ANALYSIS OF LOW RRR SRF CAVITIES[*]

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Abstract

Recent findings in the superconducting radio-frequency (SRF) community have shown that introducing certain impurities into high-purity niobium can improve quality factors and accelerating gradients. Success has been found in nitrogen-doping, diffusion of the native oxide into the niobium surface, and thin films of alternate superconductors atop a niobium bulk cavity. We question why some impurities improve RF performance while others hinder it. The purpose of this study is to characterize the impurity profile of niobium with a low residual resistance ratio (RRR) and correlate these impurities with the RF performance of low RRR cavities so that the mechanism of recent impurity-based improvements can be better understood and improved upon. Additionally, we perform a low temperature bake on the low RRR cavity to evaluate how the intentional addition of oxygen to the RF layer affects performance. We have found that low RRR cavities experience low temperature-dependent BCS resistance behavior more prominently than their high RRR counterparts. The results of this study have the potential to unlock a new understanding on SRF materials.

INTRODUCTION

As we approach the theoretical limit of niobium for superconducting radio-frequency (SRF) cavities, the last decade has brought immense improvements in quality factor (Q_0) and accelerating gradients though intentionally added impurities into the niobium surface [1,2]. Many SRF studies follow a “clean bulk dirty surface” technique to optimize the BCS resistance by adding extrinsic impurities to the surface layer of high purity niobium [3,4]. Advancements have been made with nitrogen through N-doping, where cavities experience an anti Q_0 slope and record breaking Q_0’s at mid fields [5–7]. Oxygen added through a low temperature bake (LTB) has also provided high Q_0’s and mitigation of the high field Q_0 slope typically seen in electropolished (EP) niobium cavities [8,9].

The success of intentionally added impurities to the niobium surface has drawn deeper questions about how these impurities affect cavity behavior, and has prompted an investigation of cavities with a low residual resistance ratio (RRR). Low purity niobium has been studied before in the context of cost reduction [10]; here we are looking through the lens of using the intrinsic impurities as a resource to optimize the BCS resistance. RRR and mean free path (mfp) have a direct relationship, so we might expect experience low BCS resistance behavior at low RRR, as seen in Fig. 1. We ask if the intrinsic impurities perform similar functions as extrinsic impurities which have been shown to improve performance.

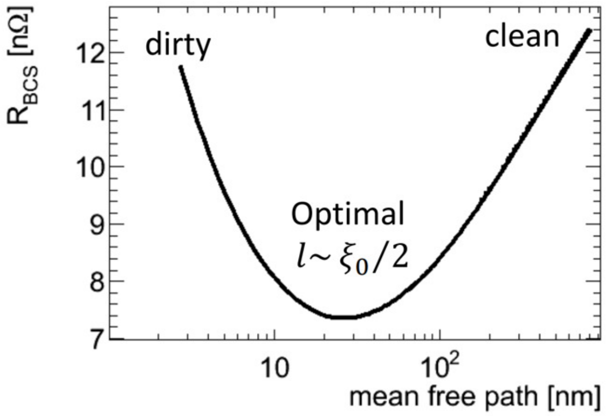

Figure 1: BCS resistance versus mean free path shows an optimization in BCS resistance for moderately dirty surface, adapted from [11].

In this study, we investigate a single-cell TESLA-shaped 1.3 GHz cavity with RRR 61 and primary impurity tantalum at weight percent 0.0193. First, the cavity receives EP treatment to give a uniform surface layer same as the bulk [12]. The testing involves a measurement of Q_0 versus accelerating gradient in the vertical test stand [2], as well as frequency versus temperature [13]. We compare the performance of this cavity with its high RRR counterpart in EP condition to understand how the intrinsic impurities affect the bulk and surface behavior of the cavity. Then, we perform a LTB at 120 °C for 48 hours and repeat the testing to evaluate how the addition of the surface oxide to the RF layer further affects performance.

