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# Industrialization of the nitrogen-doping preparation for SRF cavities for LCLS-II☆

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ABSTRACT

The Linac Coherent Light Source II (LCLS-II) is a new state-of-the-art coherent X-ray source being constructed at SLAC National Accelerator Laboratory. It employs 280 superconducting radio frequency (SRF) cavities in order operate in continuous wave (CW) mode. To reduce the overall cryogenic cost of such a large accelerator, nitrogen-doping of the SRF cavities is being used. Nitrogen-doping has consistently been shown to increase the efficiency of SRF cavities operating in the 2.0 K regime and at medium fields (15–20 MV/m) in vertical cavity tests and horizontal cryomodule tests. While nitrogen-doping's efficacy for improvement of cavity performance was demonstrated at three independent labs, Fermilab, Jefferson Lab, and Cornell University, transfer of the technology to industry for LCLS-II production was not without challenges. Here we present results from the beginning of LCLS-II cavity production. We discuss qualification of the cavity vendors and the first cavities from each vendor. Finally, we demonstrate that nitrogen-doping has been successfully transferred to SRF cavity vendors, resulting in consistent production of cavities with better cryogenic efficiency than has ever been achieved for a large-scale accelerator.



## 1. Introduction

The Linac Coherent Light Source II (LCLS-II) is a new 4 GeV X-ray light source to be constructed in the existing SLAC tunnel. It consists of 280 SRF cavities operating in continuous wave (CW) mode [1]. Construction of the cryomodules is being carried out by the partner labs, Fermilab and Jefferson Lab. In the R&D phase of the project, Cornell University also participated as a partner lab in SRF cavity development. The cryogenic operating costs of the linac would be quite high with cavities prepared with standard methods, such as those used in the European XFEL (electropolished surfaces and 120 °C bake) [2], which typically produce cavities with $Q_0$'s on the order of 1.5–2×$10^{10}$. LCLS-II will be constructed with two 4 kW cryoplants. To significantly reduce the operating cost of the machine, operation of the linac with a single cryoplant would be ideal. However to achieve this single-plant operation, significant improvement in the state-of-the-art for cryogenic efficiency of the SRF cavities is required. Therefore a new cavity preparation method, nitrogen-doping, has been developed to significantly raise the intrinsic quality factor, $Q_0$, of the cavities and thus lower the cryogenic load per cavity. If an average $Q_0$ of 2.7×$10^{10}$ in the SRF cavities could be obtained, it would yield an approximate 2 K load of 3.7 kW, low enough for single-cryoplant operation.

Nitrogen-doping [3], discovered in 2013 by Grassellino et al. and further developed by the R&D efforts for LCLS-II at Fermilab, Jefferson Lab, and Cornell University has been shown to improve $Q_0$ in SRF cavities. At the partner labs, $Q_0$'s on the order of 2.7×$10^{10}$ or higher at 2.0 K and 16 MV/m have been consistently demonstrated [4,5] in realistic cryomodule environments such as the Cornell Horizontal Test Cryomodule which is a close representation of a short version of a full LCLS-II cryomodule. The production of nitrogen-doped cavities outside of the R&D environment however had not been previously done. Early stages of LCLS-II development, knows as the "R&D phase" resulted in many studies on the viability of nitrogen-doping as a cavity preparation

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method for production. The procurement and technical oversight of the LCLS-II nine-cell cavities is the responsibility of Jefferson Lab as part of a contract executed between the industrial vendors and JLab.

The success of LCLS-II depends greatly on the ability of cavity vendors to successfully reproduce the high $Q_0$ results achieved at the partner labs throughout LCLS-II production. Here we present on the effort to transfer this technology to cavity vendors and the first results from LCLS-II production.

## 2. Nitrogen-doping background

Nitrogen-doping of SRF cavities consists of heat treating the cavities at high temperature in a nitrogen-atmosphere in a ultra-high vacuum (UHV) furnace [3,6]. This is typically done at 600–1000 °C in a pressure of some tens of millitorr. This process results in two effects:

1. The formation of a niobium-nitride phase on the surface of the niobium.
2. Nitrogen diffusion into the bulk of the niobium (40–50 μm for the LCLS-II recipe).

The nitride on the surface is quite lossy, resulting in $Q_0$'s on the order of 1×108 if not removed. Therefore, following the doping phase in the furnace, the first few microns of the surface are removed, typically with an electropolish (EP) which produces very smooth surfaces. It is important to note that success of the doping process is dependent on the substrate being electropolished prior to nitrogen-doping so that there is a smooth starting surface.

The cavities are fabricated from sheet niobium at the cavity vendors. The full cavity preparation method used in LCLS-II is (note that the numbers shown in parenthesis are values that were used after the recipe change which will be discussed in a later section):

1. Bulk EP of 140 (200) μm.
2. Degas in UHV furnace in vacuum at 800 °C (900 °C) for 3 h.
3. Nitrogen-doping in 26 mTorr of nitrogen gas for 2 min. at 800 °C.
4. Annealing in vacuum for 6 min. at 800 °C.
5. Light EP of 5–7 μm.

This "recipe" is typically referred to as the "2/6 N-doping" as a reference to steps 3 and 4 and had been shown during the R&D phase of the LCLS-II project to consistently produce good results [7]. A flowchart of cavity preparation after fabrication is shown in Fig. 1. Full details of the vendors' cavity preparation specifics including clean room and vendor qualification have been previously presented [8] and closely follow the parameters used for the XFEL Project [2].

