Document Approval:

Originator: Dan Gonnella, LCLS-II-HE Deputy Cryogenics System Manager **• Content/Format • Req ID's/Source ID's • Verif. Planning • SME Input, as appl**
Reviewer: Ted Price – System Engineering Lead Ted Price Ted Price (Dec 27, 2020 09:57 PST) **• Clarity • Format • Req ID's/Traceability • Change Control, as appl**
Reviewer: Rich Poliak – Quality Assurance Manager Rich Poliak Rich Poliak (Dec 30, 2020 11:49 PST) **• General QA Provisions • Req's Validation/Verification**
Reviewer: Josh Kaluzny, LCLS-II-HE FNAL CAM Joshua Kaluzny Joshua Kaluzny (Jan 6, 2021 20:28 CST) **• Concurrence • Scope Alignment • Execution at PLs, as appl**
Reviewer: Katherine Wilson, LCLS-II-HE JLab CAM Katherine Wilson (Jan 4, 2021 16:46 EST) **• Concurrence • Scope Alignment • Execution at PLs, as appl**
Reviewer: Tug Arkan, LCLS-II-HE FNAL STL Tug Arkan Tug Arkan (Dec 20, 2020 14:42 CST) **• Concurrence • Scope Alignment • Execution at PLs, as appl**
Reviewer: John Hogan, LCLS-II-HE JLab STL John Hogan **• Concurrence • Scope Alignment • Execution at PLs, as appl**
Approver: Joel Fuerst, LCLS-II-HE Cryogenic System Manager **• Articulation • Meets Higher Level Expectations • Alt. CAM/SM Informed**
Approver: Marc Ross, LCLS-II-HE Technical Director **• Scope Alignment**

See *Document Review/Approval Matrix of Responsibilities*

Revision History

Revision	Date Released	Description of Change
R0	1/7/2021	Original Release.

1 Scope

This document captures 1.3 GHz cryomodule performance requirements, requirements documentation, verification documentation, and method of verification. Physics requirements for the cryomodules are given as a reference in Table 1. Many requirements are verified by design studies or prototype measurements. Those requirements to be verified by testing during cryomodule production are documented in cryomodule travelers.

Minimum acceptance criteria for production cryomodules are listed in Table 2 and include functional requirements for critical components. Due to the nature of variations in performance of some components, minimum performance of an individual component may not meet *average* requirements for the fully installed systems, e.g. for the cavity gradient. These minimum performance criteria address possible production variations that may lead to individual cryomodules not performing at the level of the average cryomodule in some parameters, while the assembled linac will meet the physics and functional requirements. Test results will be monitored to track the average of required parameters for all cryomodules to be installed, in order to ensure appropriate feedback to production processes when performance changes are noted or improvements needed. These results will be recorded in the partner lab traveler systems, Vector and Pansophy.

The minimum acceptance criteria that must be achieved for verification cryomodule in test at Fermilab are listed in Table 3. These acceptance criteria must be fulfilled in order to demonstrate that the cryomodule design and assembly practices are acceptable. Additionally these criteria demonstrate the success of the new doping protocol at the cavity vendor. This set of criteria shall be used to gate the production readiness review and allow beginning of the production cryomodule assembly at the respective workstations listed in Table 3 as well as gate the doping of the production SRF cavities. In addition to the acceptance criteria outlined in Table 3, the verification cryomodule must also meet all of the minimum acceptance criteria in Table 2.

If a criterion is not met it should trigger a non-conformance report for review, and should not prohibit work from continuing. Each cryomodule testing NCR must be dispositioned by the Cryogenics System Manager prior to warm up. Separately, a cryomodule test plan and traveler are under development to detail the full set of test and measurement procedures, record measurements, and provide hold points for acceptance review. A pre-warmup review with the Cryogenics System management will be held for each cryomodule following the conclusion of testing, but prior to warm up. This review will serve as a time to present the data that was measured, ensure that all NCRs have been dispositioned, and receive agreement that no additional tests need to be carried out. Clearance for warm up shall be given by the Deputy Cryogenics System Manager and Cryogenics System Manager.

