FLUX EXPULSION TESTING FOR LCLS-II-HE CAVITY PRODUCTION

J. T. Maniscalco[1,2,*], D. Savransky[2,†], S. Aderhold[1], T. T. Arkan[3], D. Bafia[3],
M. E. Bevins[2], M. Checchin[1], D. Gonnella[1], A. Grabowski[2], J. Hogan[1],
J. Kaluzny[3], R. D. Porter[1], S. Posen[3], C. E. Reece[2], J. Vennekate[2]
[1]SLAC National Accelerator Laboratory, Menlo Park, CA, USA
[2]Thomas Jefferson National Accelerator Facility, Newport News, VA, USA
[3]Fermi National Accelerator Laboratory, Batavia, IL, USA

Abstract

Nitrogen-doped niobium SRF cavities are sensitive to trapped magnetic flux, which decreases the cavity intrinsic Q_0. Prior experimental results have shown that heat treatments to 900 °C and higher can result in stronger flux expulsion during cooldown; the precise temperature required tends to vary by vendor lot/ingot of the niobium material used in the cavity cells. For LCLS-II-HE, to ensure sufficient flux expulsion in all cavities, we built and tested single-cell cavities to determine this required temperature for each vendor lot of niobium material to be used in cavity cells. In this report, we present the results of the single-cell flux expulsion testing and the Q_0 of the nine-cell cavities built using the characterized vendor lots. We discuss mixing material from different vendor lots, examine the lessons learned, and finally present an outlook on possible refinements to the single-cell technique.

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. The cavities in the new cryomodules are being prepared with "2N0" nitrogen doping.

Nitrogen-doped cavities exhibit an increase in the residual surface resistance if flux is trapped in the cavity walls during cooldown or quench [1]. For LCLS-SC, a CW machine, it is critical to minimize these losses to keep the heat load within the capacity of the cryoplant. Prior work has shown that high-temperature (T ≥ 900 °C) heat treatments can improve the flux expulsion efficiency of niobium, but that the precise temperature required for sufficient expulsion can vary between niobium suppliers and even from batch to batch at a given supplier [2]. Generally, higher temperature treatments result in better flux expulsion. On the other hand, treatments at too high of a temperature can soften the niobium, increasing the risk of damage during handling and transport. This is a particular risk for the LCLS-II-HE cavities, which travel thousands of miles by air from the supplier in Europe to Fermilab and Jefferson Lab, and then thousands more by road to SLAC. Therefore, it is desirable to find the minimum heat treatment temperature required for sufficient flux expulsion for each batch of material.

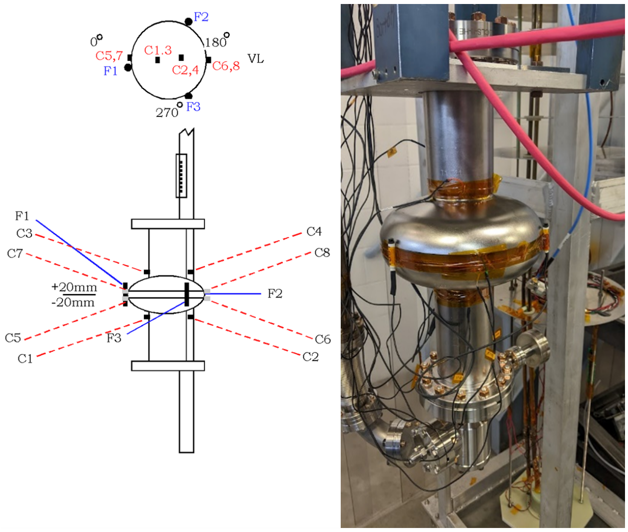

Figure 1: Illustration of the test setup. Left-hand diagram shows the positions of the thermometers (C) and magnetometers (F). Right-hand photo shows the instrumented cavity on the test insert.

For LCLS-II-HE, the niobium material was separated into "heat lots" at the supplier, each composed of sheets from two ingots. Each heat lot contains approximately 150 sheets, enough material for eight cavities. One single-cell cavity was constructed from each heat lot, using two non-sequential sheets. These were prepared with the first portion of the LCLS-II-HE cavity recipe, including bulk EP, and treated in the supplier's furnace at 900 °C. The cavities were then shipped under vacuum and ready for test to Jefferson Lab.

At Jefferson Lab, each single-cell cavity underwent studies to measure its flux expulsion characteristics and determine the appropriate heat treatment temperature for the corresponding material batch. The required temperatures for each material lot were passed along to the cavity supplier to be used in the 9-cell cavity production processes.