To understand the improvement in $Q_0$ due to nitrogen-doping, one must first look at how $Q_0$ is defined. $Q_0$ is inversely proportional to the surface resistance, $R_s$, of the SRF cavities [9],

$$Q_0 = \frac{G}{R_s}, \tag{1}$$

where $G$ is the geometry factor, calculated from EM codes (270.7 Ω for Tesla shaped cavities [10] used in LCLS-II). The surface resistance can be further broken down into two components,

$$R_s = R_{BCS}(T, \ldots) + R_{res}, \tag{2}$$

where $R_{BCS}$ is the so-called BCS resistance which is dependent on temperature and the BCS properties of the material, and $R_{res}$ is the residual resistance which is made up of all temperature-independent components of the surface resistance. $R_{res}$ is predominantly made up of losses from trapped magnetic flux, hydrides, and oxides. Both components of $R_s$ can also be dependent on the magnitude of the RF field, $E_{acc}$.

Nitrogen-doping improves $Q_0$ by primarily affecting the BCS resistance component. The impregnation of nitrogen atoms into the niobium bulk causes a lowering of the mean free path of the material, which in turn lowers $R_{BCS}$ at low fields to near its minimum, to approximately 6–8 nΩ (compared with 10–12 nΩ in standard prepared cavities). Additionally, nitrogen-doping results in the introduction of an "anti-$Q$ slope" in which $R_{BCS}$ decreases as $E_{acc}$ is increased from ~ 5 to ~ 20 MV/m, in turn raising the $Q_0$ even further [11], as opposed to cavities prepared with standard methods, in which $Q_0$ typically decreases as $E_{acc}$ is increased. This exact cause of this lowering of $R_{BCS}$ further is at this time not well understood. At 16 MV/m and 2.0 K, the combination of these two effects typically results in a $R_{BCS}$ of 4–6 nΩ [12]. Therefore, a good cross-check on if the nitrogen-doping process was carried out successfully is to check $R_{BCS}$. This will be used later on to demonstrate the successful transfer of nitrogen-doping from the partner labs to the cavity vendors for LCLS-II.

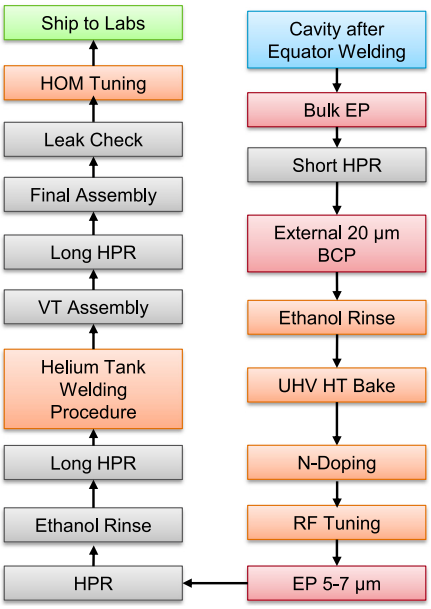


**Fig. 1.** A flow chart showing the cavity preparations steps after fabrication.

In addition to the lowering of $R_{BCS}$, lowering of the mean free path also results in nitrogen-doped cavities being more sensitive to trapped magnetic flux [13]. This means that for same the amount of trapped flux, N-doped cavities will have a larger $R_{res}$ than undoped cavities. This effect can be mitigated with efficient flux expulsion, typically achieved by large spatial temperature gradients during the superconducting transition [14], or by tightly controlling the ambient magnetic field. In addition to this drawback, cavity quench fields have been shown to be lower in nitrogen-doped cavities than in cavities prepared with other methods [6]. The exact amount that the quench field is lowered is strongly related to the exact doping recipe used. Heavier dopings typically lead to lower quench fields. This effect needs to be carefully considered when deciding on a cavity preparation recipe. In the case of LCLS-II, with operation at 16 MV/m, lowering of the quench field by ~ 30 % (which is typical from the 2/6 recipe) would not impede the ability of the machine to operate at the design gradient.

## 3. Transfer to vendors

For LCLS-II, two vendors were chosen to produce cavities: Research Instruments GmbH (RI) and Ettore Zanon S.p.a. (EZ), the same vendors used during the European XFEL project [2]. To protect confidentiality, in the remainder of this paper the vendor names will be omitted.

### 3.1. Vendor qualification

Prior to production beginning, the two cavity vendors' nitrogen-doping capabilities were qualified to produce cavities with similar

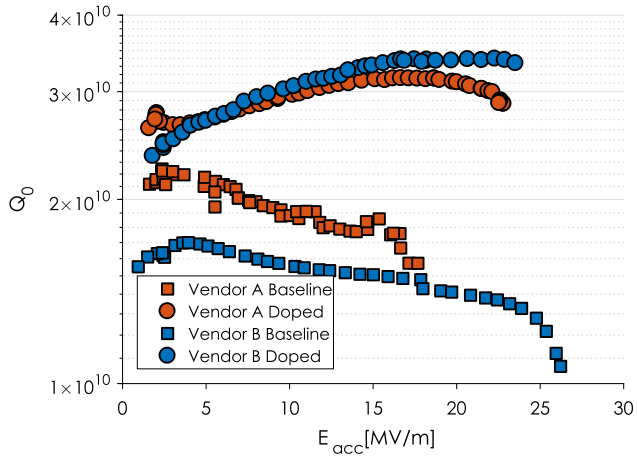


**Fig. 2.** $Q_0$ versus $E_{acc}$ at 2.0 K for two of the vendor qualification cavities (one for each vendor, TB9AES014 for Vendor A and TB9AES023 for Vendor B). Baseline test, prior to nitrogen-doping, and final test after nitrogen-doping by the vendors is shown.