Table 1 Cryomodule Physics Requirements and Verification Process

Sub-System	Parameter	Value	Units	Comment / Cryo Systems implications	Physics requirement documents		Cryo Systems requirements, specifications, and interface documents		Other reference or verification documents		Production verification Documents or process		Verification method
Cryo Systems					Title	Number	Title	Number					
1	Nominal beam energy	8	GeV	Cavity operating gradient and sufficient number of cavities. Heat load at required gradient is within cooling capacity; cavity Q0 vs E is within acceptance limits.	LCLS-II-HE Parameters PRD Linac Requirements PRD SCRF 1.3 GHz Cryomodule PRD	LCLS-II-HE-1.1-PR-0039 LCLS-II-HE-1.1-PR-0018 LCLSII-HE-1.2-PR-0029	1.3 GHz Superconducting RF Cryomodule Cryogenic System Integration	LCLSII-HE-1.2-FR-0052 LCLSII-4.1-FR-0327	Gradient optimization Cryogenic Heat Load Conceptual Design Report Final Design Report	LCLSII-4.5-EN-0217 LCLSII-4.5-EN-0179 LCLSIIHE-DR-0001 LCLSII-HE-1.1-DR-0084	Cryomodule traveler		Measure minimum CW voltage produced by each cryomodule
2	Maximum beam power	1.2	MW	Heat load at required gradient and beam current is within cooling capacity; cavity Q0 vs E is within acceptance limits. Adequate HOM damping (see section below).	LCLS-II-HE Parameters PRD	LCLS-II-HE-1.1-PR-0039	1.3 GHz Superconducting RF Cryomodule Cryogenic System Integration	LCLSII-HE-1.2-FR-0052 LCLSII-4.1-FR-0327	Gradient optimization Conceptual Design Report Final Design Report	LCLSII-4.5-EN-0217 LCLSII-4.5-EN-0179 LCLSIIHE-DR-0001 LCLSII-HE-1.1-DR-	Beam commissioning		Beam measurement
3	Maximum bunch rate	0.929	MHz	Heat load at required gradient and beam current is within cooling capacity; cavity Q0 vs E is within acceptance limits. Adequate HOM damping (see section below).	LCLS-II-HE Parameters PRD Linac Requirements PRD	LCLS-II-HE-1.1-PR-0039 LCLS-II-HE-1.1-PR-0018	1.3 GHz Superconducting RF Cryomodule Cryogenic System Integration	LCLSII-HE-1.2-FR-0052 LCLSII-4.1-FR-0327	Gradient optimization Cryogenic Heat Load Conceptual Design Report Final Design Report	LCLSII-4.5-EN-0217 LCLSII-4.5-EN-0179 LCLSIIHE-DR-0001 LCLSII-HE-1.1-DR-	Beam commissioning		Beam measurement
4	Maximum bunch charge	0.3	nC	Heat load at required gradient and beam current is within cooling capacity; cavity Q0 vs E is within acceptance limits. Adequate HOM damping (see section below) and beamline HOM absorber (see section below). Adequate BPM resolution (see section below).	LCLS-II-HE Parameters PRD Linac Requirements PRD	LCLS-II-HE-1.1-PR-0039 LCLS-II-HE-1.1-PR-0018	1.3 GHz Superconducting RF Cryomodule Cryogenic System Integration	LCLSII-HE-1.2-FR-0052 LCLSII-4.1-FR-0327	Gradient optimization Cryogenic Heat Load Conceptual Design Report Final Design Report	LCLSII-4.5-EN-0217 LCLSII-4.5-EN-0179 LCLSIIHE-DR-0001 LCLSII-HE-1.1-DR-0084	Beam commissioning		Beam measurement
5	Nominal bunch charge	0.1	nC	Heat load at required gradient and beam current is within cooling capacity; cavity Q0 vs E is within acceptance limits. Adequate HOM damping (see section below) and beamline HOM absorber (see section below). Adequate BPM resolution (see section below).	LCLS-II-HE Parameters PRD Linac Requirements PRD	LCLS-II-HE-1.1-PR-0039 LCLS-II-HE-1.1-PR-0018	1.3 GHz Superconducting RF Cryomodule Cryogenic System Integration	LCLSII-HE-1.2-FR-0052 LCLSII-4.1-FR-0327	Gradient optimization Cryogenic Heat Load Conceptual Design Report Final Design Report	LCLSII-4.5-EN-0217 LCLSII-4.5-EN-0179 LCLSIIHE-DR-0001 LCLSII-HE-1.1-DR-0084	Beam commissioning		Beam measurement
6	Minimum bunch charge	0.01	nC	Heat load at required gradient and beam current is within cooling capacity; cavity Q0 vs E is within acceptance limits. Adequate HOM damping (see section below) and beamline HOM absorber (see section below). Adequate BPM resolution (see section below).	LCLS-II-HE Parameters PRD Linac Requirements PRD	LCLS-II-HE-1.1-PR-0039 LCLS-II-HE-1.1-PR-0018	1.3 GHz Superconducting RF Cryomodule Cryogenic System Integration	LCLSII-HE-1.2-FR-0052 LCLSII-4.1-FR-0327	Gradient optimization Cryogenic Heat Load Conceptual Design Report Final Design Report	LCLSII-4.5-EN-0217 LCLSII-4.5-EN-0179 LCLSIIHE-DR-0001 LCLSII-HE-1.1-DR-0084	Beam commissioning		Beam measurement
7	Linac availability	99.87	%	Includes cavities, cavity tuners, RF input coupler, cryomodule vacuum, ... Initial availability lower, 99.80%	Availability PRD	LCLSII-1.1-PR-0163			Cryomodule Availability Simulations	LCLSII-4.1-EN-0395	Cryosystems Availability Simulations	LCLSII-4.1-EN-0395	Simulations using available MTTF data
8	Systems lifetime	20	years				1.3 GHz Superconducting RF Cryomodule Cryogenic System Integration	LCLSII-HE-1.2-FR-0052 LCLSII-4.1-FR-0327	Final Design Report Reliability of the LCLS II SRF Cavity Tuner	LCLSII-HE-1.1-DR-0084 Proceedings of SRF2015, Whistler, BC, Canada, THPB065	Final Design Report	LCLSII-HE-1.1-DR-0084	Specifications and prototype lifetime testing
9	Linac tunnel longitudinal slope	0.5	%	Lower toward east studies Limits 2-phase pipe extent to individual cryomodules to maintain LHe level			1.3 GHz Superconducting RF Cryomodule Cryogenic System Integration	LCLSII-HE-1.2-FR-0052 LCLSII-4.1-FR-0327	Final Design Report	LCLSII-HE-1.1-DR-0084	Final Design Report	LCLSII-HE-1.1-DR-0084	Design
10	Linac tunnel transverse slope	0.6	deg	lower toward south			1.3 GHz Superconducting RF Cryomodule Cryogenic System Integration	LCLSII-HE-1.2-FR-0052 LCLSII-4.1-FR-0327	Final Design Report	LCLSII-HE-1.1-DR-0084	Final Design Report	LCLSII-HE-1.1-DR-0084	Design studies
11	Temperature range in the linac tunnel	40-100	°F	Inpacts cryomodule stands compliance for expansion and contraction			Cryogenic System Integration	LCLSII-4.1-FR-0327			LCLS-II Cryomodule Stand Analysis	LCLSII-4.5-EN-0418	Design studies
12	Cryogenic distribution in the linac tunnel			ODH, no liquid nitrogen in the tunnel			1.3 GHz Superconducting RF Cryomodule	LCLSII-HE-1.2-FR-0052			Final Design Report	LCLSII-HE-1.1-DR-0084	Design studies
1.3 GHz Cryomodules													
1.3 GHz cryomodules													
13	Cavity spacing within a cryomodule	~35	cm	"the cavities are spaced by roughly 35 cm so that the center of each cavity is separated by exactly 6 RF wavelengths"	SCRF 1.3 GHz Cryomodule PRD	LCLSII-HE-1.2-PR-0029			Master Spreadsheet (Fermilab TeamCenter)	ED0001152	Master Spreadsheet (Fermilab TeamCenter)	ED0001152	Design studies
14	Cavity spacing between adjacent cryomodules	~2.5	m	"the center of the last cavity and the center of the first cavity in the subsequent cryomodule are spaced by 11 RF wavelengths, roughly 2.5 meters"	SCRF 1.3 GHz Cryomodule PRD	LCLSII-HE-1.2-PR-0029			Top Level Assembly Drawing (Fermilab TeamCenter)	F10009945	Top Level Assembly Drawing (Fermilab TeamCenter)	F10128458	Design studies
15	Beamline vacuum chamber diameter	various		"...aperture of the [device] will be equal or larger than the aperture of the SCRF cavities." "The absorber aperture may be smaller than that of the SCRF cavities."	SCRF 1.3 GHz Cryomodule PRD	LCLSII-HE-1.2-PR-0029	1.3 GHz Superconducting RF Cryomodule	LCLSII-HE-1.2-FR-0052	Final Design Report	LCLSII-HE-1.1-DR-0084	Assembly, Cavity String LCLS-II	F10009887	Design studies
16	Beamline vacuum chamber coating	≥10 µm		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 um.	SCRF 1.3 GHz Cryomodule PRD	LCLSII-HE-1.2-PR-0029	1.3 GHz Superconducting RF Cryomodule	LCLSII-HE-1.2-FR-0052	Final Design Report	LCLSII-HE-1.1-DR-0084	Beam tube d	F10009424	Manufacturing specification
17	Number of cavities per cryomodule	8			SCRF 1.3 GHz Cryomodule PRD LCLS-II-HE Parameters PRD	LCLSII-HE-1.2-PR-0029 LCLS-II-HE-1.1-PR-0039	1.3 GHz Superconducting RF Cryomodule	LCLSII-HE-1.2-FR-0052	Cryogenic Heat Load Conceptual Design Report Final Design Report	LCLSII-4.5-EN-0179 LCLSIIHE-DR-0001 LCLSII-HE-1.1-DR-0084	Final Design Report	LCLSII-HE-1.1-DR-0084	Design studies
18	Total number of installed studies cryomodules	55			SCRF 1.3 GHz Cryomodule PRD LCLS-II-HE Parameters PRD	LCLSII-HE-1.2-PR-0029 LCLS-II-HE-1.1-PR-0039	1.3 GHz Superconducting RF Cryomodule	LCLSII-HE-1.2-FR-0052	Cryogenic Heat Load Conceptual Design Report Final Design Report	LCLSII-4.5-EN-0179 LCLSIIHE-DR-0001 LCLSII-HE-1.1-DR-0084	Final Design Report	LCLSII-HE-1.1-DR-0084	Design
19	Number of installed cryomodules in studies L0	1			SCRF 1.3 GHz Cryomodule PRD	LCLSII-HE-1.2-PR-0029	Cryogenic Distribution System	LCLSII-4.9-FR-0057	Cryogenic Heat Load Conceptual Design Report Final Design Report	LCLSII-4.5-EN-0179 LCLSIIHE-DR-0001 LCLSII-HE-1.1-DR-0084	Final Design Report	LCLSII-HE-1.1-DR-0084	Design
20	Number of installed cryomodules in studies L1	2			SCRF 1.3 GHz Cryomodule PRD	LCLSII-HE-1.2-PR-0029	Cryogenic Distribution System	LCLSII-4.9-FR-0057	Cryogenic Heat Load Conceptual Design Report Final Design Report	LCLSII-4.5-EN-0179 LCLSIIHE-DR-0001 LCLSII-HE-1.1-DR-0084	Final Design Report	LCLSII-HE-1.1-DR-0084	Design