RESULTS

Quality Factor

We measure the Q_0 at a given gradient by maintaining the cavity at its resonant frequency, pumping power in, and then measuring the reflected and transmitted power [14]. The Q_0 is defined as the ratio of the energy gain per RF period and dissipated power.

The Q_0 at 2 K is graphed in Fig. 2. The transition from EP to LTB condition in the low RRR cavity shows a slight increase in Q_0 at low gradients, as well as improved performance through higher gradients. All cavities’ performance is similar at mid gradients. Oxygen improves performance of low RRR cavity but in a different way than we see in high RRR cavities, as the LTB treatment delays Q_0 slope in low

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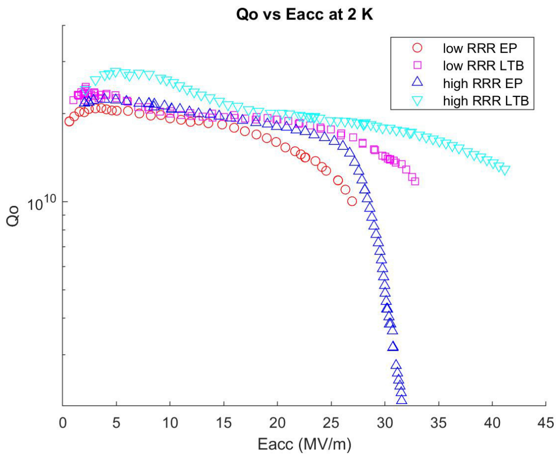

Figure 2: Quality factor at 2 K versus accelerating gradient for EP and LTB on low RRR, comparing to their high RRR counterparts.

RRR with a less extreme difference than for high RRR. The low RRR cavity did not show a strong high field Q_0 slope in EP condition, so the transition to LTB was not as drastic. In the LTB test, the low RRR cavity does not experience the bump of anti Q_0 slope at low gradient shown on the high RRR. We are also unable to reach as high gradient in the low RRR test in both EP and LTB, which is likely due to its higher concentration of intrinsic impurities.

Surface Resistance

We define the surface resistance as the geometry factor of the cavity divided by the Q_0. The surface resistance can be broken down into the residual resistance and BCS resistance by separating the 2 K and low T tests. The residual resistance (R_r) is not temperature-dependent and taken at low T, coming from impurities in the superconducting lattice as well as any trapped flux from cooldown or quench. The BCS resistance (R_{BCS}) is temperature-dependent and calculated by the difference between the total surface resistance at 2 K and low T, caused by the breakdown of cooper pairs with increasing temperature.

In Fig. 3, there is a significant offset in R_r between low and high RRR, especially at mid gradient. The low RRR EP and LTB curves are nearly colinear until around 20 MV/m. It is reassuring that the addition of oxygen to the RF layer did not further increase the resistive effect of the intrinsic impurities in the material. This split is analogous to the high RRR EP and LTB that occurs around 25 MV/m at a lower resistance. It is of interest how the low and high RRR LTB curves are nearly parallel at mid and high gradient. This clarifies the effect of a uniform distribution of impurities in the bulk.

In Fig. 4, we note the low BCS resistance behavior of the low RRR cavity. At all points, the low RRR R_{BCS} is equal to or below that of its high RRR counterpart. The benefit of the low RRR is most prominent at mid gradients and is completely lost at high gradients. The LTB high and low RRR are colinear until 10 MV/m, but then show a similar behavior of the local maximum and then decrease. It is promising that the LTB lowered the BCS resistance at all gradients from the EP test, so making the surface even dirtier allowed for lower BCS resistance even with a less clean bulk. It is not clear yet if we have reached the optimized surface dirtiness or if we could go even further.