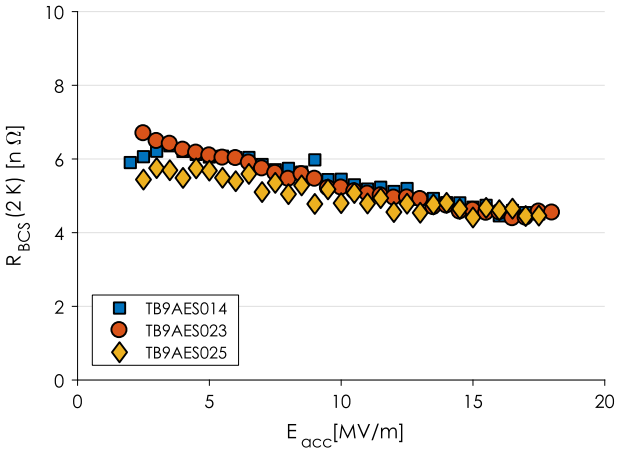


**Fig. 3.** $R_{BCS}$ versus $E_{acc}$ at 2.0 K for the three vendor qualification cavities that were field emission free. $R_{BCS}$ decreases from 6–7 nΩ at low fields to ~ 4 nΩ at 16 MV/m. Errors on $R_{BCS}$ are ~ 20%.

**Table 1**
Results from the vendor qualification cavities.

| Cavity | Vendor | $Q_0$, baseline[1] | $Q_0$, N-doped[1] | $R_{BCS}$ [nΩ][1] |
|---|---|---|---|---|
| TB9AES014 | A | $1.8\times10^{10}$ | $3.2\times10^{10}$ | 4.5 |
| TB9AES023 | B | $1.5\times10^{10}$ | $3.4\times10^{10}$ | 4.6 |
| TB9AES025 | A | $1.1\times10^{10}$ | $3.6\times10^{10}$ | 4.6 |
| RI023[2] | B | $1.9\times10^{10}$ | N/a | N/a |

[1] Measured at 16 MV/m and 2.0 K. Errors on $Q_0$ are 10% and on $R_{BCS}$ 20% Numbers presented here were as measured with stainless steel blanks on both sides of the cavity. This leads to an additional 1.6 nΩ of $R_{res}$ (production 9-cells have only one blank which contributes to additional $R_{res}$).

[2] Field emission onset at 6.5 MV/m, measurement stopped at ~ 7 MV/m.

performance to what was achieved in the R&D phase ($Q_0 \geq 2.7\times10^{10}$ at 16 MV/m and 2.0 K). Two 9-cell cavities were provided to each vendor to carry out the nitrogen-doping process. These four cavities had a long history of R&D work and were tested prior to being sent to the vendors. They were manufactured with material from ATI Wah-Chang. This qualification was meant solely to qualify the vendors' ability to carry out the nitrogen-doping process, their procedures for manufacturing SRF cavities and carrying out clean room work was assumed to be well controlled since they had just completed the XFEL production. Carrying out the nitrogen-doping procedures on an industrial scale requires furnace temperature and pressure control in the regime where the doping takes place (800 °C and 25 mTorr) along with stable processes for light electropolishing after the doping stage. The baseline $Q_0$ vs $E_{acc}$ test of two of these cavities (one for each vendor) is shown in Fig. 2 in squares. Baseline $Q_0$'s at 16 MV/m were on the order of $1–2\times10^{10}$, typical for cavities prepared with standard methods. Also present is a strong medium field $Q$ slope (MFQS) in which the $Q_0$ decreases as the gradient is increased from 5 to 20 MV/m. A summary of the values measured before and after nitrogen-doping are given in Table 1. Errors on $Q_0$ and $E_{acc}$ in vertical test at Fermilab and Jefferson Lab are typically on the order of 10% [15].

Following nitrogen-doping, three of the cavities performed very well. Fig. 2 shows two of these cavities, with $Q_0$'s higher than $3\times10^{10}$ at 16 MV/m and a very strong anti-$Q$ slopes. The third cavity performed similarly. The fourth cavity, prepared by Vendor B, had strong field emission starting around 6.5 MV/m. This was most likely due a dirty assembly and would be repaired with a re-rinse, not necessarily related to the nitrogen-doping process.

While the $Q_0$ results demonstrate the vendors ability to produce cavities that reach high $Q_0$ with the N-doping process, it is important to further investigate the $R_{BCS}$ behavior of the cavities to ensure that the doping is at the same level (same $R_{BCS}$) as was achieved during R&D. $R_{BCS}$ can be extracted from $Q_0$ measurements by measuring $Q_0$ at multiple temperatures between 1.4 and 2.1 K. Fitting via BCS theory then enables $R_s$ to be separated into $R_{BCS}$ and the temperature independent component, $R_{res}$. This method results in errors on $R_{res}$ and $R_{BCS}$ on the order of 20%. For more details on the extraction of material properties and $R_{BCS}$ from RF measurements along with error analysis see [6,16]. Fig. 3 shows $R_{BCS}$ at 2.0 K versus $E_{acc}$ for the three cavities that were tested without field emission. All three cavities show a decreasing $R_{BCS}$ between 5 and 16 MV/m, as expected for N-doped cavities. $R_{BCS}$ decreases from 6–7 nΩ at low fields to ~ 4 nΩ at 16 MV/m, consistent with measurements on R&D cavities.