Sub-System	Parameter	Value	Units	Comment / Cryo Systems implications	Physics requirement documents	Cryo Systems requirements, specifications, and interface documents	Other reference or verification documents	Production verification Documents or process	Verification method
21	Number of installed cryomodules in studies L2	12			SCRF 1.3 GHz Cryomodule PRD LCLSII-HE-1.2-PR-0029	Cryogenic Distribution System LCLSII-4.9-FR-0057	Cryogenic Heat Load LCLSII-4.5-EN-0179 Conceptual Design Report LCLSIIHE-DR-0001 Final Design Report LCLSII-HE-1.1-DR-0084	Final Design Report LCLSII-HE-1.1-DR-0084	Design
22	Number of installed cryomodules in studies L3	13			SCRF 1.3 GHz Cryomodule PRD LCLSII-HE-1.2-PR-0029	Cryogenic Distribution System LCLSII-4.9-FR-0057	Cryogenic Heat Load LCLSII-4.5-EN-0179 Conceptual Design Report LCLSIIHE-DR-0001 Final Design Report LCLSII-HE-1.1-DR-0084	Final Design Report LCLSII-HE-1.1-DR-0084	Design
23	Number of installed cryomodules in studies L4	27			SCRF 1.3 GHz Cryomodule PRD LCLSII-HE-1.2-PR-0029	Cryogenic Distribution System LCLSII-4.9-FR-0057	Cryogenic Heat Load LCLSII-4.5-EN-0179 Conceptual Design Report LCLSIIHE-DR-0001 Final Design Report LCLSII-HE-1.1-DR-0084	Final Design Report LCLSII-HE-1.1-DR-0084	Design
24	Beam current for initial heat load calculation	300	µA	for beam induced losses	SCRF 1.3 GHz Cryomodule PRD LCLSII-HE-1.2-PR-0029		Cryogenic Heat Load LCLSII-4.5-EN-0179 Final Design Report LCLSII-HE-1.1-DR-0084	Cryogenic Heat Load LCLSII-4.5-EN-0179	Design studies
25	Captured dark current	<30	nA	per cryomodule, in each direction, at 20.8 MV/m	SCRF 1.3 GHz Cryomodule PRD LCLSII-HE-1.2-PR-0029	Cryogenic System Integration LCLSII-4.1-FR-0327	Radiation Fields from Field Emission at the SCRF cavities of LCLS-II RP-15-03 Final Design Report LCLSII-HE-1.1-DR-0084	Cryomodule traveler	Measure dark current produced by each cryomodule
26	Integrated radiation dose near quadrupole	<100	Mrad	20-years operation	SCRF 1.3 GHz Cryomodule PRD LCLSII-HE-1.2-PR-0029	Final Design Report LCLSII-HE-1.1-DR-0084 Cryogenic System Integration LCLSII-4.1-FR-0327	Radiation Fields from Field Emission at the SCRF cavities of LCLS-II RP-15-03	Radiation Fields from Field Emission at the SCRF cavities of LCLS-II RP-15-03	Simulations
27	Cryomodule length including interspace region	12.22	m		SCRF 1.3 GHz Cryomodule PRD LCLSII-HE-1.2-PR-0029	LCLS-II 1.3GHz Cryomodule Mechanical Design ED0004361		Top Level Assembly Drawing (Fermilab TeamCenter) F10009945	Design studies
28	Fundamental power coupler configuration			power couplers mounted on right side of cryomodule looking downstream, to allow access from walkway in linac tunnel	SCRF 1.3 GHz Cryomodule PRD LCLSII-HE-1.2-PR-0029	LCLS-II 1.3GHz Cryomodule Mechanical Design ED0004361	Top Level Assembly Drawing (Fermilab TeamCenter) F10009945	Top Level Assembly Drawing (Fermilab TeamCenter) F10009945	Design studies
1.3 GHz cavities									
29	RF Frequency	1.3	GHz	1.3 GHz using TESLA cavity design. Allows implementation of related technologies developed for FLASH, ILC, XFEL, etc.	LCLS-II-HE Parameters PRD LCLS-II-HE-1.1-PR-0039 SCRF 1.3 GHz Cryomodule PRD LCLSII-HE-1.2-PR-0029	1.3 GHz Superconducting RF Cryomodule LCLSII-HE-1.2-FR-0052 0084 Cryogenic System Integration LCLSII-4.1-FR-0327 1.3 GHz Cryomodule Technical Description LCLSII-HE-1.2-ES-0060	Cryomodule design methodology LCLSII-4.5-EN-0186 Conceptual Design Report LCLSIIHE-DR-0001 Final Design Report LCLSII-HE-1.1-DR-	Cryomodule traveler	Measure cavity performance at 1.3 GHz
30	RF pulse mode			CW. Requires modifications to existing pulsed SRF technology designs developed for FLASH. ILC, XFEL.	SCRF 1.3 GHz Cryomodule PRD LCLSII-HE-1.2-PR-0029	1.3 GHz Superconducting RF Cryomodule LCLSII-HE-1.2-FR-0052 Cryogenic System Integration LCLSII-4.1-FR-0327 0084 1.3 GHz Cryomodule Technical Description LCLSII-HE-1.2-ES-0060	Cryomodule design methodology LCLSII-4.5-EN-0186 Cryogenic Heat Load LCLSII-4.5-EN-0179 Conceptual Design Report LCLSIIHE-DR-0001 Final Design Report LCLSII-HE-1.1-DR-	Cryomodule traveler	Measure cavity performance with CW RF power
31	Cavity nominal gradient	20.8	MV/m	with <10 nA per cryomodule captured dark currrent (each direction) and 100 Mrad near quadrupoles in 20 years operation	LCLS-II-HE Parameters PRD LCLS-II-HE-1.1-PR-0039 SCRF 1.3 GHz Cryomodule PRD LCLSII-HE-1.2-PR-0029	1.3 GHz Superconducting RF Cryomodule LCLSII-HE-1.2-FR-0052 Cryogenic System Integration LCLSII-4.1-FR-0327	Conceptual Design Report LCLSIIHE-DR-0001 Final Design Report LCLSII-HE-1.1-DR-0084 Cryogenic Heat Load LCLSII-4.5-EN-0179 Acceptance Criteria and Test Procedures	Cryomodule traveler	Measure cavity gradient
32	Installed 1.3 GHz voltage	8.64	GV	At nominal cavity gradient, includes overhead for beam de-phasing and redundancy.	LCLS-II-HE Parameters PRD LCLS-II-HE-1.1-PR-0039		Conceptual Design Report LCLSIIHE-DR-0001 Final Design Report LCLSII-HE-1.1-DR-0084	Cryomodule traveler	Measure minimum CW voltage produced by each cryomodule
33	Accelerating cavity type			"TESLA-Technology", 9-cell, L-band, R/Q 1012 Ω, 1.0377 studies m active length. Cavity properties drive performance and heatload.	SCRF 1.3 GHz Cryomodule PRD LCLSII-HE-1.2-PR-0029	1.3 GHz Superconducting RF Cryomodule LCLSII-HE-1.2-FR- 0052 Cryogenic System Integration LCLSII-4.1-FR-0327	Conceptual Design Report LCLSIIHE-DR-0001 Final Design Report LCLSII-HE-1.1-DR-0084 Cryogenic Heat Load LCLSII-4.5-EN-0179	Final Design Report LCLSII-HE-1.1-DR-0084	Design
34	Cavity qualification gradient in vertical test	23	MV/m	and field emitted current 0 pA in each direction, with $Q0 \geq 2.5 \times 10^{10}$	LCLS-II-HE Parameters PRD LCLS-II-HE-1.1-PR-0039 SCRF 1.3 GHz Cryomodule PRD LCLSII-HE-1.2-PR-0029	SRF Dressed Cavity Technical Specification LCLSII-HE-1.2-TS-0085	Final Design Report LCLSII-HE-1.1-DR-0084 Final Report on LCLS-II Cavity Test Acceptance Criteria and Test Procedures LCLSII-4.5-EN-0590	Cavity traveler	Measure cavity gradient
35	Number of HE accelerating cavities	160			LCLS-II-HE Parameters PRD LCLS-II-HE-1.1-PR-0039	1.3 GHz Superconducting RF Cryomodule LCLSII-HE-1.2-FR- 0052 Cryogenic System Integration LCLSII-4.1-FR-0327	Conceptual Design Report LCLSIIHE-DR-0001 Final Design Report LCLSII-HE-1.1-DR-0084 Cryogenic Heat Load LCLSII-4.5-EN-0179	Final Design Report LCLSII-HE-1.1-DR-0084	Design studies
36	Installed cavity redundancy	6	%	With 18 of the 280 cavities unpowered the linac will still achieve 4.0 GeV	LCLS-II-HE Parameters PRD LCLS-II-HE-1.1-PR-0039 SCRF 1.3 GHz Cryomodule PRD LCLSII-HE-1.2-PR-0029		Conceptual Design Report LCLSIIHE-DR-0001 Final Design Report LCLSII-HE-1.1-DR-0084	Cryomodule traveler	Measure minimum CW voltage produced by each cryomodule
37	Installed energy overhead for feedback	1	%		LCLS-II-HE Parameters PRD LCLS-II-HE-1.1-PR-0039 Linac Requirements PRD LCLS-II-HE-1.1-PR-0018		Conceptual Design Report LCLSIIHE-DR-0001 Final Design Report LCLSII-HE-1.1-DR-0084	Cryomodule traveler	Measure minimum CW voltage produced by each cryomodule