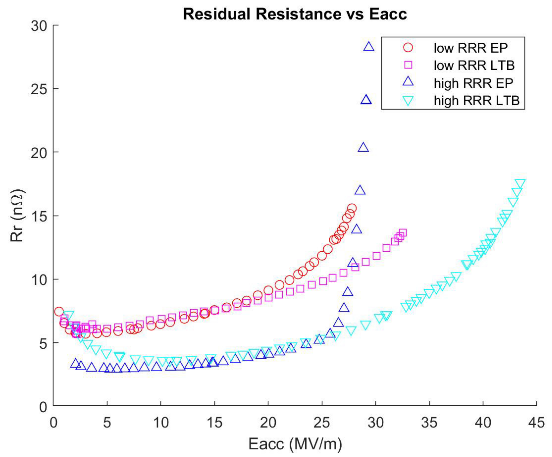

Figure 3: Residual resistance (at low T) versus accelerating gradient for low RRR, comparing to high RRR.

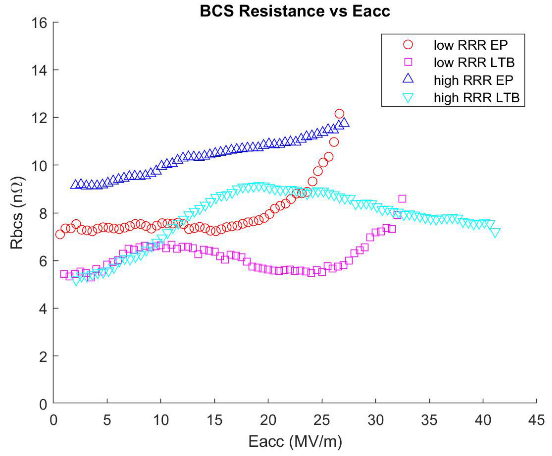

Figure 4: BCS resistance versus accelerating gradient for low RRR, comparing to high RRR.

Frequency versus Temperature

Frequency versus temperature measurements are taken while warming up the cavity, as the resonance frequency drops at transition and stabilizes when the cavity is normal-conducting [15]. By adjusting the temperature, the change in resonant frequency we observe reflects a change in the penetration depth ($\Delta\lambda$) of the material [13].

In Fig. 5 we see the frequency changes around 7.5 kHz through the superconducting transition, which corresponds to a 300 nm change in penetration depth. Zooming in, Fig. 6 shows how the LTB cavity's resonant frequency changes around 300 Hz more than the EP, and the EP experiences

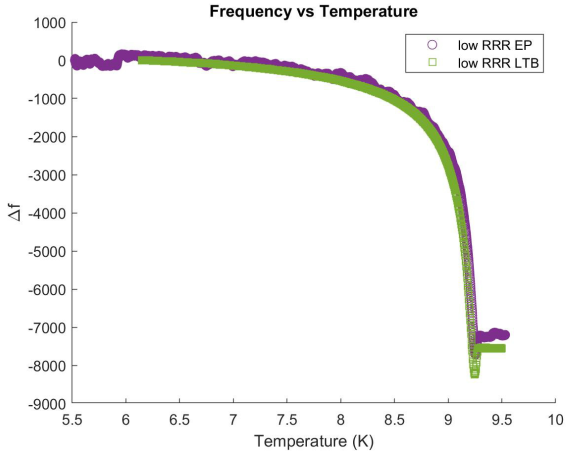

Figure 5: Frequency versus temperature for low RRR EP and LTB.

another oscillation before settling at a constant frequency post transition temperature (Tc). The existence of the dip in the EP curve suggests the doped-like behavior of the low RRR cavity [16]. The experimental Tc is the point right after the dip, which is around 9.29 K for both EP and LTB. We can estimate the mean free path through the SRIMP program, which calculates a fit through BCS theory [3,17]. The program does not have the capability to handle the dip, so we define the fit Tc as the the point with the same frequency across the dip from the experimental Tc, which is 9.236 K for EP and 9.222 K for LTB [13].

