LCLS-II SRF CAVITY PROCESSING PROTOCOL DEVELOPMENT AND BASELINE CAVITY PERFORMANCE DEMONSTRATION*

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Abstract

The Linac Coherent Light Source-II Project will construct a 4 GeV CW superconducting RF linac in the first kilometer of the existing SLAC linac tunnel. The baseline design calls for 280 1.3 GHz nine-cell cavities with an average intrinsic quality factor Q_0 of 2.7×10^{10} at 2K and 16 MV/m accelerating gradient. The LCLS-II high Q_0 cavity treatment protocol utilizes the reduction in BCS surface resistance by nitrogen doping of the RF surface layer, which was discovered originally at FNAL. Cornell University, FNAL, and TJNAF conducted a joint high Q_0 R&D program with the goal of (a) exploring the robustness of the N-doping technique and establishing the LCLS-II cavity high Q_0 processing protocol suitable for production use, and (b) demonstrating that this process can reliably achieve LCLS-II cavity specification in a production acceptance testing setting. In this paper we describe the LCLS-II cavity protocol and analyze combined cavity performance data from both vertical and horizontal testing at the three partner labs, which clearly shows that LCLS-II specifications were met, and thus demonstrates readiness for LCLS-II cavity production.

INTRODUCTION

The very significant successes of the LCLS research program have produced a keen interest in the high research value of high repitition rate coherent photon sources. In order to expedite realization of such a facility in the US, the US DOE asked SLAC to rework their proposed LCLS-II concept into one providing MHz pulse structure via the use of CW SRF technology in the old SLAC tunnel. [1] Rather than take the time to develop an optimized purpose-built SRF accelerator, the decision was taken to seek to adopt the electron accelerator system developed for the European XFEL project, making only necessary changes to enable CW operation.

The principal characteristic that required adaptation relates to the significance of the increased dynamic cryogenic load. Re-engineering of the cryogenic plumbing internal to the cryomodules and also the distribution system was required. The scale of the required cryoplant was also quite significant. Extrapolation from the heatload performance of the EXFEL cryomodules implied either two or three plants of the scale of the CEBAF 2 K Central Helium Liquefier would be required.

Contemporaneous with the reworking of the LCLS-II construction project, a technical route to lowering of CW SRF cryogenic loads by factors of more than 50% via diffusion of nitrogen impurities in the cavity was discovered at FNAL. [2] This lowering of the rf surface resistance, frequently known as "high Q_0," stimulated great interest because of the prospect of dramatic cost savings in both capital and operations. High temperature diffusion of small amounts of foreign atoms into the niobium rf surface was found empirically to yield the dramatically improved performance. [2,3] Using nitrogen for this purpose was found to be accomplished quite conveniently, with only small alteration of the rather standard cavity treatment processes used for EXFEL, 12GeV CEBAF, ILC R&D, and other projects.

This set of circumstances set the stage for a focused R&D effort to probe the reliability of such new treatment methods, and to flush out specifications of the cryomodule environmental conditions required to realize the new performance standards in operational conditions.

JOINT HIGH Q_0 R&D PROGRAM

In order to support the rapid development of procedures to minimize the LCLS-II cryogenic heat load FNAL, JLab, and Cornell University were asked to join the LCLS-II collaboration in R&D on methods to confidently maximize the Q_0 of nine-cell cavities for use in LCLS-II linac. [4,5]

The initial work centered on development of systematic methods for controlled high-temperature diffusion doping of Nb cavities with nitrogen, controlled thickness removal of the interior surface of the doped Nb cavity by electropolishing, and the development of well-specified and controlled cool-

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down and test conditions, which yield minimized surface resistance contributions from environmental magnetic flux. Throughout the R&D program, collaborative interaction between the three labs was maintained to build cross-checks and confidence in results and interpretations.