The large improvement in $Q_0$ at 16 MV/m and 2.0 K along with the strong anti-Q slope and $R_{BCS}$ of ~ 4 nΩ for three of the four cavities provides significant evidence for the nitrogen-doping being successfully carried out at the vendors. These three cavities clearly qualify and meet the expectations for LCLS-II. The fourth cavity was dominated by field emission at low fields. The project considered this to be an issue with cavity preparation in the clean room, rather than an issue with the nitrogen-doping. Therefore, both vendors were deemed qualified and production was allowed to start. These first results demonstrate the first time that cavity vendors have produced SRF cavities with $Q_0$'s over $3\times10^{10}$ at 2.0 K, a significant improvement over previous projects. In addition to the furnace nitrogen doping; temperature controlled electropolishing (surface temperature between 20 to 25 degree C) using external thermal-couple feedback was also transferred to industry for the first time and has been previously presented [17]. This involved different acid temperatures and cathode configurations than was used for the XFEL project.

### 3.2. First results from production from vendor B

Full cavity production for LCLS-II began in mid-2016 at both cavity vendors, with Vendor B beginning slightly before of Vendor A. Material for the production cavities was procured from Tokyo Denkai (TD) and OTIC Ningxia (NX). Cavity preparation was carried out according to the procedure given earlier. A bulk EP of 140 μm and a degas temperature in the furnace of 800 °C was implemented. Cavities were shipped from the vendors fully dressed in helium vessels and under vacuum. Upon arrival at Fermilab and Jefferson Lab, they were inspected and assembled onto vertical test (VT) stands.

Cavities are considered to be qualified for string assembly if they meet the LCLS-II specification of $2.7\times10^{10}$ at 16 MV/m and 2.0 K in a 5 mG ambient magnetic field (the specification for the ambient field in the cryomodule) and free of field emission at fields below 19 MV/m.

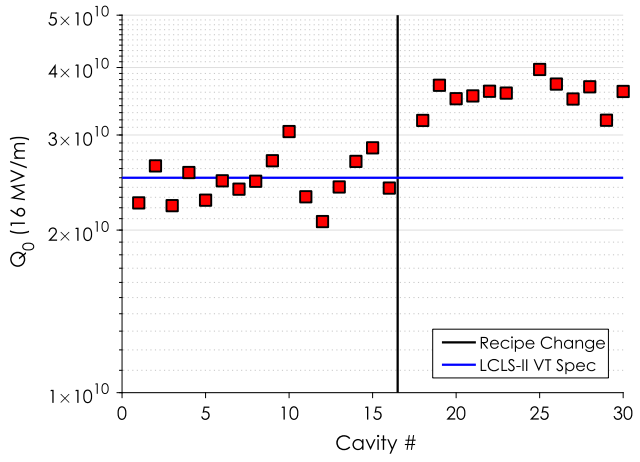


**Fig. 4.** $Q_0$ at 16 MV/m and 2.0 K for cavities produced at Vendor B in the first stages of production. Also shown (blue line) is the LCLS-II $Q_0$ specification of $2.5\times10^{10}$ and the point where the degas temperature was increased from 800 to 900 °C (black line). Errors on $Q_0$ are ~ 10%. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

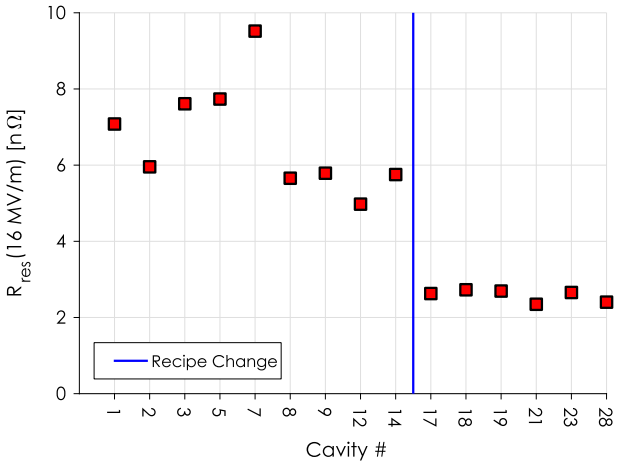


**Fig. 5.** Residual resistance, $R_{res}$, at 16 MV/m for cavities from Vendor B in which low temperature data was measured, enabling the extraction of material parameters. The recipe change clearly shows a significant change in the $R_{res}$ primarily by improving flux expulsion in the cavities. Errors on $R_{res}$ are ~ 10%.

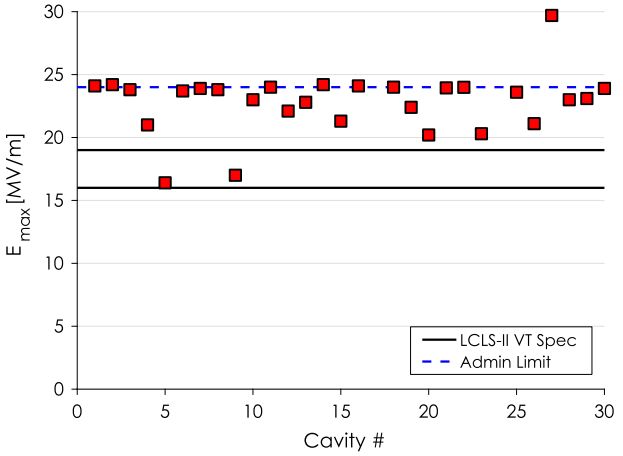


**Fig. 6.** Maximum accelerating gradient, $E_{acc}$ for the cavities produced at Vendor B in the first stages of production. An administrative limit of 24 MV/m is in place for all cavities tested at Jefferson Lab and cavities with serial numbers below 17 at Fermilab. Errors on $E_{acc}$ are ~ 10%.

