RF PERFORMANCE OF NITROGEN-DOPED PRODUCTION SRF CAVITIES FOR LCLS-II*

D. Gonnella†[1], S. Aderhold[2], A. Burrill[1], E. Daly[3], K. Davis[3], A. Grassellino[2], C. Grimm[2],
T. Khabiboulline[2], F. Marhauser[3], O. Melnychuk[2], A. Palczewski[3], S. Posen[2], M. Ross[1],
D. Sergatskov[2], and K. Wilson[3]
[1]SLAC National Accelerator Laboratory, Menlo Park, CA 94025 USA
[2]Fermi National Accelerator Laboratory, Batavia, IL 60510 USA
[3]Thomas Jefferson National Accelerator Facility, Newport News, VA 23606 USA

Abstract

The Linac Coherent Light Source II (LCLS-II) requires 280 9-cell superconducting RF cavities for operation in continuous wave mode. Two vendors have previously been selected to produce the cavities, Research Instruments GmbH and Ettore Zanon S.p.a. Here we present results from manufacturing and cavity preparation for the cavities constructed at these two vendors for LCLS-II. We show how the cavity preparation method has been changed mid-production in order to improve flux expulsion in the cavities and maintain high performance in realistic magnetic field environments (~5 mG). Additionally, we show that the nitrogen-doping process has been carried out successfully and repeatedly on over 70 cavities.

INTRODUCTION

The Linac Coherent Light Source II (LCLS-II) is a new x-ray light source being built at SLAC which utilizes the latest superconducting RF (SRF) technology. The machine will operate 280 Tesla-shape [1] 9-cell 1.3 Ghz cavities in continuous wave (CW) mode [2]. Operating in CW mode at sufficiently high gradients requires that the cavities have very low cryogenic losses in order to maintain economic viability of the machine. LCLS-II has chosen to operate the cavities at an accelerating gradient of 16 MV/m with a Q_0 of $2.7{\times}10^{10}$ (~10 W of dissipated power at 2 K). The choice of these parameters enables the machine to be run with one 4 kW cryoplant. In addition to these specifications, the cavities must reach 19 MV/m in vertical test in order to account for errors in the gradient measurement and provide sufficient head room for the operating gradients in the cryomodule. Here we present on the results from the first cavities prepared in production for LCLS-II.

CAVITY PREPARATION

In order to meet the ambitious Q_0 specification of $2.7{\times}10^{10}$ at 16 MV/m and 2.0 K, the SRF cavities for LCLS-II are being prepared with nitrogen-doping. Nitrogen-doping has been shown repeatedly to produce Q_0's significantly higher than with standard cavity preparation methods [3, 4]. Nitrogen-doping typically consists of treating a niobium SRF cavity at high temperature in a low-pressure nitrogen atmosphere. It consistently produces 1.3 GHz cavities with Q_0's on the order of $2.7{\times}10^{10}$ or higher by lowering of the temperature-dependent BCS resistance (R_{BCS}). Typical nitrogen-doped cavities have R_{BCS} on the order of 4-7 nΩ at 16 MV/m.

For LCLS-II, niobium sheet was procured from two vendors, Tokyo Denkai and OTIC Ningxia. The cavities are being fabricated by two vendors, Ettore Zanon S.p.a. and Research Instruments GmbH. Thus far into cavity production, material from Tokyo Denkai has primarily been used. The cavities have been prepared with two different cavity preparation recipes as outlined in Table 1. Cavities are given a bulk electropolish (EP) (first 140 μm and later 200 μm) followed by a degas in vacuum at high temperature (first 800°C then 900°C). Throughout this paper, the amount of removal by EP is measured by weight. Next comes the nitrogen-doping step which is carried out at 800°C in ~25 mTorr of nitrogen gas for two minutes followed by an additional 6 minutes of vacuum annealing. Finally the cavities are given a light EP of 5-7 μm. This recipe is known as the "2/6" nitrogen-doping recipe. The motivation for changing the recipe during production will be discussed in the next section. Results shown here will primarily focus on cavities produced at one vendor, denoted "Vendor B" from now on. A thorough discussion of vendor production and progress is presented in [5].

