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See *Document Review/Approval Matrix of Responsibilities*

Revision History

Revision	Date Released	Description of Change
R2	6/22/2022	Updated $Q_{ext,1}$ acceptance range. Corrected typographical errors. Updated serialized requirement references in Table 1.
R1	10/22/2021	Updated frequency acceptance range.
R0	5/17/2021	Original Release.

Table of Contents

1 Introduction

This document lays out the procedures and acceptance criteria for the vertical testing of the dressed 1.3 GHz cavities for LCLS-II-HE. The vertical acceptance test is a critical and mandatory step in the cavity qualification process. After each cavity is tested, the Cavity Technical Board (CTB) will review the results of the test against the acceptance criteria and, based on this review, either approve the cavity for cryomodule string assembly or route the cavity for retesting or reprocessing as necessary.

During the production phase of LCLS-II-HE, Jefferson Laboratory (JLab) and Fermilab (FNAL), the partner labs (PL), will be receiving dressed 1.3 GHz nine-cell cavities from the cavity vendor(s). These cavities will be shipped to the PLs under vacuum and equipped with the antennas, valve, and burst disk necessary for vertical test. Following an incoming inspection, these cavities will be prepared for vertical test (VT), cooled to 2.0 K, and tested according to the procedures defined in this document.

2 Review of Test Results and Dispositioning of Cavities by Cavity Technical Board

The CTB, a body of SRF subject matter experts (SMEs) representing all three partner laboratories, will review the results of each cavity test and deliberate on the path forward for each cavity.

In general, if the CTB finds that a cavity clearly meets or exceeds the acceptance specifications, the cavity will be deemed “qualified” and cleared for cryomodule string assembly. If the CTB finds that a cavity clearly fails to meet the qualification criteria, the cavity will be deemed “not qualified”. Depending on the nature of the failure to qualify, the CTB will assign the cavity for retest, light reprocessing, vendor rework, sidelining, or rejection.

If the CTB finds that a cavity meets the acceptance criteria “marginally” or “inconclusively”, they may assign the cavity for light rework or retest (as with a “not qualified” cavity) or, if including the cavity in question into an upcoming cryomodule string will not cause the cryomodule to fail its qualification (according to the judgement of the CTB), accept the cavity on the condition that it be included in the given cryomodule string. Classification of a test result as “marginal” or “inconclusive” and subsequent dispositioning will be determined at the discretion of the CTB on a cavity-by-cavity basis. Below are some possible scenarios where the CTB might decide on these classifications:

- Marginal qualification:
  - Acceptance threshold criterion within uncertainty range of cavity test result
  - Peak accelerating gradient does not meet acceptance threshold, but cavity could be grouped with other qualified cavities into a cryomodule string that meets cryomodule specifications
- Inconclusive result:
  - Cavity test result has too large an uncertainty range to conclusively judge against acceptance criterion
  - CTB has reason to believe that cavity test procedures were performed incorrectly
  - Cavity test include contradictory results

These lists should not be considered exhaustive.

3 Vertical Test Acceptance Criteria

Table 1 summarizes the criteria for qualification of a cavity based on the results of its vertical test. These criteria have been determined in order to ensure that the cryomodules assembled using these cavities meet the LCLS-II-HE cryomodule acceptance criteria defined in LCLSII-HE-1.2-PP-0255. The criteria are described and motivated in detail below.

Table 1: Vertical test acceptance criteria for dressed 1.3 GHz LCLS-II-HE cavities.