However, the coupler side of the cavities used for LCLS-II have a short beam tube which can lead to additional losses when a stainless steel blank is installed during vertical test (the tuner side of the cavity has been modified from the TESLA design to have a longer beam tube, similar to the modifications done for XFEL). This additional loss will not be present when the cavities are assembled in a cryomodule. This single flange has been shown to lead to an increase in $R_{res}$ of 0.8 nΩ [5]. Therefore, the vertical test specification has been lowered from 2.7 to $2.5\times10^{10}$ for cavities tested in this manner. A cavity that reaches $2.5\times10^{10}$ in vertical test should reach $2.7\times10^{10}$ in the cryomodule, all other factors being equal. In addition to the $Q_0$ specification, cavities need to reach 19 MV/m in VT. This increase of 3 MV/m from the spec of 16 gives enough headroom to account for errors on the gradient measurement during testing.

In the beginning of production, cavities were tested in dewars that had their ambient magnetic field compensated. This was intended to lower as much as possible the contribution of trapped magnetic flux to $R_{res}$. Typically this resulted in average ambient magnetic fields of 1–3 mG on the cavity surface.

Fig. 4 shows $Q_0$ at 16 MV/m and 2.0 K for cavities produced by Vendor B. Also shown is the LCLS-II $Q_0$ specification of $2.5\times10^{10}$. Cavities 1 through 16 were denoted "first-article cavities" and produced with the protocols described above. It is clear from Fig. 4 that these cavities performed worse than expected. $Q_0$'s were spread between 2 and $2.7\times10^{10}$, about half qualifying and half not. These results, while better than the previous state-of-the-art as demonstrated by the European XFEL [2], were not nearly as great as the vendor qualification cavities.

Further investigation by means of low-temperature data (separation of $R_{res}$ and $R_{BCS}$ via the means discussed in the previous section) and flux expulsion measurements shed more light on the cause of the low $Q_0$'s as shown in Fig. 4. Fig. 5 shows the residual resistance, $R_{res}$, at 16 MV/m for a subset of the cavities from Vendor B tested at low-temperature. We can see that $R_{res}$ for the first article cavities was significantly higher than would be expected: ranging from 5 to 9 nΩ. For reference, cavities from the vendor qualification and R&D phases showed $R_{res}$ closer to 2 nΩ. This will be explored in the next section.

Fig. 6 shows the maximum accelerating gradient for the first ~ 30 cavities produced by Vendor B. An administrative limit on the gradient of 24 MV/m was put in place for the first 16 cavities at both partner labs, but was removed after cavity 16 for cavities tested at Fermilab. As is clear from Fig. 6, nearly all cavities tested reach above 20 MV/m. Only two cavities from Vendor B in the first 30 did not reach the LCLS-II specification of 19 MV/m. This is an important result because it demonstrates that quench fields in nitrogen-doped cavities exceed what is required for an accelerator operating in the medium field region.

### 3.3. Change of production recipe

The increase in $R_{res}$ in the first article cavities from Vendor B has been attributed to two effects: the cavities expelling flux worse than expected and the bulk EP removal being insufficient to reach below the damage layer of the niobium. In well prepared cavities tested in very low ambient magnetic fields, constructed of material that expels flux well, one typically can expect $R_{res}$ on the order of 1–2 nΩ. Therefore, having $R_{res}$ higher than 5 nΩ is very concerning.

In addition to the production cavities, four single-cell cavities were built from the production material to further explore cavity behavior. It was found through studies on these single-cell cavities that there was an additional 1–2 nΩ present in the cavities which disappeared after additional bulk EP [18]. This was attributed to the damage layer (created during rolling of the niobium) not being fully removed by the 140 μm EP. While important, this does not account for the majority of the increase in $R_{res}$ in the first production cavities.

Studies from Posen et al. on the production single-cell cavities along with cavities made from ATI Wah-Chang material (same material as vendor qualification cavities) further studied the impact of flux trapping on cavities [19]. Prior to the work by Posen, spatial temperature gradients during the normal conducting/superconducting transition were thought to be the largest contributor to the trapped flux efficiency of SRF cavities. Posen found that cavities made from niobium from different vendors but treated the same displayed very different flux expelling properties: some expelled magnetic flux very well while others did so poorly, even at very large temperature gradients. ATI Wah-Chang material which was used in many of the R&D cavities expelled flux very well while the production material from TD and NX expelled poorly. Moreover, poor expelling behavior could be improved by heat treating at temperatures higher than 800 °C.

The $R_{res}$ in the first production cavities was about 3–6 nΩ higher than expected. This is made up of 1–2 nΩ from the damage layer (insufficient bulk EP removal) and 2–4 nΩ from trapped magnetic flux. While the cavities were tested in low fields (1–3 mG), nearly all of this ambient field was trapped in the cavities' walls, directly leading to an increase in $R_{res}$. It is important to note that Vendor B followed the recipe and production methods as required. The issues with cavity performance was solely related to the material used. The project management therefore made two changes to the cavity preparation steps prior to the production of more cavities: the bulk EP was increased from 140 to 200 μm and the degas temperature in the furnace was increased from 800 to 900 °C. This change was implemented on CAV0017 from Vendor B and CAV0208 from Vendor A.

Following the recipe change, $R_{res}$ was indeed improved significantly. Fig. 5 shows $R_{res}$ for Vendor B cavities after and including CAV0017. It is clear that two things happened after the recipe changed: the total $R_{res}$ was decreased to an acceptable value, and the spread in $R_{res}$ across multiple cavities was decreased significantly. This decrease in spread can be attributed to the fact that nearly 100% of the ambient field is being expelled, so the cavities are less sensitive to the exact magnetic field environment they are tested in. The recipe change's effect on $Q_0$ can also be observed in Fig. 4. Cavities to the right of the black line (which denotes the recipe change) show $Q_0$'s higher than $3\times10^{10}$, consistent with the cavities from the vendor qualification stage. It is also important to note that cavities after the recipe change were typically tested in uncompensated ambient magnetic field environments. Because of the improved flux expulsion, $Q_0$ performance still exceeded the LCLS-II specifications even in a 5–10 mG ambient field environment.

