:

Longitudinal (Z) ±0.5”

Transverse (X) ±0.5”

Vertical (Y) ±0.5”

1. Alignment

Cavity and magnet positioning will be transferred to a retroreflector survey system on the outside of the cryomodule. Cavity and magnet alignment relative to the external survey system will be to within 0.5 mm (rms).

1. Shipping [[2, 3](#_References)]
2. Provisions will be made to limit the loads seen by the Cryomodule to
	1. Maximum transmitted vertical shock acceleration < 1.5 g
	2. Maximum transmitted transverse shock acceleration < 1.5 g
	3. Maximum transmitted longitudinal shock acceleration < 1.5 g
3. A bonded and insured transport company shall be used.
4. All overland transport shall be on air-ride suspension trucks
5. Shock recording shall be provided on the cryomodule as well as on the shipping container.
6. Rigging
7. SLAC requires swivel hoist rings and/or lifting fixture when lifting with an overhead crane. [[4](#_References)]
8. Lifting fixtures will go through a design review and load test. A written and reviewed lifting procedure is required at SLAC [[5](#_References)]. Any design of lifting hoisting/lifting arrangement is governed by: DOE-STD-1090-2007, DOE Standard for Hoisting and Rigging. Four lift points on each Cryomodule are preferred. The lift attachment point must be above the calculated Cryomodule Center of Gravity. Past experience shows that a cryomodule experiences maximum rigging shocks during lifting and landing with a crane from a flat surface. In to minimize the shocks, the lifting fixture must have an adjustable center of gravity feature so that the modules center of gravity can be adjusted in the raised position. The cryomodule shall never be put on a hard surface (cement or wood cribbing) in order to minimize the shocks. A synthetic/composite soft but strong compressive strength cribbing material is recommended.
9. Electronic assembly travelers (high level assembly and sub-assemblies) shall be used throughout the production of the cryomodules. The travelers will detail step by step assembly, quality assurance tasks and procedures. Lead cryomodule production engineer shall ensure that the travelers are followed strictly. Each step of the traveler will have a date and person name stamp in order to monitor and record the assembly tasks. Quality assurance steps shall be gated steps and that the assembly shall not proceed unless the gate is cleared. Nonconformance reports (NCR) and Discrepancy reports shall be used and shall be gated steps as well.

## Cryogenic

1. Anchoring and thermal contraction of each cryogenic circuit will consider worst case pressure, temperature and alignment extremes
2. All cryogenic circuits will be designed to allow cool down or warm up independent of the state of other circuits
3. Cryomodule MAWP:

|  |  |  |
| --- | --- | --- |
| **Region** | **Warm MAWP (bar)** | **Cold MAWP (bar)** |
| 2 K, low pressure space  | 2.0 | 4.0 |
| 2 K, positive pressure piping (separated by valves from low P space) | 20.0 | 20.0 |
| 5 K piping  | 20.0 | 20.0 |
| 70 K piping  | 20.0 | 20.0 |
| Insulating vacuum space  | 1 atm external with full vacuum inside0.5 positive differential internal |  |
| Cavity vacuum  | 2.0 bar external with full vacuum inside0.5 positive differential internal | 4.0 bar external with full vacuum inside0.5 positive differential internal |
| Beam pipe vacuum outside of cavities | 1 atm external with full vacuum inside0.5 positive differential internal | 1 atm external with full vacuum inside0.5 positive differential internal |

1. The cryomodule system in combination with the distribution system shall provide for protection from over pressure of all circuits
2. Helium piping and vessels shall be protected from exceeding their MAWP by means of relief valves and/or rupture disks in accordance with pressure vessel and piping standards.
3. Worst-case localized heat flux to liquid helium temperature metal surfaces with loss of vacuum to air shall be assumed to be 4.0 W/cm2 [[6](#_References)]. Longitudinal effects due to cryopumping and finite air influx will be considered when determining the affected area at any instance of time.
4. Worst-case localized heat flux to liquid helium temperature surfaces covered by at least 5 layers of multi-layer insulation (MLI) shall be assumed to be 0.6 W/cm2 [[6](#_References)]. Longitudinal effects due to cryopumping and finite air influx will be considered when determining the affected area at any instance of time.
5. Consideration of back pressure and flow resistance from vent discharge lines and piping downstream of the relief valves must be included in the design.
6. Relief valves and rupture disks for helium will be part of a vent piping system for ducting helium from the tunnel and most likely will not be mounted directly on the cryomodules or distribution system.
7. The insulating vacuum is to be protected from over pressurization by means of a spring-loaded lift plate.
8. Worst case piping ruptures internal to the insulating vacuum shall be analyzed to determine lift plate size.
9. Provisions shall be provided to allow free passage of the helium out past thermal shield and MLI to the lift plate.
10. Thermal shields and thermal intercepts
11. There shall be one level of radiative thermal shield at the nominally 70 K level.
12. A thermal radiation shield at the 5 K level is not included.
13. Thermal intercepts at the 5 K level shall be available for the support structure, input couplers, warm-to-cold beam tube transitions in the distribution system, and higher order mode (HOM) absorbers, if any.
14. Thermal intercepts at the 70 K level shall be available for support structures, input couplers, instrument wires, tuner wires, RF cables, liquid supply valve, warm-to-cold beam tube transitions, and any other components of the cryomodule for which interception of heat at a higher level than 2 K is beneficial.
15. The thermal shield shall be 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.)
16. Thermal shield trace piping shall be arranged such that counter flow heat transfer does not inhibit cool-down of the thermal shield.
17. System insulating vacuum, thermal shield, and thermal intercept system shall provide for reasonable static heat load
18. Instrumentation necessary to measure all warm up or cool down constraints
19. The cryogenic circuits shall be supplied with flanged connections for individual cryomodule testing which can be removed for welded connection in the tunnel