CAVITY RF RESULTS

All production cavities for LCLS-II are tested at 2.0 K up to a maximum field of 24 MV/m, administratively limited in order to reduce the risk of field emission activation. Some cavities were tested beyond this limit. Figure 1 shows the Q_0 of the first ~60 cavities tested at 16 MV/m from Vendor B. The point at which the recipe change is marked along with the LCLS-II specification of $2.5{\times}10^{10}$ (lowered from $2.7{\times}10^{10}$ for vertical test due to the inclusion of a stainless steel blank on one side of the cavity leading to an increase in R_{res} of ~0.8 nΩ). A full discussion of the Q_0 performance and the recipe change will be given in the following section.

Figure 2 shows the maximum gradient reach for cavities produced at vendor B. Note that all cavities shown exceed the 16 MV/m specification and all but two exceed 19 MV/m.

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[†] gonnella@slac.stanford.edu

Table 1: The nitrogen-doping recipes carried out on cavities for LCLS-II

Recipe	Bulk EP	Furnace Degas Temperature	Degas Time	N-Doping Temperature	N-Doping Time	N-Doping Pressure	Anneal Time	Final EP
Original[1]	140 μm	800°C	3 hours	800°C	2 min	25 mTorr	6 min	5-7 μm
Revised[2]	200 μm	900°C	3 hours	800°C	2 min	25 mTorr	6 min	5-7 μm

[1] Original recipe on Vendor B cavities CAV0001-CAV0016 and Vendor A cavities CAV200-207.

[2] Revised recipe on Vendor B cavities CAV0017 and above and Vendor A cavities CAV208 and above.

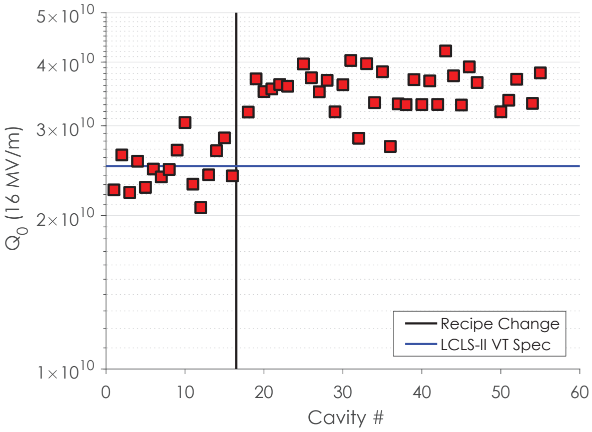

Figure 1: Q_0 at 16 MV/m and 2.0 K for cavities produced for LCLS-II with both recipes at vendor B. The vertical test specification of 2.5×10^{10} is shown as is the point where the recipe change was made. It is clear that the average Q_0 improved dramatically after the recipe change. Cavities with Q_0's of 3.5-4×10^{10} are now produced reliably.

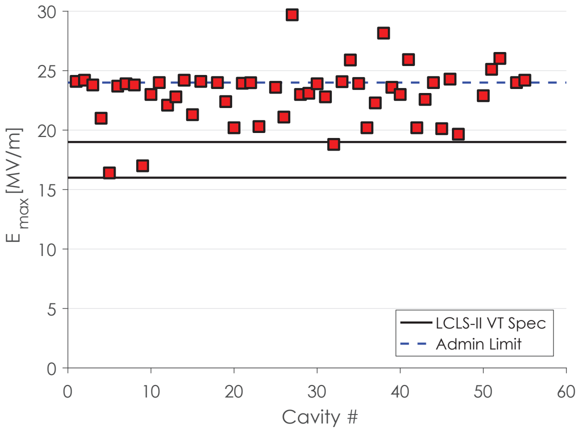

Figure 2: Maximum gradient reached in production LCLS-II cavities produced by vendor B. The cavities must reach a field of 19 MV/m. An administrative limit is placed on the cavity tests at 24 MV/m which has been exceeded in some cases.

