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Revision History

Revision	Date Released	Description of Change
R1	12/8/2016	Various changes reflecting maturity in design and updated Physics Requirements.
R0	9/28/2015	Original Release.

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1 Purpose

Fermilab and Jefferson Lab are collaborating with SLAC on their LCLS-II upgrade project by supplying SRF design and fabrication expertise [1]. A harmonic linearizer (HL) operating at 3.9 GHz, 3 times the frequency of the LCLS-II main Linac, will be installed between L1 and BC1 (See Figure 1) and used to offset the non-linear sine-wave energy variation along the bunch induced by 1.3 GHz acceleration. The HL section consists of two cryomodules each containing 8 cavities resonating at 3.9 GHz. Table 1 provides the basic parameters. The accelerating structures will utilize superconducting RF cavities packaged in cryomodules based on the design developed for the European XFEL (EuXFEL) and the ILC. The cryomodule design will be modified to allow operation in the CW mode.

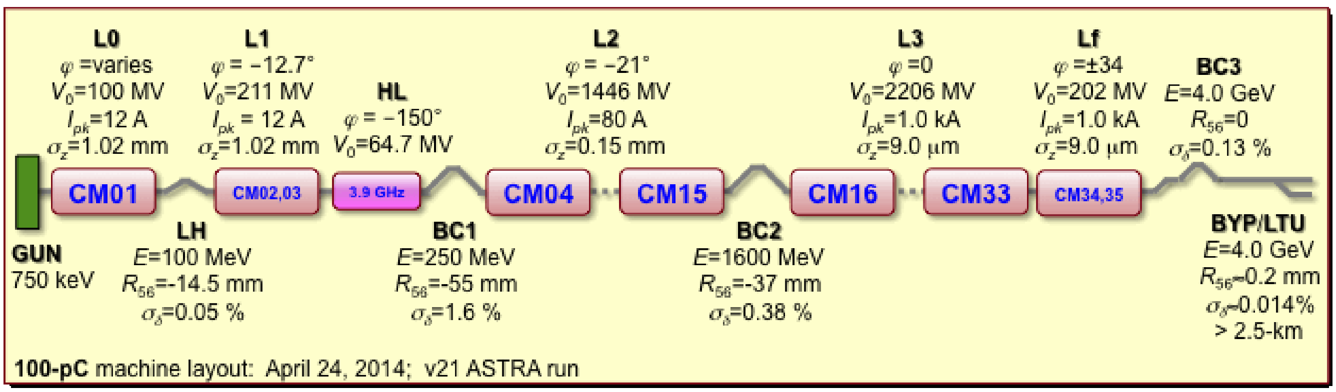

Figure 1: LCLS-II Layout. The magenta box labeled 3.9 is the location of the 3.9 GHz Harmonic Linearizer cryomodules.

The 3.9 GHz cryomodules incorporate many of the features of the 1.3 GHz cryomodules [2] and builds on past experience at Fermilab, DESY, and LASA/INFN on design and operation of 3.9 GHz systems now in operation and proposed. Table 1.1 lists the Functional parameters for the 3.9 GHz cryomodules and is not an exhaustive parameter list. Parameters of a Physics nature are listed in the Physics Requirements document [3].

Table 1-1. 3.9 GHz Functional Parameters.

Parameter	Nominal	Minimum	Maximum	Units
Cavity length (L)	0.346			Meter
R/*Q*	750			Ω
Geometry constant (*G*)	275			Ω

Coarse (slow) tuner range	750			kHz
Fine (fast) tuner range	~1			kHz
Lorentz detuning	≤1.2			$Hz/(MV/m)^2$
Peak detune (with piezo tuner control)	30			Hz
Q_{ext} (fixed)	2.7×10^7	2.4×10^7	3×10^7	
RF beam power per cavity (@ 300 μA)	1.20		1.48	kW
RF power needed per cavity (with overhead)	0.5		.94	kW
Cavity dynamic load (@ 2 K)	14.3 (E_{acc} = 13.4 MV/m, Q0 = 2.0 x 10^9)		23.6 (E_{acc} = 14.9 MV/m, Q0 = 1.50 x 10^9)	W

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. LH will be incorporated into the upstream string.

This document provides the functional requirements to be used for the design, fabrication, testing, installation and commissioning of the 3.9 GHz Harmonic Linearizer superconducting RF cryomodules in support of the SLAC National Accelerator Laboratory LCLS-II project.

