

## LCLS-II-HE CAVITY QUALIFICATION TESTING

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### Abstract

Acceptance testing of the LCLS-II-HE production cavities is approximately 65% complete. In this report, we present details of the test results, including summaries of the quench fields, intrinsic quality factors, and experience with field emission. We also offer an outlook on the remaining tests to be performed.

### INTRODUCTION

LCLS-II-HE is an ongoing project to upgrade LCLS-SC, the superconducting part of the X-ray free electron laser at SLAC National Accelerator Laboratory. Among other improvements, the project will extend the linac with 23 additional cryomodules, increasing the target beam energy to 8 GeV. To fill the cryomodules, the project has procured 192 new nine-cell cavities from an industrial supplier in Europe, following the “2N0” nitrogen doping recipe developed during the project’s R&D phase.

The cavity supplier mechanically fabricates the cavities from niobium sheets, processes the surface (including high-temperature furnace treatments, electropolishing, and high-pressure rinsing), installs the liquid helium jacket, and mounts all antennas and accessories required for vertical test. The cavities are shipped under vacuum to the partner laboratories, Fermilab and Jefferson Lab, where they undergo acceptance testing.

Additionally, the project has engaged in an effort to recover spare cavities from the earlier LCLS-II project and remediate them to the LCLS-II-HE performance requirements. The remediation procedures have varied depending on the cavity, with some receiving only high pressure rinse (HPR) and others undergoing electropolishing (EP) or other chemical surface treatments.

The cavities are tested vertically at the partner laboratories at 2.0 K, under static beamline vacuum. The full test procedure and qualification criteria have been reported previously [1]. Key requirements include a peak accelerating gradient  $E_{\text{acc}} \geq 23$  MV/m and intrinsic quality factor  $Q_0(E_{\text{acc}} = 21 \text{ MV/m}) \geq 2.5 \times 10^{10}$ , with no detectable field emission radiation present.

At time of writing, 156 new cavities have been received from the supplier. Of these, 115 have been qualified for assembly into cryomodules, 16 are disqualified, 19 are undergoing HPR, 1 is “on hold” with marginal  $Q_0$  performance,

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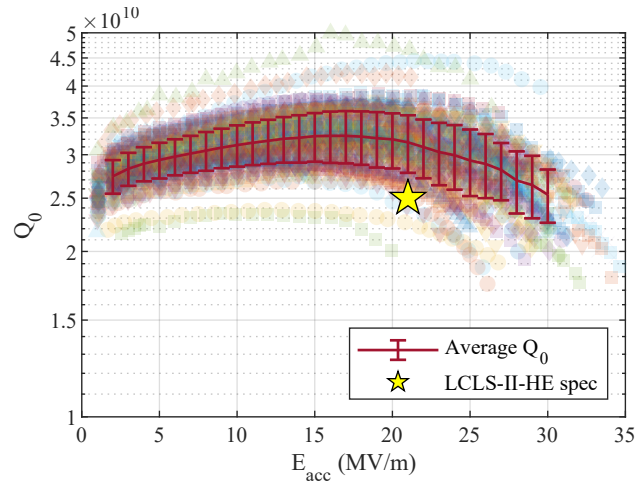


Figure 1: Intrinsic quality factor  $Q_0$  as a function of accelerating gradient  $E_{\text{acc}}$  for all production LCLS-II-HE cavities without field emission in vertical test (131 cavities). Red error bars show the average  $Q_0$  with a  $\pm 1\sigma$  interval, up to an arbitrary limit of 30 MV/m.

and the remainder are awaiting first test. The remediation effort has yielded 12 qualified cavities. In addition, 12 of the disqualified cavities will be reprocessed at the cavity supplier.

