INVESTIGATION OF THE ORIGIN OF THE ANTI-Q-SLOPE*

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Abstract

The surface resistance of a superconductor, a property very relevant to SRF accelerators, has long been known to depend on the strength of the surface magnetic field. A recent discovery showed that, for certain surface treatments, microwave cavities can be shown to have an inverse field dependence, dubbed the "anti-Q-slope", in which the surface resistance decreases over an increasing field. Here we present an investigation into what causes the anti-Q-slope in nitrogen-doped niobium cavities, drawing a direct connection between the electron mean free path of the SRF material and the magnitude of the anti-Q-slope. Further, we incorporate residual resistance due to flux trapping to calculate an optimal mean free path for a given trapped flux.

INTRODUCTION

Nitrogen doping of niobium, a hot topic in the field of superconducting radio-frequency (SRF) accelerator physics, has sparked much interest due to the observed phenomenon of the so-called "anti-Q-slope". Cavities are treated with nitrogen gas in a furnace, which diffuses nitrogen into the RF penetration depth of the material. The result, as initially observed at Fermilab [1], is a field-dependent BCS surface resistance that tends to *decrease* as RF field strength increases, in contradiction to the behavior typically shown in SRF cavities. As a result, the quality factor of these cavities, inversely proportional to the surface resistance R_s, tends to increase with the RF field strength.

Recent theoretical work [2] offers an explanation for this phenomenon. According to the theory, the high-frequency oscillating field impingent on the surface changes the density of states of the quasiparticles in such a way that their number density tends to decrease with increasing field strength. This decreased density leads to decreased RF power dissipation and thus decreased surface resistance.

This effect is mediated, however, by the overheating of the Bogoliubov quasiparticles: they absorb energy from the RF field and dissipate the energy through their coupling with the lattice phonons. A lag in the energy transfer away from the quasiparticles causes them to increase in temperature relative to the lattice; this increase in turn results in an increase in the surface resistance.

In this work, we seek to find a link between this overheating phenomenon and the electron mean free path ℓ, the quantity typically used to quantify the level of nitrogen doping for a particular sample or cavity. Once armed with such a link, we seek to find an optimal mean free path to balance the effects of the anti-Q-slope with the increased sensitivity to trapped magnetic flux observed in nitrogen-doped cavities [3]. This study is an expansion on work previously shown at IPAC 2016 [4].

QUASIPARTICLE OVERHEATING

For this study, we considered RF test data for nine separate nitrogen-doped cavity tests, with mean free path ℓ ranging from 4 to over 200 nm. These tests measured the temperature-dependent BCS surface resistance R_{BCS} as a function of peak surface magnetic field B_{pk} at a range of temperatures, typically between 1.6 K and 2.1 K. Circles in Fig. 1 show typical experimental data of this type. All cavities tested were 1.3 GHz single-cell TESLA-shape cavities, using a vertical test setup.

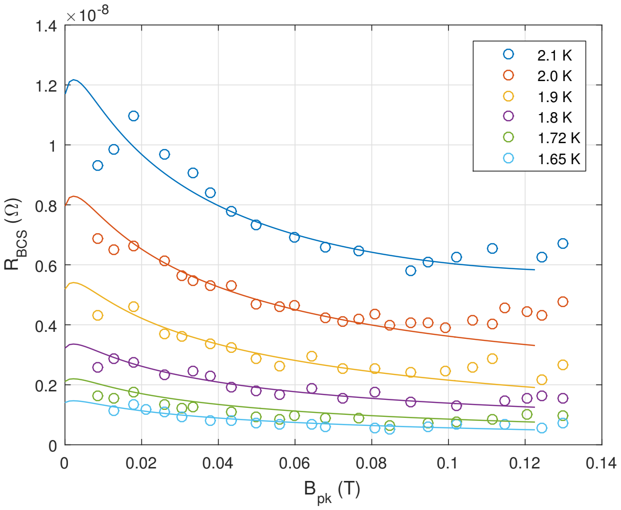

Figure 1: Typical R_{BCS} vs. B_{peak} test results for a nitrogen-doped cavity, with theoretical fits overlayed. The mean free path for this cavity was measured to be 34 ± 10 nm, with the fitted overheating corresponding to $\alpha(2.1\ \mathrm{K}) = 0.44$.