### 3.4. Vendor a procedures modification

Early results from cavities produced by Vendor A were also poorer than desired. While they also suffered from the issues described in the previous section regarding the damage layer and inefficient flux expulsion, more pressing issues were also present. Fig. 7 shows $Q_0$ at 16 MV/m and 2.0 K for cavities produced by Vendor A. We can see that even after the recipe change at CAV0208, $Q_0$'s were significantly lower than the LCLS-II $Q_0$ specification in the early stages of production. This was due primarily to a strong $Q$-slope which began between 12 and 16 MV/m which dragged the $Q_0$ down. In addition to poor $Q_0$ performance, the strong $Q$-slope led to the cavities quenching at fields significantly lower than was required by the project. Fig. 8 shows the maximum gradient achieved in the Vendor A cavities. Again, an administrative limit on the gradient at 24 MV/m was implemented. Only a subset of the cavities met the specification of 19 MV/m, with some not even reaching 16 MV/m. Due to this poor performance, a stop work order was given and LCLS-II personnel went on-site to Vendor A to investigate the cause of the $Q$-slope and low quench fields.

A thorough investigation of the procedures at Vendor A found that the EP parameters used during the bulk EP step were not in line with what was being done at Vendor B or what is typically done at Jefferson Lab. Both vendors were given specific electropolishing parameters,

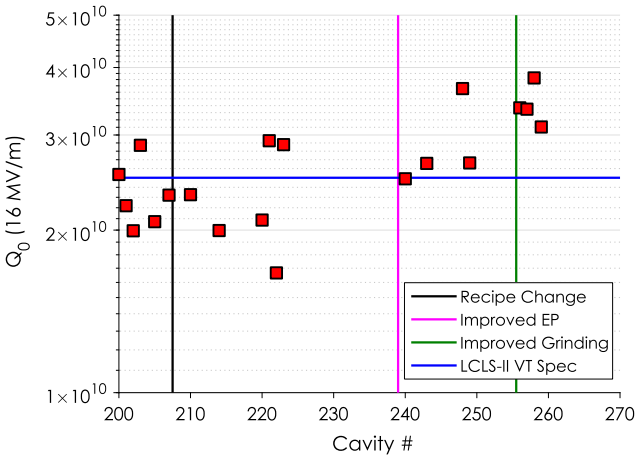


**Fig. 7.** $Q_0$ at 16 MV/m and 2.0 K for cavities produced at Vendor A. Also shown is the LCLS-II $Q_0$ specification of $2.5\times10^{10}$ (blue line), the point where the degas temperature was increased from 800 to 900 °C (black line at CAV0208), the point at which the improved EP was implemented (magenta line at CAV0240), and the point at which new grinding was implemented (green line at CAV0256). Errors on $Q_0$ are ~ 10%. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

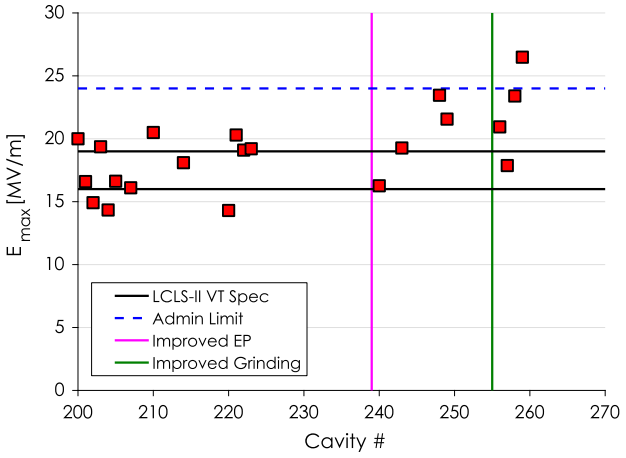


**Fig. 8.** Maximum accelerating gradient, $E_{acc}$, for the cavities produced at Vendor A. Also shown is the point in time in which the new EP parameters were implemented (magenta line at CAV0240) and the new grinding was implemented (green line at CAV0256). Errors on $E_{acc}$ are ~ 10%. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

cathode design, and operation conditions as detailed in [17]. Vendor A however, did not follow the prescribed recipe, specifically the cathode configuration and temperatures used during the EP were different. This caused the EP to no longer be operating in the polishing regime but in the etching regime, which produces a rough surface. This was in line with what was done for XFEL however with a final flash BCP, the effect on cavity performance was likely masked. A rough surface was indeed observed in a cavity from Vendor A, as shown in Fig. 9. Surface roughness was measured with a laser confocal microscope and found to be more than 15 μm, significantly higher than what would be expected from an EP surface, and in fact as rough as the surface typically produced with buffer chemical polish (BCP). It was therefore theorized that this surface roughness was leading to the strong $Q$-slope since N-doping on rough surfaces such as those prepared with BCP typically have poor performance [3]. This poor EP procedure was not originally found during vendor qualification since it was assumed that the vendors could produce cavities with good EP based on the XFEL experience.