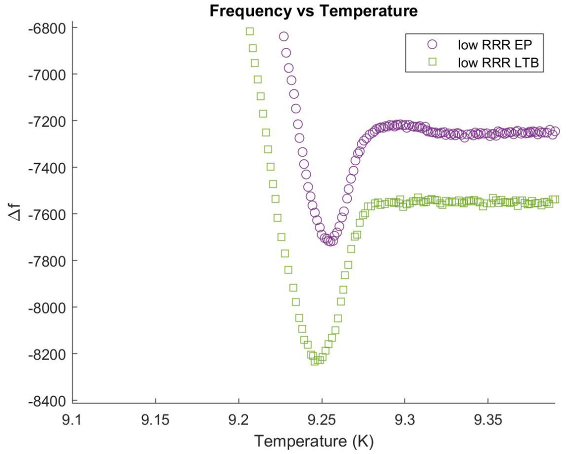

Figure 6: Zoom in of dip on frequency versus temperature for low RRR EP and LTB.

The EP data should be straightforward, as it has a uniform density of impurities. However, fitting its $\Delta\lambda$ versus temperature has proven more difficult than expected because of the shakiness of the curve at lower temperatures, and the shape of the dip with the bump made it difficult to choose a Tc to use for the fit. We obtained a best fit by restricting the Tc to 9.234 K and the temperature range from 8 K to 9.2 K. This fit found mfp 522 nm with uncertainty 29 nm and gap 2.17 with uncertainty .03. This mfp suggests we have not reached the minimum of R_{BCS} with the EP treatment, which is in agreement with the RF performance shown in Fig. 4.

For the LTB, the oxygen only diffuses around 60 nm into the bulk, so it does not make sense to fit the entire 300 nm of the $\Delta\lambda$. Having the mean free path changing due to the oxygen concentration gradient creates a difficult fit. In this range, the oxygen concentration ranges from its maximum value at the surface to nearly none as we approach the bulk,so we expect the mfp and gap values predicted to be somewhere in between the true surface and bulk values. The fit found mfp 64.7 nm with an uncertainty 6.9 nm and the gap 2.32 with uncertainty .04. The decrease in mfp from the LTB is in agreement with the decrease seen in the R_{BCS}. The increase in gap is analogous to the behavior of doped cavities [16].

CONCLUSION

Low RRR cavity behaves quite differently than typical high RRR cavities. This difference is most notable in the EP testing, as the intrinsic impurities protect the cavity from a high field Q_0 slope and significantly improve the BCS resistance. There is more similarity in the performance of the LTB cavities in terms of the offset of the residual resistance and the shape of the BCS resistance curves. It is an important finding that adding oxygen to the surface of a cavity with a high concentration of intrinsic impurities will improve performance.

The frequency versus temperature dips and fitted mfp and gap highlight the doped behavior of the low RRR cavity. Finding the mean free path of the cavities is a difficult measurement, especially in a cavity with a vastly varying concentration of impurities from LTB. Because our interest lies in optimizing the BCS resistance through the mfp, it will be important to continue working with the SRIMP program and also explore other methods of calculating the mfp. It appears that the low temperature bake brought the low RRR cavity closer to this optimization, but we believe there is more that can be done to explore the low BCS behavior of low RRR material.

REFERENCES

[1] S. Belomestnykh, S. Posen, D. Bafia, S. Balachandran, M. Bertucci, A. Burrill, A. Cano, M. Checchin, G. Ciovati and L. D. Cooley, *et al.*, “Key directions for research and development of superconducting radio frequency cavities”, Submitted to *Proceedings of the US Community Study on the Future of Particle Physics (Snowmass 2021)*, 2022. `arXiv:2204.01178[physics.acc-ph]`

[2] M. Checchin, “Physics of Limiting Phenomena in Superconducting Microwave Resonators: Vortex Dissipation, Ultimate Quench and Quality Factor Degradation Mechanisms”, Ph.D. thesis, Phys. Dept., Illinois Institute of Technology, 2016.

[3] J. Bardeen, L. N. Cooper, and J. R. Schrieffer, *Phys. Rev.* **108**, 1175, 1957.