Due to the very constrained timescale for LCLS-II decision making, a rather forward-leaning style was chosen for this R&D effort. This approach tackled multiple problems simultaneously rather than serially, allowing the more significant issues to be revealed and addressed early at the expense of detailed clarity. While clear proof-of-principle demonstration of high Qs with single cell cavities existed from prior work at FNAL, [2,6] there existed uncertainty as to performance sensitivity to exposure duration, anneal time, removal amount and geometric complexity. JLab undertook a matrix study varying doping amount and removal amounts for a set of nine single-cell cavities. [7] Cornell began systematic tests particularly related to magnetic field sensitivity [8,9] and quench fields [10] of doped single cells. FNAL continued researching one versus two steps diffusion doping recipes for single cell and nine cells, [6] magnetic shielding requirements for high Q_0, [11] cool-down studies which lead to the finding of efficient magnetic flux expulsion via fast cooling with large spatial thermal gradients. [12,13] A correlation was established with increased doping tending to lower the quench gradient of a given cavity. [6,14,15] By Fall of 2014 the collaboration had validated the proposed "2N6A" 800°C heat treatment followed by a 5 μm electropolish on numerous nine-cell cavities.

Sensitized to the need to demonstrate adequate magnetic field control, the collaboration undertook several "horizontal" cavity tests that more closely approached the operational conditions in a linac. [16–20]

CAVITY PROCESSING PROTOCOL DEVELOPMENT

Building upon the single cell doping recipe development at FNAL, Cornell and Jlab [4,6,21], two protocols were chosen to be implemented on nine-cell cavities. Both doping protocols involved first degassing at 800°C for 3 hours in high vacuum, followed by

A 2 minutes ≈25 mTorr nitrogen injection and subsequent 6 minutes anneal at 800°C in high vacuum (previously explored with promising results on single cells at FNAL [22]), followed by 5 μm electropolishing (EP) removal ("2N6A" protocol), or

B 20 minutes ≈25 mTorr nitrogen injection and subsequent 30 minutes anneal at 800°C in high vacuum followed by 15 μm EP removal ("20N30A" protocol).

Several nine-cell cavities were treated with the two recipes at the different labs to obtain statistics on Q_0 and quench fields achieved via the two two doping protocols. Figure 1 summarizes the results for Q_0 at 16 MV/m and 2K and the quench fields obtained. It is clear that while both recipes yield very high Q_0 reliably above 2.7×10^{10}, the quench fields are lowered compared to standard surface treatments. Interestingly, quench fields cluster around a value which is ≈16 MV/m for the "20N30A" recipe and ≈22 MV/m for the "2N6A" recipe. These findings seem to indicate that higher nitrogen levels are associated with lower quench fields, consistent with previous findings on single cell cavities. Other considerations went into the final choice of the LCLS-II doping recipe, e.g. the sensitivity to increased residual surface resistance from trapped magnetic field, which also favors the choice of lower nitrogen doping levels. [9,23] Therefore the "2N6A" recipe as summarized in Fig. 2 was chosen as the baseline protocol for LCLS-II.

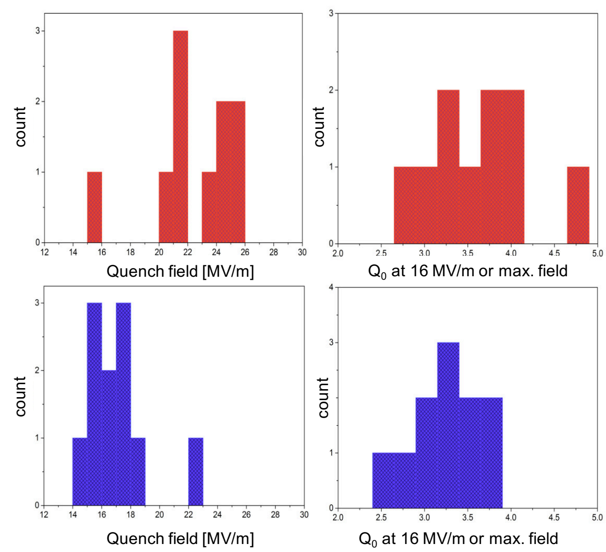

Figure 1: Top: 2K nine-cell cavity performance values using the "2N6A" nitrogen doping recipe. Average quench field: 22.2 MV/m. Average Q_0: 3.6×10^{10}. Bottom: 2K nine-cell cavity performance values using the "20N30A" nitrogen doping recipe. Average quench field: 16.3 MV/m. Average Q_0: 3.2×10^{10}.