### VERTICAL TEST RESULTS

The cavities have generally shown strong performance, with a large majority exceeding the qualification requirements. While field emission radiation has been a recurring issue (discussed in further detail below), nearly all unaffected cavities exceed the performance specifications. Figure 1 illustrates the  $Q_0$  vs.  $E_{\text{acc}}$  results for all cavities without field emission. This includes cavities that had previously exhibited field emission but which were recovered by HPR or otherwise. In total, 120 cavities out of 131 without field emission met all performance requirements; five additional cavities were accepted with accelerating gradient below the nominal threshold for vertical test but above the threshold for cryomodule performance (20.8 MV/m) since they could be matched with high-gradient cavities in cryomodule strings. Four cavities were disqualified due to low quench fields and one was disqualified due to low  $Q_0$ . As mentioned above, one cavity has been temporarily set aside due to its “marginal”  $Q_0 = 2.25 \times 10^{10}$ : this is below the nominal ac-

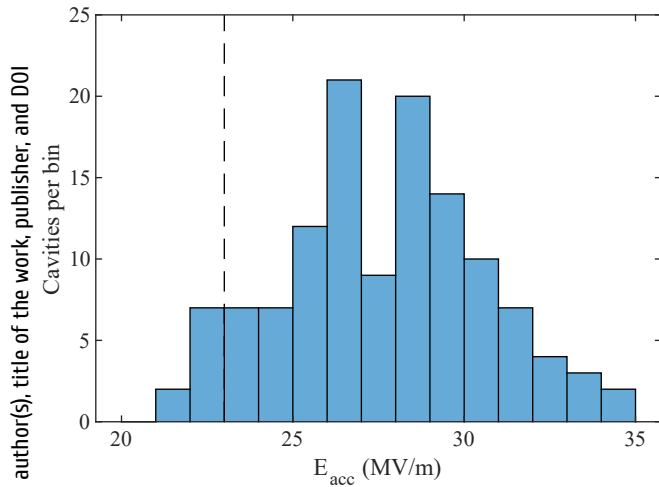


Figure 2: Histogram of accelerating gradient  $E_{acc}$  for all production LCLS-II-HE cavities without field emission in vertical test (131 cavities). Dashed line indicates the acceptance threshold.

ceptance threshold but high enough that a cryomodule built with this cavity would still meet the heat load requirements if the other seven cavities showed average performance. This cavity will be included in a late cryomodule string only if necessary.

Figure 2 breaks down the accelerating gradient performance in a histogram. The cavities reached an average maximum gradient of  $E_{acc} = 27.3 \pm 3.5$  MV/m. This dramatic improvement over the LCLS-II cavities, which had an average gradient of  $22.0 \pm 3.9$  MV/m, illustrates the success of the R&D effort to improve the nitrogen doping protocol.

Figure 3 shows a similar breakdown of the quality factor performance, as measured at  $E_{acc} = 21$  MV/m. Here, only one cavity had  $Q_0$  too low to be accepted, and as discussed above one showed marginal performance. The remaining cavities without field emission that reached at least 21 MV/m had an average quality factor  $Q_0(21 \text{ MV/m}) = 3.20 \pm 0.38 \times 10^{10}$ . This is strikingly close to the performance of the LCLS-II cavities, which had an average  $Q_0(21 \text{ MV/m}) = 3.18 \pm 0.44 \times 10^{10}$  (again considering only those cavities with sufficiently high gradient).

The very low rejection rate due to low  $Q_0$  is a success of the flux expulsion characterization strategy used for cavity fabrication. This effort is discussed elsewhere at this conference [2].

Of the 125 cavities with acceptable performance, four unfortunately suffered damage to the helium vessel bellows after vertical test. These cavities cannot be accepted for cryomodule string assembly with this damage due to the risk posed to the cryogenic system (material fatigue may cause a leak). Six more were contaminated with field emitters after clean tests, with four of these caused by cryomodule string disassemblies, one by a vacuum leak through an angle valve, and one by a failed test of a string assembly nitrogen