For each temperature, theoretical predictions were fitted to experimental data by adjusting the "overheating parameter" α, which controls the extent to which the quasiparticles overheat under the RF field. Also shown in Fig. 1 are the fit results for the given cavity test data.

With our fitted values of α for each cavity at each temperature, we calculated the "normalized overheating parameter" α', given by Eqs. (1)–(3). Here, T_0 is the experimental bath temperature, T is the quasiparticle temperature, R_{s0} is the low-field surface resistance, B_c is the thermodynamic critical field, Y quantifies the electron-phonon energy transfer rate, d is the thickness of the cavity wall, κ is the thermal

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conductivity, h_K is the Kapitza interface conductance, and H_a is the applied surface magnetic field.

$$\alpha' = \alpha \frac{2\mu_0^2 T_0}{R_{s0} B_c^2} \tag{1}$$

$$\alpha' = \left(\frac{1}{Y} + \frac{d}{\kappa} + \frac{1}{h_K} \right) \tag{2}$$

$$T - T_0 = \frac{1}{2} \alpha' H_a^2 R_s(H_a, T) \tag{3}$$

The normalization in Eq. (1) largely eliminates any temperature dependence. By averaging the values of α' for each cavity and plotting this as a function of mean free path, we see a roughly linear correspondence in the region of $0 < \ell < 50$ nm. Figure 2 shows this key result. The result of a linear fit $\alpha' = \gamma + \beta\ell$ gives fit parameters $\gamma = 0.02 \pm 0.21 \times 10^{-3}$ K m^2/W and $\beta = 2.1 \pm 0.8 \times 10^4$ K m/W.

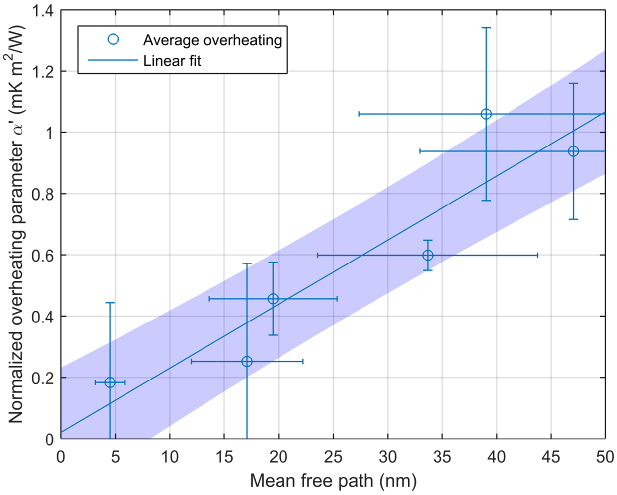

Figure 2: The normalized overheating parameter α', averaged over temperatures ranging from 1.8 to 2.1 K fitted for each cavity, shown as a function of mean free path ℓ. The linear fit equation corresponds to $\alpha' = \gamma + \beta\ell$, with values of γ and β as given in the text. The shaded area represents the 1σ confidence interval.

We have thus established a link between the level of nitrogen doping, quantified by the mean free path, and the characteristics of the anti-Q-slope, controlled by the overheating of the quasiparticles. In general, shorter mean free path corresponds with less overheating and therefore a more drastic reduction in R_{BCS}.

It is important to note here that this fit result is only valid in this region of short mean free path; at longer mean free path, experimentally observed behavior diverges from theoretical predictions given by [2].

OPTIMIZING THE MEAN FREE PATH

With respect to the anti-Q-slope, our result above suggests that the shortest mean free path achievable should be preferable. However, nitrogen-doped niobium cavities also show a greatly increased sensitivity of the residual resistance to trapped magnetic flux [3]. When a cavity is cooled in an ambient magnetic field, magnetic flux can be pinned in the SRF material; these instances of flux pinning are a known contributor to the temperature-independent residual resistance R_0. This contribution rises in proportion to the amount of flux trapped by a factor heavily dependent on the mean free path. Figure 3 shows experimental flux trapping sensitivity data with fitted theoretical curves, previously shown in [3].