Qualification Parameter	Vertical Test Acceptance Condition	Relevant Cryomodule Acceptance Criteria	Parent Requirement
Resonant frequency of accelerating mode (f_0)	f_0 = 1300.3 ± 0.2 MHz	Cavity frequency = 1300.00 ± 0.02 MHz	PRD0029.3001
Peak accelerating gradient (E_{acc})	$E_{acc} \geq 23.0$ MV/m (May change during production according to Section 3.2.1)	Cavity nominal gradient ≥ 20.8 MV/m	PRD0029.3002
Intrinsic quality factor (Q_0) measured at T = 2.0 K, E_{acc} = 20.8 MV/m	$Q_0 \geq 2.5\times10^{10}$	Cavity average $Q_0 \geq 2.7\times10^{10}$	PRD0029.4005
Field emission	No detectable field-emission-induced radiation up to peak gradient	Cryomodule captured dark current < 30 nA	PRD0029.4007
Multipacting	Any multipacting must be fully processed before final Q_0 vs. E_{acc} measurements		PRD0029.3002
High-Q antenna coupling in operating mode ($Q_{ext,1}$)	$1.1\times10^{10} \leq Q_{ext,1} \leq 3.1\times10^{10}$		PRD0029.3002 PRD0029.4005
Field probe coupling in operating mode ($Q_{ext,2}$)	$7.5\times10^{11} \leq Q_{ext,2} \leq 2.5\times10^{12}$	$7.5\times10^{11} \leq Q_{ext,2} \leq 2.5\times10^{12}$ [see note]	PRD0029.3002 PRD0029.4005
HOM antenna coupling in operating mode ($Q_{ext,HOM}$)	$Q_{ext,HOM} \geq 2.7\times10^{11}$	$Q_{ext,HOM} \geq 2.7\times10^{11}$ [see note]	PRD0029.4018
HOM coupler emitted power (P_{HOM}) measured at E_{acc} = 20.8 MV/m	$P_{HOM} \leq 1.7$ W	$P_{HOM} \leq 1.7$ W	PRD0029.4018

Note on **Table 1**: At time of writing this document, cryomodule requirements for $Q_{ext,2}$ and $Q_{ext,HOM}$ in LCLSII-HE-1.2-PP-0255 are outdated or missing. Corrected requirements are included in a pending revision to that specification.

3.1 Resonant Frequency of Accelerating Mode (f_0)

The resonant frequency of the accelerating mode of the cavity in vertical test (not equipped with a tuner) must be 1300.3 ± 0.2 MHz. The cavity tuner installed during cryomodule string assembly applies a compressive force on the cavity, decreasing the resonant frequency to the linac operating frequency of 1300.00 MHz.

3.2 Peak Accelerating Gradient (E_{acc})

The nominal accelerating gradient for LCLS-II-HE cryomodules is 20.8 MV/m. Several factors may lead to cavities reaching lower gradients after cryomodule assembly than in the vertical acceptance test. One such gradient degradation factor is error in the vertical test field measurement calibration, which may be conservatively estimated at ±10%. Another factor is "introduced" gradient degradation caused by some change to the cavity between the acceptance test and cryomodule test; this change may be an introduced or relocated field emitter on the cavity surface, multipacting due to adsorbed gases, or something else. To mitigate the risk of gradient degradation, cavities in vertical test must exceed 23.0 MV/m in order to qualify for cryomodule string assembly.

3.2.1 Variable Peak Gradient Acceptance Threshold

If the LCLS-II-HE cryomodules are found during production to exceed the 20.8 MV/m target operating gradient, the CTB may decide to lower the vertical test peak accelerating gradient acceptance threshold. This will allow for lower cavity rework rates while still achieving target performance in the linac. The threshold may be adjusted periodically according to cavity gradient performance in vertical test and cryomodule test in order to ensure that the LCLS-II HE accelerator meets its gradient and cryogenic heat load requirements.

Engineering note LCLSII-HE-1.2-EN-0247 describes a statistical model of linac accelerating voltage given cavity gradient performance in vertical test and cryomodule gradient degradation factors. The model takes into account the following parameters, associated cavity by cavity:

- Peak accelerating gradient of cavities in vertical test
- Intrinsic quality factor of cavities in vertical test
- Peak accelerating gradient of cavities in cryomodule test
- Intrinsic quality factor of cavities in cryomodule test
- Suspected reason for gradient degradation, if any (e.g. multipacting, introduced field emitter)

The model then yields the following statistical parameters:

- Statistical distribution of vertical test gradient performance
- Rates and magnitudes of gradient degradation, by degradation pathway

The rates of gradient degradation are fed back into the model, with optional adjustment after expert analysis by the CTB. The model then yields the following predictive outputs:

- Expected vertical test performance of remaining cavities
- Expected cryomodule test performance of remaining cavities
- Optimal vertical test gradient acceptance threshold, predicted to
  - Ensure sufficient accelerating voltage in linac
  - Ensure cryogenic heat load of linac within specification
  - Minimize rates of cavity rework/rejection after vertical test

The CTB will periodically run the model as cavities and cryomodules are tested to project the performance of cavities and cryomodules still to be constructed. At weekly meetings, the CTB will review new vertical test and cryomodule test results with the help of the EN-0247 model. Input data to the model will also include test results from the verification cryomodule (vCM).

