ANALYSIS OF MEAN FREE PATH AND FIELD-DEPENDENT SURFACE RESISTANCE*

J. T. Maniscalco†, F. Furuta, D. L. Hall, P. N. Koufalis, M. Liepe
CLASSE, Cornell University, Ithaca, NY, 14853, USA

Abstract

Work from Cornell in 2016 built on recent theoretical research in the field of SRF to link the electron mean free path to the field-dependent BCS surface resistance. This research relates the magnitude of the "anti-Q-slope", the puzzling reduction of surface resistance with increasing RF field intensity observed in certain cavities, to the doping level of nitrogen-doped niobium, quantified by the mean free path: shorter mean free paths correspond directly with stronger anti-Q-slopes. The theoretical connection comes through the overheating of the quasiparticles, which more effectively transfer their energy to the lattice at short mean free paths. In this report, we present an update of this analysis, investigating recent test results of low-temperature-doped single-cell and nine-cell cavities. We also study the theoretical implications for cavities at frequencies higher and lower than the often-studied 1.3 GHz.

INTRODUCTION

The anti-Q-slope is a phenomenon observed in impurity-doped niobium superconducting radio-frequency (SRF) cavities in which the microwave surface resistance of the cavity decreases as the strength of the field in the cavity increases. The magnitude of the reduction in surface resistance depends strongly on the level of doping, quantified by the electron mean free path in the RF penetration layer. This has mostly been observed and studied in nitrogen-doped niobium since the discovery of the phenomenon in 2013 [1, 2], but recent results suggest that similar results may be obtained in niobium doped at low temperatures (120-160° C, as compared to 800-1000° C typical of nitrogen doping) with carbon and oxygen [3].

Theoretical work in 2014 proposed a mechanism for the anti-Q-slope phenomenon: currents induced in the cavity surface by the RF field significantly modify the electron density of states, "smearing" out the superconducting energy gap peak and thereby reducing the microwave surface resistance [4]. This reduction is counteracted by the overheating of quasiparticles (*i.e.* unpaired, normal-conducting electrons) in the RF surface layer due to inefficient energy transfer from the power dissipated by the field out to the cooling bath outside the cavity wall: the quasiparticles equilibrate at a higher temperature than the bath, which in turn increases the BCS surface resistance.

* This work was supported in part by the U.S. National Science Foundation under Award No. PHY-1549132, the Center for Bright Beams, and under NSF Award No. PHY-1416318. The nine-cell cavity was provided by KEK as a part of US/Japan program for Cooperation in High Energy Physics.

† jtm288@cornell.edu

In our work in 2016, we demonstrated that the theory indeed matches experimental results for nitrogen-doped cavities with mean free paths $\ell < 50$ nm [5]. Moreover, we showed that the magnitude of quasiparticle overheating, which controls the magnitude of the anti-Q-slope and is encapsulated in the normalized overheating parameter α', depends very strongly on ℓ.

In this report, in the section below, we present new findings comparing experimental results of low-temperature doped cavities to theoretical predictions. In addition, in the following section, we consider the implications of the theory and our model of the mean-free-path-dependent quasiparticle overheating for cavities at 650 MHz, 2.6 GHz, and 3.9 GHz.

ANALYSIS OF LOW-TEMPERATURE DOPED CAVITY TEST RESULTS

We analyzed RF test data from two recent cavity tests at Cornell, both cavities prepared with low-temperature doping. The first test was a single-cell TESLA [6] cavity prepared with a 48-hour bake at 160° C in an impure nitrogen atmosphere and a 168-hour (*i.e.* 7-day) anneal in vacuum; the second test was a nine-cell TESLA cavity with the same doping step but with a 48-hour anneal. Both cavities were tested under continuous-wave (CW) RF power in the vertical test dewars at Cornell.

In our analysis, we used BCS fitting of low-field quality factor Q_0 vs. temperature T and frequency f vs. T to extract the critical temperature T_c, energy gap $\Delta/k_B T_c$, and mean free path ℓ; the nine-cell cavity had $\ell \approx 1$ nm and the single-cell cavity had $\ell \approx 7.5$ nm. We then used further BCS fitting of Q_0 vs. peak surface magnetic field B_{pk} at many temperatures to calculate the field-dependent BCS surface resistance R_{BCS} and residual resistance R_0.

Following this extraction of material parameters and surface resistance, we performed theoretical fits to the R_{BCS} vs. B_{pk} data, using the methods described in reference [5], fitting all data at all temperatures at once to a single value of the normalized overheating parameter α' and of the systematic-error-correcting scaling factor s.

