ISBN: 978-3-95450-215-8 ISSN: 2226-0366 doi:10.18429/JACoW-LINAC2022-TU1AA03

R&D TOWARDS HIGH GRADIENT CW CAVITIES

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Abstract

We discuss Fermilab's recent progress in the surface engineering of superconducting radio-frequency (SRF) cavities geared toward producing simultaneously high quality factors and high accelerating gradients in cryomodules. We investigate possible microscopic mechanisms that drive improved performance by carrying out sequential RF tests on cavities subjected to low temperature baking. We compare performance evolution to observations made with material science techniques and find correlations with material parameters. We also discuss other key advancements that enable high gradient operation in cryomodules.

INTRODUCTION

Bulk Nb superconducting radio-frequency (SRF) cavities remain as the primary accelerating technology for current and future accelerators. While these resonant structures are capable of sustaining high Q_0 at high accelerating electric fields E_{acc} in continuous wave (CW) operation, the realization of the next generation of accelerators relies on the further advancement of these metrics as this translates into potentially dramatic reductions in associated cryogenic and construction costs. To further improve these metrics, fundamental R&D aimed at understanding the microscopic mechanisms that drive RF losses in these structures is required. Moreover, other key technologies which improve or preserve the gradient reach of cavities, such as the *in situ* mitigation of field emission in a cryomodule, must be explored.

In this contribution, we present recent efforts at Fermilab that focus on extending the performance of bulk Nb SRF cavities. First, we discuss new insights on the role of impurities in the performance of SRF cavities by studying the evolution of cavity $Q_0(E_{acc})$ as we gradually increase the concentration of thermally diffused oxygen impurities within the RF layer *via* sequential vacuum baking treatments. By correlating cavity performance with observations made in time-of-flight secondary ion mass spectrometry, we confirm the positive role that diffused oxygen from the native niobium oxide has on cavity performance. We show evidence that diffused oxygen captures hydrogen and prevents the precipitation of poorly superconducting niobium nano-hydrides. In turn, this results in i) the elimination of high field Q-slope up to quench after *in situ* vacuum baking and ii) the ability to tune cavity quench field by simple thermal diffusion. Next, we discuss two new technologies which enable a dramatic improvement in cavity performance. First, as part of the ILC cost reduction program, we demonstrate the new 2-step baking + cold electropolishing (EP) surface treatment, which has been shown to consistently yield single-cell cavities of ultra-high gradients (>49 MV/m) and nine-cell cavities which routinely quench at high gradients. The second key technology is plasma processing, which has been recently fully validated for 1.3 GHz cryomodules, and has the potential to mitigate hydro-carbon related field emission and multipacting *in situ*. Lastly, we briefly discuss the application of these recent advancements in SRF technology to a new proposed accelerator, namely, in a linac to replace the current booster at Fermilab which will enable 2.4 MW of power on target for LBNF/DUNE.

EXTENDING MICROSCOPIC UNDERSTANDING OF THE ROLE OF IMPURITIES IN CAVITIES

One major performance determining factor of bulk Nb SRF cavities is the impurity structure within the first 100 nm from the inner RF surface. By combining various chemical and baking treatments, it is possible to tailor this impurity structure to redirect supercurrent flow and/or minimize deleterious inclusions that ultimately limit RF performance. Fig. 1 depicts four different cavities subjected to four such surface treatments: N-doping [1], N-Infusion [2], 120 C LTB [3], and electropolishing [3].

Cavities subjected to EP are clean from extrinsic impurities except for hydrogen. As shown in Fig. 1, cavities subjected to this surface treatment yield a dramatic decrease in Q_0 above 25 MV/m, dubbed the high field Q-slope (HFQS). It is now well known that this phenomenon is driven by the breakdown of proximity coupled niobium nano-hydrides which precipitate at cryogenic temperatures [4].