Most cavities reach the administrative limit of 24 MV/m, providing significant headroom for operation in cryomodules. This also demonstrates that the "2/6" nitrogen-doping recipe used, does not lead to a reduction in quench field large enough to impact operation at medium fields.

Recipe Change

RF results from the original recipe as outline in Table 1 proved good but not great. In low magnetic field environments, Q_0's averaged below 2.5×10^{10} with many cavities in the region of 2.2-2.3×10^{10} and a few above 2.5×10^{10}. This performance, while good by previous state-of-the-art cavity preparation methods is not as good as cavities in the R&D stage of the LCLS-II production and is not sufficient for the high demands of LCLS-II. Therefore a recipe change was required to improve performance. Two factors were found to be the cause of the low Q_0 through studies on single-cell cavities made with production niobium sheet: insufficient bulk material removal leading to a slight increase in residual resistance (R_{res}) and poor flux expulsion when compared with prototype material from ATI Wah-Chang.

These two effects were addressed by increasing the bulk removal from 140 to 200 μm and increasing the furnace degas temperature from 800 to 900°C. Increasing the temperature has been shown to improve flux expulsion in single-cell cavities manufactured from the same production material [6]. The effect of this change can be seen in Fig. 3. At 16 MV/m, the original recipe led to an increase of ~5.5 nΩ when increasing the ambient field from 5 to 10 mG. With the revised recipe this change dropped to $<$ 0.5 nΩ. This change is a direct result of improved flux expulsion with the revised recipe.

The change in ΔR_{res} is translated to a dramatic improvement in Q_0. In Fig. 1, above cavity 16, the average Q_0 significantly increases. Cavities now routinely exceed 3×10^{10} with some cavities even reaching as high as 4×10^{10}. It is also important to note that all cavities prepared with the original recipe were tested in ambient magnetic fields that were carefully controlled and therefore well below 5 mG. After the recipe change, cavities were tested in higher fields, upwards of 10 mG and still maintained high Q_0.

BCS RESISTANCE

Nitrogen-doped cavities are characterized by improvement in their temperature-dependent BCS resistance, R_{BCS}, via two mechanisms: an overall lowering of R_{BCS} at low fields due to a lowering of the mean free path, and the introduction of an anti-Q slope which enables R_{BCS} to decrease as the accelerating gradient is raised [4]. R_{BCS} is therefore

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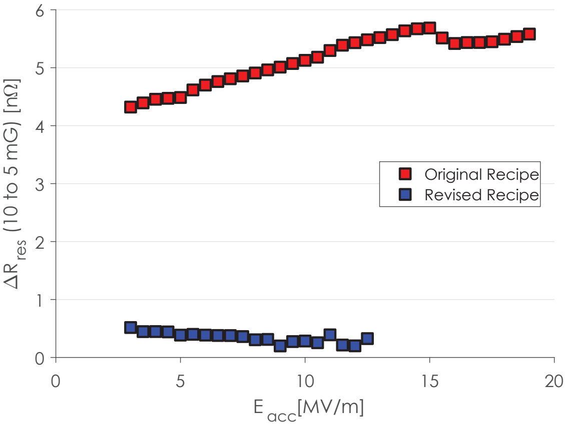

Figure 3: The change in residual resistance between cooldowns in 10 and 5 mG ambient magnetic fields with similar cool down conditions on two cavities: one with the original recipe, one with the revised recipe. At 16 MV/m, the original recipe led to an increase of ∼5.5 nΩ when increasing the ambient field from 5 to 10 mG. With the revised recipe this change dropped to < 0.5 nΩ.

a good measurement of the strength of the nitrogen-doping in an SRF cavity. During the LCLS-II R&D phase, it was confirmed that R_{BCS} at 16 MV/m and 2.0 K should be on the order of 4-6 nΩ [4].