SINGLE-CELL TESTING

Procedure

The flux expulsion characteristics of the single-cell cavities were measured using a procedure similar to the one developed for LCLS-II [3]. Each cavity was equipped with a payload of thermometers and flux-gate magnetometers,

---

[*] jamesm@slac.stanford.edu
[†] dsavr@jlab.org

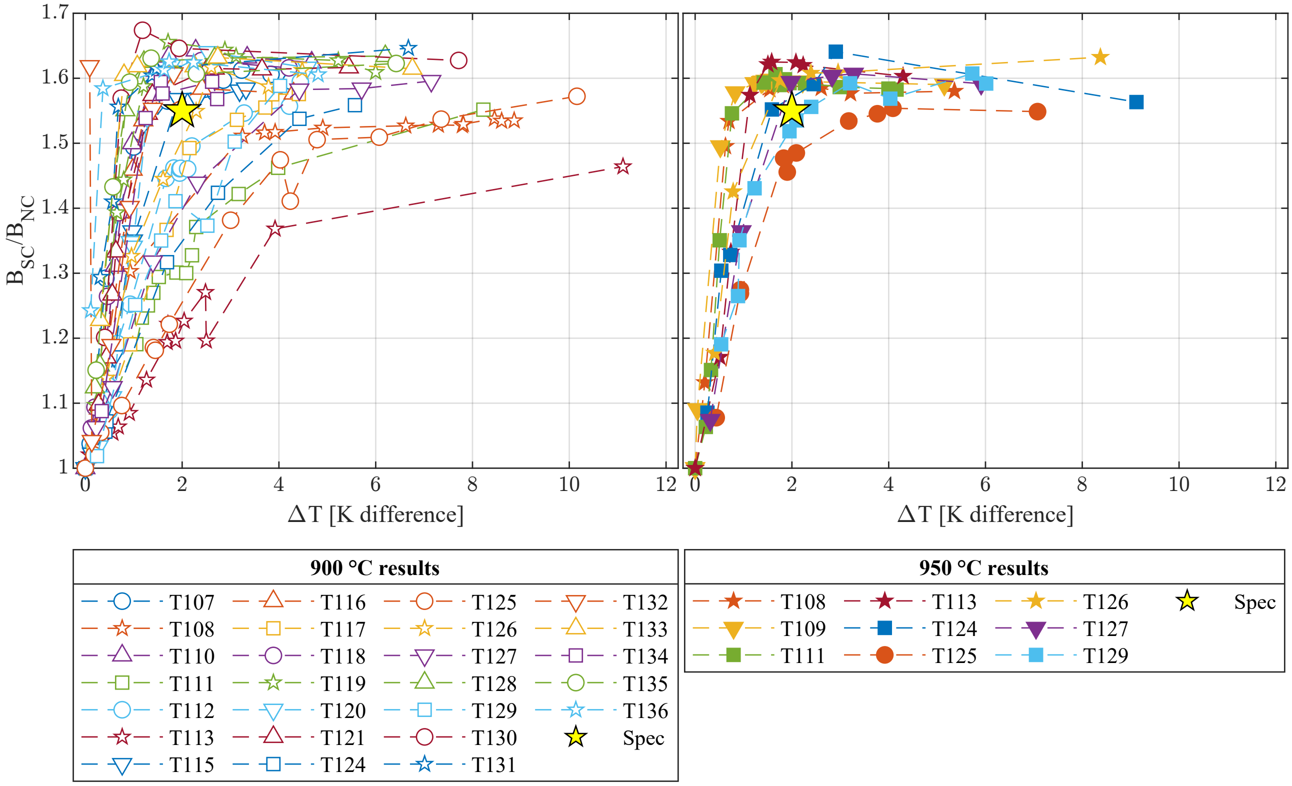

Figure 2: Results of the single-cell flux expulsion characterization tests after treatment at 900 °C (left) and 950 °C (right).

installed in a vertical test dewar with applied magnetic field, and repeatedly thermal cycled around the critical transition temperature with varying thermal gradient. Figure 1 illustrates the configuration of the cavity and sensors on the test insert.

The flux expulsion ratio, defined as the ratio of magnetic flux near the cavity equator in the superconducting state to that in the normal-conducting state $B_{\mathrm{SC}}/B_{\mathrm{NC}}$, was measured as a function of the temperature difference ΔT across the cell ($d \approx 11$ cm). Each cavity was first tested as received from the cavity vendor after the initial 900 °C treatment. The cavities were tested against an acceptance threshold of $B_{\mathrm{SC}}/B_{\mathrm{NC}}(\Delta T = 2\ \mathrm{K}) \geq 1.55$. Cavities that did not meet this requirement were re-treated at 950 °C in a Jefferson Lab vacuum furnace, then retested as above.