Nitrogen has been a key impurity in mitigating HFQS and enabling excellent RF performance in SRF cavities. It has been shown by Grassellino *et al.* that dilute and uniform concentrations of nitrogen interstitial are capable of yielding ultra-high Q_0 at moderately high gradients in cavities [1]. On the other hand, nitrogen infusion shows that surfaces which contain a sharp concentration gradient of N within the RF layer produce very high gradients with moderately high Q_0's [2].

Another key surface treatment is the 120 C *in situ* vacuum bake, which has been shown to mitigate HFQS and yield cavities with high gradients at moderate Q_0, the so-called 120 C bake effect. This surface treatment requires that a cavity be fully assembled for testing and be evacuated prior to undergoing an *in situ* vacuum bake at 120 C in a low temperature oven. It has only been recently found by Romanenko *et al.* that oxygen diffused from the native niobium oxide is respon-

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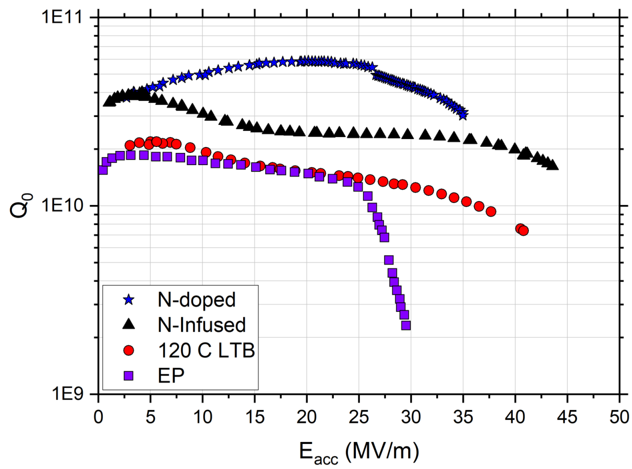

Figure 1: Q_0 vs E_{acc} of 1.3 GHz bulk Nb SRF cavities at 2 K after various surface treatments.

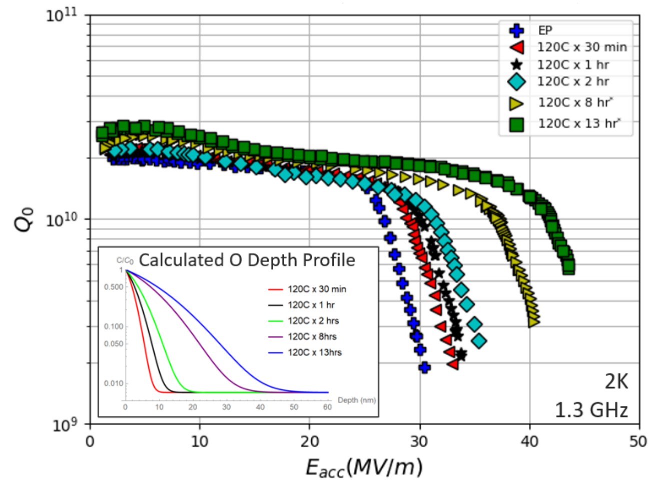

Figure 2: Q_0 vs E_{acc} of cavity TE1RI003 after sequential rounds of *in situ* vacuum baking at 120 C. Inset shows the calculated oxygen depth profile for each studied surface treatment.

sible for the 120 C bake effect as it captures free hydrogen and prevents the precipitation of poorly superconducting niobium nano-hydrides, thus enabling higher gradients [5–7]. This surface treatment is somewhat analogous to the nitrogen infusion surface treatment, showing higher accelerating gradients while exhibiting a sharp concentration gradient within the RF surface. Recent work has highlighted that high quality factors are also obtainable using dilute and uniform concentrations of oxygen impurities [7, 8], again analogous to the nitrogen treatment of nitrogen doping.

The similarities in cavity performance between treatments which utilize either oxygen or nitrogen impurities suggests that similar mechanisms are at play. Indeed, Ford *et al.* have speculated that N and O are both capable of capturing H and minimizing the volume fraction of proximity coupled niobium nano-hydrides [9]. As a result, it is likely that observations made using one particular impurity are applicable to those made using another impurity. However, there likely remains some level of impurity dependence.