2 Scope

Functional Requirements for the 3.9 GHz Cryomodules are presented. Additional detail can be found in the LCLS-II 3.9 GHz Cryomodule Physics Requirements Document [3], the Linac PRD [4], the Cryogenic Systems Integration Functional Requirements Document [5], as well as the Engineering Specification Documents for other cryomodules' components.

3 Definitions

Term	Definition
CW	Continuous wave operating mode

EuXFEL	European X-ray Free Electron Laser
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

4 References

1	LCLS-II Conceptual Design Report
2	1.3 GHz Superconducting RF Cryomodule FRSD, LCLSII-2.5-FR-0053-R1
3	SCRF 3.9 GHz Cryomodule PRD, LCLSII-4.1-PR-0097-R2
4	Linac Requirements PRD, LCLSII-2.4-PR-0041
5	Cryogenic Systems Integration FRSD, LCLSII-4.1-FR-0327-R1
6	LCLS-II Cryogenic Heat Load, LCLSII-4.5-EN-0179
7	Worker Safety and Health Program, 10 C. F. R. Part 851, February 9, 2006.
8	Pressure Safety Requirements per ES&H Manual Chapter 14, LCLS-II-1.2-EN-0020-R1.
9	Fermilab ES&H Manual, http://esh.fnal.gov/xms/ESHQ-Manuals/FESHM
10	Seismic Design Specifications for Buildings, Structures, Equipment, and Systems: 2011, SLAC-I-720-0A24E-001-R003, October 3, 2011. 8
11	3.9 GHz Cryomodule Crating and Shipping Specification, Fermilab 1353-ES-296438-B, February 24, 2009
12	Transportation of Cryomodules, DESY EV 010-04-S1, September 27, 2007
13	Hoisting and Rigging, SLAC-I-720-0A29Z-001-R023.3, September 4, 2013
14	Hoisting and Rigging Review of Conformance Form, SLAC-I-730-0A21J-021-R002, August 31, 2009
15	Cryomodule Design Heat Flux for Vacuum Failures, LCLSII-4.5-EN-0214
16	Producing Very Low Particle UHV Vacuum Components, Fermilab ADDP-ME-000145
17	ASTA Beamline Vacuum Specification, Fermilab ED0000572.
18	ASTA Beamline Vacuum Certification Specification, Fermilab ED0000573
19	Design & Test of the Prototype Tuner for 3.9 GHz SRF Cavity for LCLS II Project, MOPOB32 at NAPAC 2016
20	Beam Position Monitor Physics Requirements Document, LCLSII-2.4-PR-0136-R2.

5 Key Assumptions, Interfaces and Constraints

(a) Necessary enclosures, support structures and utilities are available prior to the installation of the 3.9 GHz cryomodules

(b) Of the 16 sixteen cavities to be installed, nominally 14 of them will be operating at a given time

(c) 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.

i. 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.

ii. 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.

iii. 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 “45 K” in this document.

iv. 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.

(d) The LCLS-II cryogenic system total heat load is itemized in LCLSII-4.5-EN-0179, “LCLS-II Cryogenic Heat Load” [6] and includes an expected heat load for these cryomodules based on a nominal accelerating gradient = 13.4 MV/m and $Q_0 \geq 2.0 \times 10^9$ at an operating temperature = 2 K. A value of $Q_0 \geq 2.5 \times 10^9$ 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

(e) Indoor storage of cryomodules is available on-site prior to installation

(f) Controls system is provided elsewhere

(g) Electrical grounding is determined and provided elsewhere

(h) Cryomodule cool down and warm up limitations

Applies to warm shield and cavity circuits

i. Rate limit < 10K/hour

ii. ΔT limit <50K longitudinally

iii. ΔT limit <15K radially in 300 mm gas return pipe

(i) 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).

(j) The JT heat exchanger will be supplied externally as a part of the cryogenic distribution system

(k) Each cryo module will have its own JT valve supplying LHe to its cavities

(l) Distribution of cryogenic circuits is internal to the cryomodule

(m) 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.

(n) Cavities will be oriented such that couplers are on alternating sides of the cryomodule to reduce transverse kicks.

6 Requirements

6.1 General

(a) The system is expected to operate for 20 years

(b) The cryomodules are subject to comply with 10 C. F. R. 851 [7] and Pressure systems Requirements per SLC ES&H Manual Chapter 14 [8]. To achieve this, the cryomodules are designed to comply with the Fermilab ES&H Manual (FESHM) [9], in particular, FESHM chapters 5031, 5031.1, 5031.6, 5032, 5033

(c) System will be manufactured using industry accepted QA procedures and standards

(d) ISO accepted testing procedures and standards shall be used for system and component tests

(e) An external lug will be supplied for connection of an electrical grounding cable.

