5th North American Particle Accel. Conf. NAPAC2022, Albuquerque, NM, USA JACoW Publishing
ISBN: 978-3-95450-232-5 ISSN: 2673-7000 doi:10.18429/JACoW-NAPAC2022-THYE5

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 performed surface treatments, low temperature baking and nitrogen-doping, on low RRR cavities to evaluate how the intentional addition of more impurities 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 [3–5]. 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 [6–8]. 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 [9, 10]. The performance of these surface treatments is shown in Fig. 1.

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 in the past for the purpose of cost reduction and possible high Q_0 [11]. In this study, we look to use the intrinsic impurities as a resource

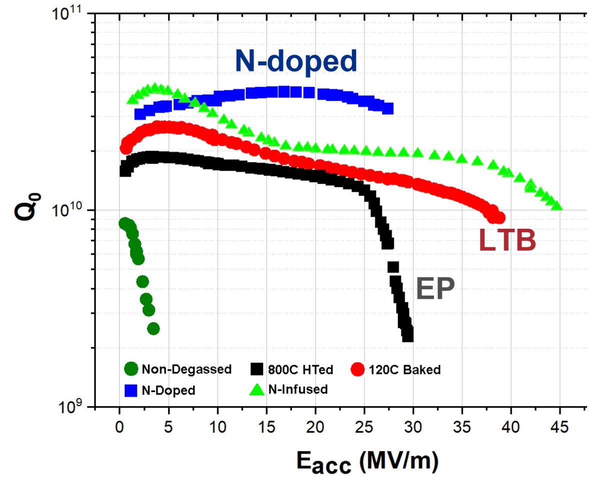

Figure 1: Comparison of quality factor versus gradient for surface treatments, adapted from [6].

to optimize the BCS resistance and understand the mechanism of impurity-based improvements. 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. 2. We ask if the intrinsic impurities can improve performance, as we observe in extrinsic impurities.

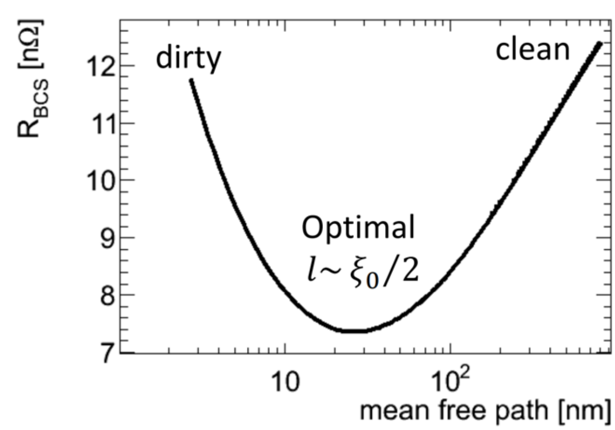

Figure 2: BCS resistance versus mean free path shows an optimization in BCS resistance for moderately dirty surface, adapted from [12].

In this study, we investigate a single-cell TESLA-shaped 1.3-GHz cavity with RRR 61. First, the cavity receives EP treatment to make the surface layer and bulk uniform [13]. The measurements in the vertical test stand include Q_0 versus accelerating gradient at 2 K and low temperature (< 1.5 K) [2]. We define the surface resistance as the geome-

* This manuscript has been authored by Fermi Research Alliance, LLC under Contract No. DE-AC02-07CH11359 with the U.S. Department of Energy, Office of Science, Office of High Energy Physics. This work was supported by the University of Chicago.
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ISBN: 978-3-95450-232-5 ISSN: 2673-7000 doi:10.18429/JACoW-NAPAC2022-THYE5

try factor of the cavity divided by the Q_0; this can be broken down into the residual resistance and BCS resistance. 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. Since the last report [14], we additionally investigate the effect of adding nitrogen to the dirty bulk by performing N-doping with the standard 2/6 + 5-μm recipe [15].

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 [16]. The Q_0 is defined as the ratio of the energy gain per RF period and dissipated power. The measurements of Q_0 at 2 K are graphed in Fig. 3.