Modifications to the procedure since the LCLS-II effort include the addition of a second set of thermometers and the increase in the strength of the applied magnetic field from 10 mG to 20 mG. These serve to increase the measurement sensitivity. The required ΔT was also decreased from 5 K to 2 K to ensure acceptable performance of the final cavities over a wider range of cooldown rates.

Single-Cell Results

For LCLS-II-HE, a total of 27 single-cell cavities were tested. Out of the 27, 18 met the required performance with the initial 900 °C heat treatment from the cavity supplier. The remaining nine single cells that did not meet the specification were re-treated at 950 °C. Seven cavities were able to meet the LCLS-II-HE flux expulsion specification after the second heat treatment. Two out of the nine cavities that were re-treated missed the flux expulsion specification by a small margin but were accepted "as-is" to avoid further softening of the material by additional treatment at a higher temperature. Figure 2 shows these results.

NINE-CELL CAVITY PRODUCTION AND PERFORMANCE

The heat treatment temperatures required for each heat lot, as determined by the single-cell test results, were transmitted to the cavity supplier. The first 30 nine-cell production cavities were built using sheets of unique origin (*i.e.*, all sheets in any given cavity came from the same heat lot). After the initial period of cavity production, this requirement was relaxed in the interest of schedule efficiency and waste reduction: the material lots were combined according to required heat treatment temperature, such that each cavity was built using material identified to have the same required temperature. Finally, a batch of four cavities was built using end groups requiring 950 °C treatment and dumbbells requiring 900 °C. For these "mixed 900/950" cavities, the end groups received the 950 °C treatment prior to equator welding. Following completion of the equator welding, the entire cavities were treated at 900 °C.

The completed nine-cell production cavities were equipped with vertical test accessories and shipped under vacuum to the partner laboratories for acceptance testing. At time of writing, 151 cavities have been tested at least once. In vertical test, the qualification threshold for intrinsic

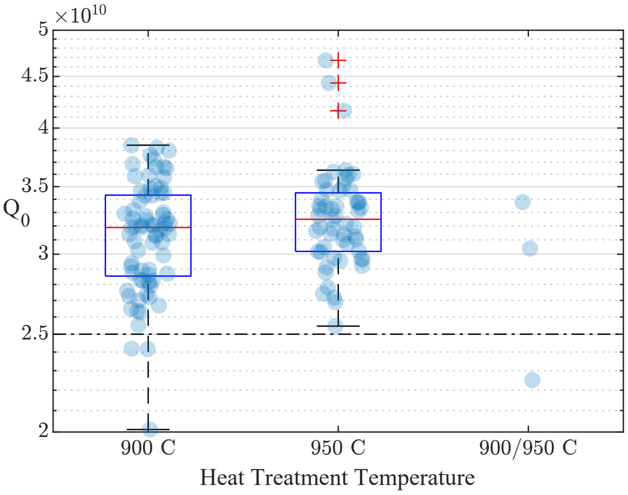

Figure 3: Boxplots of quality factor measured in vertical test at 21 MV/m for nine-cell cavities without field emission. Cavities are sorted by heat treatment temperature.

quality factor Q_0 is 2.5×10^{10} measured at $E_{acc} = 21$ MV/m and $T = 2.0$ K [4].

Figure 3 summarizes the Q_0 performance of the cavities, measured at the LCLS-II-HE nominal operating gradient of 21 MV/m, with cavities grouped by heat treatment temperature. Cavities with field emission are omitted from this analysis. The median Q_0 for each of the three groups—900 °C, 950 °C, and mixed 900/950 °C—are all above 3.0×10^{10}. All cavities, with the exception of four, had quality factors above the qualification threshold of 2.5×10^{10}. Of the four that did not meet the threshold, two were accepted as-is and integrated into cryomodule strings with high-performing cavities to balance the heat load. One has been set aside as “marginal”, potentially to be used similarly in a future cryomodule. The last one has been disqualified due to the low Q_0.

Considering separately the cavities made with mixed lots and those made with pure lots reveals that the mixed material cavities generally had higher Q_0. Figure 4 shows the cavity Q_0 for the mixed material cavities of each temperature category as well as the four lots from which “pure” cavities were made (T107, T108, T109, and T110). In the case of the mixed material cavities, all but one cavity exceed the performance spec. Furthermore, the median Q_0 was above 3.0×10^{10} for all mixed material groups. On the other hand, two out of the four pure lots (T107 and T110) have markedly lower Q_0 than the other two pure lots and the mixed lots. While all T110 cavities exceed the performance threshold, three out of seven T107 cavities fall below the spec.