R_{BCS} is typically extracted by taking Q_0 versus E_{acc} data at multiple temperatures, enabling the R_{res} component of R_s to be removed at 2.0 K. Figure 4 shows R_{BCS} versus E_{acc} for a subset of LCLS-II production cavities from both vendors which had low temperature data taken (cavities prepared with both recipes are shown). The anti-Q slope is clearly present in all cavities shown, demonstrating a decrease in R_{BCS} from 6-7 nΩ at low fields to 4-5 nΩ at 16 MV/m. Additionally, Fig. 5 shows R_{BCS} at 16 MV/m and 2.0 K for the same cavities. From this it is clear that R_{BCS} for the production cavities is what is expected for nitrogen-doped cavities prepared with the 2/6 recipe. This demonstrates that the nitrogen-doping was successfully transferred from the partner labs and the R&D phase to production at cavity vendors.

CONCLUSIONS

Results from the first ∼60 cavities from Vendor B are very promising. After a recipe change due to the need for more efficient flux expulsion, Q_0's in production cavities are typically higher than $3{\times}10^{10}$ with some reaching as high as $4{\times}10^{10}$. Flux expulsion was indeed improved dramatically after the furnace degas temperature was raised. Likewise, gradient reach has been fantastic, with most cavities reaching above 20 MV/m and a significant number reaching the administrative limit of 24 MV/m. Finally, the nitrogen-doping protocol was successfully transferred to both cavity vendors. Cavities reliably show a strong anti-Q slope and R_{BCS} at

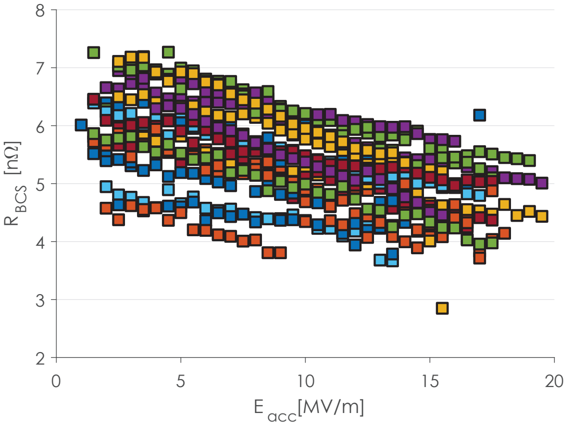

Figure 4: R_{BCS} at 2.0 K versus E_{acc} for a subset of production cavities tested at low temperatures. All cavities shown display the characteristic anti-Q slope (decreasing R_{BCS} with increasing E_{acc}) between 5 and 20 MV/m. This demonstrates that the nitrogen-doping is being successfully carried out in production.

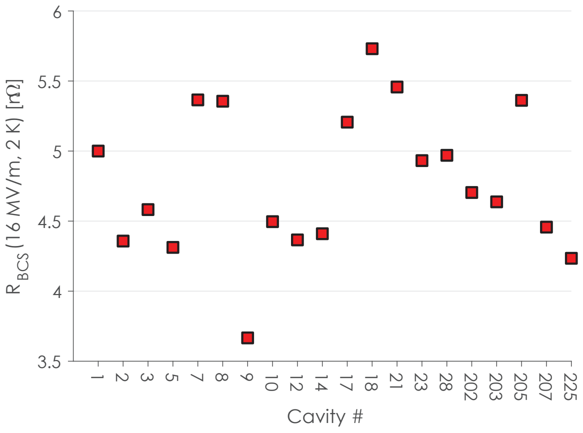

Figure 5: R_{BCS} at 16 MV/m and 2.0 K for cavities shown in Fig. 4. All cavities show a R_{BCS} less than 6 nΩ, consistent with expectations from R&D and prototype cavities. Nitrogen-doping has been successfully transferred to the vendors for production.

16 MV/m and 2.0 K of 4-5 nΩ, consistent with expectations from the R&D phase.

Production will continue and all cavities are expected to be received by the end of 2017. We expect to continue having great results in terms of Q_0 and gradient reach. Future work will focus on ensuring Q_0 performance is maintained through Vendor A.

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