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LCLS-II-HE VERTICAL ACCEPTANCE TESTING PLANS*

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Abstract

LCLS-II-HE has performance requirements similar to but generally more demanding than those of LCLS-II, with an operating gradient of 21 MV/m (up from 16 MV/m in LCLS-II) and tighter restrictions on field emission and multipacting. In this paper, we outline the requirements for the 1.3 GHz cavities and the plans for qualification of these cavities by vertical test. We discuss lessons learned from LCLS-II and highlight the changes implemented in the vertical test procedure for the new project.

INTRODUCTION

LCLS-II-HE is a new electron linac being built at SLAC. The LCLS-II-HE accelerating cavities are fundamentally similar to those in LCLS-II: they are mechanically identical niobium 1.3 GHz TESLA-style 9-cell cavities, they are built using a vendor supply chain also used for LCLS-II, and they will be prepared using nitrogen doping. However, the LCLS-II-HE cryomodules have higher performance requirements than those in LCLS-II, with a target cryomodule gradient of 20.8 MV/m at an average Q_0 of 2.7×10^{10} [1]. Through R&D efforts the nitrogen doping protocol has been improved in order to achieve these performance goals [2]. Further, lessons learned from LCLS-II have been implemented to counter multipacting and field emission, both of which affected many cavities in LCLS-II and will pose a problem for LCLS-II-HE if unaddressed, as noted elsewhere [3].

As in LCLS-II, the cavities will be studied under vertical test at the partner laboratories Jefferson Lab (JLab) and Fermilab (FNAL), with each lab testing approximately half of the cavities. LCLS-II-HE has established the cavity technical board (CTB), a body of SRF experts representing SLAC, JLab, and FNAL; the CTB will examine the test results of each cavity and accept or reject the cavities for assembly into cryomodule strings based on these results.

The criteria and procedures described here have been reported previously in internal project documentation [4] and are largely based on those developed for LCLS-II [5].

VERTICAL TEST ACCEPTANCE CRITERIA

Table 1 summarizes the performance criteria that the cavities must meet in vertical test (VT) in order to qualify for string assembly. In cases where cavities do not meet the requirements, the CTB will deliberate to decide on any remedial action required. The exception to this is in cases of only minor and common light reprocessing tasks, such as a routine re-rinse if field emission is detected.

Resonant Frequency

The resonant frequency of the accelerating π mode of the cavities is required to be 1300.25 ± 0.10 MHz in the vertical test. This is slightly higher than the operating frequency in the cryomodules, 1300.00 MHz, to allow for preloading of the compressive tuners in the cryomodule. The lack of tuners in VT also drives the larger acceptance range for f_0. This is the same acceptance condition as in LCLS-II.

Peak Accelerating Gradient

Cavities tested in VT are required to reach a peak accelerating gradient (*i.e.* the ultimate quench gradient after all field emission and multipacting processing is finished) of at least 23 MV/m. This is larger than the cryomodule peak gradient requirement of 20.8 MV/m. The difference allows for a conservative margin of measurement uncertainty of 10% and mitigates risk of gradient degradation due to field emission or other factors introduced between VT and cryomodule installation.

In addition, the CTB will have the option of establishing a variable peak gradient acceptance threshold (see also [3] in these proceedings). Aided by a statistical model [6] of cavity gradient performance, the CTB may raise or lower the 23 MV/m threshold in order to ensure cryomodule requirements are met while also maximizing cavity yield. As an example of a situation where this might be used, if the cavity gradients and quality factors were routinely exceeding performance thresholds, the CTB might decide to lower the gradient threshold and accept cavities with lower peak gradients so long as cryomodules would still meet the average E_{acc} and Q_0 requirements.

Intrinsic Quality Factor

The intrinsic quality factor Q_0 measured in VT is required to exceed 2.5×10^{10} measured at $T = 2$ K and $E_{\mathrm{acc}} = 20.8$ MV/m. This corresponds to a microwave surface resistance $R_s = 11.1$ nΩ. This Q_0 acceptance threshold is slightly lower than the average quality factor of 2.7×10^{10} required in the cryomodule; the difference is due to the RF losses caused by the stainless steel end flanges installed on the cavity beam tubes during vertical test. These flanges, removed before cryomodule assembly, dissipate power with an equivalent Q of 3.6×10^{11}, or 0.75 nΩ of residual resis-

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Table 1: Summary of Vertical Test Acceptance Requirements for the LCLS-II-HE Cavities. Also shown are the related cryomodule acceptance criteria where relevant and different from the criteria required in vertical test.