Sub-System	Parameter	Value	Units	Comment / Cryo Systems implications	Physics requirement documents	Cryo Systems requirements, specifications, and interface documents	Other reference or verification documents	Production verification Documents or process	Verification method
38	Cavity operating temperature	2	K		Linac Requirements PRD LCLS-II-HE-1.1-PR-0018 SCRF 1.3 GHz Cryomodule PRD LCLSII-HE-1.2-PR-0029	Cryogenic System Integration LCLSII-4.1-FR-0327 1.3 GHz Superconducting RF Cryomodule LCLSII-HE-1.2-FR-0052	Cryogenic System Operating Temperature LCLSII-4.5-EN-0185 Conceptual Design Report LCLSIIHE-DR-0001 Final Design Report LCLSII-HE-1.1-DR-0084 Cryogenic Heat Load LCLSII-4.5-EN-0179 Final Report on LCLS-II Cavity Test Acceptance Criteria and Test Procedures LCLSII-4.5-EN-0590 CM Instrumentation Specification LCLSII-4.5-ES-0415 LCLS-II Production Cryomodule P&I diagram F10040796	Cryomodule traveler	Measure presssure in 2-phase pipe
39	Cavity average Q0	$2.7x10^{10}$		less than ±20% variation in Q0 average of 1/Q0 < $1/2.7x10^{10}$	LCLS-II-HE Parameters PRD LCLS-II-HE-1.1-PR-0039 SCRF 1.3 GHz Cryomodule PRD LCLSII-HE-1.2-PR-0029	1.3 GHz Superconducting RF Cryomodule LCLSII-HE-1.2-FR-0052	Conceptual Design Report LCLSIIHE-DR-0001 Final Design Report LCLSII-HE-1.1-DR-0084 Cryogenic Heat Load LCLSII-4.5-EN-0179 Final Report on LCLS-II Cavity Test Acceptance Criteria and Test Procedures LCLSII-4.5-EN-0590 Final Report on the LCLS-II High Qo R&D Program LCLSII-8.2-EN-0523	Cryomodule traveler	Measure cavity Q0 with CW RF power
40	Cavity minimum Q0	$1.5x10^{10}$		at 20.8 MV/m	SCRF 1.3 GHz Cryomodule PRD LCLSII-HE-1.2-PR-0029		Final Report on LCLS-II Cavity Test Acceptance Criteria and Test Procedures LCLSII-4.5-EN-0590	Cryomodule traveler	Measure cavity Q0 with CW RF power
41	Beam power loss per injector cryomodule cavity	1	W	"...beam losses in the cryomodule(s) should be less than 1 W per rf cavity"	LCLS-II SCRF Injector System LCLSII-2.2-PR-0084		Radiation Fields from Field Emission at the Measured dark current of ~ 0.1 nA at APEX prototype exceeds LCLS-II requirement by 3 orders of magnitude RP-15-03	Radiation Fields from Field RP-15-03	Simulations
1.3 GHz cryomodule alignment				When cold					
42	Cryomodule alignment resolution wrt linac centerline, transverse (X, Y)	0.1	mm	installation requirement, CM must have survey fiducials to allow this	SCRF 1.3 GHz Cryomodule PRD LCLSII-HE-1.2-PR-0029	1.3 GHz Cryomodule External Physical Interfaces LCLSII-4.5-IC-0661	See Alignment Workshop, May 22, 2015. https://indico.fnal.gov/conferenceDisplay.py? confId=9994https://indico.fnal.gov/conferenceDisplay.py?confId=9994	SLAC Survey & Alignment	Measurement during CM
43	Cryomodule alignment resolution wrt linac centerline, longitudinal (Z)	0.2	mm	installation requirement, CM must have survey fiducials to allow this	SCRF 1.3 GHz Cryomodule PRD LCLSII-HE-1.2-PR-0029	1.3 GHz Cryomodule External Physical Interfaces LCLSII-4.5-IC-0661	See Alignment Workshop, May 22, 2015. https://indico.fnal.gov/conferenceDisplay.py? confId=9994https://indico.fnal.gov/conferenceDisplay.py?confId	SLAC Survey & Alignment	Measurement during CM installation
44	Cavity X,Y misalignments wrt cryomodule	1	mm	alignment of internal components within the cryomodule	SCRF 1.3 GHz Cryomodule PRD LCLSII-HE-1.2-PR-0029	1.3 GHz Superconducting RF Cryomodule LCLSII-HE-1.2-FR-0052	See Alignment Workshop, May 22, 2015. https://indico.fnal.gov/conferenceDisplay.py? confId=9994https://indico.fnal.gov/conferenceDisplay.py?co	Cryomodule traveler	Measurement during CM assembly
45	Quadrupole X,Y misalignments wrt cryomodule	1	mm	alignment of internal components within the cryomodule	SCRF 1.3 GHz Cryomodule PRD LCLSII-HE-1.2-PR-0029	1.3 GHz Superconducting RF Cryomodule LCLSII-HE-1.2-FR-0052	See Alignment Workshop, May 22, 2015. https://indico.fnal.gov/conferenceDisplay.py? confId=9994https://indico.fnal.gov/conferenceDisplay.py?co nfId=9994	Cryomodule traveler	Measurement during CM assembly
46	BPM X,Y misalignments wrt cryomodule	1	mm	alignment of internal components within the cryomodule	SCRF 1.3 GHz Cryomodule PRD LCLSII-HE-1.2-PR-0029	1.3 GHz Superconducting RF Cryomodule LCLSII-HE-1.2-FR-0052	See Alignment Workshop, May 22, 2015. https://indico.fnal.gov/conferenceDisplay.py? confId=9994https://indico.fnal.gov/conferenceDisplay.py?confId	Cryomodule traveler	Measurement during CM assembly
47	Cryomodule X,Y misalignments wrt linac	0.3	mm	installation requirement, CM must have survey fiducials to allow this	SCRF 1.3 GHz Cryomodule PRD LCLSII-HE-1.2-PR-0029	1.3 GHz Cryomodule External Physical Interfaces LCLSII-4.5-IC-0661	See Alignment Workshop, May 22, 2015. https://indico.fnal.gov/conferenceDisplay.py? confId=9994https://indico.fnal.gov/conferenceDisplay.py?co	Cryomodule traveler	Measurement during CM assembly
48	Cavity Z misalignments wrt cryomodule	2	mm	alignment of internal components within the cryomodule	SCRF 1.3 GHz Cryomodule PRD LCLSII-HE-1.2-PR-0029	1.3 GHz Superconducting RF Cryomodule LCLSII-HE-1.2-FR-0052	See Alignment Workshop, May 22, 2015. https://indico.fnal.gov/conferenceDisplay.py? confId=9994https://indico.fnal.gov/conferenceDisplay.py?co	Cryomodule traveler	Measurement during CM assembly
49	Quadrupole Z misalignments wrt cryomodule	2	mm	alignment of internal components within the cryomodule	SCRF 1.3 GHz Cryomodule PRD LCLSII-HE-1.2-PR-0029	1.3 GHz Superconducting RF Cryomodule LCLSII-HE-1.2-FR-0052	See Alignment Workshop, May 22, 2015. https://indico.fnal.gov/conferenceDisplay.py? confId=9994https://indico.fnall.gov/conferenceDisplay.py?co	Cryomodule traveler	Measurement during CM assembly
50	BPM Z misalignments wrt cryomodule	2	mm	alignment of internal components within the cryomodule	SCRF 1.3 GHz Cryomodule PRD LCLSII-HE-1.2-PR-0029	1.3 GHz Superconducting RF Cryomodule LCLSII-HE-1.2-FR-0052	See Alignment Workshop, May 22, 2015. https://indico.fnal.gov/conferenceDisplay.py? confId=9994https://indico.fnal.gov/conferenceDisplay.py?co	Cryomodule traveler	Measurement during CM assembly
51	Cryomodule Z misalignments wrt linac	2	mm	installation requirement, CM must have survey fiducials to allow this	SCRF 1.3 GHz Cryomodule PRD LCLSII-HE-1.2-PR-0029	1.3 GHz Cryomodule External Physical Interfaces LCLSII-4.5-IC-0661	See Alignment Workshop, May 22, 2015. https://indico.fnal.gov/conferenceDisplay.py? confId=9994https://indico.fnal.gov/conferenceDisplay.py?co	Cryomodule traveler	Measurement during CM assembly
52	Cavity tilt misalignments	0.5	mrad	alignment of internal components within the cryomodule	SCRF 1.3 GHz Cryomodule PRD LCLSII-HE-1.2-PR-0029	1.3 GHz Superconducting RF Cryomodule LCLSII-HE-1.2-FR-0052	See Alignment Workshop, May 22, 2015. https://indico.fnal.gov/conferenceDisplay.py? confId=9994https://indico.fnal.gov/conferenceDisplay.py?co	Cryomodule traveler	Measurement during CM assembly
53	Quadrupole tilt misalignments	3	mrad	alignment of internal components within the cryomodule	SCRF 1.3 GHz Cryomodule PRD LCLSII-HE-1.2-PR-0029	1.3 GHz Superconducting RF Cryomodule LCLSII-HE-1.2-FR-0052	See Alignment Workshop, May 22, 2015. https://indico.fnal.gov/conferenceDisplay.py? confId=9994https://indico.fnal.gov/conferenceDisplay.py?co	Cryomodule traveler	Measurement during CM assembly
54	BPM tilt misalignments	3	mrad	alignment of internal components within the cryomodule	SCRF 1.3 GHz Cryomodule PRD LCLSII-HE-1.2-PR-0029	1.3 GHz Superconducting RF Cryomodule LCLSII-HE-1.2-FR-0052	See Alignment Workshop, May 22, 2015. https://indico.fnal.gov/conferenceDisplay.py? confId=9994https://indico.fnal.gov/conferenceDisplay.py?co	Cryomodule traveler	Measurement during CM assembly
55	Cryomodule tilt misalignments	0.05	mrad	installation requirement, CM must have survey fiducials to allow this	SCRF 1.3 GHz Cryomodule PRD LCLSII-HE-1.2-PR-0029	1.3 GHz Cryomodule External Physical LCLSII-4.5-IC-0661 Interfaces	See Alignment Workshop, May 22, 2015. https://indico.fnal.gov/conferenceDisplay.py? confId=9994https://indico.fnal.gov/conferenceDisplay.py?c	Cryomodule traveler	Measurement during CM assembly
56	Cavity roll misalignments	10	mrad	alignment of internal components within the cryomodule	SCRF 1.3 GHz Cryomodule PRD LCLSII-HE-1.2-PR-0029	1.3 GHz Superconducting RF Cryomodule LCLSII-HE-1.2-FR-0052	See Alignment Workshop, May 22, 2015. https://indico.fnal.gov/conferenceDisplay.py? confId=9994https://indico.fnal.gov/conferenceDisplay.py?co nfId=9994	Cryomodule traveler	Measurement during CM assembly
57	Quadrupole roll misalignments	3	mrad	alignment of internal components within the cryomodule	SCRF 1.3 GHz Cryomodule PRD LCLSII-HE-1.2-PR-0029	1.3 GHz Superconducting RF Cryomodule LCLSII-HE-1.2-FR-0052	See Alignment Workshop, May 22, 2015. https://indico.fnal.gov/conferenceDisplay.py?c confId=9994https://indico.fnal.gov/conferenceDisplay.py?co	Cryomodule traveler	Measurement during CM assembly
58	BPM roll misalignments	3	mrad	alignment of internal components within the cryomodule	SCRF 1.3 GHz Cryomodule PRD LCLSII-HE-1.2-PR-0029	1.3 GHz Superconducting RF Cryomodule LCLSII-HE-1.2-FR-0052	See Alignment Workshop, May 22, 2015. https://indico.fnal.gov/conferenceDisplay.py? confId=9994https://indico.fnal.gov/conferenceDisplay.py?co	Cryomodule traveler	Measurement during CM assembly
59	Cryomodule roll	2	mrad	installation requirement, CM must have survey fiducials to allow this	SCRF 1.3 GHz Cryomodule PRD LCLSII-HE-1.2-PR-0029	1.3 GHz Cryomodule External Physical LCLSII-4.5-IC-0661 Interfaces	See Alignment Workshop, May 22, 2015. https://indico.fnal.gov/conferenceDisplay.py? confId=9994https://indico.fnal.gov/conferenceDisplay.py?co nfId=9994	SLAC Survey & Alignment	Measurement during CM installation

