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THE IMPORTANCE OF THE ELECTRON MEAN FREE PATH FOR SUPERCONDUCTING RF CAVITIES*

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Abstract

Theoretical results offer a potential explanation for the anti-Q-slope, the phenomenon of decreasing microwave surface resistance with increasing radio-frequency electromagnetic field strength. This effect has been observed in niobium doped with impurities, chiefly nitrogen, and has been put to use in the Linac Coherent Light Source II (LCLS-II) accelerator currently under construction. Our work, presented here, finds a strong link between the electron mean free path, the main measure of impurity doping, to the overheating of quasiparticles in the RF penetration layer. This is an important effect that adjusts the magnitude of the theoretical anti-Q-slope by providing a mechanism to counteract it and introduce a surface resistance that increases with field strength. We discuss our findings in a study of niobium cavities doped at high temperature (800-990 °C) as well as new analysis of low-temperature-doped cavities.

INTRODUCTION

This work is a continuation of research previously published in Ref. [1]; some of the earlier results are summarized here for completeness.

A classic observation in the field of SRF is the dependence of the BCS surface resistance on the electron mean free path ℓ. This resistance reaches a minimum when $\ell \approx \xi_0/2$, where ξ_0 is the clean coherence length [2]. In 2013, researchers at Fermilab and Jefferson Lab discovered an additional effect linked to the mean free path, namely that niobium SRF cavities doped with impurities (and thus with shorter mean free paths than clean niobium) under certain conditions exhibit a microwave surface resistance that decreases as the strength of the RF magnetic field in the cavity increases [3,4]. This phenomenon, now commonly referred to as the "anti-Q-slope", has been studied at length in nitrogen-doped niobium cavities, and has been employed in the ongoing LCLS-II project [5–8]. In general, nitrogen-doped SRF cavities reach peak quality factors two to four times higher than their undoped brethren, due to the combination of the above two effects. Figure 1 shows characteristic RF performance of a nitrogen-doped cavity in comparison with an undoped electropolished cavity.

Recent theoretical work by A. Gurevich (ODU) offers a mechanism to explain the reduction in surface resistance that manifests as the anti-Q-slope [9]. Magnetic fields parallel to

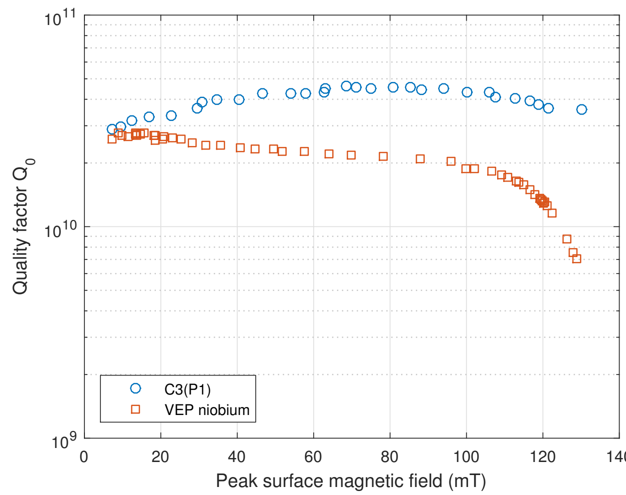

Figure 1: Comparison of intrinsic quality factor Q_0 as a function of surface magnetic field $B_{\rm pk}$ for a nitrogen-doped cavity (blue circles) and an electropolished niobium cavity (red squares).

the surface of a superconductor excite screening currents on the surface which prevent magnetic flux from entering the superconducting bulk. These currents can be strong enough to significantly modify the density of states of the quasiparticles (unpaired, normal-conducting electrons). For materials with sufficiently sharp energy gap peaks, this modification smears out the peak, both lowering the effective energy gap and decreasing the total number of available states near the gap. Under the right conditions, this increases the pair-breaking energy, which decreases the density of normal-conducting electrons and thus decreases the microwave surface resistance.

