9th International Particle Accelerator Conference IPAC2018, Vancouver, BC, Canada JACoW Publishing
ISBN: 978-3-95450-184-7 doi:10.18429/JACoW-IPAC2018-WEPMF046

MODELING OF THE FREQUENCY AND FIELD DEPENDENCE OF THE SURFACE RESISTANCE OF IMPURITY-DOPED NIOBIUM*

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Abstract

The anti-Q-slope, a field-dependent decrease in surface resistance observed in impurity-doped niobium, has been investigated extensively in 1.3 GHz cavities. New early research into this effect has recently been performed at higher and lower frequencies, revealing an additional dependence on frequency: the anti-Q-slope is stronger at higher frequencies and weaker at lower frequencies. Several models have been proposed to explain the anti-Q-slope, with varying success in this new frequency-dependent regime. In this work, we analyze recent experimental data from a low-temperature-doped 1.3 GHz cavity and a high-temperature nitrogen-doped 2.6 GHz cavity and discuss the implications of these results on the proposed models.

INTRODUCTION

Niobium cavities for superconducting radio-frequency (SRF) accelerators have historically exhibited a "Q-slope", *i.e.* a decrease in the intrinsic quality factor Q_0 with increasing surface magnetic field H. This decrease in Q_0 corresponds from a field-dependent increase in the superconducting Bardeen-Cooper-Schrieffer (BCS) surface resistance R_s, which is the chief loss mechanism for SRF accelerating cavities [1, 2].

In the last few years, much effort has gone into the investigation of the "anti-Q-slope", or "Q-rise", a field-dependent *decrease* in the BCS resistance that can result in a quality factor that increases with field strength [3–6]. This effect has mostly been encountered and studied in 1.3 GHz niobium cavities doped with nitrogen at the 1 at.% level or lower in a high-temperature vacuum furnace; the success of the new technology has led to its use in the upcoming LCLS-II accelerator [7].

Unfortunately, the fundamental cause of this anti-Q-slope remains elusive. Several theoretical models and sketches have been proposed to explain the phenomenon as arising from a smearing of the superconducting density of states [8], from the transition to non-equilibrium superconductivity [9], from the proximity effect in a disordered composite of niobium and niobium alloys [10], and other sources. The most striking results fitting theory to experimental data have been achieved with A. Gurevich's model [8], for 1.3 GHz niobium cavities doped with nitrogen to an electron mean free path $\ell < 50$ nm [6] and for "low-temperature" (160 °C) impurity-doped 1.3 GHz niobium cavities [11, 12].

More recently, nitrogen doping has been studied at frequencies beyond the 1.3 GHz standard in the SRF community today, both higher (2.6 GHz, 3.9 GHz) and lower (650 MHz, 500 MHz) [9,13,14]. Quite interestingly, the field-dependent decrease in the BCS resistance persists at higher frequency, with the normalized magnitude and slope of the decrease becoming more dramatic with increasing frequency for cavities with similar doping levels (as quantified by the mean free path). Equally interesting, the BCS resistance for doped niobium at 650 MHz and 500 MHz shows no anti-Q-slope, instead exhibiting an increasing BCS resistance similar to that in undoped niobium.

LOW-TEMPERATURE DOPING RESULTS

In previous reports, we have shown experimental BCS resistance data at 1.3 GHz from a single-cell and a nine-cell cavity, exposed to a continuously flowing atmosphere of impure nitrogen gas at 160 °C for 48 hours, with the single-cell cavity receiving an additional annealing step in vacuum at 160 °C for 168 hours (seven days) [11, 12]. These cavities, which exhibited electron mean free paths of 7 and 1 nm, respectively, showed remarkably good agreement with Gurevich's theory of the anti-Q-slope and with our expansion of that model linking the electron mean free path with the quasiparticle overheating parameter in the theory [6, 8].

Here we present new results from this low-temperature doping program, in this instance from a 1.3 GHz cavity that received an 800 °C degas followed by 48 hours at 160 °C in a 40 mTorr (5.3 Pa) argon/carbon dioxide mixture [15]. This cavity showed a strong anti-Q-slope. From RF measurements we calculated an electron mean free path $\ell = 9$ nm for the cavity.

As in our earlier work, we extracted the BCS resistance as a function of field over many temperatures and performed theoretical fits to these data, using a single value for the normalized overheating parameter α' for all temperatures [6]. The results of this fitting routine are shown in Fig. 1. For our fit, we found $\alpha' = 2.9 \pm 3.8$ mK m^2/W. This result is consistent with our model of α' vs. ℓ; Fig. 2 plots this new result over our previous findings. Again, the results here are consistent with the previous work.

This is particularly interesting because nitrogen, the dopant which has been most consistently implicated in studies of the anti-Q-slope, is only present in minute quantities in this cavity. Instead, this cavity shows high concentrations of oxygen and carbon dissolved in the surface [15].

Additional results from this test are presented in [15].

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* 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-1734189. Travel to IPAC 2018 supported by NSF, APS-DPB, and TRIUMF.