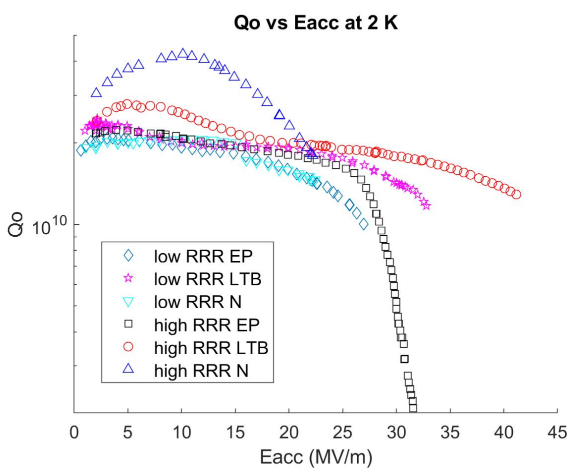

Figure 3: Quality factor at 2 K versus accelerating gradient for EP, LTB, and N-doping on low and high RRR.

The low RRR cavity after the LTB shows a slight increase in Q_0 at low gradients, as well as improved performance through higher gradients, compared to the EP test. The performance after EP and LTB treatments for high and low RRR 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 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 significant anti-Q_0 slope at low gradient seen 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.

The performance after N-doping is quite similar to EP at low and high gradients. The cavity experienced multipacting quenches above 16 MV/m, which trapped magnetic flux and worsened the performance up to its ultimate quench at 22 MV/m. The quality factor of the N-doped low RRR cavity is significantly lower than that of the high RRR, but they reach similar maximum gradients. We observe a slight anti-Q_0 slope on the low RRR, but much less extreme than the high RRR. N-doping the cavity with the 2/6 + 5-μm recipe did not improve the Q_0 of the low RRR cavity, which is not a traditional behavior of high RRR N-doped cavities.

Residual Resistance

The residual resistance (R_r) taken at low T is not temperature-dependent, coming from impurities in the superconducting lattice as well as any trapped flux from cooldown or quench. The R_r measurements are shown in Fig. 4. We observe a significant offset in R_r between low and high RRR for all surface treatments, especially at mid gradient.

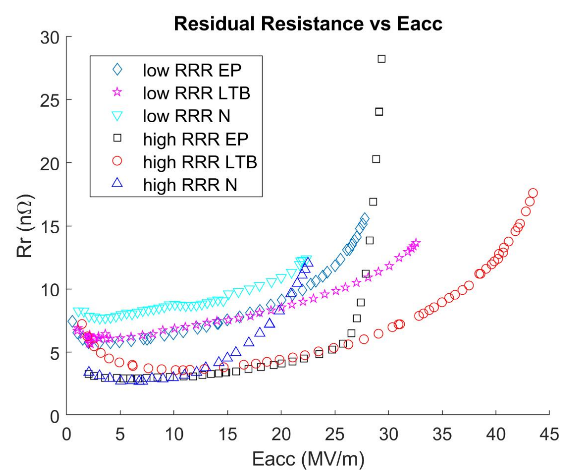

Figure 4: Residual resistance (at low T) versus accelerating gradient for low and high RRR.

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 that of the high RRR EP and LTB which occurs around 25 MV/m at a lower resistance. The offset of the low and high RRR LTB curves clarifies the effect of a uniform distribution of impurities in the bulk.

The low RRR N-doped curve is slightly higher than the corresponding EP and LTB curves. It is also larger than the high RRR N-doped curve, except at high gradient. Because N-doping introduces impurities further into the bulk than LTB, it is possible this caused the increase in R_r. Another possible cause is the flux trapped through the multipacting quenches during the 2 K test.

BCS Resistance

The BCS resistance (R_{BCS}) is calculated by taking the difference between the total surface resistance at 2 K and low T. This temperature-dependent component of the resistance is

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caused by the breakdown of cooper pairs with increasing temperature [3, 15]. In Fig. 5, we draw attention to the low BCS resistance behavior of the low RRR cavity.

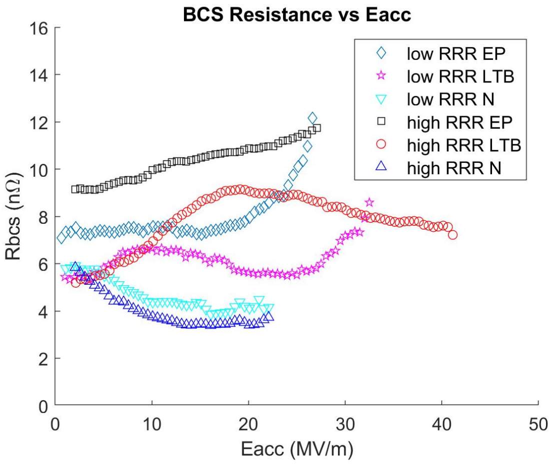

Figure 5: BCS resistance versus accelerating gradient for low and high RRR.