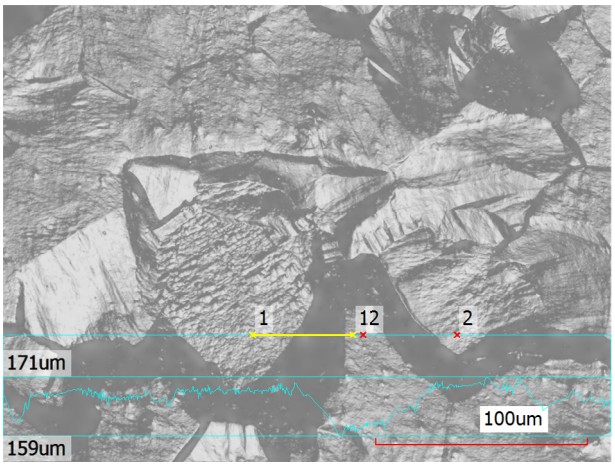


**Fig. 9.** Surface roughness of a Vendor A cavity prepared with the original bulk EP parameters. Image taken with a laser confocal microscope and courtesy of Y. Trenikhina at FNAL.

**Fig. 10.** Example defect on side wall of Vendor A cavity after 275 micron EP.

Following the discovery of the improper EP procedures, work at Vendor A was stopped and LCLS-II staff assisted them in modifying the procedure to keep the acid temperature low and produce an EP with the desired surface. Four cavities were produced using the new EP method and tested at Fermilab. These were cavities 240, 243, 248, and 249 shown between the magenta and green lines in Figs. 7 and 8. Unfortunately, the $Q$-slope was still present in three of the four cavities, resulting in low $Q_0$ and low quench fields. The surface roughness from the EP was not the fundamental cause of the poor performance.

Further investigation was conducted at Vendor A into the cavity fabrication methods. Visual inspection of a few cavities after the bulk EP showed the presence of visible defects even after EP's as large as 275 μm. An example of one of these defects is shown in Fig. 10. It was found that these defects were the result of grinding half cells prior to cavity welding. This grinding was being done to a uniform smoothness with flapper-style grinding wheels and resulted in normal conducting media being buried into the surface. After the bulk EP, this media could have been uncovered but not removed by the electropolishing chemistry, which would lead to losses when the cavity was tested. This method of grinding was different from what was specified in the contract and thus was not caught by project personnel until a thorough review of the fabrication procedures at Vendor A was completed. This was in direct violation of the cavity contract as global grinding, or any grinding on the cavity surfaces was required to be cleared by the contract holder prior to being done.

After the discovery of this grinding method and the embedded media, a thorough review of Vendor A's cavity fabrication procedures was done. Uniform grinding was no longer carried out and instead specific defects were individually ground with a much less aggressive grinding media. Since this change in procedures, four cavities have been produced by Vendor A. These four cavities CAV0256-259 were prepared with the new grinding procedure and the new EP. Their results are also shown on Figs. 7 and 8, to the right of the green line. All four cavities showed no evidence of the $Q$ slope that was present before. This led to them all qualifying in terms of $Q_0$ performance at 16 MV/m. Three of the four cavities exceeded 19 MV/m, with one quenching at 17 MV/m. This is most likely due to the natural spread in quench fields. As shown previously, Vendor B has produced a small number of cavities that quenched around this field level. Therefore, Vendor A has been deemed to be producing acceptable cavities for LCLS-II and has resumed full production.

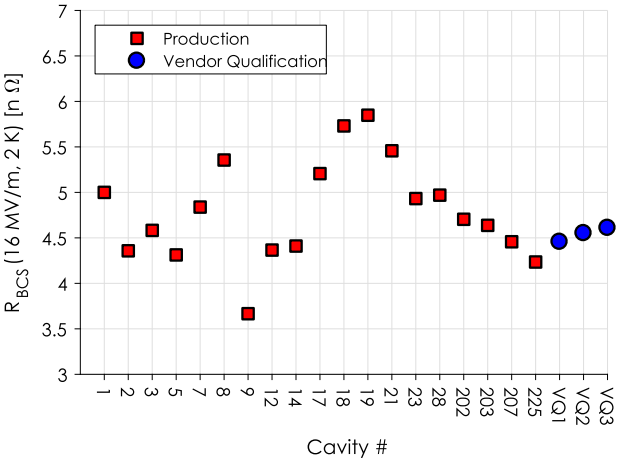


**Fig. 11.** BCS resistance, $R_{BCS}$, at 16 MV/m and 2.0 K for the cavities in which low temperature data was measured and the three vendor qualification cavities. Errors on $R_{BCS}$ are ~ 20%.

### 3.5. BCS resistance in production

As discussed previously, $R_{BCS}$, the temperature-dependent component of $R_s$, is a good measurement of the nitrogen-doping level in a given cavity. The "2/6" N-Doping recipe has been shown to consistently produce an $R_{BCS}$ of 4–6 nΩ at 16 MV/m and 2.0 K during R&D and the vendor qualification stage. Therefore, we would expect similar results from production cavities doped in a similar manner. It is important to note that the degas temperature and the bulk EP should not impact $R_{BCS}$. These recipe changes were implemented to improve $R_{res}$ and are carried out prior to the doping step. Therefore we should see little to no impact of the recipe change on $R_{BCS}$.

Unfortunately, $R_{BCS}$ cannot be extracted for all production cavities. Due to time constraints, low-temperature data was only measured on a subset of cavities to check that the doping was successful in production. Fig. 11 shows $R_{BCS}$ at 16 MV/m and 2.0 K for the cavities in which low-temperature data was measured. In addition to the production cavities, data for the vendor qualification cavities are shown for reference. The spread in $R_{BCS}$ ranges from ~ 3.5 to ~ 6 nΩ, consistent with the measurements done on the vendor qualification cavities and the cavities in the R&D phase.