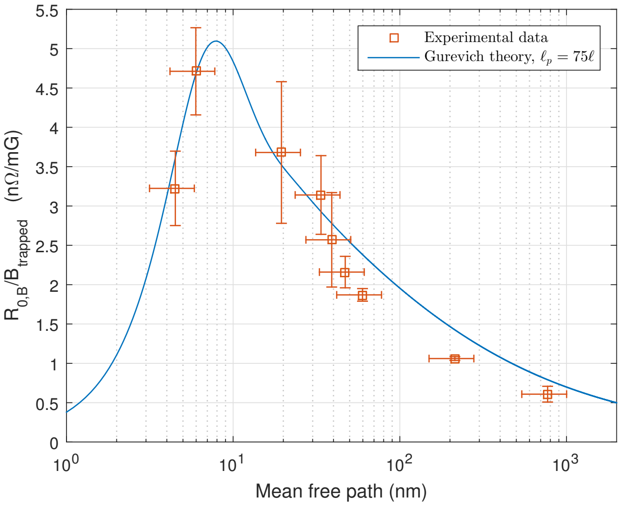

Figure 3: The sensitivity of the residual resistance R_0 to trapped magnetic flux, shown as a function of mean free path ℓ, with experimental data and fitted theoretical prediction (as previously reported in [3]).

Given these two dependencies of the BCS resistance and the residual resistance on the mean free path, we can use the theoretical calculations to find an optimal mean free path for cavities with a given trapped flux benchmark. Figure 4 shows the result of this optimization. In the diagram, BCS resistance is taken at 16 MV/m and 2 K, the operating conditions for the upcoming LCLS-II accelerator, which uses nitrogen-doped cavities. Residual resistance is taken as a function of mean free path and trapped flux according to the results of [3]. Contours and colors indicate the total surface resistance under these conditions for a given mean free path and trapped flux.

For a fixed mean free path for a nitrogen-doped cavity, decreasing trapped flux is always preferable. However, due to the difficulties introduced by the complexity of a full accelerator cryomodule, it may be more useful to consider the achievable trapped flux benchmark, *i.e.* the level of trapped flux which all cavities can be kept below. The dashed line in Fig. 4 indicates the optimal mean free path for a given trapped flux benchmark. If, for example, a cryomodule could be limited to 3 mG of trapped magnetic flux, the corresponding optimal doping level would be $\ell \approx 100$ nm. If the trapped flux benchmark could be set at 1 mG, the optimal mean free path would be $\ell \approx 40$ nm.

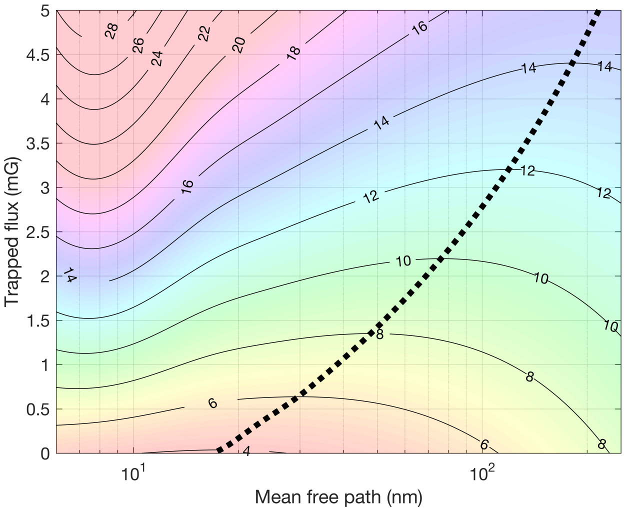

Figure 4: Contours and colors demonstrate the total surface resistance R_s as a function of mean free path ℓ (horizontal axis) and trapped magnetic flux B_{trapped} (vertical axis). Dashed line indicates the optimal mean free path for a given amount of trapped flux. Calculations are made for single-cell TESLA cavities at E_{acc} = 16 MV/m at 2 K.

SUMMARY

We have drawn a direct link between the doping level of nitrogen-doped cavities, quantified by the mean free path, and the properties of the field-dependent reduction in BCS surface resistance known as the anti-Q-slope. This connection is made through the overheating of the Bogoliubov quasiparticles: longer mean free paths correspond with higher overheating, which results in a diminished anti-Q-slope. Combining the predictions from this link with calculations of the residual resistance due to trapped magnetic flux, we calculate the optimal mean free path for a given trapped flux, temperature, and accelerating gradient.

FURTHER READING

For further information on this topic, please refer to the corresponding arXiv submission arXiv:1607.01411.

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