VERTICAL QUALIFICATION TESTING

Once the "2N6A" protocol was chosen as the baseline, almost all of the 18 nine-cell cavities for the two LCLS-II prototype cryomodules were treated with this recipe. FNAL treated and qualified 10 cavities for the prototype cryomodule to be assembled and tested at FNAL, and JLab and Cornell treated and qualified the remaining 8 cavities for the prototype cryomodule to be assembled and tested at JLab. Table 1 summarizes all cavity performance test results.

The cavities were first tested bare in vertical test dewars at the three different facilities, and world record results were obtained with an average Q_0 of $\approx 3.5 \times 10^{10}$ at 16 MV/m, 2K and an average quench field of ≈22 MV/m. Figure 3 shows the 2K performance of these N-doped cavities.

The best 16 cavities were then welded onto helium jackets [24] and re-tested post helium vessel welding at JLab and FNAL. The average Q_0 still remained very high at

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Table 1: Performance of the N-doped 9-cell cavities for the LCLS-II prototype cryomodules. VT: vertical test. HT: horizontal test. Adm.: administrative field limit. Q_0 values are corrected for cavity flange losses during performance testing, which will not be present in LCLS-II cryomodule installation.

Cavity ID	2K Q_0 at 16 MV/m VT, bare [1E10]	2K Q_0 at 16 MV/m VT, dressed [1E10]	2K Q_0 at 16 MV/m HT [1E10]	Max. E_{acc} latest test [MV/m]	ΔR VT bare to VT dressed [nΩ]	ΔR VT dressed to HT dressed [nΩ]	Note
ACC015	3.5			24.0			
AES016	3.0			20.2			
AES019	3.2	3.1		18.8	0.3		a.
AES021	3.4	2.8	3.1	23.0	1.7	-0.9	a.
AES022	3.1			26.2			
AES024	3.2	3.2		22.0	0.0		a.
AES026	2.8	2.8		21.4	0.0		a.
AES027	3.6	2.7	2.8	22.8	2.5	-0.4	a.
AES028	3.5	3.0		23.0	1.3		a.
AES029	3.6	3.6		23.7	0.0		
AES030	2.9	2.5		18.2	1.5		
AES031	3.5		2.4 (8MV/m)	19.4			b.
AES032	4.2	2.8		23.0 (adm.)	3.2		
AES033	3.9	3.6		21.3	0.6		
AES034	3.9	3.5		22.5	0.8		
AES035	3.6	2.9	3.0	17.5	1.8	-0.3	c.
AES036	4.1	3.7		19.0 (adm.)	0.7		
Average	**3.5**	**3.1**	**3.0**	**21.6**	**1.1**	**-0.5**	

a. Dressed VT test in VT2 dewar, which has ≈ 5 mG higher fields than VT1 used in VT test of bare cavity.
b. HOM coupler heating in horizontal test due to manufacturing error.
c. Unknown quench drop from 23 MV/m undressed to 20 MV/m in horizontal test to 17.5 fully dressed.

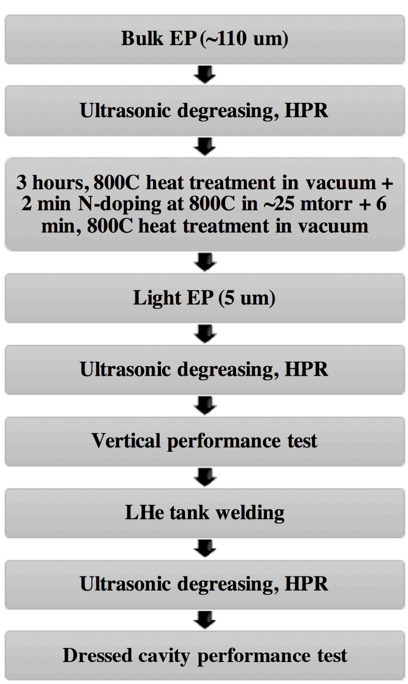

Figure 2: Baseline cavity preparation process for LCLS-II production cavities.