## Beam tube requirements

1. Beam tube extensions between cavities and at cryomodule ends are to be “particle free” and cleaned for UHV like the cavities themselves.
2. Attachments to the beam tube, such as vacuum valves and beam position monitors are to be clean and “particle free”. Particle free UHV cleaning and work standards need to be strictly followed.
3. An evaluation of the RF characteristics of the bellows and any beam pipe cross section changes or asymmetries will be required prior to the preparation of the cryomodule Engineering Specification Document.

## Cryomodule insulating vacuum system

1. Vacuum vessel provides the insulating vacuum space
2. Evacuated multi-layer insulation (MLI) shall be used within the cryomodule
3. MLI shall be used on the thermal radiation shield
4. MLI shall be used on colder piping and vessels under the thermal radiation shield to reduce boil-off rates from loss of vacuum incidents. In the case of the helium vessel, MLI will be installed on the helium vessel, under the outer layer of magnetic shielding.

## Coupler vacuum requirements

UHV standards need to be followed. Components need to be cleaned to particle free UHV standards prior installation. The hook up of the pumping manifolds to the valve on the coupler pumping lines shall be done with particle free UHV working protocols. Softwall Class 100 portable cleanrooms shall be used. Oil-free roughing pump, turbo mechanical pump shall be used to pump down the lines and when good vacuum levels are reached (less than 1 x 10 ^-6 Torr) the ion pump installed for individual cryomodules shall be turned. The titanium sublimation pump installed directly on top of the ion pump shall be run to achieve ultra high vacuum levels [[7](#_References)].

## Tuning requirements

The preferred slow/fast tuner is the Saclay-1 type, whose basic parameters are listed below. Similar end lever designs will be considered that provide cost savings, improved lifetime and ease of access (in particular, being able to change out the motor and/or piezo actuators without removing the cold mass from the vacuum vessel).

The reliability of both tuning mechanisms is critical to the linac performance. Assuming that the cryomodules will only be warmed up once every five years, and that failure of either the slow or fast mechanism requires that cavity be detuned and not powered, the lifetimes need to be such that this occurs for less than 6% of cavities during this period.

|  |
| --- |
| TUNER |
| Tuner mechanism | End Lever |
| Tuner stiffness | ~ 40 N/μm |
| Slow Actuator |
| Type | Stepping motor |
| Freq change per step | ~ 1 Hz |
| Range | Several 100 kHz |
| Fast Actuator |
| Type | Piezo Stack |
| Max Voltage (Warm) | 200 V |
| Blocking force | 3 kN |
| Tuning range | ~ 1 kHz |
| Tuning sensitivity | < 1 Hz/V |
| Tuning speed | Up to a few kHz |

## Magnet requirements

The magnet package should generate the quadrupole field for beam focusing, and dipole fields to correct the beam orbit in the vertical and horizontal planes. The main magnet specifications are shown below.

|  |  |  |
| --- | --- | --- |
| Parameter | Unit | Value |
| Integrated peak gradient | T | 1.5 |
| Aperture ≥ | mm | 78 |
| Magnet physical length ≤ | mm | 320 |
| Magnet width and height ≤ | mm | 250 |
| Operating current ≤  | A | 25 |
| Field non-linearity at 5 mm radius ≤ | % | 0.05 |
| Dipole trim coils integrated strength  | T-m | 0.01 |
| Magnetic center offset in cryomodule ≤ | mm | 0.5 |
| Quadrupole azimuthal offset in cryomodule (roll) ≤ | mrad | 0.3 |
| Magnet cooling liquid helium temperature | K | 2.2 |
| Magnet cooling time (same as SCRF) | hours | 44 |

For easy access and installation the magnet package with rigidly attached BPM should be mounted at the end of the cryomodule. The magnet should be splittable in the vertical plane to facilitate magnet mounting around the beam pipe (outside of clean room), and based on the “superferric” configuration with racetrack superconducting coils.

NbTi superconducting coils and current leads are conduction cooled by pure aluminum thermal sinks, and should not have helium vessels. The magnet cooling is provided by the LHe supply pipe.

Each racetrack coil will have a heater to force the coil in the normal condition if the design is shown to not be cryogenically stable.