DISCUSSION

Impact on Cavity Performance

The results above show that the effort to ensure high Q_0 by identifying the required heat treatment temperature for each niobium lot has been largely successful. Only four out of the 126 field-emission-free cavities tested so far had Q_0 below the nominal acceptance threshold of 2.5×10^{10} (cavities with field emission are omitted from this study so that the results are not skewed by the effect of field emission on Q_0), and two of these four have been able to be accepted despite missing the threshold. A more detailed report on the vertical test results is given elsewhere at this conference [5].

Initial Q_0 measurements in cryomodule tests are also positive. At time of writing, all cryomodules using cavities from this production run are well within the dynamic heat load acceptance range. Further details of the cryomodule tests are presented elsewhere in these proceedings [6]. For the moment, these results are limited; at time of writing, Q_0 measurements have been performed on three cryomodules using these cavities. Cryomodule testing will continue over the next few years, and the final performance characteristics will not be measured until after installation in 2025.

Effect of Mixing Material Lots

While the results of this effort have been quite positive overall, the performance of lot T107 indicates that our process of identifying required heat treatment temperatures can be improved. The single-cell test result for this lot showed sufficient flux expulsion after the initial 900 °C treatment. However, the nine-cells produced from this lot had significantly lower Q_0 than the other cavities, with three of seven cavities below the nominal acceptance threshold. One hypothesis for this behavior is that some of the material in the lot in question may have required treatment at a higher temperature. As discussed above, each heat lot is composed of material from two ingots; it is possible that one of the ingots required a higher heat treatment for adequate flux expulsion. Separating the sheets by ingot instead of heat lot, with a single cell cavity for each ingot, may have been more successful at identifying the correct heat treatment temperature. Recent work has shown that grain growth during heat treatment is correlated with improvements in flux expulsion [7], and we

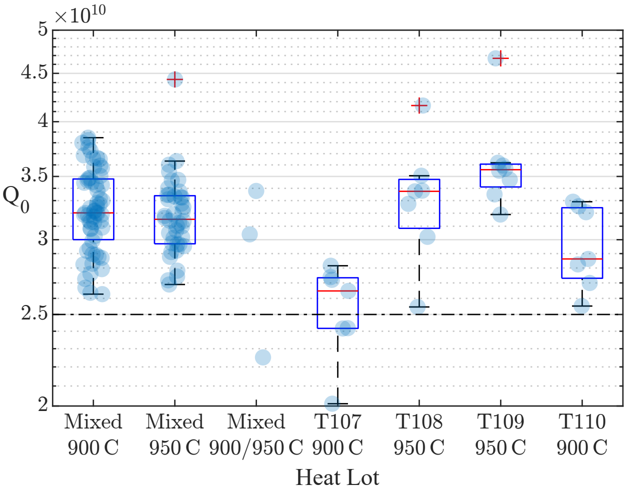

Figure 4: Boxplots of quality factor measured in vertical test at 21 MV/m for nine-cell cavities without field emission. Cavities are sorted by material composition.

may suppose that these are more strongly correlated to the material origin and forging of the ingot than to the grouping of multiple ingots during the sheet processing steps into a “heat lot”.

We began the intermixing of sheet material from different lots with schedule efficiency and waste minimization in mind: it simplified the logistics of part storage and half-cell deep drawing, and it ensured that all sheets from each lot could be used. Despite this, building cavities using sheets from multiple heat lots yielded cavities with sufficiently high Q_0. Out of 97 of these mixed-material cavities tested at time of writing, only one had Q_0 below the acceptance threshold. The mixing limits our ability to study the effectiveness of the identification procedure lot by lot, but it also presents a strategy for mitigating the effects of mis-characterizing a lot as in the case of T107. If a cavity contains material from a lot assigned the incorrect temperature, the poor flux expulsion and low Q_0 of that part of the cavity would be mitigated by the inclusion of correctly identified material. In effect, the impact of misidentifying a lot would be smeared out, slightly decreasing Q_0 for many cavities rather than having a dramatic effect on a small number of cavities. This yields more cavities that meet the qualification threshold.