Sub-System	Parameter	Value	Units	Comment / Cryo Systems implications	Physics requirement documents	Cryo Systems requirements, specifications, and interface documents	Other reference or verification documents	Production verification Documents or process	Verification method
1.3 GHz fundamental power coupler									
60	Nominal Qext	6×10^{7}			SCRF 1.3 GHz Cryomodule PRD LCLSII-HE-1.2-PR-0029 SSA Based RF Systems and LLRF Requirements LCLS-II-HE-1.3-PR-0030		Cryogenic Heat Load LCLSII-4.5-EN-0179	Cryomodule traveler	Measurement
61	Qext range	1×10^{7} – 1×10^{8}			SCRF 1.3 GHz Cryomodule PRD LCLSII-HE-1.2-PR-0029			Final Design Report LCLSII-HE-1.1-DR-0084	Simulation
62	Nominal power rating	4.6	kW		SCRF 1.3 GHz Cryomodule PRD LCLSII-HE-1.2-PR-0029		Results of the cavity Intergrated tests in Horizontal Test Stand at FNAL (AES021, AES028 and AES027) LCLS-II TN-15-43	Cryomodule traveler	Measurement
63	Maximum power rating	7	kW		SCRF 1.3 GHz Cryomodule PRD LCLSII-HE-1.2-PR-0029			Final Design Report LCLSII-HE-1.1-DR-0084	Simulation
64	Fundamental power coupler dipole deflection	$\leq 3\times10^{-3}$			SCRF 1.3 GHz Cryomodule PRD LCLSII-HE-1.2-PR-0029		Coupler RF Kick in the 1.3 GHz LCLS-II Accelerating Cavity LCLS-II-TN-14-04	Coupler RF Kick in the 1.3 GHz LCLS-II Accelerating Cavity LCLS-N-14-04	Simulation
1.3 GHz cavity tuner									
65	Slow tuner range	<-670 kHz		motor-driven system	SCRF 1.3 GHz Cryomodule PRD LCLSII-HE-1.2-PR-0029	Cryomodule SRF Cavity Tuner	Final Design Report LCLSII-HE-1.1-DR-0084 Tuner electro-mechanical design LCLSII-4.5-EN-0221 Results of the cavity Intergrated tests in LCLSII-TN-15-43 Horizontal Test Stand	Cryomodule traveler	Measurement
66	Slow tuner resolution	1.8	Hz	motor-driven system	SCRF 1.3 GHz Cryomodule PRD LCLSII-HE-1.2-PR-0029	Cryomodule SRF Cavity Tuner	Final Design Report LCLSII-HE-1.1-DR-0084 measurement Tuner electro-mechanical design LCLSII-4.5-EN-0221 measurement	Tuner electro-mechanical design LCLSII-4.5-EN-0221 Results of the cavity Intergrated tests in Horizontal Test Stand at FNAL LCLSII-TN-15-43	Prototype Prototype
67	Fast tuner range	±1 kHz		piezo system	SCRF 1.3 GHz Cryomodule PRD LCLSII-HE-1.2-PR-0029	Cryomodule SRF Cavity Tuner LCLSII-4.5-ES-0385	Final Design Report LCLSII-HE-1.1-DR-0084 Tuner electro-mechanical design LCLSII-4.5-EN-0221 Results of the cavity Intergrated tests in LCLSII-TN-15-43 Horizontal Test Stand	Cryomodule traveler	Measurement
68	Fast tuner resolution	<1	Hz	piezo system	SCRF 1.3 GHz Cryomodule PRD LCLSII-HE-1.2-PR-0029	Cryomodule SRF Cavity Tuner LCLSII-4.5-ES-0385	Final Design Report LCLSII-HE-1.1-DR-0084 Tuner electro-mechanical design LCLSII-4.5-EN-0221 Results of the cavity Intergrated tests in Horizontal Test Stand at FNAL (AES021; AES028 and AES027) LCLSII-TN-15-43	Tuner electro-design LCLSII-4.5-EN-0221 Results of the cavity Intergrated tests in Horizontal Test Stand at FNAL (AES021; AES028 and AES027) LCLSII-TN-15-43	Prototype measurement
1.3 GHz RF field and LLRF									
69	Field amplitude stability per cryomodule	0.01	%, RMS	integrated through 8 cavities in a cryomodule from CM02 onward, assuming uncorrelated errors between cavities first cavities in L0 (CM01) have similar tolerance per cavity.	SCRF 1.3 GHz Cryomodule PRD LCLSII-HE-1.2-PR-0029		Performance and Functional Requirements for the LCLS-II Low Level RF System LCLSII-2.7-FR-0371 Low Level Radio Frequency ESD LCLSII-4.1-ES-0569	Prototype cryomodule measurement	Measurement
70	Field amplitude stability per cavity	0.03	%	for cavities other than the first cavities in CM0, which have tolerance 0.01% per cavity.	SCRF 1.3 GHz Cryomodule PRD LCLSII-HE-1.2-PR-0029		Performance and Functional Requirements for the LCLS-II Low Level RF System LCLSII-2.7-FR-0371 Low Level Radio Frequency ESD LCLSII-4.1-ES-0569	Prototype cryomodule measurement	Measurement
71	Field phase stability per cryomodule	0.01	deg, RMS	integrated through 8 cavities in a cryomodule from CM02 onward, assuming uncorrelated errors between cavities; first cavities in L0 (CM01) have similar tolerance per cavity.	SCRF 1.3 GHz Cryomodule PRD LCLSII-HE-1.2-PR-0029		Performance and Functional Requirements for LCLSII-2.7-FR-0371 Low Level Radio Frequency ESD LCLSII-4.1-ES-0569	Prototype cryomodule	Measurement
72	Field phase stability per cavity	0.03	deg	for cavities other than the first cavities in CM0, which have tolerance 0.01 deg per cavity.	SCRF 1.3 GHz Cryomodule PRD LCLSII-HE-1.2-PR-0029		Performance and Functional Requirements for the LCLS-II Low Level RF System LCLSII-2.7-FR-0371 Low Level Radio Frequency ESD LCLSII-4.1-ES-0569	Prototype cryomodule measurement	Measurement
73	Cavity field probe external Q	7.5×10^{11} – 2.5×10^{12}		Nominal 1.0×10^{12}, too low gives insufficient signal, too high results in cable heating			Performance and Functional Requirements for The LCLS-II Low Level RF System LCLSII-2.7-FR-0371	Prototype cryomodule measurement	Measurement
1.3 GHz cavity HOMs									
74	Cavity HOM QL	$<1\times10^{6}$		monopole and dipole	SCRF 1.3 GHz Cryomodule PRD LCLSII-HE-1.2-PR-0029		Final Design Report LCLSII-HE-1.1-DR-0084	Resonant excitation of high order modes in superconducting RF cavities of LCLS II linac LCLS-II -TN-15-06	Calculation
75	Cavity monopole HOM maximum R/Q	175	Ω	TN uses calculated R/Q for LCLS-II cavities	SCRF 1.3 GHz Cryomodule PRD LCLSII-HE-1.2-PR-0029		Resonant excitation of high order modes in superconducting RF cavities of LC LS II linac LCLS-II-TN-15-06	Resonant excitation of high order modes in superconducting RF cavities of LCLS II linac LCLS-II -TN-15-06	Calculation
76	Cavity dipole HOM maximum R/Q	3×10^{5}	Ω/m	TN uses calculated R/Q for LCLS-II cavities	SCRF 1.3 GHz Cryomodule PRD LCLSII-HE-1.2-PR-0029		Resonant excitation of high order modes in superconducting RF cavities of LC LS II linac LCLS-II-TN-15-06	Resonant excitation of high order modes in superconducting RF cavities of LCLS II linac LCLS-II -TN-15-06	Calculation
77	HOM coupler dipole deflection	3×10^{-3}			SCRF 1.3 GHz Cryomodule PRD LCLSII-HE-1.2-PR-0029		Final Design Report LCLSII-HE-1.1-DR-0084	Coupler RF Kick in the 1.3 GHz LCLS-II Accelerating Cavity LCLS-II -TN-14-04	Simulation
78	Number of cavity HOM couplers per	2			SCRF 1.3 GHz Cryomodule PRD LCLSII-HE-1.2-PR-0029		Final Design Report LCLSII-HE-1.1-DR-0084	Final Design Report LCLSII-HE-1.1-DR-0084	Design studies