This decrease in resistance is counteracted by a field-dependent increase in resistance due to the overheating of quasiparticles in the RF surface. The electromagnetic field oscillating in the cavity dissipates power into the surface due to the surface resistance; inefficiencies in transporting this thermal energy out to the cryogenic bath cooling the cavity result in an increase of the temperature of the electrons on the surface. This then results in a feedback effect, where the increasing power dissipated at higher fields leads to an increasing surface resistance. The magnitude of this overheating effect is controlled by the "overheating parameter" α', with contributions from the electron-phonon energy transfer rate Y, the thermal conductivity κ, and the Kapitza resistance h_K. In the linear approximation of low overheating, α' has the following definition:

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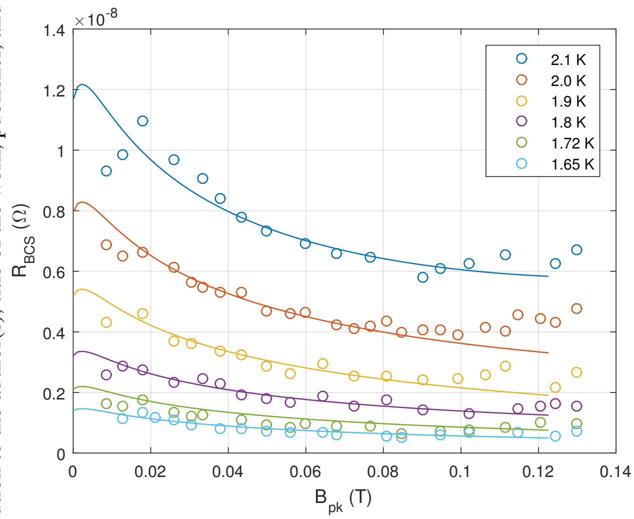

Figure 2: Example R_{BCS} vs. B_{pk} data from cavity C3(P1) and fit results, with $\ell = 34 \pm 10$ nm and $\alpha' = 6.9 \pm 0.6$ mK m^2/W.

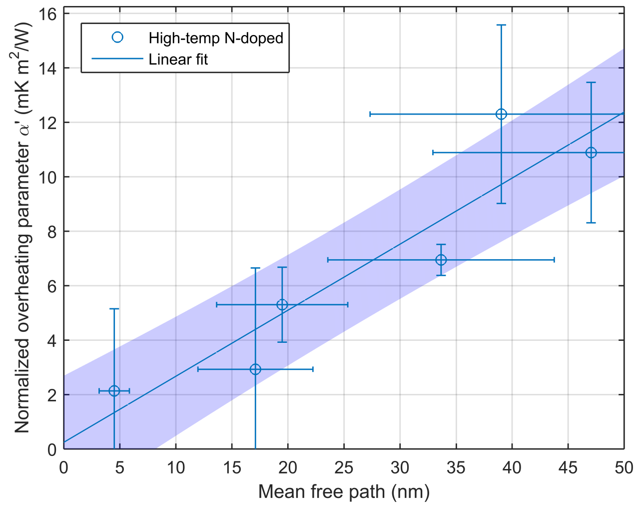

Figure 3: Fit results of overheating parameter α' vs. mean free path ℓ, along with a linear fit with $\alpha' = \beta\ell + \gamma$, with $\beta = 2.4 \pm 1.4 \times 10^5$ K m/W and $\gamma = 0.3 \pm 4.2 \times 10^{-4}$ K m^2/W.

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

Here, d refers to the thickness of the walls of the cavity. The overheating parameter is widely variable over different surface preparations, and by tuning α' one may control the magnitude of the anti-Q-slope and the field at which the surface resistance begins to increase.

HIGH-TEMPERATURE DOPING

In our work, we prepared many single-cell 1.3 GHz TESLA-shape cavities with varied high-temperature doping protocols, which are summarized in Table 1. Using these treatments, we produced cavities with mean free paths ranging from 4 nm to over 200 nm. We performed vertical RF tests of these cavities under CW power at Cornell's SRF test facility, measuring quality factor Q_0 vs. temperature T, resonant frequency f vs T, and Q_0 vs. peak surface magnetic field B_{pk} at many temperatures for each cavity. From these experimental data, we extracted material parameters such as the energy gap $\Delta/k_B T_c$ and ℓ as well as the (temperature dependent) BCS portion of the surface resistance, R_{BCS}, and the (temperature-independent) residual resistance R_0 as functions of field strength.