At all points of the EP and LTB tests, the low RRR R_{BCS} is equal to or below that of its high RRR counterpart. The benefit of the low RRR with these treatments is most prominent at mid gradients and is completely lost at high gradients. The LTB high and low RRR are equal 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.

The N-doped test of the low RRR cavity showed slightly higher R_{BCS} than that of the high RRR, but significantly reduced from the EP and LTB tests. The decrease of R_{BCS} with field emphasizes the anti-Q_0 slope of the N-doped low RRR, which is difficult to discern from the Q_0 curve alone. N-doping showed additional improvement of the R_{BCS} from the EP and LTB tests, but it is surprising that the low RRR is larger than its high RRR counterpart. A possible explanation is that the 2/6 + 5-µm recipe produces an "overdoped" effect on a cavity with more intrinsic impurities, since this recipe was optimized for a high RRR material.

CONCLUSION

The low RRR cavity behaves quite differently than high RRR cavities, with lower BCS resistance, larger residual resistance, lower quality factor, and lower accelerating gradient in general. The intrinsic impurities affect the performance of the cavity for all surface treatments examined.

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 result that adding oxygen to the surface of a cavity with a high concentration of intrinsic impurities will improve performance. It appears that the low temperature bake brought the low RRR cavity closer to the optimization of the BCS resistance. The N-doping test showed increased residual resistance from the other low RRR tests, but also showed a further decrease in the BCS resistance. The introduction of nitrogen to the surface layer produced mixed results and requires further optimization.

The next step is to re-test the N-doped cavity after high-pressure rinsing to avoid the multipacting behavior and reduce the effects of trapped flux. Afterward, the optimization of N-doping for the low RRR material will be studied through small EP removals of the surface layer. By understanding how oxygen and nitrogen interact with the intrinsic impurities, we can gain insight how to develop a new surface treatment involving these impurities.

REFERENCES

[1] S. Belomestnykh *et al.*, "Key directions for research and development of superconducting radio frequency cavities", in *Proc. of Snowmass 2021*, Snowmass, CO, USA, 2022. doi:10.48550/arXiv.2204.01178

[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, "Theory of Superconductivity", *Phys. Rev.*, vol. 108, p. 1175, 1957. doi:10.1103/PhysRev.108.1175

[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, p. 014018, Jan. 2022. doi:10.1103/PhysRevApplied.17.014018

[5] V. Ngampruetikorn and J. A. Sauls, "Effect of inhomogeneous surface disorder on the superheating field of superconducting RF cavities", *Phys. Rev. Res.*, vol. 1, p. 012015, 2019. doi:10.1103/PhysRevResearch.1.012015

[6] 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.* vol. 26, p. 102001, 2013. doi:10.1088/0953-2048/26/10/102001

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

[8] P. Dhakal, "Nitrogen doping and infusion in SRF cavities: A review", *Physics Open*, vol. 5, p. 100034, 2020. doi:10.1016/j.physo.2020.100034

[9] 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. 2019, pp. 488–493. doi:10.18429/JACoW-SRF2019-TUP061

ISBN: 978-3-95450-232-5 ISSN: 2673-7000 doi:10.18429/JACoW-NAPAC2022-THYE5

[10] 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. 2021, pp. 871–875. doi:10.18429/JACoW-SRF2021-THPTEV016

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

[12] 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

[13] F. Furuta, D. J. Bice, A. C. Crawford, and T. J. Ring, "Fer-milab EP Facility Improvement", in *Proc. SRF'19*, Dresden, Germany, Jun. 2019, pp. 453–455. doi:10.18429/JACoW-SRF2019-TUP022

[14] K. Howard, D. Bafia, A. Grassellino, and Y.-K. Kim, "Analysis of Low RRR SRF Cavities", in *Proc. IPAC'22*, Bangkok, Thailand, Jun. 2022, pp. 783–786. doi:10.18429/JACoW-IPAC2022-TUOXSP2

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

[16] H. Padamsee, J. Knobloch, and T. Hays, *RF Superconductivity for Accelerators*, Second Edition, Wiley-VCH Verlag GmbH and Co., KGaA, Weinheim, 2008. doi:10.1063/1.882759