Sub-System	Parameter	Value	Units	Comment / Cryo Systems implications	Physics requirement documents		Cryo Systems requirements, specifications, and interface documents		Other reference or verification documents		Production verification Documents or process		Verification method
	cavity												
79	Maximum cavity HOM coupler absorbed power	<50	W		SCRF 1.3 GHz Cryomodule PRD	LCLSII-HE-1.2-PR-0029					Resonant excitation of high order modes in superconducting RF cavities of LCLS II linac	LCLS-II-TN-15-06	Calculation
1.3 GHz cryomodule HOM absorber													
80	Maximum beamline HOM absorbed power	50	W		SCRF 1.3 GHz Cryomodule PRD	LCLSII-HE-1.2-PR-0029	1.3 GHz Superconducting RF ule	LCLSII-HE-1.2-FR-0052	Final Design Report	LCLSII-HE-1.1-DR-0084	Some Wakefield Effects in the Superconducting RF Cavities of LCLS-II	LCLS-II TN-13-04	Calculation
81	Number of beamline HOM absorbers	1		one located at the end of each 1.3 GHz cryomodule, one located upstream of the first of the 3.9 GHz cryomodules	SCRF 1.3 GHz Cryomodule PRD	LCLSII-HE-1.2-PR-0029	1.3 GHz Superconducting RF ule	LCLSII-HE-1.2-FR-0052	Final Design Report	LCLSII-HE-1.1-DR-0084	Final Design Report	LCLSII-HE-1.1-DR-0084	Design studies
1.3 GHz Cryomodule Magnets													
82	Maximum beam energy in a cryomodule	10	GeV	for magnet design	SCRF 1.3 GHz Cryomodule PRD Magnets PRD	LCLSII-HE-1.2-PR-0029 LCLS-II-HE-1.3-PR-0033	Cryomodule Magnet	LCLSII-4.5-ES-0355			Final Design Report	LCLSII- 1.1-DR-0251	Design studies
83	Quadrupole minimum stable operating integrated gradient	0.5	kG		SCRF 1.3 GHz Cryomodule PRD	LCLSII-HE-1.2-PR-0029	Cryomodule Magnet	LCLSII-4.5-ES-0355	Cryomodule Production Magnets Test Program Performance of Conduction Cooled Splittable Superconducting Magnet Package for Linear Accelerators	LCLSII-4.5-EN-611 LCLSII-4.5-EN-0578	Cryomodule traveler		Measurement
84	Quadrupole maximum stable operating integrated gradient	20	kG	for matching and future upgrades	SCRF 1.3 GHz Cryomodule PRD Magnets PRD	LCLSII-HE-1.2-PR-0029 LCLS-II-HE-1.3-PR-0033	Cryomodule Magnet	LCLSII-4.5-ES-0355	Cryomodule Production Magnets Test Program Performance of Conduction Cooled Splittable Superconducting Magnet Package for Linear Accelerators	LCLSII-4.5-EN-611 LCLSII-4.5-EN-0578	Cryomodule traveler		Measurement
85	Quadrupole gradient stability	0.02	%	ΔK/K, RMS	SCRF 1.3 GHz Cryomodule PRD Magnets PRD	LCLSII-HE-1.2-PR-0029 LCLS-II-HE-1.3-PR-0033	Cryomodule Magnet Power Supply Cryomodule Magnet	LCLSII-4.5-ES-0477 LCLSII-4.5-ES-0355	Existing similar design power supplies are stable to 0.01 % of the DC current set point		SPEAR3 Intermediate DC magnet power supplies	Proceedings of EPAC 2004, Lucerne, Switzerland	Measurement
86	Quadrupole maximum unpowered residual field	8	G		SCRF 1.3 GHz Cryomodule PRD	LCLSII-HE-1.2-PR-0029	Cryomodule Magnet	LCLSII-4.5-ES-0355			Cryomodule traveler		Measurement
87	Quadrupole maximum unpowered residual field at the nearest cavity surface	few	mG		SCRF 1.3 GHz Cryomodule PRD	LCLSII-HE-1.2-PR-0029					In Situ Cryomodule Demagnetization	LCLSII- 4.5-EN-0482	Measurement
88	b2/b1	0.01		harmonics at 10 mm radius	Magnets PRD	LCLS-II-HE-1.3-PR-0033	Cryomodule Magnet	LCLSII-4.5-ES-0355	Performance of Conduction Cooled Splittable Superconducting Magnet Package for Linear Accelerators Cryomodule Production Magnets Test Program	LCLSII-4.5-EN-0578 LCLSII-4.5-EN-611	Cryomodule traveler		Measurement
89	b5/b1	0.1		harmonics at 10 mm radius	Magnets PRD	LCLS-II-HE-1.3-PR-0033	Cryomodule Magnet	LCLSII-4.5-ES-0355	Performance of Conduction Cooled Splittable Superconducting Magnet Package for Linear Accelerators Cryomodule Production Magnets Test Program	LCLSII-4.5-EN-0578 LCLSII-4.5-EN-611	Cryomodule traveler		Measurement
90	Field flatness ±	vario	cm	depends on location in lattice – see PRD	Magnets PRD	LCLS-II-HE-1.3-PR-0033	Cryomodule Magnet	LCLSII-4.5-ES-0355			Cryomodule traveler		Measurement
91	Quadrupole magnet aperture	7	cm	larger than the 1.3 GHz cavities	SCRF 1.3 GHz Cryomodule PRD Magnets PRD	LCLSII-HE-1.2-PR-0029 LCLS-II-HE-1.3-PR-0033	Cryomodule Magnet	LCLSII-4.5-ES-0355			Final Design Report	LCLSII- 1.1-DR-0251	Design studies
92	Dipole corrector maximum stable operating integrated gradient	50	Gm		SCRF 1.3 GHz Cryomodule PRD Steering Corrector Magnets PRD	LCLSII-HE-1.2-PR-0029 LCLSII-HE-1.3-PR-0037	Cryomodule Magnet	LCLSII-4.5-ES-0355	Performance of Conduction Cooled Splittable Superconducting Magnet Package for Linear accelrators	LCLSII-4.5-EN-0578	Cryomodule traveler		Measurement
93	Dipole corrector minimum stable operating integrated gradient	1	Gm		SCRF 1.3 GHz Cryomodule PRD	LCLSII-HE-1.2-PR-0029	Cryomodule Magnet	LCLSII-4.5-ES-0355	Performance of Conduction Cooled Splittable LCLSII-4.5-EN-0578 Superconducting Magnet Package for Linear Accelerators		Cryomodule traveler		Measurement
94	Dipole corrector stability	0.02	%	ΔΘ/Θ, RMS	SCRF 1.3 GHz Cryomodule PRD Steering Corrector Magnets PRD	LCLSII-HE-1.2-PR-0029 LCLSII-HE-1.3-PR-0037	Cryomodule Magnet Power Supply Cryomodule Magnet	LCLSII-4.5-ES-0477 LCLSII-4.5-ES-0355	Existing similar design power supplies are stable to 0.01 % of the DC current set point		SPEAR3 Intermediate DC magnet power supplies	Proceedings of EPAC 2004, Lucerne, Switzerland	Measurement
95	Dipole corrector maximum unpowered residual integrated gradient	2	mG-m		SCRF 1.3 GHz Cryomodule PRD	LCLSII-HE-1.2-PR-0029	Cryomodule Magnet	LCLSII-4.5-ES-0355			Cryomodule traveler		Measurement
96	Quadrupole vibration tolerance, both X and Y	0.12	µm	Above 10–100 Hz, feedback mitigates effects of lower frequency motion. Modal analysis and use of existing cryomodule design based on XFEL suggest no amplification of motion at quadrupole at frequencies above beam feedback range. Ground motion coupling to magnet is not expected to result in excessive vibration	Quadrupole Magnet Vibration Requirements	LCLS-II-HE-1.3-PR-0062	1.3 GHz Cryomodule Technical Description	LCLSII-HE-1.2-ES-0060			Quadrupole Vibration Measurements of a TESLA Type II Cryomodule	EUROTeV-Report-2006-036	Measurement
97	Number of quadrupoles per cryomodule	1			SCRF 1.3 GHz Cryomodule PRD	LCLSII-HE-1.2-PR-0029			Final Design Report	LCLSII-	Top Level Assembly Drawing (Fermilab TeamCenter)	F10009945	Design studies
98	Quadrupole strength for heat load calculations	11	kG	corresponding to beam energy 6 GeV	SCRF 1.3 GHz Cryomodule PRD	LCLSII-HE-1.2-PR-0029			Cryogenic Heat Load	LCLSII-	Cryogenic Heat Load	LCLSII-4.5-EN-0179	Calculation
1.3 GHz Cryomodule BPM													
99	Position resolution	200	µm	for button BPM	Beam Position Monitor	LCLSII-2.4-PR-0136	Cold Button Beam Position Monito r	LCLSII-4.5-ES-0403			Final Design Report	LCLSII-1.1-DR-0251	Design studies
100	Charge resolution	1	pC	for button BPM	Beam Position Monitor	LCLSII-2.4-PR-0136	Cold Button Beam Position Monito r	LCLSII-4.5-ES-0403			Final Design Report	LCLSII-1.1-DR-0251	Design studies