Figure 1 shows the results of these fits for the nine-cell cavity, and Fig. 2 shows the results for the single-cell. These results show that the anti-Q-slope exhibited by the low-temperature-doped cavities is compatible with the theory. Further, the very low overheating extracted from these fits is compatible with our model, which correlates short mean free paths with efficient quasiparticle-phonon energy transfer and thus low overheating [5].

ISBN 978-3-95450-182-3

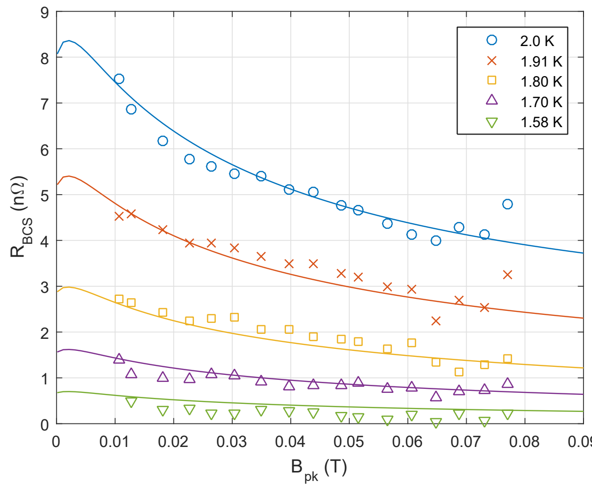

Figure 1: Field-dependent BCS surface resistance R_{BCS} data for the 160° C-doped nine-cell cavity, with theoretical fit results. Theoretical curves correspond to $\alpha' = 0.19$ mK m^2/W.

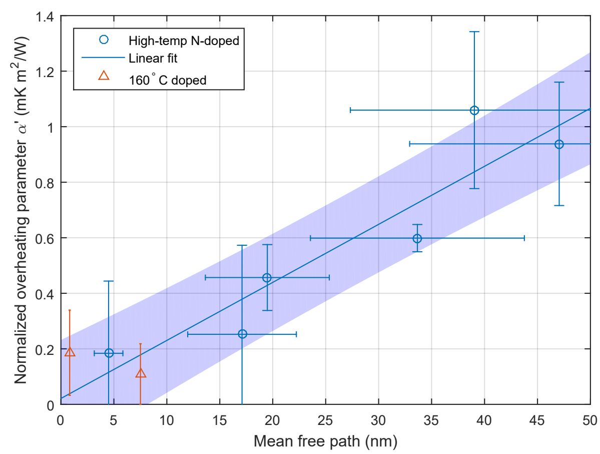

Figure 3: Normalized overheating parameter α' as a function of mean free path ℓ High-temperature nitrogen-doped and fit originally published in reference [5]; new data for cavities doped at 160° C is displayed here over the original plot.

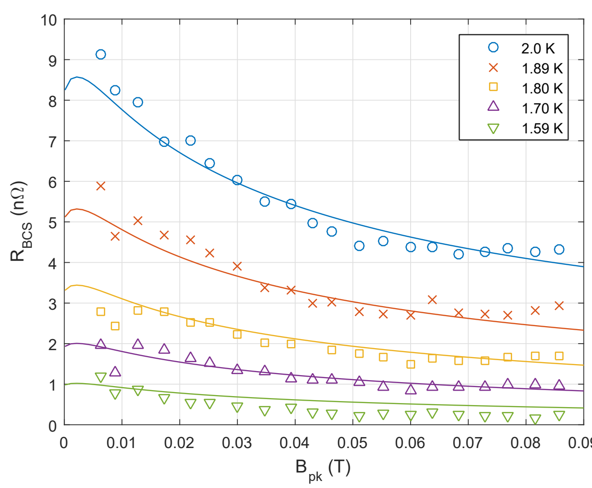

Figure 2: Field-dependent BCS surface resistance R_{BCS} data for the 160° C-doped single-cell cavity, with theoretical fit results. Theoretical curves correspond to $\alpha' = 0.11$ mK m^2/W.

Figure 3 shows the plot of α' vs. ℓ previously published in reference [5], now with the results of these two cavities overlaid on the original data. As the plot shows, these new results are quantitatively consistent with the model, despite the significant differences in doping procedure.

THEORETICAL PREDICTIONS AT ALTERNATIVE FREQUENCIES

As alternative SRF materials beyond the traditional niobium become more viable for use in accelerators, it is a worthwhile exercise to consider frequencies apart from the 1.3 GHz that has dominated the SRF community for the last several years, with recent major projects including LCLS-II [7] and E-XFEL [8] choosing that frequency. Lower frequencies offer a potentially drastic decrease in surface resistance and thus operating costs, and higher frequencies offer both lower construction costs and a better likelihood of producing defect-free surfaces due to the significantly smaller size of the cavities.