The earliest point at which the CTB will decide to adjust the peak gradient acceptance threshold from the initial value of 23.0 MV/m will be after JLab and FNAL have each completed and tested at least one cryomodule. The CTB will then reevaluate and if necessary adjust the gradient acceptance threshold after a cryomodule is tested or after ten cavities are tested vertically, whichever comes first since the last reevaluation.

If the CTB adjusts the gradient acceptance threshold, revisions to the vertical test travelers will be issued reflecting the new threshold.

3.3 Intrinsic Quality Factor (Q_0)

The average (harmonic mean) quality factor of cavities installed in LCLS-II-HE cryomodules is specified to exceed 2.7×10^{10} at the operating gradient. Cavities tested vertically are equipped with stainless steel flanges at the end of each beam tube. The flange on the short beam tube on the coupler side of the cavity dissipates power with an external quality factor of 3.6×10^{11} (equivalent to a residual resistance of approximately 0.75 nΩ); the flange on the long beam tube has a negligible impact on Q. Accounting for these additional losses, the acceptance threshold quality factor of 2.7×10^{10} in the cryomodule translates to the vertical test acceptance criteria of $Q_0 = 2.5\times10^{10}$. The intrinsic quality factor must meet or exceed this threshold when measured at 2.0 K at the target operating gradient of E_{acc} = 20.8 MV/m.

If field emission or multipacting are detected during vertical test and are subsequently processed away (see relevant sections below), the cavity must be shown to meet this threshold after processing is completed.

3.4 Field Emission

Radiation from field emission is of particular concern for LCLS-II-HE. Dark current radiation impacts cryomodule component lifetimes and poses a long-term risk due to activation of materials in the accelerator housing. In addition, when field emission causes heating, increasing the dynamic heat load of cavities in the cryomodules, gradients must be lowered to avoid cavity quench. Although the cryomodule acceptance criteria allow for a small amount of dark current, prior experience has shown that field emission almost never improves, and indeed usually gets worse, when comparing cavities in vertical test to later cryomodule performance. As a result, LCLS-II HE cavities in vertical test must have no detectable field emission up to the quench field in order to qualify for string assembly.

If field emission is detected below the ultimate quench field but conditions away during testing, the CTB will examine the cavity test results with special care to determine if the cavity's performance is acceptable.

3.5 Multipacting

LCLS-II-HE cavities must be shown to be free of multipacting in vertical test. If any suspected multipacting quenches are encountered during vertical test, an effort must be made by the test operator(s) to identify the quench as stemming from multipacting, and subsequently to condition the multipacting away and reach the ultimate quench field of the cavity. If multipacting is conditioned away during the cavity test, the cavity must be shown to be free of multipacting from low field up to the ultimate quench field.

3.6 High-Q Antenna Coupling Factor ($Q_{ext,1}$)

The high-Q fixed antenna is used to excite the cavity field and to measure the quality factor and field strength in vertical test. The acceptance range of the coupling factor of the high-Q antenna is $1.1\times10^{10} \le Q_{ext,1} \le 3.1\times10^{10}$. Outside of this range, uncertainties on the cavity measurements may become too large for the measurements to be reliable.

3.7 Field Probe Coupling Factor ($Q_{ext,2}$)

The nominal coupling factor for the field probe antenna in the LCLS-II-HE cavities is $Q_{ext,2} = 1.0\times10^{12}$. It is critical that the measured $Q_{ext,2}$ not stray too far from the nominal value: coupling that is too strong will cause excessive heating of RF cables, and coupling that is too weak will not be sufficient to drive the low-level RF system. Performance is not expected to change between vertical test and cryomodule operation, so the vertical test acceptance range is the same as that in the cryomodule acceptance criteria, $7.5\times10^{11} \le Q_{ext,2} \le 2.5\times10^{12}$.