Qualification Parameter	Acceptance Condition	Relevant Cryomodule Acceptance Criteria
Resonant frequency of accelerating mode (f_0)	f_0 = 1300.25 ± 0.10 MHz	f_0 = 1300.00 ± 0.02 MHz after tuning
Peak accelerating gradient ($E_{acc,pk}$)	$E_{acc,pk} \geq 23.0$ MV/m	$E_{acc,pk} \geq 20.8$ MV/m
Intrinsic quality factor (Q_0) measured at T = 2.0 K, E_{acc} = 20.8 MV/m	$Q_0 \geq 2.5 \times 10^{10}$	$Q_0 \geq 2.7 \times 10^{10}$
Field emission	No detectable field emission radiation up to $E_{acc,pk}$	Cryomodule captured dark current < 30 nA
Multipacting	Any multipacting must be fully processed before final Q_0 vs. E_{acc}	none
High-Q antenna coupling in operating mode ($Q_{ext,1}$)	$1.1 \times 10^{10} \leq Q_{ext,1} \leq 1.9 \times 10^{10}$	none
Field probe coupling in operating mode ($Q_{ext,2}$)	$7.5 \times 10^{11} \leq Q_{ext,2} \leq 2.5 \times 10^{12}$	same as in VT
HOM antenna coupling in operating mode ($Q_{ext,HOM}$)	$Q_{ext,HOM} \geq 2.7 \times 10^{11}$	same as in VT
HOM coupler emitted power (P_{HOM}) at E_{acc} = 20.8 MV/m	$P_{HOM} \leq 1.7$ W	same as in VT

tance. The Q_0 requirement has not changed since LCLS-II except for the gradient at which it is measured.

Field Emission

The LCLS-II-HE cavities must show no detectable field emission up to the peak accelerating gradient in order to qualify. This is a change from LCLS-II, which allowed a small amount of field emission dark current at high gradient. A lesson learned from the earlier project is that field emission detected in vertical test almost never improves after cryomodule assembly and often actually gets worse. Another lesson learned is that external radiation monitor signals are not easily correlated to dark current, especially across multiple VT facilities, so getting a reliable dark current measurement is difficult. Moreover, since LCLS-II-HE will operate at a higher gradient, dark current radiation is of greater concern than in the earlier project.

If any field emission is detected during VT, the test operator may attempt to process the field emission away (see "Field Emission and Multipacting" below). If field emission is successfully processed, a final Q_0 vs. E_{acc} curve must be measured to confirm that the cavity still meets the other acceptance criteria. A thermal cycle may be necessary if quenching the cavity has lowered Q_0.

If field emission is present and cannot be processed away, the cavity will be cleaned with high-pressure rinsing and tested again. If field emission is still present after this rinse, the cavity will require further reprocessing before it can be accepted.

Multipacting

Cavities in VT must have all multipacting processed away before the final Q_0 vs. E_{acc} measurements are taken. This is a new requirement introduced for LCLS-II-HE. At 20.8 MV/m, the LCLS-II-HE target accelerating gradient lies within the multipacting band of TESLA cavities [7], so it is critical that any multipacting encountered be identified and attempts to process it away be made in order to push the cavity to its limits and determine its true peak gradient. If any such processing occurs, as with field emission, a final Q_0 vs. E_{acc} curve must be measured to confirm that the cavity still meets the other acceptance criteria.

There is no cryomodule requirement directly related to multipacting measured in vertical test, since it is expected that multipacting due to adsorbed gases will reappear after the cavities are vented for string assembly, and that the results of any multipacting processing performed in VT will not persist in the cryomodule. Cryomodule testing and commissioning procedures will include efforts to identify and process multipacting.

Antenna External Quality Factors

$Q_{ext,1}$, the external quality factor of the high-Q fixed antenna, is required to fall between 1.1×10^{10} and 1.9×10^{10}. In this range, the cavity with $Q_0 \approx 2.5 \times 10^{10}$ will be mod-

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erately overcoupled. The range is bounded in order to limit measurement uncertainty, and reflects the range in place at the end of LCLS-II cavity production. The high-Q coupler is only used in vertical test, so there is no corresponding cryomodule requirement.