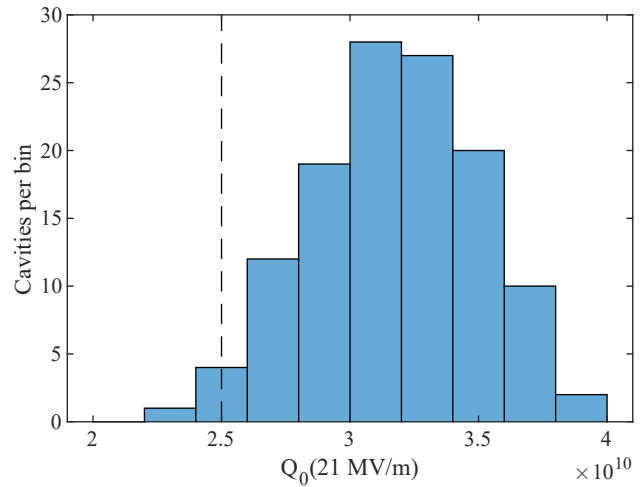


Figure 3: Histogram of intrinsic quality factor  $Q_0$  for all production LCLS-II-HE cavities without field emission in vertical test (131 cavities). Dashed line indicates the acceptance threshold. Cavities that did not exceed 21 MV/m are excluded.

purge system. This leaves, at time of writing, 115 qualified cavities.

So far, four cryomodules using these production cavities have been built and fully or partially tested. Nearly half the cavities exceed the cryomodule test administrative gradient limit (26 MV/m), and all are well within the cryogenic heat load requirements. These results are discussed in detail elsewhere [3].

Of the 12 remediated LCLS-II cavities that meet the LCLS-II-HE requirements, nine have been used in cryomodule strings so far. Since the surface processing histories of these cavities vary greatly, they have been omitted from the statistics above.

### Field Emission

Out of the 151 cavities tested so far, 37 exhibited field emission radiation in the first test as received from the cavity supplier. These were disassembled and re-rinsed with HPR. An additional two cavities had cold leaks and were also disassembled and re-rinsed. Six more cavities were contaminated with field emitters after acceptable vertical tests, as described above. For LCLS-II-HE, re-rinsing is carried out by the partner laboratories; Fermilab engages the facilities at Argonne, while JLab uses their own clean room facility. Cavities are generally re-rinsed and re-tested up to four times before being disqualified.

In total, 45 cavities so far have undergone re-rinse or are scheduled for re-rinse. From these, 19 have been successfully recovered and now meet the performance requirements. One has been disqualified after the source of the field emission was identified as a scratched area on one of the higher-order mode couplers. Four have been disqualified due to persistent field emission, two of which were from the six contaminated after earlier qualification. Two more were

awaiting re-rinse or re-test when they were disqualified due to bellows damage. The remaining 19 field-emitting cavities are in line for re-rinse/re-test. Based on the success rates at each re-rinse step, we project a final total of seven cavities to be disqualified due to field emission.

### Other Vertical Test Issues

Several other issues have been encountered during vertical test. Two of these, namely multipacting and parasitic excitation of the  $7\pi/9$  mode, were foreseen before testing began [1]. Indeed, these have both been prevalent throughout testing so far.

Multipacting, as identified by intermittent quench behavior with radiation bursts encountered in the range of 17–23 MV/m, has been observed on roughly one quarter of the cavity tests. Most of these cavities were able to reach higher gradients after quench processing. There also appears to be a slight surplus of cavities with gradients limited to this range; it is possible that some cavities are limited by stubborn multipacting without a radiation signature. This will be studied in further detail in the future.

Parasitic mode excitation, on the other hand, has been observed on more than 70% of cavity tests, with onset at  $E_{\text{acc}} = 20.2 \pm 1.1$  MV/m. This range overlaps the expected onset range for multipacting, suggesting that the phenomenon is related to secondary electron emission. This hypothesis is supported by prior work studying passband mode excitation by field emitters [4]. When encountered, this phenomenon limits the achievable gradient in a cavity's vertical test, since the peak surface field in the  $7\pi/9$  mode exceeds that of the  $\pi$  mode for the same stored energy.

Recently, a system has been developed at JLab to suppress the parasitic mode by low-level RF feedback [5]. Early

results on LCLS-II-HE cavity tests have been successful. A similar system may be developed at Fermilab.

## OUTLOOK

Delivery and test of cavities from the supplier will continue through Spring 2024. Based on the performance characteristics detailed above, we expect a total of 170 qualified and 22 disqualified cavities from the production order. Of the 12 cavities undergoing reprocessing at the supplier, we expect nine to qualify based on earlier reprocessing success rates. Considering finally the 12 LCLS-II cavities successfully recovered already, we project a final count of 191 qualified cavities, leaving a buffer of seven cavities over the 184 required to complete the LCLS-II-HE project.

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