[4] T. Kubo, “Effects of Nonmagnetic Impurities and Subgap States on the Kinetic Inductance, Complex Conductivity, Quality Factor, and Depairing Current Density”, *Phys.*

Rev. Applied, vol. 17, 014018, Jan. 2022. `doi:10.1103/PhysRevApplied.17.014018`

[5] A Grassellino *et al.*, “Nitrogen and argon doping of niobium for superconducting radio frequency cavities: a pathway to highly efficient accelerating structures”, *Supercond. Sci. Technol.* **26**, 102001, 2013. `doi:10.1088/0953-2048/26/10/102001`

[6] D. Gonnella *et al.*, “Industrialization of the nitrogen-doping preparation for SRF cavities for LCLS-II”,*Nucl. Instrum. Methods Phys. Res. A*, **882**, pp. 143–150, 2018. `doi:10.1016/j.nima.2017.11.047`

[7] P. Dhakal, “Nitrogen doping and infusion in SRF cavities: A review”, *Physics Open*, **5**, 100034, 2020. `doi:10.1016/j.physo.2020.100034`

[8] D. Bafia, A. Grassellino, O. Melnychuk, A. Romanenko, Z. H. Sung, and J. Zasadzinski, “Gradients of 50 MV/m in TESLA Shaped Cavities via Modified Low Temperature Bake”, in *Proc. SRF’19*, Dresden, Germany, Jun.-Jul. 2019, pp. 488–493. `doi:10.18429/JACoW-SRF2019-TUP061`

[9] D. Bafia, A. Grassellino, and A. S. Romanenko, “The Role of Oxygen Concentration in Enabling High Gradients in Niobium SRF Cavities”, in *Proc. SRF’21*, East Lansing, MI, USA, Jun.-Jul. 2021, pp. 871–875. `doi:10.18429/JACoW-SRF2021-THPTEV016`

[10] G. Ciovati, P. Dhakal, and G. R Myneni, “Superconducting radio-frequency cavities made from medium and low-purity niobium ingots”, *Supercond. Sci. Technol.*, **29**, 064002, 2016. `doi:10.1088/0953-2048/29/6/064002`

[11] A. Miyazaki, "Basics of RF superconductivity and Nb material", SRF2021 Tutorial, East Lansing, Michigan, Jun. 23-25, 2021. `https://indico.frib.msu.edu/event/38/attachments/159/1139/SRF2021_lecture_miyazaki_ver4.pdf`

[12] F. Furuta, D. J. Bice, A. C. Crawford, and T. J. Ring, “Fermilab EP Facility Improvement”, in *Proc. SRF’19*, Dresden, Germany, Jun.-Jul. 2019, pp. 453–455. `doi:10.18429/JACoW-SRF2019-TUP022`

[13] D. Bafia, "Exploring and Understanding the Limitations of Nb SRF Cavity Performance", Ph.D. thesis, Phys. Dept., Illinois Institute of Technology, 2020.

[14] H. Padamsee, J. Knobloch, and T. Hays, *RF Superconductivity for Accelerators*, Second Edition, Wiley-VCH Verlag GmbH and Co., KGaA, Weinheim, 2008.

[15] M. Martinello *et al.*, “Effect of interstitial impurities on the field dependent microwave surface resistance of niobium”, *Appl. Phys. Lett.* **109**, 062601, 2016. `doi:10.1063/1.4960801`

[16] D. Bafia, M. Checchin, A. Grassellino, A.S. Romanenko, and J. Zasadzinski, “Investigating the Anomalous Frequency Variations Near Tc of Nb SRF Cavities”, in *Proc. SRF’21*, East Lansing, MI, USA, Jun.-Jul. 2021, pp. 885–892. `doi:10.18429/JACoW-SRF2021-FROFDV03`

[17] J. Halbritter, “Fortran Program for the Computation of the Surface Impedance of Superconductors”, Internal Notes, *KFZ Karlsruhe* **3/70 – 6**, 1970. `doi:10.5445/IR/270004230`