Using our model of quasiparticle overheating as a function of electron mean free path, we have calculated predictions of the field-dependent BCS surface resistance for nitrogen-doped niobium cavities at 650 MHz, 1.3 GHz, 2.6 GHz, and 3.9 GHz, with a mean free path of 20 nm. These were calculated with an overheating parameter $\alpha' = 0.4$ mK m^2/W, consistent with $\ell = 20$ nm, at bath temperatures T_0 of 1.6 K and 2.0 K.

Figure 4 below shows the results at 1.6 K, and Fig. 5 shows the results at 2.0 K. In general, these results are promising for frequencies in the UHF band up to the S band, though at higher temperatures the high-frequency cavities become less viable. This largely comes down to the fact that the quasiparticle overheating ΔT goes linearly with the power dissipated by the field and thus linearly with the surface resistance; the BCS resistance itself has a frequency-squared dependence.

At 2.6 GHz and 3.9 GHz, the greatly increased surface resistance serves to magnify the effect of the quasiparticle overheating, to the point where the anti-Q-slope is almost completely eliminated at 2 K and 3.9 GHz. Further, for mean free paths longer than 20 nm, this overheating will increase in magnitude, in principle eliminating the anti-Q-slope in high-frequency cavities.

At 650 MHz, however, this dependence on frequency works out to be an advantage. Because of the drastically lower BCS resistance, the overheating is minimal, especially at 1.6 K. Conversely with the findings for high-frequency cavities, these results imply that low-frequency cavities could be doped to a longer mean free path and still exhibit strong anti-Q-slopes while potentially avoiding the low quench fields that plague strongly doped cavities [9].

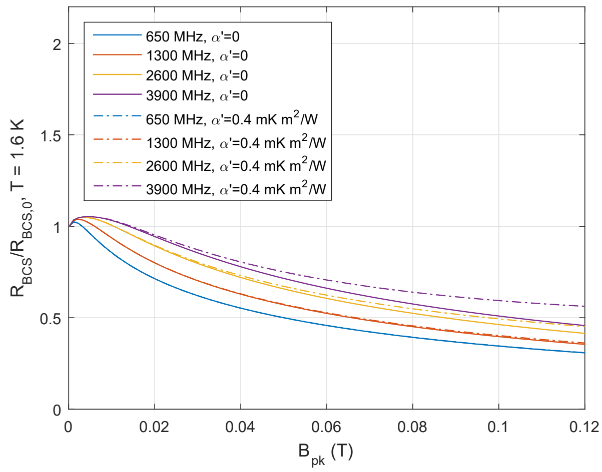

Figure 4: Theoretical predictions of the anti-Q-slope at 650 MHz, 1.3 GHz, 2.6 GHz, and 3.9 GHz, for $\alpha' = 0$ and $\alpha' = 0.4$ mK m^2/W, at 1.6 K.

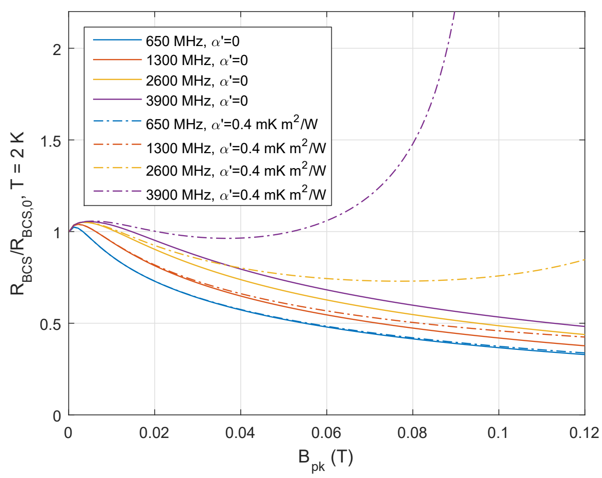

Figure 5: Theoretical predictions of the anti-Q-slope at 650 MHz, 1.3 GHz, 2.6 GHz, and 3.9 GHz, for $\alpha' = 0$ and $\alpha' = 0.4$ mK m^2/W, at 2 K.

In all, these results suggest that a wide range of frequencies may be viable for the anti-Q-slope in impurity-doped niobium cavities.