6.2 Operating

(a) 3.9 GHz accelerating structures

(b) Operating Parameters (nominal and tolerances)

Operating pressures

Cavity bath – $P \geq 1600 \pm 20$ [Pa]

Cold intercept circuit – $0.3 \leq P \leq 1.8$ [MPa]

Warm shield circuit – $0.3 \leq P \leq 1.8$ [MPa]

Operating temperatures

Cavity bath – at saturation [$1.8\ K \leq T \leq 2.1\ K$]

Cold shield circuit – $(5.0 \pm 0.5) \leq T \leq (8 \pm 0.5)$ [K]

Warm shield circuit – $(30 \pm 5) \leq T \leq (80 \pm 5)$ [K]

6.3 Mechanical

(a) 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 [10].

(b) Stand requirements

i. The stand will be a two piece assembly; an adjustable stand connected to the cryomodule and a base plate.

ii. The base plate will be surveyed and anchored to the tunnel floor by SLAC at a fixed elevation offset relative to the beam center line.

iii. The fully assembled cryomodule supports should be powder coated to protect against corrosion due to tunnel leakage.

iv. Care should be taken to protect powder coating during transportation, lifting and rigging.

v. 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”

Adjustability precision will be consistent with the alignment tolerances.

(c) Cavity and magnet positioning will be transferred to a retroreflector survey system on the outside of the cryomodule. Cavity and magnet motion due to contraction during cooldown is known and consistent and will be factored in to the final cryomodule survey. Cavity and magnet alignment relative to the external survey system will be to within values specified in the SCRF 3.9 GHz Cryomodule Physics Requirements Document [3].

(d) Shipping [11, 12]

i. Provisions will be made to limit the loads seen by the 3.9 GHz Cryomodules to
   a. Maximum transmitted vertical shock acceleration < 1.5 g
   b. Maximum transmitted transverse shock acceleration < 1.5 g
   c. Maximum transmitted longitudinal shock acceleration < 1.5 g

ii. A bonded and insured transport company shall be used.

iii. All overland transport shall be on air-ride suspension trucks

iv. Shock recording shall be provided on the cryomodule as well as on the shipping container.

v. The shipping containment shall ensure that the cryomodule remains dry.

vi. The cryostat vacuum space shall be sealed and shipped under a slight positive pressure using dry nitrogen.

(e) Rigging

i. SLAC requires swivel hoist rings and/or lifting fixture when lifting with an overhead crane [13].

ii. Lifting fixtures will go through a design review and load test. A written and reviewed lifting procedure is required at SLAC [14]. 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 be never 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.

(f) 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.

6.4 Cryogenic

(a) Anchoring and thermal contraction of each cryogenic circuit will consider worst case pressure, temperature and alignment extremes

(b) All cryogenic circuits will be designed to allow cool down or warm up independent of the state of other circuits

(c) Cryomodule MAWP:

Region	Warm MAWP (bar)	Cold MAWP (bar)
2 K, low pressure space	2.05	4.1

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

(d) The 3.9 GHz cryomodules in combination with the distribution system shall provide for protection from over pressure of all circuits

i. 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.

ii. 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/cm^2. Longitudinal effects due to cryopumping and finite air influx will be considered when determining the affected area at any instance of time [15].

iii. 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/cm^2. Longitudinal effects due to cryopumping and finite air influx will be considered when determining the affected area at any instance of time [15].

iv. Consideration of back pressure and flow resistance from vent discharge lines and piping downstream of the relief valves must be included in the design.

v. 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.

vi. The insulating vacuum is to be protected from over pressurization by means of a spring-loaded lift plate.

vii. Worst case piping ruptures internal to the insulating vacuum shall be analyzed to determine lift plate size.

viii. Provisions shall be provided to allow free passage of the helium out past thermal shield and MLI to the lift plate.

(e) Thermal shields and thermal intercepts

i. There shall be one level of radiative thermal shield at the nominally 45 K level.

ii. A thermal radiation shield at the 5 K level is not included.

iii. 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.

iv. Thermal intercepts at the 45 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.

v. 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.)

vi. Thermal shield trace piping shall be arranged such that counter flow heat transfer does not inhibit cool-down of the thermal shield.

vii. System insulating vacuum, thermal shield, and thermal intercept system shall provide for reasonable static heat load

(f) Instrumentation necessary to measure all warm up or cool down constraints

(g) The cryogenic circuits shall be supplied with flanged connections for individual cryomodule testing which can be removed for welded connection in the tunnel

6.5 Beam tube requirements

(a) Beampipe apertures of devices installed in cryomodules will be equal to or larger than the aperture of the SCRF cavities.