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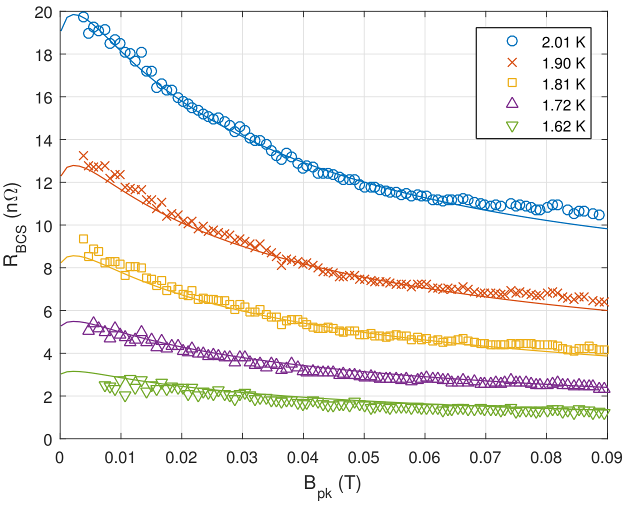

Figure 1: Experimental results with theoretical fitting for the Ar/CO_2-baked cavity, with $\ell = 9$ nm. Points are the experimental BCS surface resistance. Lines are the theoretical fit to the data, with $\alpha' = 2.9 \pm 3.8$ mK m^2/W.

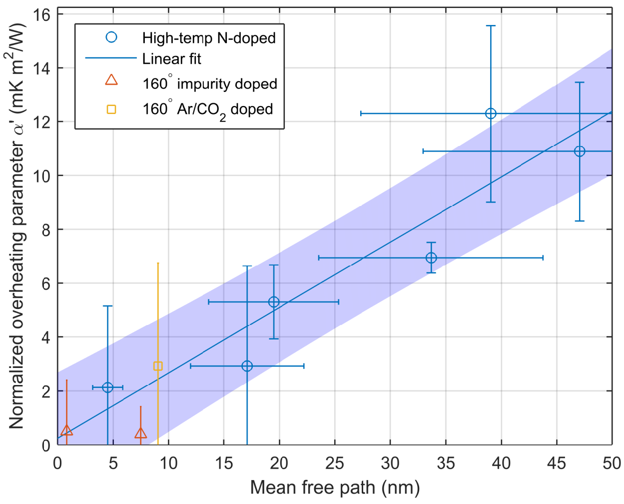

Figure 2: Updated fit results for the normalized overheating parameter α' as a function of mean free path ℓ for 1.3 GHz doped cavities. The blue line is the model fit to our prior high-temperature doping data [6]. The new point on this plot is the yellow square at $\ell = 9$ nm.

HIGH-FREQUENCY NITROGEN DOPING RESULTS

At Cornell, we have commenced our high-frequency doping program, beginning with 2.6 GHz cavities. Here we show experimental results for a cavity that received the “2/6” nitrogen-doping bake (three hours in vacuum to degas, followed by two minutes of 40 mTorr (5.3 Pa) nitrogen, followed by six minutes in vacuum to anneal, all at 800 °C) and 6 μm of vertical electropolishing (VEP). We again extracted the BCS surface resistance at many field levels and temperatures and performed fits to the Gurevich theory, with a single value of α'. The results of this fit are shown in Fig. 3. Additional results from this test are presented in [13].

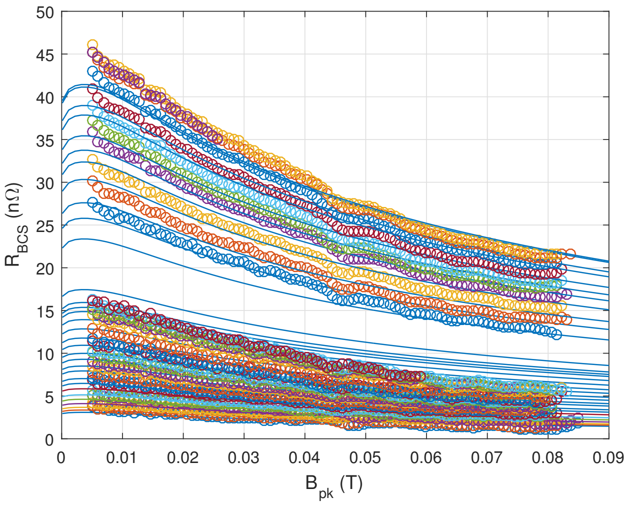

Figure 3: Experimental results with theoretical fitting for the 2.6 GHz 2/6-doped cavity. Temperatures range from 1.55 K (lowest resistance) up to 2.10 K (highest resistance). Points are the experimental BCS surface resistance, and lines are the theoretical fit to the data, with $\alpha' = 0$. The experimental anti-Q-slope exceeds the strongest theoretical prediction.

As these results show, the theory does not produce a good fit to the data, at least compared to the quality of fits for 1.3 GHz doped cavities (such as those in Fig. 1). The best fit of this lightly-doped ($\ell = 46$ nm) 2.6 GHz cavity was produced with zero quasiparticle overheating, *i.e.* $\alpha' = 0$ mK m^2/W. Even in this limit, the theory cannot reproduce a drop in resistance as significant as the one measured experimentally. This is a signal that the theory needs expansion to cover other experimentally observed cases.

