STUDIES ON THE FIELD DEPENDENCE OF THE BCS SURFACE RESISTANCE * †

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Abstract

Experiments have shown that the temperature-dependent portion of the RF surface resistance of SRF materials also exhibits a dependence on the magnitude of the surface field, manifested as a "Q-slope" or "anti-Q-slope" in the medium field region. Recent theoretical work proposes an explanation of the anti-Q-slope in dirty-limit superconductors. In this report, we compare theoretical predictions with the results of systematic experimental studies on the RF field dependence of the surface resistance using 1.3 GHz niobium SRF cavities with a wide range of mean free paths. We find very good agreement between theory and experiment in the dirty limit, with some divergence as the cavities approach the clean limit.

INTRODUCTION

When a superconductor is exposed to a radio-frequency (RF) electromagnetic field, there develops a non-zero surface resistance R_s. Superconducting radio-frequency (SRF) accelerator cavities provide just such an environment. One can can determine the average surface resistance R_s of the superconducting cavity wall by measuring the quality factor Q_0 of an SRF cavity and using the following relation with G, the "geometry factor" of the cavity:

$$R_s = \frac{G}{Q_0} \tag{1}$$

Further, R_s can be split into two components, the first being the temperature-dependent Bardeen-Cooper-Schreiffer (BCS) surface resistance R_{BCS} and the second being the temperature-independent residual resistance R_{res}.

Experimental results, including those analyzed in this report, have shown a dependence of R_{BCS} on the magnitude of the surface magnetic field, often termed "Q-slope" [1]. In typical SRF cavities, R_s increases (Q decreases) as the field strength increases. More recently, results of niobium cavities with short mean free path ℓ (the "dirty limit"), achieved by doping the niobium with nitrogen via high-temperature treatment in a low pressure N_2 gas, have demonstrated an "anti-Q-slope". In this instance, the surface resistance tends to decrease (thus Q increases) as the field strength increases [2, 3]. This remarkable phenomenon has been put to use in the forthcoming LCLS-II accelerator, an XFEL at the SLAC National Accelerator Laboratory.

Recent theoretical work has been put forward by A. Gurevich to offer an explanation for this effect [4]. In the analysis that follows, we study R_{BCS} vs. B_{pk} (peak surface magnetic field) results for a total of eight different N-doped cavities with different mean free paths ranging from 4 nm to 250 nm, comparing experimental measurements with the predictions of the theory [3, 5, 6]. Our findings show a very good agreement between theory and experiment in the dirty limit.

METHODS

We extracted R_{BCS} vs. B_{pk} from RF surface resistance measurements at various temperatures and field for 1.3 GHz single-cell ILC-style cavities under eight different N-doping treatments, using BCS fitting to separate R_{BCS} and R_{res} at each field value. Next, given material properties extracted from RF surface impedance measurements of the cavities (ξ, λ, T_c, etc.), we generated R vs B curves from the theory using a range of values of the quasiparticle overheating parameter α for one temperature on each cavity, typically 2.1 K In the 2014 theory, α determines the extent to which the quasiparticles overheat above the ambient experimental temperature; higher α corresponds with higher overheating. For each α, we used a reduced-χ^2 optimization mechanism to find the best scaling factor s=$R_{\mathrm{BCS,meas}}$ / $R_{\mathrm{BCS,thy}}$, applied as a linear scaling of the generated R vs B curve, with a typical range of $s = 0.88 \pm 0.11$. This scaling factor is not mentioned in the theory, but it likely accounts for small systematic errors in measurements of R_{BCS}. We then chose the α with the lowest χ^2_{red}. Following this, we generated new values of α using the relation in Eq. 2, based on the initial value of the surface resistance R_{s0} and the experimental temperature T_0, and the same properties for the calibration curve. Finally, we generated new R vs B curves at other temperatures using the new values of α.

$$\alpha(T_0) = \alpha(T_{\mathrm{cal}}) \frac{T_{\mathrm{cal}}}{R_{s0,\mathrm{cal}}} \frac{R_{s0}}{T_0} \tag{2}$$

RESULTS AND ANALYSIS

Of the eight cavities considered, six showed very good agreement between theory and experiment. These six cavities were in the dirty limit, with mean free path less than 50 nm. Cavity LTE1-4 serves as a good example of the overall results of this analysis; Figure 1 shows the results of the fitting process described above for this cavity. For LTE1-4, α was fitted at 2.1 K and found to be 0.7±0.1.