With the above considerations, we present here experimental data which delineates the precise role of impurities in cavity performance. We choose to use thermally diffused oxygen from the bulk niobium oxide as this method minimizes the probability of introducing other impurities.

Experimental

We used an ensemble of TESLA-shaped 1.3 GHz Nb single cell SRF cavities that were initially treated with a bulk removal via electropolishing from the inner RF surface post initial fabrication and an 800 C degas step [3]. All cavities were then subjected to a 40 µm removal of the inner surface via standard EP. The cavities were then assembled for testing and evacuated. Most cavities were tested at this point to get a baseline, which will be referred to as "EP".

Cavities were subjected to sequential rounds of *in-situ* low temperature baking at various temperatures ranging from 90 C up to 200 C, diffusing oxygen from the native oxide toward the bulk according to Fick's law. After each step of treatment, cavities were RF tested at a temperature of 2 K. Most tests were repeated at <1.5 K to enable a precise measure of the onset of HFQS. All studied surface treatments were designed to ensure that the native oxide remained intact and served as a passivating layer against extrinsic impurities. This ensured that only oxygen diffused from the native oxide served as the primary diffusant of interest in these studies. In total, we have performed over 60 surface treatments and subsequent RF measurements.

To minimize the possibility of trapping of magnetic flux through superconducting transition, we used Helmholtz coils to provide a zero field environment and a fast cool down protocol to produce a sufficient thermal gradient along the length of the cavity [10]. Only tests that showed minimal field emission are presented here.

Results

Role of Diffused Oxygen in Mitigating HFQS We first investigated the role of thermally diffused oxygen from the native oxide toward the bulk in mitigating HFQS. Fig. 2 plots the RF results of TE1RI003 after sequential rounds of *in situ* vacuum baking at 120 C. The baseline EP test showed the expected onset of HFQS at 25 MV/m; the max gradient was power limited. After baking at 120 C for 30 minutes, the HFQS onset shifted up to 27 MV/m; max gradient was again limited by available RF power. Following an additional 30 minute bake, for a net treatment of 120 C for 1 hour, HFQS onset shifted further up to 29 MV/m and quench occurred at 34.4 MV/m. Subsequent treatment and testing showed that both the field of HFQS onset and quench field increased with integrated bake duration.

To correlate cavity performance with the material evolution, we used the TOF-SIMS results presented by Romanenko *et al.* [5,6], which shows that oxygen diffuses from the native niobium oxide toward the bulk according to a simple

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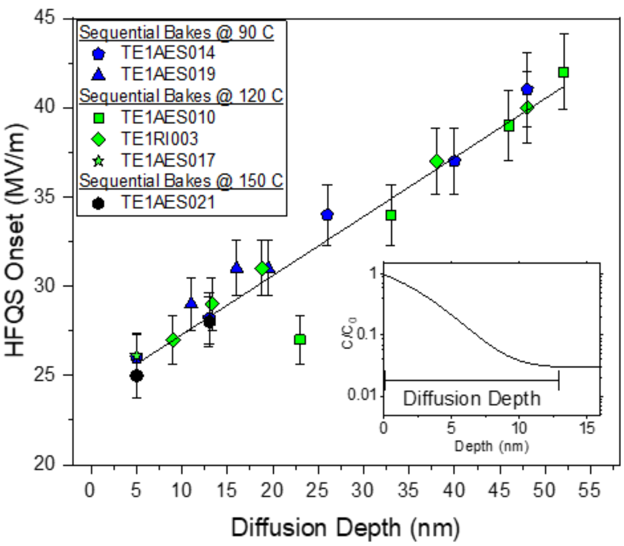

Figure 3: High field Q-slope onset plotted against the calculated diffusion depth. Inset defines the so-called diffusion depth (see text for more details).