The external quality factor of the field probe, $Q_{\mathrm{ext},2}$, is required to fall between 7.5×10^{11} and 2.5×10^{12}. The coupling cannot be too strong, in order to prevent heating of components in the insulation vacuum, and it also cannot be too small, so that the low-level RF system has a reliable pickup signal. The acceptance range reflects the range in place at the end of LCLS-II cavity production.

The external quality factors of the two higher order mode antennas (HOMs), as measured in the fundamental mode, are required to be greater than 2.7×10^{11}. This is to prevent heating of the HOM components, which are not cooled by the 2 K liquid helium, and other components in the isolation vacuum such as half-cells #1 and #18 of the cavities. This acceptance threshold is the same as the one used at the end of LCLS-II cavity production.

As an additional check on HOM coupling, the power picked up by the HOM antennas with the cavity in the fundamental mode at 20.8 MV/m must not exceed 1.7 W. This measurement is made at high field, while the $Q_{\mathrm{ext,HOM}}$ measurement described above is made at low field. The power threshold has increased compared to LCLS-II; the increase corresponds to the increase in power due to the higher accelerating gradient.

VERTICAL TEST PROCEDURE

Vertical acceptance testing for the LCLS-II-HE cavities will take place at the vertical tests stands (VTS) at JLab and FNAL. They will arrive from the cavity vendor under vacuum and equipped for test with a high-Q fixed antenna, all-metal angle valve, burst disk, and stainless steel end flange blanks. In preparation for test, the cavities will be equipped with Cernox thermometers and fluxgate magnetometers. The procedure is largely the same as what was used for LCLS-II.

Cavities will be "fast-cooled" in a liquid helium bath in an area of high magnetic hygiene, with ambient fields no stronger than 5 mG (0.5 μT). In order to make sure that flux is sufficiently expelled from the cavity, the temperature differential from the top to the bottom of the cavity must be at least 50 K/m when the bottom of the cavity goes through the superconducting critical temperature $T_c \approx 9.2$ K. After the fast cooldown, the cavities will be brought to 2.00 ± 0.02 K for testing under RF power.

RF Measurements

RF testing will begin with calibration measurements at low field ($E_{\mathrm{acc}} = 6$ to 8 MV/m), consisting of at least five "RF Off" decay measurements to calibrate Q_0 and E_{acc} steady-state power measurements.

Following calibration, Q_0 vs. E_{acc} curves will be measured at a resolution of 1 MV/m or finer to characterize cavity performance, starting from $E_{\mathrm{acc}} = 1$ MV/m and extending up to the cavity's peak accelerating gradient (*i.e.* ultimate quench field). Each measurement point will also include forward, reflected, and transmitted power measurements (field probe and HOMs), temperatures, and signals from VTS radiation monitors.

Field Emission and Multipacting

VT operators will take care to identify any quenches that may have occurred due to multipacting or field emission, and note any radiation signals observed during the test. Operators will attempt to process any encountered field emission if it is deemed safe to do so. If multipacting is encountered, operators will likewise attempt to process through and push the cavity to its ultimate quench field. As described in the requirements, a final set of RF measurements must be taken after all field emission and multipacting processing is completed.

Parasitic 7π/9 Mode Excitation

During the production phase of LCLS-II and the R&D phase of LCLS-II-HE, as well as the during the EuXFEL project (which features similar 1.3 GHz 9-cell TESLA cavity geometry), many cavities were observed in vertical test to suffer from parasitic excitation of the $7\pi/9$ mode. The cause of this excitation, which is gradual but tends to strengthen at higher fields, remains unknown, but is suspected to be related to multipacting or field emission. The $7\pi/9$ mode is stronger in some cells than the fundamental mode, so parasitic excitation may lead to premature quench.

In LCLS-II-HE, if this excitation is encountered in vertical test (as noted by a spectrum analyzer), testing will continue in a "quasi-pulsed mode" to allow for quick measurements before the $7\pi/9$ mode grows in amplitude too much and causes a cavity quench or interferes with power measurements.

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