≈ 3.1 × 10^{10} at 16 MV/m, 2K. Vertical test results of the

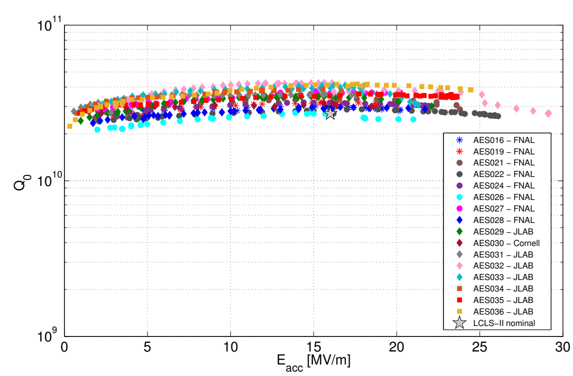

Figure 3: 2K Q_0 vs E_{acc} performance of bare N-doped cavities in vertical test. Q_0 values are corrected for cavity flange losses during performance testing, which will not be present in LCLS-II cryomodule installation.

dressed N-doped nine-cell cavities are shown in Fig. 4. A small degradation in Q_0 (refer to Fig. 5) and quench fields was observed in some cavities as tested in the jacketed state. At FNAL the slightly lower Q is justified by the different dewar conditions with remnant fields ≈5 mGauss higher than in the dewar used for testing the bare cavities. A small ≈10% degradation in quench field was observed in some cavities, of yet unknown origin.

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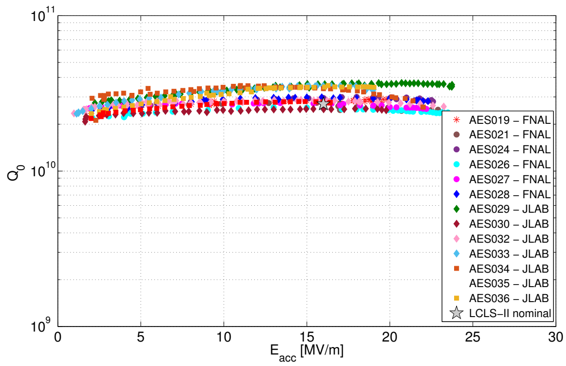

Figure 4: 2K Q_0 vs E_{acc} performance of dressed N-doped cavities in vertical test. Q_0 values are corrected for cavity flange losses during performance testing, which will not be present in LCLS-II cryomodule installation.

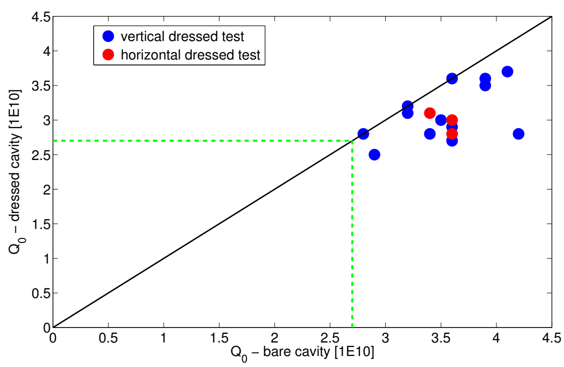

Figure 5: Comparisons of 2K Q_0 at 16 MV/m in horizontal test before and after LHe tank welding ("dressing"). Q_0 values are corrected for cavity flange losses during performance testing, which will not be present in LCLS-II cryomodule installation.