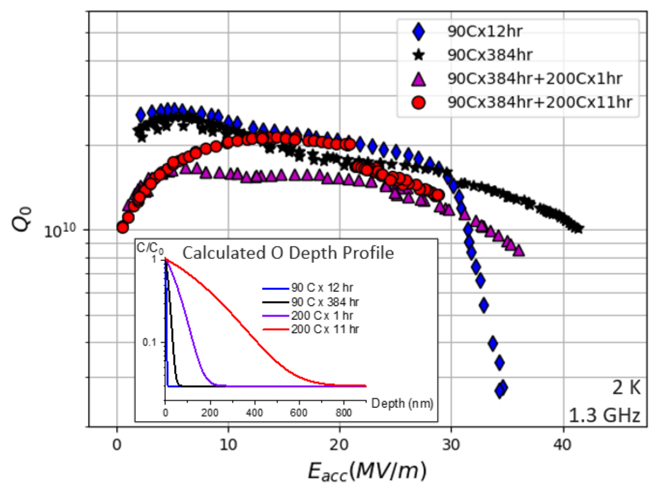

Figure 4: Q_0 vs E_{acc} of cavity TE1AES019 after sequential rounds of *in situ* vacuum baking at either 90 C or 200 C. Inset shows oxygen depth profile for each studied surface treatment.

Fick's diffusion model. Using this model with a built-in bulk concentration term to fit the TOF-SIMS data in those works, we calculated the O concentration depth profile and plotted the depth at which it achieved the bulk value (see insets in Fig. 2 and Fig. 3) against the field of HFQS onset at $T < 1.5$ K for each studied RF test. The results are shown in Fig. 3.

We find that the field of HFQS onset varies linearly with the depth to which oxygen diffuses for all studied temperatures. This supports the role of oxygen in the mitigation of HFQS in the 120 C baking effect as presented by Romanenko *et al.* and suggests that as oxygen diffuses deeper, it captures free hydrogen and inhibits the formation of proximity coupled nano-hydrides within the RF layer.

Role of Diffused Oxygen in Tuning Cavity Quench Field We next investigated the role of thermally diffused oxygen in tuning cavity performance. Here, we focus particularly on the evolution of quench field but a more in-depth analysis of cavity performance evolution may be found in [7]. Fig. 4 presents RF data acquired on cavity TE1AES019 after sequential rounds of *in situ* vacuum baking at temperatures of 90 C and 200 C. We note that the cavity maintained vacuum throughout the entire study. The test post baking at 90 C for 12 hours showed HFQS onset at 29 MV/m; the cavity quenched at 36.2 MV/m at low temperature (not pictured). The cavity then underwent a very long bake at 90 C for an integrated duration of 384 hours which showed no HFQS up to quench at 43 MV/m. We then baked the cavity further at 200 C for 1 hour. The RF results in Fig. 4 showed that the quench field reduced to 38 MV/m. Furthermore, the Q_0 at all fields decreased and the curve shape showed a slight rounding at mid-field. For the final treatment, the cavity underwent another *in situ* bake at 200 C for an additional 10 hrs. The resulting performance shows an improvement in Q_0 and the anti Q-slope behavior that is characteristic of N-doped cavities [1]. We note again that oxygen is the primary diffusant of interest in these studies. This further reinforces the theory that diffused oxygen indeed performs a similar role as nitrogen in the performance of Nb SRF cavities.

Fig. 5 plots the highest measured quench field for every RF test against the calculated diffusion depth. Data from Posen *et al.* is also shown [11]. The quench field follows a non-monotonic relationship with the calculated diffusion depth, showing a peak near 60 nm. The initial increase in quench may be understood by assuming the hydride model: fewer hydrides in the RF layer results in less RF heating that might otherwise drive thermo-magnetic quench.