Sub-System	Parameter	Value	Units	Comment / Cryo Systems implications	Physics requirement documents		Cryo Systems requirements, specifications, and interface documents			Other reference or verification documents	Production verification Documents or process	Verification method	
101	Stay-clear minimum internal diameter	70	mm		Beam Position Monitor Requirements PRD	LCLSII-2.4-PR-0136	Cold Button Beam Position	r	LCLSII-4.5-ES-0403		LCLS-II Cold BPM Assembly	FNAL/Teamcenter F10023160	Design studies
102	BPM alignment tolerance	0.5	mm		Beam Position Monitor Requirements PRD	LCLSII-2.4-PR-0136	Cold Button Beam Position	r	LCLSII-4.5-ES-0403		LCLS-II Cold BPM Assembly	FNAL/Teamcenter F10023160	Design studies
103	BPM drift tolerance	0.2	mm/week		Beam Position Monitor Requirements PRD	LCLSII-2.4-PR-0136	Cold Button Beam Position	r	LCLSII-4.5-ES-0403		LCLS-II Cold BPM Assembly	FNAL/Teamcenter F10023160	Design studies
104	BPM offset tolerance	0.2	mm		Beam Position Monitor Requirements PRD	LCLSII-2.4-PR-0136	Cold Button Beam Position	r	LCLSII-4.5-ES-0403		LCLS-II Cold BPM Assembly	FNAL/Teamcenter F10023160	Design studies
105	Number of BPMs	1		one per cryomodule, cold button BPMs	SCRF 1.3 GHz Cryomodule PRD Beam Position Monitor Requirements PRD	LCLSII-HE-1.2-PR-0029 LCLSII-2.4-PR-0136					Top Level Assembly Drawing (Fermilab TeamCenter)	F10009945 Design studies	

The boxes below indicate where the acceptance criteria is verified in travelers L2HE-LERF-CM-ACTS and L2HE-CMA-CM-ASSY (only criteria #22).