3.8 Higher-Order Mode Antenna Coupling Factor ($Q_{ext,HOM}$) and Power (P_{HOM})

The higher-order mode (HOM) antennas must reject the 1.3 GHz accelerating mode to minimize loss of RF power to couplers and heating of components in the cryomodule isolation vacuum. For vertical test acceptance, the $Q_{ext,HOM}$ coupling factor must exceed 2.0×10^{11}. Both HOM couplers must meet this acceptance condition. In addition, as an equivalent redundant check, the emitted power from the accelerating mode from each HOM coupler must be verified to be less than 1.7 W when the cavity is excited to an accelerating gradient of E_{acc} = 20.8 MV/m.

4 Test Procedure

4.1 Instrumentation and Fixtures

As described in Section 01, the LCLS-II-HE 1.3 GHz cavities will arrive at the partner laboratories under vacuum, equipped with the antennas and vacuum fixtures necessary for vertical test. Antennas to be installed are the high-Q fixed antenna, the field probe antenna, and both HOM antennas. The short end beam tube (coupler side) will be sealed with a blank-off flange valve assembly, including a burst disk and an all-metal right angle valve fitted with a VCR adapter flange. The long end beam tube (bellows side) will be sealed with a blank-off flange. The bellows will be secured with a bellows brace assembly including split ring, brace arms, and protective covers.

Some additional instrumentation must be installed on the cavity before vertical test:

A minimum of 3 Cernox thermometers must be installed. At least one sensor must be placed at the height of each of the following locations on or near the cavity (such as on an instrumentation rod):

- Short beam tube
- Long beam tube
- Cell 5 equator

Alternatively, if 4 Cernox thermometers are installed, they must be placed at the heights of the following locations on or near the cavity:

- Short beam tube
- Long beam tube
- Cell 4 equator
- Cell 6 equator

At least two flux gate magnetometers must be installed on or near the cavity. At least one sensor must be placed at the height of each of the following locations:

- Cell 1 equator
- Cell 9 equator

Additional thermometers and magnetometers may be installed. The installation locations of all thermometers and magnetometers must be recorded in the vertical test traveler document.

At least one radiation monitor must be installed in the vertical test stand, outside of the dewar on or near the cavity axis. Due to the highly directional nature of cavity field emission radiation, the location of the radiation sensor(s) should be consistent between tests in a given vertical test stand. The general location of the sensor(s) should be recorded in the vertical test traveler document.

The cavities must remain under vacuum for the vertical test. Active pumping is permitted but not required.

4.2 Cooldown

For the vertical test, the cavities will first be "fast-cooled" with liquid helium from 300 K to approximately 4.2 K. The residual magnetic field exposed to the cavity must be no stronger than 5 mG as the cavity passes through its superconducting transition temperature, approximately 9.2 K. Active compensation may be used to reach this level of magnetic hygiene. The temperature gradient across the length of the cavity must be at least 50 K/m when the bottom of the cavity goes through the superconducting transition to ensure maximum expulsion of magnetic flux. The ambient field at room temperature and the thermal gradient at the transition temperature should both be recorded in the vertical test traveler.

If the initial cooldown does not meet the required thermal gradient, the cavity may need to be thermally cycled (see Section 4.3.6) in an effort to achieve acceptable flux expulsion. The operator should make at least initial Q_0 vs. E_{acc} measurements to determine whether a thermal cycle is necessary.

After the initial fast cooldown, the cavities will be cooled to the testing temperature of 2.00±0.02 K.

4.3 RF Test

4.3.1 Calibration

For calibration of the RF test, a minimum of five "RF Off" [1] decay measurements will be taken and averaged for calibration of the Q_0 and E_{acc} measurements. These calibration measurements must be performed in the E_{acc} = 6–8 MV/m range.

4.3.2 2.0 K Q_0 vs. E_{acc} Measurements

After calibration, the test operator will measure Q_0 as a function of E_{acc} from 1 MV/m up to the cavity quench field. Measurements will be taken in steps no larger than 1 MV/m. Each measurement point must include the following data, at a minimum, including uncertainty range when appropriate:

- Date and time
- E_{acc}
- Q_0
- f_0
- Incident power (P_i)
- Reflected power (P_r)
- Transmitted power (P_t)
- HOM_A and HOM_B power (P_{HOMA}, P_{HOMB})
- Q_{ext} for high-Q antenna, field probe, and both HOMs
- Power measurement calibration factors
- Temperature of all installed thermometers
- Radiation measurement of all installed radiation detectors

4.3.3 Field Emission and Multipacting Quenches

The operator must carefully observe the test to identify any field emission or multipacting quench events.