CONCLUSIONS

We have examined test results of low-temperature-doped niobium SRF cavities and found that their behavior is consistent with recent theoretical descriptions of the anti-Q-slope. We found that the quasiparticle overheating parameter and mean free path of these cavities is consistent with our model developed from results of cavities doped at high temperature. We also calculated theoretical predictions for impurity-doped niobium cavities at alternate frequencies, finding that frequencies from the UHF band up to the S band may be viable for the operation of these cavities. Low frequency cavities may be particularly attractive for doping due to their significantly lower quasiparticle overheating, though high frequencies cavities may be equally attractive due to lower material costs and increased ease of creating clean, defect-free surfaces.

REFERENCES

[1] A. Grassellino, A. Romanenko, D. Sergatskov, O. Melnychuk, Y. Trenikhina, A. Crawford, A. Rowe, M. Wong, T. Khabiboulline, and F. Barkov, "Nitrogen and argon doping of niobium for superconducting radio frequency cavities: a pathway to highly efficient accelerating structures," *Superconductor Science and Technology*, vol. 26, no. 10, p. 102001, 2013. [Online]. Available: http://stacks.iop.org/0953-2048/26/i=10/a=102001

[2] P. Dhakal, G. Ciovati, G. R. Myneni, K. E. Gray, N. Groll, P. Maheshwari, D. M. McRae, R. Pike, T. Proslier, F. Stevie, R. P. Walsh, Q. Yang, and J. Zasadzinzki, "Effect of high temperature heat treatments on the quality factor of a large-grain superconducting radio-frequency niobium cavity," *Phys. Rev. ST Accel. Beams*, vol. 16, p. 042001, Apr 2013. [Online]. Available: http://link.aps.org/doi/10.1103/PhysRevSTAB.16.042001

[3] P. N. Koufalis, D. L. Hall, M. Liepe, and J. T. Maniscalco, "Effects of Interstitial Oxygen and Carbon on Niobium Superconducting Cavities," *arXiv preprint 1612.08291*, 2016.

[4] A. Gurevich, "Reduction of dissipative nonlinear conductivity of superconductors by static and microwave magnetic fields," *Phys. Rev. Lett.*, vol. 113, p. 087001, Aug 2014. [Online]. Available: https://link.aps.org/doi/10.1103/PhysRevLett.113.087001

[5] J. T. Maniscalco, D. Gonnella, and M. Liepe, "The importance of the electron mean free path for superconducting radio-frequency cavities," *Journal of Applied Physics*, vol. 121, no. 4, p. 043910, 2017. [Online]. Available: http://dx.doi.org/10.1063/1.4974909

[6] B. Aune, R. Bandelmann, D. Bloess, B. Bonin, A. Bosotti, M. Champion, C. Crawford, G. Deppe, B. Dwersteg, D. A. Edwards, H. T. Edwards, M. Ferrario, M. Fouaidy, P.-D. Gall, A. Gamp, A. Gössel, J. Graber, D. Hubert, M. Hüning, M. Juillard, T. Junquera, H. Kaiser, G. Kreps, M. Kuchnir, R. Lange, M. Leenen, M. Liepe, L. Lilje, A. Matheisen, W.-D. Möller, A. Mosnier, H. Padamsee, C. Pagani, M. Pekeler, H.-B. Peters, O. Peters, D. Proch, K. Rehlich, D. Reschke, H. Safa, T. Schilcher, P. Schmüser, J. Sekutowicz, S. Simrock, W. Singer, M. Tigner, D. Trines, K. Twarowski, G. Weichert, J. Weisend, J. Wojtkiewicz, S. Wolff, and K. Zapfe, "Superconducting TESLA cavities," *Phys. Rev. ST Accel. Beams*, vol. 3, p. 092001, Sep 2000. [Online]. Available: http://link.aps.org/doi/10.1103/PhysRevSTAB.3.092001

[7] M. Liepe, R. Eichhorn, F. Furuta, G. Ge, D. Gonnella, G. Hoffstaetter, A. Crawford, A. Grassellino, A. Hocker, O. Melnychuk, A. Romanenko, A. Rowe, D. Sergatskov, R. Geng, A. Palczewski, C. Reece, and M. Ross, "The Joint High Q0 R&D Program for LCLS-II," in *Proceedings of IPAC14, Dresden, Germany*, 2014.

[8] *E-XFEL Technical Design Report*. DESY 2006-097, Hamburg, July 2007.

[9] D. Gonnella, R. Eichhorn, F. Furuta, M. Ge, T. Gruber, G. Hoffstaetter, J. Kaufman, P. N. Koufalis, M. Liepe, and J. T. Maniscalco, "Improved N-doping protocols for SRF cavities," in *Proceedings of IPAC2016, Busan, Korea*, 2016.

ISBN 978-3-95450-182-3