The magnet package should be installed in the cryomodule using standard SRF cavity supports which provide magnet positioning within the tolerances specified in Table 6.12.1 of the LCLS-II CDR [[1](#_References)]. The installation process should be based on the magnet yoke fiducials, and the quadrupole magnet center position measurements at the room temperature.

All magnets for LCLS-II should be subject to cold tests in the conduction cooling mode including magnetic measurements.

The magnet package should be protected by external dump resistors permanently connected to the windings.

The magnet package should have the following instrumentation: voltage taps for the coil and current leads based on the magnet protection requirements, as well as thermal sensors for each coil.

## Coupler requirements

The table below lists the coupler specifications.

|  |  |  |
| --- | --- | --- |
| **Item** | **Spec** | **Comment** |
| Design | EuXFEL Coupler | 2009 Drawing Package with exceptions noted below |
| Max Input Power | 7 kW CW |  |
| Max Reflected Power from Cavity | 7 kW CW | Assume would run with full reflection |
| Minimum Qext Foreseen | 1e7 | Allows 16 MV/m with no beam and 6.6 kW input, and allows 6 MW beams with 33 kW input |
| Maximum Qext Foreseen | 5e7 | Match for 0.3 mA beams at 16 MV/m, 26 Hz BW  |
| Reduction in Antenna Length | 8.5 mm | Maintain 3 mm rounding |
| Range of Antenna Travel | +/- 7.5 mm | Range measured |
| Predicted Qext Min Range |  3.6e6 – 4.7e6 – 7.5e6 | Assuming +/- 5 mm transverse offsets |
| Predicted Qext Max Range | 1.0e8 – 1.1e8 – 1.5e8 | Assuming +/- 5 mm transverse offsets |
| Warm Section Outer Conductor Plating | 10 um +/- 5 umRRR = 30-80 | Nominal EuXFEL |
| Warm Section Inner Conductor Plating | 100 um +/- 10 umRRR = 30-80 | Modified – Temp Rise < 150 degC for 14 kW |
| Cold Section Outer Conductor Plating | 10 um +/- 5 umRRR = 30-80 | Nominal EuXFEL |
| Center Conductor HV Bias | Optional | Use flex copper rings that can be replaced with existing capacitor rings if HV bias needed |
| Warm and Cold e-Probe Ports Required | No | Do not expect multipacting at low power |
| Warm Light Port Required | No | Do not expect arcs at low power |
| Motorized Antenna | Yes – max step = 50 um | Changes Qext by 1% |
| RF Processing | 7 kW CW with full reflection – vary reflected phase by 180 deg  | For initial couplers, use pulse power processing at SLAC |

## Magnetic shielding requirements

The remnant magnetic field at any SRF cavity surface in the cryomodule must be limited to avoid the significant increase in cavity residual resistance (Q0 degradation) which occurs when magnetic flux is trapped as the cavity is cooled below critical temperature (9.2K). The magnetic shielding must attenuate the Earth’s magnetic field, and the magnetic field generated by all surrounding components, both internal and external to the cryomodule, to Rmag <5 mG at the cavity surface.

To minimize remnant field, no magnetic (μ>1.1) components, such as flanges and bolts, may be used in the cryomodule. The cryomodule-internal magnet shall be designed with low fringe fields, even at maximum operational field. In addition, the magnetic shielding design must account for the shielding holes which are necessary for helium vessel cryogenic piping, mechanical supports, etc. The shielding design shall avoid holes close to the high surface magnetic field region of the cavity equators to the extent possible.

 The as-built magnetic shielding shall be tested to ensure conformity to the specification, for each shielding assembly. Stainless steel components will need to be verified that they have not become magnetized during cutting or welding tasks. A model may be devised to allow a reliable room temperature conformity check for shielding which operates at colder temperatures. Transportation and assembly procedures must be specified to ensure the magnetic shielding material is not subject to mechanical impact.

## Beam Line Absorber Requirements

The beam pipe interconnection region between the cryomodules will include a beam line absorber. Its purpose is to absorb a large portion of the HOM propagating mode power in a ring of lossy ceramic tiles (~ 300 square cm surface area) that are thermally isolated from the 2 K beamline and cooled at 70 K through thermal conduction. With the low LCLS II beam current, the power absorbed in each device is expected to be below the 10 W level for non-resonant mode excitations while it is designed to handle 100 W loads (< 140 deg temperature gradient in the ceramic ring).

## Beam Position Monitor, BPM

The bpm resolution for 100 pC bunches is required to be 10 microns or better in both planes, and the bunch signals need to fully damp down between bunches (one microsecond minimum spacing). The bpm aperture should be larger than the 70 mm cavity iris diameter, which makes achieving this resolution non-trivial. The Saclay reentrant style bpm is being considered as it is designed to be easily cleanable, but its resolution needs to be demonstrated for this application. The mode polarizations needed to be aligned to the bpm geometric axes to a level such that x-y coupling for 1 mm bunch offsets produces a < 5 micron systematic error.

# References

|  |  |
| --- | --- |
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