If field emission is encountered during test, the operator should use their best judgment and local radiation safety guidelines to decide whether it is safe to attempt to condition the field emission away, or whether it is appropriate to stop testing. In case of doubt, the operator should contact the CTB or an SME representative thereof for an expert opinion on the best path forward.

Multipacting quenches in TESLA/ILC-style cavities, like those used in LCLS-II-HE, typically occur in the E_{acc} = 17–21 MV/m range. If the cavity quenches and the reason for the quench is identified as multipacting, the operator should attempt to condition the multipacting in order to reach higher E_{acc}.

If any significant Q_0 degradation occurs during or as a result of the conditioning of field emission or multipacting, a full Q_0 vs. E_{acc} curve must be taken from low field up to the ultimate quench field after all processing is finished. This final curve must adhere to the requirements laid out in Section 4.3.2.

If, after processing, the cavity fails to meet the Q_0 acceptance level due to this degradation, but would have met the acceptance level if the degradation had not occurred (in the judgment of the operator), the cavity should be thermally cycled (see Section 4.3.6) and measured again.

If field emission or multipacting is present and does not condition away, or if no effort is made to condition the field emission or multipacting, the cavity should be reprocessed (see Section 5).

4.3.4 Parasitic Excitation of 7π/9 Mode

The LCLS-II and EuXFEL projects encountered occasional parasitic excitation of the 7π/9 mode (approximately 1297 MHz) in vertical test; indeed, this is the norm for LCLS-II-HE cavity tests. The cause of this excitation is not known, but it is suspected to be related to mode coupling multipacting or field emission. The 7π/9 field is stronger in some cells than the fundamental mode for a given energy, so this parasitic excitation can lead to early quench; moreover, cavity data taken while the parasitic mode is excited does not accurately characterize the cavity's performance in the cryomodule. The 7π/9 mode should be monitored during vertical test, for example by a spectrum analyzer reading the signal from the field probe over a bandwidth wide enough to cover the fundamental and 7π/9 modes.

If the 7π/9 mode is encountered during test, the operator should note this in the traveler. An effort should be made to ensure that the Q_0 vs. E_{acc} points are measured with minimal excitation of the parasitic mode. To that end, operating in a "quasi-pulsed mode" may be necessary to record clean data.

4.3.5 Q_0 vs. E_{acc} Measurements at Low Temperature

In the case that the cavity does not meet the Q_0 acceptance threshold, or in special cases where it is deemed to be scientifically important (for example, if a cavity shows exceptionally high Q_0), additional Q_0 vs. E_{acc} curves should be taken at temperatures below 2.0 K. This low temperature data will help to identify whether the low quality factor is due to elevated residual resistance (R_0) or BCS resistance (R_{BCS}). The temperatures of these additional measurements must be selected such that there is sufficient data to determine R_0 vs. E_{acc}. The curves should be measured over the same range and with the same resolution as required for the 2.0 K measurements laid out in Section 4.3.2.

The RF measurement calibration procedure should be repeated each time the cavity is stabilized at a new temperature.

4.3.6 Thermal Cycling

It may be necessary during testing to repeat the cooldown and flux expulsion procedure, as noted in Sections 4.2 and 4.3.3. In these cases, the cavity should first be warmed to at least 100 K, then the fast cool procedure described in Section 4.2 should be performed again. The operator should then proceed with the standard RF test procedures, including the measurement calibration.

5 Cavity Reprocessing

5.1 High Pressure Rinse (HPR)

If a cavity exhibits field emission or multipacting that is not conditioned away during testing, the cavity should be reprocessed with HPR and given a second vertical test.

5.2 Further Diagnostic and Remedial Activities

If a cavity is treated with additional HPR per Section 5.1 and again shows field emission or multipacting that is not conditioned away during testing, the cavity may require further diagnostic activities and/or more thorough reprocessing. These further actions will need to be decided by the CTB, and may include optical inspection, nitric rinsing, light electropolishing, or other rework.

6 References

[1] H. Padamsee, J. Knobloch and T. Hays, RF Superconductivity for Accelerators, 2nd. Ed., 2008.