(b) All vacuum chambers that are not part of the Nb cavity packages, including cavity bellows, quadrupole chamber, BPM, etc., will be Cu-coated to increase the electrical and thermal conductivity. The minimum coating thickness is 10 μm.

(c) Beam tube extensions between cavities and at cryomodule ends are to be “particle free” and cleaned for UHV like the cavities themselves [16, 17, 18].

(d) 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 [16, 17, 18].

(e) 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.

6.6 Cryomodule insulating vacuum system

(a) Vacuum vessel provides the insulating vacuum space

(b) Evacuated multi-layer insulation (MLI) shall be used within the cryomodule

(c) MLI shall be used on the thermal radiation shield

(d) 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.

6.7 Coupler vacuum requirements

UHV standards need to be followed. Components need to be cleaned to particle free UHV standards prior to installation [16, 17, 18]. The cold section of the coupler is connected to the SRF cavity in a class 10 cleanroom. The warm section of the coupler is connected under a class 100 tent after the cavity string has been inserted into the cryostat. 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 1×10^{-6} Torr) the ion pump installed for individual cryomodules shall be turned.

6.8 Tuning requirements

The preferred coarse/fine tuner is the Blade type successfully used at FLASH and to be installed on the 3.9 GHz system at the European XFEL, whose basic parameters are listed below. Modifications to the existing design 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) will be considered.

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 coarse or fine 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	Blade
Cavity longitudinal stiffness	5.4 kN/mm
Coarse Actuator	
Type	Stepping motor
Freq change per step	~ 10 Hz
Range	750 kHz
Gearbox	Planetary
Fine Actuator	
Type	Piezo Stack
Max Voltage (Warm)	120 V
Blocking force	4 kN
Tuning range	> 1 kHz
Tuning sensitivity	< 1 Hz

A prototype tuner has been tested warm which has demonstrated that the above parameters can be successfully met [19].

6.9 Magnet requirements

There will be no magnet package supplied within the 3.9 GHz cryomodules. Provisions have been made, however, to include one if deemed necessary.

6.10 Coupler requirements

The table below lists the coupler parameters.

Item	Spec	Comment
Design	Existing 3.9 GHz design with modification	Fewer bellows convolutions, increase copper plating on inner conductor
Max Combined Power (forward + reflected)	2 kW CW	
Nominal Qext Foreseen	$2.5 – 2.9 \times 10^{7}$	
Warm Section Outer Conductor Plating	10 um +/- 5 um RRR = 30-80	Nominal EuXFEL
Warm Section Inner Conductor Plating	120 um +/- 30 um RRR = 30-80	Modified – maintain temperature < 400 Kelvin

Cold Section Outer Conductor Plating	10 um +/- 5 um RRR = 30-80	Nominal EuXFEL
Center Conductor HV Bias	Optional	
Warm and Cold e-Probe Ports Required	Optional	Do not expect multipacting at low power, but include for testing
Warm Light Port Required	Optional	Do not expect arcs at low power, but include for testing
Motorized Antenna	No	Fixed coupling
RF Processing	Up to 2 kW traveling wave or 1kW standing wave w/full reflection – vary reflected phase by 180 deg	For initial couplers, use pulsed power processing at Fermilab

6.11 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 R_{mag} <15 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. 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.

6.12 Beam Line Absorber Requirements

The beam pipe interconnection region between the cryomodules will include a beam line absorber of the EuXFEL design and identical to those of the 1.3 GHz cryomodules [2]. Its purpose is to absorb a large portion of the HOM propagating mode power in a ring of lossy ceramic tiles (~ 300 cm^2 surface) 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).

6.13 Beam Position Monitor, BPM

The 3.9 GHz cryomodules will be outfitted with one BPM per cryomodule at the downstream end of each. BPM's will be identical to those of the 1.3 GHz cryomodules [20] with appropriate interfaces.

6.14 Testing, Qualification

(a) All production cavities will be vertically tested to determine qualification for dressing, at least 10% above gradient specification (18 MV/m).

(b) The first four dressed cavities will be tested at the Horizontal Test Stand. Follow-on horizontal testing will be done on approximately 20% of the remaining cavities.

(c) Completed cryomodules will be installed, cooled to 2K, and power tested using an agreed on test protocol prior to shipment to SLAC.