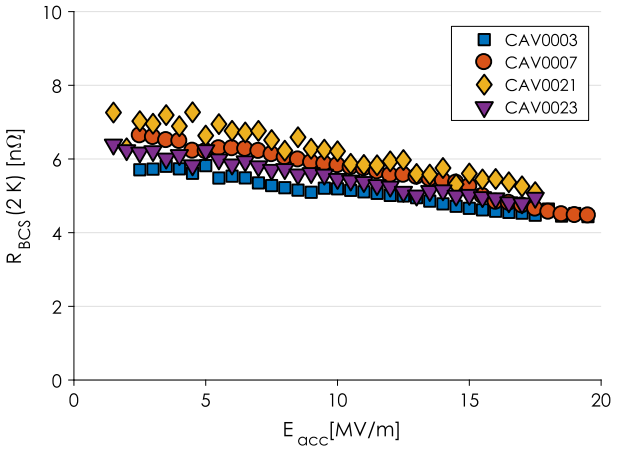


**Fig. 12.** $R_{BCS}$ versus $E_{acc}$ at 2.0 K for four characteristic cavities from the Vendor B production. The slope expected in nitrogen-doped cavities is present. Errors on $R_{BCS}$ are ~ 20%.

The spread in $R_{BCS}$ is expected due to the errors in the measurement (~ 20%) and slight variations in the final EP of the cavities. The nitrogen-doping level of a final cavity is heavily dependent on the amount of final EP carried out after the doping. It is important to note that both vendors (Vendor B with cavity indexing starting at 1, and Vendor A with cavity indexing starting at 200) show similar $R_{BCS}$. Additionally, the recipe change (at CAV0017 for Vendor B and CAV0208 for Vendor A) had no effect on $R_{BCS}$, as expected. This demonstrates that the increase of the degas temperature from 800 to 900 °C and the bulk EP from 140 to 200 μm did not affect the nitrogen-doping of the cavities. Note also that the Vendor A cavities 202, 203, and 207 were produced with NX material and all other production cavities shown were produced with TD material. Therefore we also demonstrate that the material type does not impact the N-doping.

An additional check on $R_{BCS}$ to ensure that the doping is being carried out properly is the anti-$Q$ slope, which manifests as a decreasing $R_{BCS}$ with increasing $E_{acc}$. Fig. 12 shows $R_{BCS}$ versus $E_{acc}$ at 2.0 K for a subset of four cavities produced by Vendor B. We can see clearly that a strong slope is present with $R_{BCS}$ decreasing from 6–8 nΩ at low fields to 4–5 nΩ at 16 MV/m. This is consistent with the vendor qualification cavities and cavities from the R&D phase.

These two conclusions, demonstrated in Figs. 11 and 12, that $R_{BCS}$ is on the order of 4–6 nΩ at 16 MV/m and 2.0 K and that it decreases in the medium field region provide conclusive evidence that the cavity vendors are successfully carrying out the nitrogen-doping during LCLS-II production. This is an important milestone as it shows that the industrialization of the process is realistic. Moreover, good nitrogen-doping can be consistently and successfully carried out on many cavities.

## 4. Discussion and lessons learned

The initial stages of production of LCLS-II cavities have provided many encouraging results and a few valuable lessons learned for the remainder of production and future SRF projects. We have demonstrated that nitrogen-doping has been successfully transferred to the cavity vendors. The doping process is now well controlled and BCS resistance, the true measurement of if the doping was successful, is consistent across both vendors' cavities. $R_{BCS}$ of 4–6 nΩ has been consistently achieved since the beginning of production, the lowest $R_{BCS}$ ever obtained by SRF cavity vendors.

Cavity production at Vendor B demonstrated that better cavity performance could be achieved than on previous SRF projects with the original recipe of 140 μm bulk removal and heat treatment at 800 °C, however the cavities did not meet LCLS-II specification. An increase in the amount of bulk EP and the degas temperature led to lower residual resistance and improved flux expulsion which enabled cavities to reach $Q_0$'s higher than $3\times10^{10}$, a significant improvement over the previous state-of-the-art. This change of recipe will result in at least an improvement of 300 W on the total 2 K cryogenic load of the linac. This shows the absolute importance of flux expulsion and controlling the ambient magnetic field conditions. It is relatively easy now to achieve great $Q_0$ performance in the R&D environment; doing so in a realistic cryomodule is more difficult. Improving the flux expulsion of the cavities by increasing the degas temperature provides an insurance policy on the ambient magnetic field in the cryomodule.

Cavity production at Vendor A in the early stages of production was plagued with issues in addition to the poor flux expulsion and insufficient material removal on the cavities. The EP procedures were not carefully controlled and uniform; aggressive grinding on the half cells prior to cavity welding which contradicted the specifications written in the contract resulted in poor performance. Oversight from project personnel was a necessary and important aspect of improving the performance of the Vendor A cavities. Moving forward, personnel will be on-site at both vendors often to ensure quality control.

The results presented here are very encouraging for the future of SRF. SRF cavities are now being routinely produced from industry that far exceed expectations and previous results of $Q_0$ from previous SRF projects. Nitrogen-doping has proven to be an effective means of raising the 2.0 K $Q_0$ of SRF cavities when careful attention is paid to the details. When dealing with $Q_0$'s higher than $3\times10^{10}$, small issues that lead to only a few nΩ's of additional residual resistance can lead to a drastic reduction in $Q_0$.

Production on LCLS-II cavities continues to move forward at a fast pace. It will be important to understand in the future how cavity performance in vertical test translates to performance in the cryomodules. Cryomodules present a more difficult situation since the ambient magnetic field is more difficult to control and the cooling conditions are not as optimal. The lessons learned in the early stages of LCLS-II production will be important to maintain stellar cavity performance moving forward not only in LCLS-II but in future projects.

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