Using this R_{BCS} vs. B_{pk} data, we fit predictions from the Gurevich theory, using α' as a free fitting parameter. Figure 2 shows an example of this data and the resulting fit for cavity C3(P1). In general, the theoretical fits agreed very well with the experimental data in the region where $\ell < 50$ nm; above this region, theoretical predictions do not reproduce experimental results faithfully, an effect that may be due to an inadequacy of the linear overheating approximation or due to energy gap peaks that are less sharp for lightly-doped cavities.

Figure 3 shows the results of these fits, plotting α' as a function of ℓ. There is a very strong dependence on the magnitude of quasiparticle overheating and the electron mean free path. Plotting a linear fit to this data in the region where the theory accurately predicts experimental results, *i.e.* $\ell < 50$ nm, reveals the empirical relation $\alpha' = \beta\ell + \gamma$, with $\beta = 2.4 \pm 1.4 \times 10^5$ K m/W and $\gamma = 0.3 \pm 4.2 \times 10^{-4}$ K m^2/W.

Looking back to Eq. (1), we see that the contributions to α' from the thermal conductivity κ and the Kapitza resistance h_K are unlikely to give this strong dependence on mean free path, as both are properties of the substrate cavity and should not be affected by doping level. On the other hand, the electron-phonon energy transfer rate Y is a property of the RF surface layer and thus could change with the strength of impurity doping, as measured by the electron mean free path. The observed linear relation, where longer mean free paths correspond with higher overheating, suggests that shorter mean free paths are correlated with more efficient transfer of energy from electrons to phonons and thus a higher Y and lower α'. One potential explanation for this is inelastic scattering events of electrons off of impurities in the superconducting lattice; more impurities (shorter mean free path) lead to more collisions and more efficient energy transfer.

With this linear model in hand, it is possible to generate theoretical predictions of the BCS surface resistance as a function of field for cavities with arbitrary electron mean free path (within the range of the model). However, to fully evaluate the theoretical performance of an impurity-doped SRF cavity, it is necessary to consider the sensitivity of these doped cavities to residual resistance losses due to trapped magnetic flux [8].

When a superconducting cavity is cooled across its transition temperature T_c, it has the potential to trap local ambient magnetic flux at defects. As the surrounding material be-

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Table 1: Overview of Cavity Preparations. This table previously appeared in D. Gonnella *et al.*, Journal of Applied Physics **119**, 073904 (2016) [8].

Cavity	Preparation	T_c [K]	Δ/BT_c	Mean Free Path [nm]
C3(P2)	990°C N-doping[1]+ 5 μm VEP	9.1 ± 0.1	2.05 ± 0.01	4 ± 1
C2(P2)	900°C N-doping[2]+ 18 μm VEP	9.1 ± 0.1	2.00 ± 0.01	6 ± 1
C2(P3)	900°C N-doping[2]+ 6 μm VEP	9.2 ± 0.1	1.94 ± 0.01	17 ± 5
C2(P1)	800°C N-doping[3]+ 6 μm VEP	9.3 ± 0.1	1.88 ± 0.01	19 ± 6
C3(P1)	800°C N-doping[3]+ 12 μm VEP	9.3 ± 0.1	1.91 ± 0.01	34 ± 10
C1(P1)	800°C N-doping[3]+ 18 μm VEP	9.3 ± 0.1	1.88 ± 0.01	39 ± 12
C4(P1)	800°C N-doping[3]+ 24 μm VEP	9.2 ± 0.1	1.89 ± 0.01	47 ± 14
C5(P1)	800°C N-doping[3]+ 30 μm VEP	9.2 ± 0.1	1.88 ± 0.01	60 ± 18
C5(P2)	800°C N-doping[3]+ 40 μm VEP	9.2 ± 0.1	1.94 ± 0.01	213 ± 64

[1] 100 μm vertical electropolish (VEP) [10], 800°C in vacuum for 3 hours, 990°C in 4.0 Pa (30 mTorr) of N_2 for 5 minutes.
[2] 100 μm VEP, 800°C in vacuum for 3 hours, 900°C in 8.0 Pa (60 mTorr) of N_2 for 20 minutes, 900°C in vacuum for 30 minutes.
[3] 100 μm VEP, 800°C in vacuum for 3 hours, 800°C in 8.0 Pa (60 mTorr) of N_2 for 20 minutes, 800°C in vacuum for 30 minutes.

comes superconducting, the flux is trapped in vortices with normal-conducting cores; these vortices can oscillate in the RF field of the cavity, giving rise to a component of the residual resistance. Though this phenomenon exists in clean niobium cavities, impurity-doped niobium cavities show a particularly strong sensitivity to trapped flux losses.