While Fig. 5 suggests that bulk niobium SRF cavities are capable of achieving a peak quench field of 45 MV/m, we argue that this limitation is due to a non-ideal impurity profile. The treatments studied in this work all consist of single temperature diffusion steps. We will show in the following section that considerably higher quench fields are achievable by utilizing more complicated, 2-step baking treatments and chemical treatments.

RECENT SRF R&D INNOVATIONS TO INCREASE CAVITY PERFORMANCE

In addition to the above discussed fundamental material insights, Fermilab has also recently established two technologies that further push the performance of production level cavities: i) 2-step baking + cold EP and ii) plasma processing.

2-Step Baking + Cold EP

The 2-step baking surface treatment is a slight variation of the standard 120 C *in situ* LTB treatment that enables

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31st Int. Linear Accel. Conf. LINAC2022, Liverpool, UK JACoW Publishing
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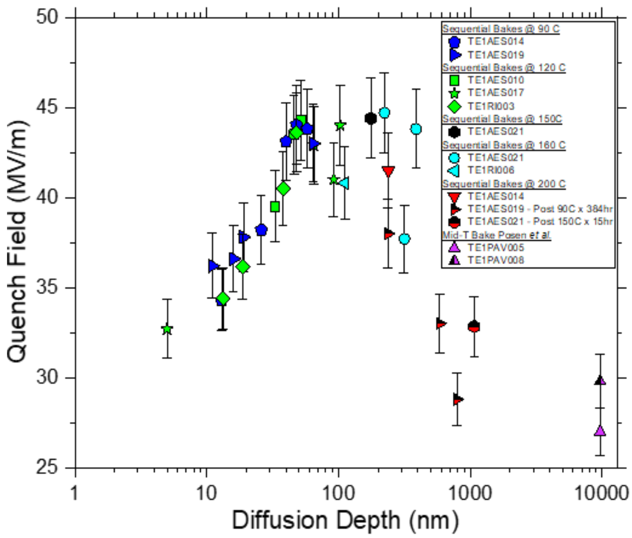

Figure 5: Highest achieved quench field for each RF test in the present study plotted against the diffusion depth. Data from Posen *et al.* comes from [11].

unprecedented accelerating gradients of over 50 MV/m in TESLA-shaped Nb SRF cavities and routinely yields cavities with gradients above 45 MV/m [12]. First, a cavity is electropolished at a low temperature. After the cavity is fully assembled for testing and evacuated, it is placed in a low temperature oven and baked first at 75 C for 4 hours before the temperature is ramped up to 120 C and baked for another 48 hrs [13].

Fig. 6 depicts a Fermilab cavity treated with the 2-step baking + cold EP surface treatment at Fermilab. The cavity exhibited a quench field of 50 MV/m, a world record for this cavity shape. The cavity was then sent as-is and under vacuum to different laboratories around the world, including JLab in Newport News, USA, DESY in Harmburg, Germany, and KEK in Tsukuba, Japan. The inter-lab measurements confirm the ultra-high gradients. Moreover, these measurements confirm the bifurfaction phenomenon characteristic of this treatment. For more on this study, please see [12, 14, 15].

As part of the ILC-cost reduction effort, Fermilab treated 8 nine-cells with the 2-step baking + cold EP surface treatment to be used in a high gradient demonstration ILC-style cryomodule (CM). First results, to be reported elsewhere, demonstrate excellent quench fields, and show that high gradients are obtainable in production level cavities.

Plasma Processing

Fermilab has recently validated the plasma processing procedure for the *in situ* mitigation of hydrocarbon-related field emission in 1.3 GHz cryomodules. The effort began with the R&D phase based on individual nitrogen doped 9-cell cavities, which successfully demonstrated the *in situ* removal of hydro-carbons while preserving RF performance [16]. The technique was then scaled up to be used on a full-scale cryomodule. The candidate CM was the verification CM for LCLS-II HE, which exhibits record-breaking performance and no field emission [17]. After *in situ* plasma processing four out of the eight cavities, the cryomodule remained field emission free and maintained performance. Moreover, those cavities which were plasma processed no longer exhibited multipacting induced quenches while those untreated were still affected by it [18]. As a result, the plasma processing technique is fully validated for 1.3 GHz CMs and can be used *in situ* to address multi-pacting and field emission.