Table 2 Production Cryomodule Minimum Acceptance Criteria

	Parameter	Value	Minimum acceptable performance during test
1	Minimum usable gradient for an individual cavity	16 MV/m	Usable gradient – the maximum gradient at which the following 3 conditions are met: • radiation level is below 50 mR/hr, • the cavity can run stably for one hour • 0.5 MV/m below the quench field. Steps 34, 44, 54, 64, 74, 84, 94, 104
2	Nominal usable gradient	20.8 MV/m	Individual cavities should reach a nominal usable gradient of 20.8 MV/m. Need to confirm with SLAC.
3	Minimum Usable CW voltage produced by an individual cryomodule	173 MV	The total CW voltage produced by cryomodule with cavities running at their usable gradients shall be ≥173 MV with all cavities powered simultaneously in GDR/SELAP mode and with the magnet at nominal operating currents for at least one hour with the dark current <30 nA. Additionally, the individual cavity gradients during this run must be recorded. Step 113
4	Stable Operation		For cavities that have a usable gradient above 20.8 MV/m, they must also be shown to be stable (no quenches or trips) at 2 hour. New yes/no field in 32, 42, 52, 62, 72, 82, 92, 102
5	Captured dark current	<30 nA	The dark current as measured by Faraday cups at each end of a cryomodule at the minimum CW voltage as defined above shall be ≤30 nA when the cavities are operated in GDR/SELAP mode with the relative phases set to accelerate speed of light electrons. This should be done in such a way to maximize the dark current measured at the F ps. Step 111
6	Individual cavity Q_0	Not a criteria. Only a measurement request. Relates to Criteria 8.	cavity Q_0's must be measured at the expected operating gradient /m or the usable gradient whichever is lower)
7	Cryomodule operating duration with RF power during test		Each cryomodule must operate at the minimum CW voltage or greater in GDR/SELAP and with the magnet at operating currents until the coupler temperatures achieve equilibrium or for a minimum of ten (10) hours with 90% operating time, whichever is less, to verify stable operation and confirm acceptable coupler heating. New yes/no field in Step 110.
8	2 K Dynamic Load at 173 MV voltage		The measured dynamic 2 K heat load of the cryomodule while operating at at total voltage of 173 MV must be ≤ 137 W (equivalent to an average Q_0 of 2.7×10^{10}). New step between 113 and 114.
9	Static heat load at 2 K		The static heat load at 2 K must be ≤7 W Step 114
10	Cryomodule thermometry		All installed thermometry shall be verified functional by observing consistency in output with operational conditions. For sensors measuring identical locations on components within a cryomodule there shall be variation of no more than 0.2 Kelvin under the same conditions at each component and under static load with no power applied to the cavities or magnets New step between 115 and 116.
11	Cavity Microphonics	<10 Hz peak to peak	The microphonics for each cavity must be 10 Hz peak to peak or less measured over a 1 hour period while at the operating gra valve regulating the liquid level (not in a locked position). Steps 38, 48, 58, 68, 78, 88, 98, 108
12	Cryomodule liquid level sensors		Liquid level sensors shall be verified functional by observing liquid levels and changes therein consistent with liquid supply rates and estimated boil-off rates New step between 115 and 116.
13	Cryomodule cryogenic valving		JT valve, CoolDown/Warm up, Bypass valves shall all be verified functional during cryomodule operations by consistency with expectations for operational performance, in particular, no valve or actuator is to have ice form on the room temperature components. New step between 115 and 116.
14	Cavity tuning to resonance during test (coarse tuner)		After cool-down to 2 K, each cavity must be able to be tuned to a resonant frequency of 1300.000 MHz. The tuner on the cavity #1 must be able to change the cavity's frequency from 1299.980MHz to 1300.020MHz. Tuners on cavities #2- #8 must be able to adjust cavity's frequency from 1299.535 MHz to 1300.020MHz. Step 22.
15	Fine tuner minimum range	0-500 Hz	Step 23

16	Heater performance		All installed heaters shall be verified functional by measuring resistance of 45±6 Ω at 2 Kelvin. Heaters must be demonstrated functional in a cryomodule as verified by heating of the helium: • Six (6) of the eight (8) heaters on the helium vessels • Two (2) of the three (3) heaters on fill lines • Both heaters on liquid level units New step between 115 and 116.
17	Fundamental power coupler 50 K coupler flange maximum temperature	200 K	Measured temperature of FPC 50 K coupler flange must be less than 200 K at the conclusion of the 10-hour full cryomodule run. Step 110
18	Fundamental power coupler warm part maximum temperature	450 K	Measured temperature of FPC warm part must be less than 450 K at the conclusion of the 10-hour full cry May not be instrumented. Mike D to look into.
19	Cavity HOM coupler rejection of 1.3 GHz power		$Q_{ext} \geq 2x10^{11}$, maximum power measured at 1.3 GHz out of a single HOM coupler is 1.7 W at 20.8 MV/m Steps 30, 40, 50, 60, 70, 80, 90, 100
20	Magnet electrical verification		The magnet package shall be verified electrically to be without shorts or opens, hi-pot test at 500 V with <1 μA under insulating vacuum, <5 μA in ambient pressure, and can be operated at a current of at least 18 A for a minimum of 30 minutes without quenching Step 28 and 29
21	BPM electrical verification and signal balance		The BPM shall be verified electrically to be without shorts or opens, with cross-talk between electrodes ≤ -30dB. The difference in S-parameter (S21) between electrodes is < 1dB over a frequency range of 0.5 to 2.5 GHz Step 27
22	Cryomodule vacuum		Cryomodule beamline vacuum prior to cooldown $1x10^{-8}$ To Step 4 Cryomodule insulating vacuum prior to cooldown $1x10^{-4}$ To Step 3 Cryomodule warm coupler vacuum prior to cooldown $1x10^{-7}$ To Step 5 Cryomodule beamline vacuum at 2 K $1x10^{-9}$ To Step 115 Cryomodule insulating vacuum at 2 K $1x10^{-6}$ To Cryomodule warm coupler vacuum at 2 K $5x10^{-8}$ To

Table 3 Verification cryomodule minimum acceptance criteria, with performance requirement validated for each criteria, and associated production workstation

	Criteria	Validates:	Workstation
1	Cavity beamline vacuum Cold (2K) $1x10^{-10}$ Torr Warm (room temperature) $1x10^{-8}$ Torr	Vacuum pumping and leak determination	WS 1 – CR Assembly
2	Center Frequency 1.300000 GHz +/- 20kHz	Cavity Fabrication Target frequency	WS 1 – CR Assembly
3	Individual cavities reach at least 20.8 MV/m	Overall Design and Assembly Validation, cavity doping recipe	WS 1 – CR Assembly
4	Field emission onset ≥ 16 MV/m for each cavity individually	Particle Free Assembly	WS 1 – CR Assembly
5	The BPM shall be verified electrically to be without shorts or opens, with cross-talk between electrodes ≤ -30dB. The difference in S-parameter (S21) between electrodes is < 1dB over a frequency range of 0.5 to 2.5 GHz.	BPM design and assembly	WS 1 – CR Assembly

6	Individual cavity $Q_0 \geq 2.7x10^{10}$ at 20.8 MV/m after a fast cool down	Magnetic Hygiene and Shielding, cavity doping recipe	WS 2/3
7	HOM $Q_{ext} \geq 2x10^{11}$, maximum power measured out of a single HOM is 1.7 W at nominal gradient of 20.8 MV/m.	HOM notch tuning	WS3
8	After cool-down to 2 K, each cavity must be able to be tuned to a resonant frequency of 1300.000 MHz. The tuner on the cavity #1 must be able to change the cavity's frequency from 1299.980MHz to 1300.020MHz. Tuners on cavities #2- #8 must be able to adjust cavity's frequency from 1299.535 MHz to 1300.020MHz.	Tuner design	WS3
9	The magnet package is verified electrically to be without shorts or opens, hi-pot test at 500 V with <1 µA under insulating vacuum, <5 µA in ambient pressure, and can be operated at a current of at least 20 A without quenching	Magnet Installation	WS3
10	Nominal FPC $Q_{ext} = 6x10^7$ with range verified from $1x10^7$ to $8x10^7$	FPC/CM design verification	WS3
11	Average CM $Q_0 \geq 2.7x10^{10}$ measured as a total dynamic 2 K heat load of ≤137 W at 173 MV total accelerating voltage, after at least 10 hours c.w. operation or until the FPC temperature reaches equilibrium	Magnetic hygiene and shielding, cavity doping recipe	WS2-5 – Final Assembly
12	Stable operation at the minimum CW voltage or greater in GDR/SELAP and with the magnet at operating currents for an extended run of 2 weeks with 90% operating time, documenting all trips.	LLRF system/Resonance control, accelerator operation	WS1-5