We find that the relation in Eq. 2 describes the temperature-dependence of the overheating parameter α in the dirty limit. Using cavity LTE1-4 as an example, fitting

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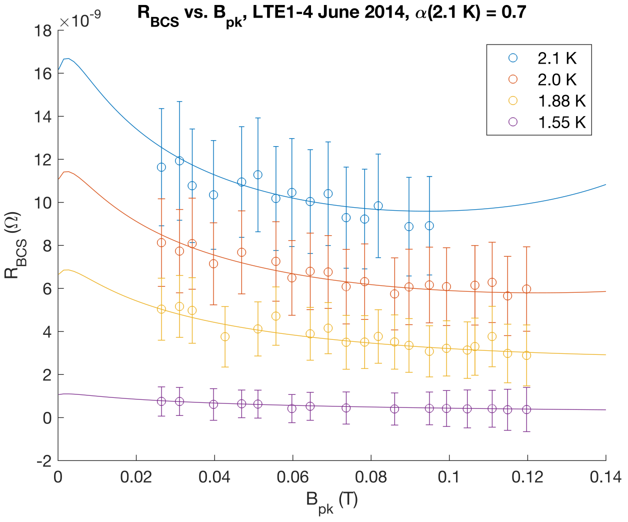

Figure 1: Fit results for cavity LTE1-4. Circles show experimental data, while lines represent the theoretical predictions after fitting the overheating parameter α. This cavity received an 800 °C nitrogen dope with 24 µm of surface removal by EP [3].

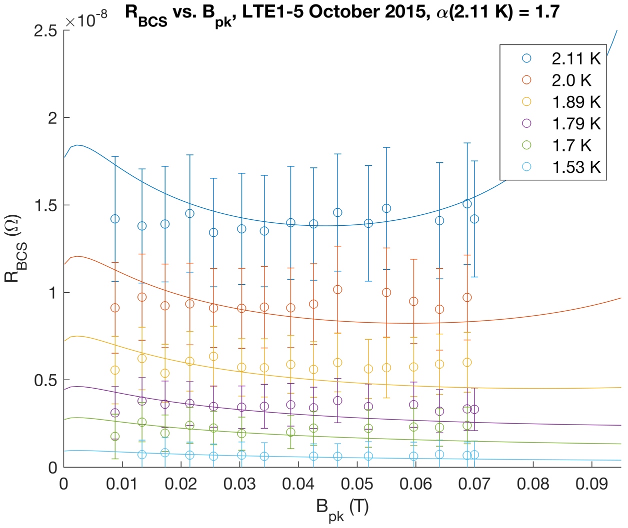

Figure 2: Fit results for cavity LTE1-5. Circles show experimental data, while lines represent the theoretical predictions after fitting the overheating parameter α. This cavity received an 800 °C nitrogen dope with 40 µm of surface removal by EP [6].

$\alpha = 0.7$ at 2.1 K generates $\alpha = 0.504$ at 2.0 K, $\alpha = 0.322$ at 1.77 K, and $\alpha = 0.063$ at 1.55 K. Figure 1 shows the agreement between the theoretical predictions from these calculated values and the experimental measurements.

In the clean limit, with mean free path greater than 50 nm, the simulation did not reproduce the measured field dependence. Figure 2 shows a typical poor fit for a clean niobium cavity. Note that the uncertainty in the experimental surface resistance is mostly systematic; the relative trends at each temperature are reliable and not in good agreement with the theory.

The stark difference in fit quality between the dirty- and clean-limit cavities behooves investigation of possible dependence of the theoretical calculations on mean free path. Though the theory does not explicitly declare any such dependence for the field-dependent component, the single adjustable parameter – that is, the overheating parameter α – offers a likely field for investigation. Indeed, when analyzing α as a function of the mean free path (Fig. 3), we see that there is a general increasing trend, setting in at a mean free path of ~20 nm. Considering the calculations of the theory, at low mean free path the small overheating parameter indicates a small $1/Y$ [4], one of the components of α, thus indicating small overheating of the quasiparticles relative to the phonons. At larger mean free path, coupling between quasiparticles and phonons weakens (there is less scattering of quasiparticles on impurities) so overheating of quasiparticles changes and alpha increases. Once alpha gets too large, the linear approximation used (described below) is no longer valid.