Previous work at Cornell developed an empirical model of these losses as a function of mean free path based on an earlier theory (also by A. Gurevich, with G. Ciovati) [8, 11]. With this model and the overheating model developed above, it is possible to generate a combined model of total surface resistance (R_{BCS} and R_0) as a function of mean free path, field, temperature, and trapped flux. Figure 4 shows the output of this model, calculated for a TESLA-shaped cavity at 16 MV/m and 2 K.

Using this model, it is possible to select a value of ℓ that best balances the losses due to trapped flux (which in general increase for shorter mean free paths) and the magnitude of the anti-Q-slope. One can select a maximum expected trapped flux in a cavity (the "best worst case"), then find the mean free path which provides the lowest overall surface resistance at the desired accelerating gradient. The dashed line in Fig. 4 shows the result of this calculation for each level of trapped flux; for example, if an accelerator cavity with the given parameters could be limited to less than 0.1 μT of trapped flux, then a stronger doping with $\ell < 40$ nm would give the greatest performance. If, on the other hand, the trapped flux were higher, such a strong doping would result in high residual resistance, making a lighter doping with longer mean free path more preferable.

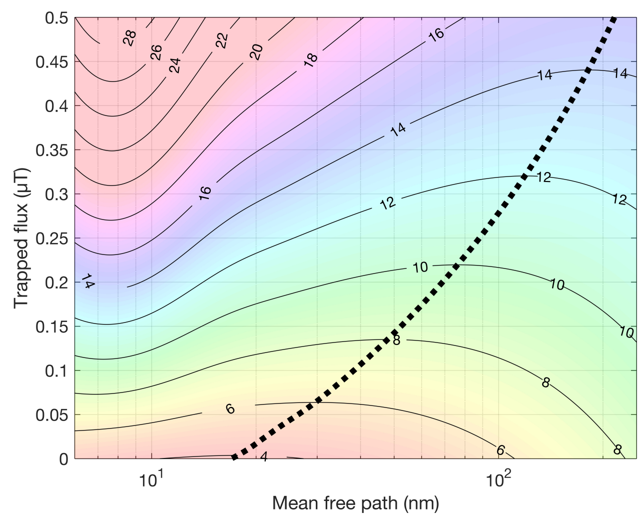

Figure 4: Combined model of surface resistance for given mean free path ℓ and amount of trapped flux $B_{trapped}$, calculated for a 1.3 GHz TESLA cavity at 16 MV/m and 2 K. Dashed line indicates optimal doping level for given maximum trapped flux.

LOW-TEMPERATURE DOPING

A more recent development in impurity-doped niobium is the discovery of "low-temperature doping" [12, 13]. This process is fundamentally similar to the traditional method of impurity doping, but with much lower temperatures (120-160 °C), longer doping and annealing times (2-7 days), and no post-dope chemical etch. Of particular relevance to these studies are the cavities baked at 160 °C, which display anti-Q-slopes very similar to those of high-temperature nitrogen-doped cavities. Chemical composition analysis reveals that the concentration of nitrogen (the chief dopant used for high-temperature doping) in these low-temperature doped cavities is very low, and that instead carbon and oxygen are likely to be the dopants relevant to the physics of the anti-Q-slope [14].