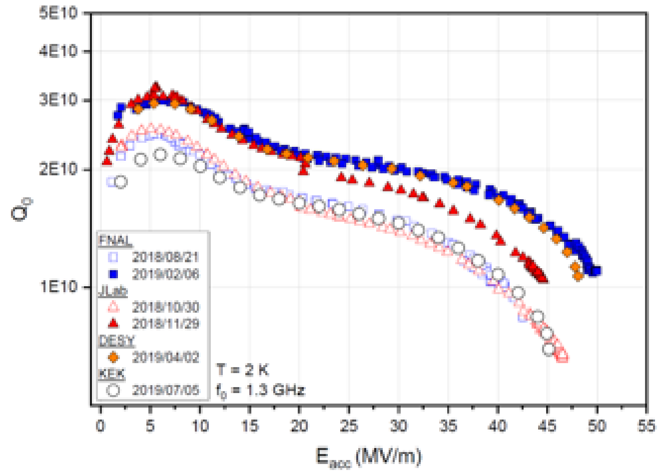

Figure 6: Q_0 vs E_{acc} of FNAL cavity TE1AES022 subjected to the 2-step bake and cold EP surface treatment at FNAL and tested at different labs across the world.

FERMILAB BOOSTER REPLACEMENT LINAC

One potential application of the above discussed SRF technologies may be in the Fermilab booster replacement linac aimed at delivering 2.4 MW of proton power on target for the Long Baseline Neutrino Facility (LBNF)/Deep Underground Neutrino Experiment (DUNE) [19]. LBNF/DUNE is Fermilab's flagship project which shoots neutrinos from the Fermilab Batavia site to Sanford, South Dakota to enable several key measurements. To obtain unambiguous, high precision measurements, the number of neutrinos delivered to the detector in South Dakota must be dramatically increased. To accomplish this, the proton power on target must be doubled from 1.2 MW to 2.4 MW. This requires proton injection into the recycler/main injector at 8 GeV. Once the proton improvement plan II (PIP-II) accelerator comes online, the current booster at Fermilab will serve as a bottleneck for this upgrade and will require replacing.

One candidate for the booster replacement is a linac based on well established SRF technology [19]. The bulk of the linac will consist of LCLS-II style cryomodules housing eight nine-cell 1.3 GHz cavities at 2 K operating in pulsed mode. The current estimate for cavity performance specifications requires Q_0 = 1E10 at gradients of 31.5 MV/m for the baseline design and a stretch goal of Q_0 = 2E10 and E_{acc} = 33.7 MV/m.

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From Fig. 6, we see that the baseline cavity specifications are far exceeded with the 2-step baking + cold EP surface treatment. The stretch goal specifications are nearly within reach, and current efforts to further improve these metrics are ongoing. Moreover, plasma processing might serve as a key technology in the *in situ* mitigation of field emission and/or multipacting, which would be critical in the preservation of linac performance.

CONCLUSIONS

In conclusion, we have discussed Fermilab's recent advancements in bulk Nb SRF cavity technology. By coupling material science observations with RF cavity measurements, we delineated the role of oxygen in cavity performance. We reported a direct correlation between the field of high field Q-slope onset and the depth to which oxygen diffuses, solidifying the role of diffused oxygen in the minimization of niobium nano-hydride precipitation. We showed that cavity performance may be tuned *via* simple thermal diffusion, enabling either high gradients or high quality factors. Moreover, we showed that the 2-step baking + cold EP surface treatment is capable of yielding record quench fields in TESLA-shaped 1.3 GHz single-cell cavities. Plasma processing was also discussed and shown to be fully validated for 1.3 GHz cryomodules. Lastly, we briefly discussed the application of these technologies to the potential booster replacement linac at Fermilab.

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