Cavities with appropriately adjusted overheating parameter $\alpha < 1$ generally showed good agreement between theory and experiment, while the two poor fits had $\alpha = 1.0 \pm 0.2$ and $\alpha = 1.7 \pm 0.5$ for $\ell = 60$ nm and $\ell = 214$ nm, respectively. One possible cause of the discrepancy between the experimental results in the long-mean-free-path limit is an assumption in the theory that the overheating of the quasiparticles is not strong, i.e. that the quasiparticle temperature T is only slightly higher than the ambient temperature T_0: $T - T_0 \ll T_0$ [4]. Further studies will be needed to determine the nature of this overheating in the clean limit.

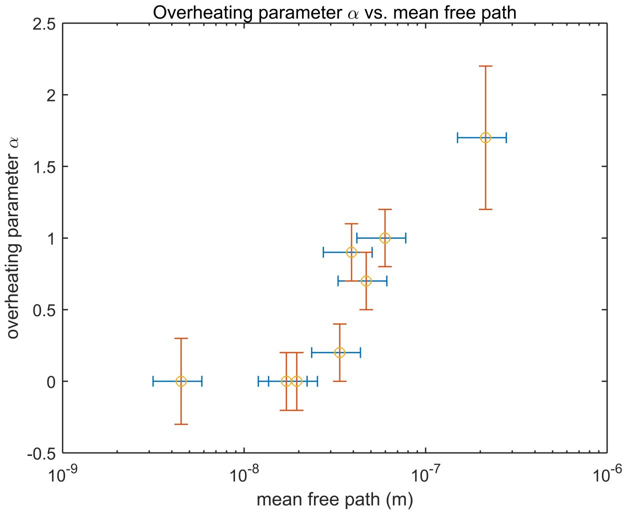

Figure 3: Overheating parameter α plotted with respect to mean free path.

Figure 4 shows the relation between our additional scaling factor s and the mean free path ℓ. For most of the cavities, this scaling factor was very near to unity. Excluding the very clean cavity, for which the theory did not generate accurate predictions of R_{BCS} vs. B_{peak}, the scaling factor had an average value of $s = 0.88 \pm 0.11$. The closeness to 1 suggests that this scaling factor may account for systematic

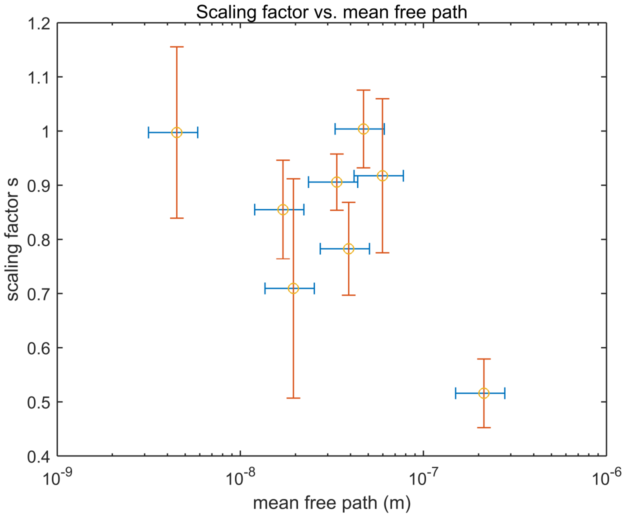

Figure 4: Scaling factor s plotted with respect to mean free path ℓ.

experimental error in the calculation of Q_0, for which we typically assign an uncertainty of ±10%.

CONCLUSIONS AND FUTURE WORK

We have analyzed SRF cavity measurements over a variety of mean free path ℓ in order to compare the measured dependence of the BCS surface resistance on surface magnetic field with the dependence predicted by recent theory. We find very good agreement between theory and experiment in the "dirty limit" of niobium SRF cavities, with mean free path ℓ less than 50 nm. We find some disagreement between theory and experiment in the clean limit, with long mean free path, indicating that another effect takes precedence in the clean limit. We find a relation between the theory's overheating parameter α and ℓ, with $\alpha \approx 0$ at low ℓ and increasing from ℓ = 20nm and upwards. This increasing trend and the failure of the theory to predict performance of clean-limit cavities suggests that the overheating becomes nonlinear as coupling between the quasiparticles and phonons weakens.

Forthcoming work will further investigate performance at long mean free path to determine the nature of the overheating of the quasiparticles and phonons in the clean limit.

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