In addition, to support our experimental results, we can compare our 2/6 doping results at 2.6 GHz with the recently presented results of a similarly prepared cavity at Fermilab [9]. We show such a comparison in Fig. 4. The two sets of data are very consistent, further suggesting that the poor fit in Fig. 3 indicates an incomplete theory rather than experimental error.

DISCUSSION

For our experimental data at 1.3 GHz, the Gurevich theory with our mean-free-path-dependent overheating expansion continues to provide good fits in the region with $\ell < 50$ nm. However, there still remain other results for doped cavities that are not well represented by the theory. These can be roughly grouped into three areas where the theory would need further expansion:

First, as we have previously reported [6], nitrogen-doped 1.3 GHz cavities with electron mean free paths in the range $50 \text{ nm} \lesssim \ell \lesssim 200$ nm show a BCS resistance that decreases with increasing field, but at a slope that is weaker than that predicted by the theory. The theory’s mechanism

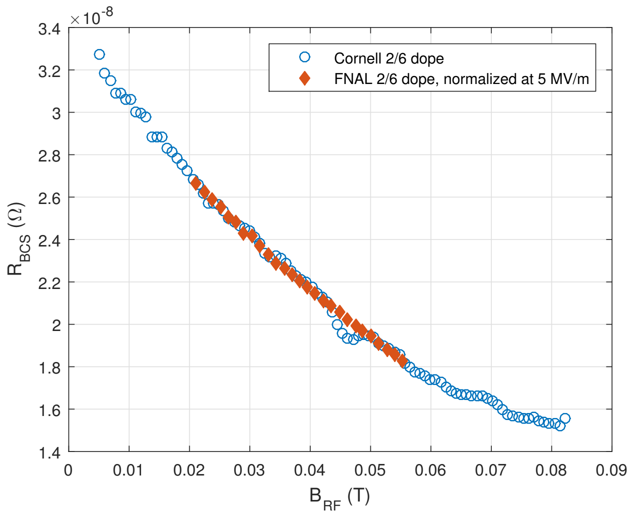

Figure 4: Comparison of 2.6 GHz experimental results of BCS resistance presented here (blue circles) with recent data from Fermilab (red diamonds) for a similarly prepared cavity, normalized at an accelerating field of 5 MV/m (peak surface magnetic field of 21 mT). The Fermilab data were originally presented in [9].

for adjusting the slope, quasiparticle overheating, causes a drastic thermal runaway for cavities with high overheating and cannot accurately reproduce the gentle decrease in resistance observed in these lightly doped cavities (see [6] for more details). This may be due to the “linearization” of the expressions for overheating in the theory; the issue may be improved by expanding these overheating terms.

Second, the theory does not reproduce the recently observed frequency dependence of the anti-Q-slope. Both our results at 2.6 GHz reported above and the similar results from Fermilab show more drastically decreasing BCS surface resistance than possible under the theory. Further, Fermilab’s results at 3.9 GHz [9] show an even steeper relative drop in BCS resistance; it is unlikely that the theory would be able to reproduce this result either. On top of this, the 2/6 doping procedure used for these cavity tests results in a rather long mean free path, around 100 nm; our results at 1.3 GHz show that shorter mean free paths correspond to steeper R_{BCS} vs. H curves, so we might expect that more strongly doped cavities with shorter ℓ may also show this steepening at higher frequencies. This is speculative but if true would also signify a departure from the theory.

Third, what remains unclear is why the dopants, nitrogen or otherwise, exhibit this drastic effect at low concentrations in niobium. The theory is applicable in the dirty limit ($\ell \lesssim \xi/2$), but the effect has not been observed in vacuum-baked cavities with short mean free paths such as those treated with the common “120 °C bake” [16]. Again, there seems to be a missing piece.

Another proposed sketch of this effect is the transition to non-equilibrium superconductivity, a high-frequency regime under which superconductors might show a similar field-dependent decrease in the surface resistance [9, 17]. This is attractive as it could provide an explanation for the observed frequency dependence. Speculatively, perhaps the impurities doped into the niobium play a role in shortening characteristic quasiparticle excitation and recombination time scales, which could lower the onset frequency for non-equilibrium superconductivity. The mechanism for the potential decrease also remains unclear.

CONCLUSIONS

We have presented new theoretical fits to experimental data of a low-temperature impurity-doped 1.3 GHz niobium cavity and to a 2/6-doped 2.6 GHz niobium cavity. The Gurevich theory produces a very good fit for the 1.3 GHz cavity that is consistent with our model of the normalized quasiparticle overheating parameter α'. However, the fit at 2.6 GHz is not as good, with the field-dependent drop in BCS resistance observed experimentally exceeding the maximum prediction of the theory. We discussed the implications of these results on the theory and on the potential role of non-equilibrium superconductivity in the anti-Q-slope phenomenon and pointed out open questions that remain to be answered by the theoretical models.

ACKNOWLEDGMENTS

Travel to IPAC’18 supported by the United States National Science Foundation, the Division of Physics of Beams of the American Physical Society, and TRIUMF

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