HORIZONTAL QUALIFICATION TESTING

CW RF testing of N-doped 9-cell cavities in horizontal configuration is critical to study of all the factors which can affect the operational Q_0 of the SRF cavities once installed in a cryomodule, and ultimately, to demonstrate control of these factors so that the very high Q_0 performance of N-doped cavities is maintained when stalled in the LCLS-II cryomodules. Testing in this configuration with operationally realistic cryogenic, vacuum, RF, and mechanical interfaces is most representative of conditions intended within the finished LCLS-II cryomodules.

Fermilab's Horizontal Test Stand (HTS), JLab's Horizontal Test Bed (HTB), and Cornell's unique one-cavity cryomodule (Horizontal-Test-Cryomodule, HTC) have been modified to allow for testing of LCLS-II 9-cell cavities under low ambient magnetic fields while allowing for fast cool-down for efficient magnetic flux expulsion. The cross-section of the HTC very closely resembles that of the planned LCLS-II cryomodules, and therefore allows performance testing of the LCLS-II cavities under highly representative of conditions.

Figure 6 shows the 2K performance curves from horizontal tests of three prototype N-doped cavities, each meeting or exceeding the LCLS-II nominal cavity gradient and Q_0 specifications, with an average 2K Q_0 of 3×10^{10}. Protocols and parameters for fast cavity cool-down in a cryomodule were developed [17–19], and efficient and reliable expulsion of ambient magnetic field resulting in low residual resistance values was demonstrated. [18, 19] Further, it was shown that the RF power coupler and the frequency tuner have no negative impact on the RF cavity performance. [19, 25] A successful fully integrated horizontal test of cavity AES021 has been performed with all auxiliary components (RF coupler, frequency tuner, and HOM antennas) in place. [26] Horizontal testing at all three partner labs demonstrated that the high Q_0 performance of N-doped cavities achieved in vertical tests can be maintained when the cavity is installed horizontally in a cryomodule configuration, [18–20] with no significant increase in surface resistance nor reduction in quench fields; see also Table 1.

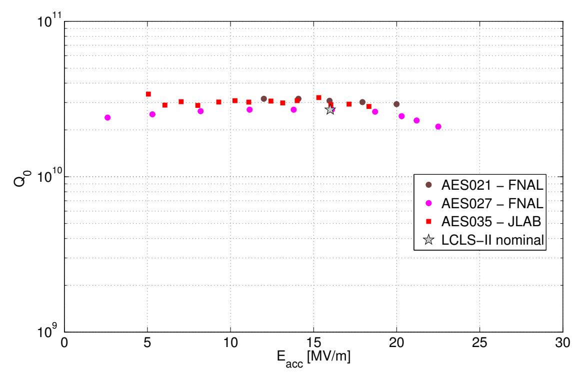

Figure 6: 2K Q_0 vs E_{acc} performance of dressed N-doped cavities in horizontal test.

CONCLUSIONS AND OUTLOOK

Responding to the needs of the LCLS-II project, the multi-lab team quickly surveyed the parameter space that yields very low-loss SRF cavities and identified a set of parameters that consistently met project goals at multiple labs.

Having "raised the bar" with improved Nb cavity surfaces, the challenge then passed to learning how to more carefully manage the magnetic field environment and cool-down dynamics in an operational setting in order to fully benefit from the improved material properties. This required implementation of new standards of "magnetic hygiene," the implications of which are forcing new material choices in cavity test stands and cryomodule hardware. Successful demonstration of high Q performance in fully dressed cavities in cryostat configurations similar to linac cryomodules builds confidence that adequate control measures have been identified.

The cavities being prepared for the two prototype cryomodules have met their performance requirements in vertical test and are being prepared for assembly into strings. The protocol for cavity processing has been fully demonstrated, frozen, and transferred to vendors for production. The cavity preparation protocol appears secure for the project.

ACKNOWLEDGMENT

Because of the scale and urgency to the LCLS-II project of developing confidence in realizing unprecedented SRF cavity performance, large numbers of staff and students associated with FNAL, Cornell, and JLab had a hand in the work summarized here. Fabrication, processing, and assembly staff, as well as many engineers and scientists were pressed in time and creativity to accomplish the past two-years' work. Our thanks go to them all.

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