From a quality standpoint, creating and testing a single cell cavity for each ingot would provide more assurance that all cavity cells would sufficiently expel flux. However, this would also pose a significant cost increase, since roughly two single cells would be needed per eight-cavity cryomodule, compared to one using our present strategy. Further, restricting nine-cell cavity production to pure ingot lots would greatly increase the number of wasted sheets, since it is unlikely that ingots would yield sheets precisely in multiples of the number of sheets per cavity. Future accelerator projects sensitive to flux trapping will need to weigh these factors.

Pre-treating half-cells before equator welding, as in the case of the mixed 900/950 °C cavities, could present improved cost and schedule efficiency by minimizing waste and potentially decreasing the total number of furnace runs required. Also, allowing cavity sub-components to be intermixed before equator welding may reduce logistics costs at the cavity supplier. In our experience, this was only partially successful in terms of quality, with two out of three cavities tested meeting the acceptance threshold. Further study would be needed to consider this strategy for future projects.

Single-Cell Testing Technique

In the lead-up to LCLS-II-HE a study was carried out to determine the feasibility of using niobium tubes instead of full cavities to characterize the flux expulsion properties of the material lots, a potentially significant cost savings. Six Nb tubes were created with accompanying single-cell cavities to study if they would exhibit similar flux expulsion results. Regrettably, this experiment had mixed results: some tube and cavity pairs exhibited close performance while others were different by orders of magnitude [8].

The main lessons learned during the thermal cycling of all the single cells were centered around increasing the fidelity of the data gathered. Early on, it was discovered that depending on the thermal gradient inside the dewar, the cavity might not cool down uniformly. This was proven when a second row of temperature sensors were added, 180 degrees removed from the first row, and it was discovered that there could be a delta of a few kelvin between the two arrays. During this time, it was also discovered that accelerating the opening of the inlet valve to the dewar allowed for a more constant gradient in the dewar, eliminating some of the strange readings (for example, the top of the cavity being colder than the middle) and reducing the temperature differences between the two thermometer arrays. Additionally, different magnetic sensors, which had a longer and more rectangular body, were used later on which allowed them to both sit closer to the cavity and sit flush to the flat surface of the equator.

OUTLOOK

At time of writing, 40 production cavities out of the 192 on order remain to be tested. Approximately 20 cavities are undergoing field emission mitigation; if successful, their Q_0 performance will be added to this analysis. When installation of the new cryomodules is complete, we will be able to perform a full study of the effectiveness of our material characterization strategy.

REFERENCES

[1] D. Gonnella and M. Liepe, “Cool Down and Flux Trapping Studies on SRF Cavities”, in *Proc. LINAC’14*, Geneva, Switzerland, Aug.-Sep. 2014, paper MOPP017, pp. 84–87.

[2] S. Posen *et al.*, “Role of magnetic flux expulsion to reach $Q_0 > 3 \times 10^{10}$ in superconducting rf cryomodules”, *Phys. Rev. Accel. Beams*, vol. 22, no. 3, p. 032001, Mar. 2019. `doi:10.1103/PhysRevAccelBeams.22.032001`

[3] A. D. Palczewski, F. Marhauser, A. Grassellino, and S. Posen, “Material Qualification of LCLS-II Production Niobium Material Including RF and Flux Expulsion Measurements on Single Cell Cavities”, in *Proc. LINAC’16*, East Lansing, MI, USA, Sep. 2016, pp. 199–202. `doi:10.18429/JACoW-LINAC2016-MOPLR026`

[4] J. T. Maniscalco *et al.*, “LCLS-II-HE Vertical Acceptance Testing Plans”, in *Proc. SRF’21*, East Lansing, MI, USA, Jun.-Jul. 2021, pp. 291. `doi:10.18429/JACoW-SRF2021-MOPCAV013`

[5] J. T. Maniscalco *et al.*, “LCLS-II-HE Cavity Qualification Testing”, presented at SRF’23, Grand Rapids, MI, USA, Jun. 2023, paper MOPMB072, this conference.

[6] J. T. Maniscalco *et al.*, “LCLS-II-HE High Gradient Cryomodule Performance”, presented at SRF’23, Grand Rapids, MI, USA, Jun. 2023, paper MOPMB073, this conference.

[7] Z. H. Sung, P. Kulyavtsev, M. Martinello, D. Gonnella, M. Ross, and S. Posen, “Evaluation of predictive correlation between flux expulsion and grain growth for superconducting radio frequency cavities,” *arXiv*, 2023. `doi:10.48550/arXiv.2303.14122`

[8] A. Palczewski, “LCLSII-HE-1.2-PM-0355”, internal record of decision, SLAC National Accelerator Laboratory, May 2021.