In recent work, we performed vertical CW RF tests of a single-cell cavity and a nine-cell cavity doped at Cornell at 160 °C in impure nitrogen gas. Both cavities were doped

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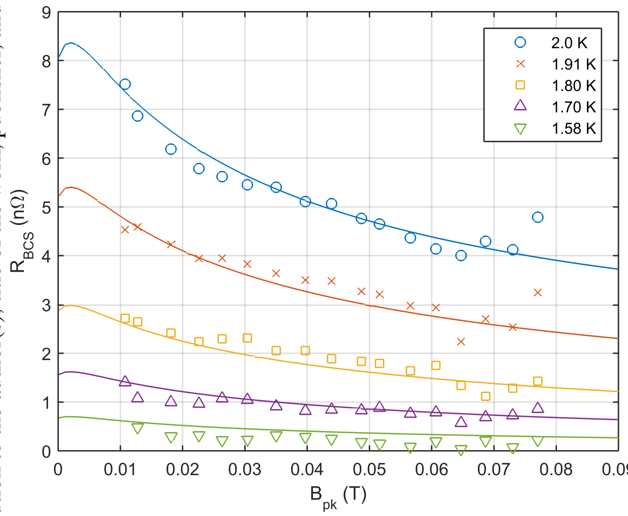

Figure 5: R_{BCS} vs. B_{pk} data from low-temperature-doped nine-cell cavity and fit results, with ℓ = 1 nm and α' = 0.5 mK m^2/W.

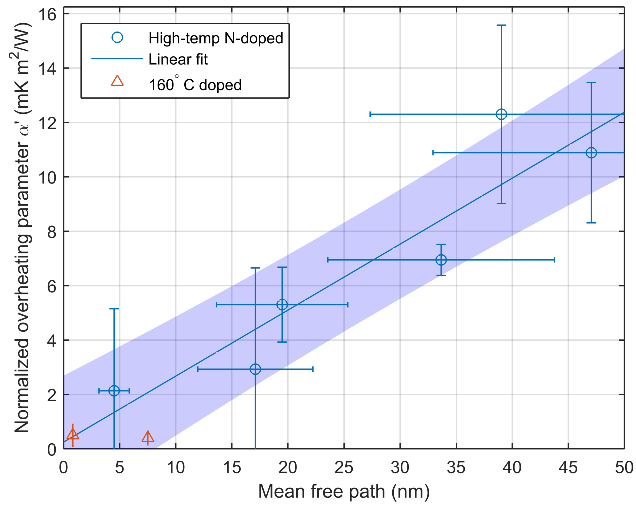

Figure 6: Fit results of overheating parameter α' vs. mean free path ℓ, along with previously described linear fit, in blue. In red are the new fit results for cavities doped at 160 °C.

for 48 hours, but the single-cell also received a 168-hour annealing step at 160 °C in vacuum. RF data analysis revealed a mean free path of 1 nm for the nine-cell cavity and 7 nm for the single-cell cavity.

We performed fits to this new RF test data using the same technique as with the nitrogen-doped cavities above, fitting a single value of the overheating parameter α' for each cavity. Figure 5 shows as an example the experimental data and theoretical fit for the nine-cell cavity; the single-cell cavity also yielded a strikingly good fit.

This is an exciting result, as it suggests that the same physics are at play in the low-temperature-doped cavities as in the high-temperature-doped ones. This is further interesting because the impurities present in the two types of cavities are quite different, both in terms of species and in concentration as a function of depth: in the low-temperature cavities, there is nearly no nitrogen, and concentrations of carbon and oxygen decrease by orders of magnitude over even hundreds of nm [15]. In comparison, traditional nitrogen-doped cavities have a high concentration of nitrogen that remains constant over many microns.

Yet another exciting result of these fits is that the overheating parameters calculated for these two cavities are consistent with the original linear model described above and developed with results from high-temperature-doped cavities. This further suggests that the same physics are in effect despite the differences in impurity content. Figure 6 shows these new results laid over the earlier results in Fig. 3.

These early results are very promising and point us on a path to study low-temperature doping, and impurity-doping of niobium in general, on a deeper and more fundamental level. Future studies at Cornell will continue to analyze low-temperature-doped cavities and their RF performance, as well as study their sensitivity to trapped flux. In addition, we plan to systematically investigate how the concentration profiles of impurities in the RF penetration layer and beyond affect performance. Further, we want to investigate how impurity doping affects the sharpness and uniformity of the energy gap, after early observations indicated that doping improved both [4].

CONCLUSIONS

The surface resistance of SRF materials has long been known to depend on the electron mean free path. Results in recent years have shown that cavities doped with impurities (and thus with short mean free path) exhibit the anti-Q-slope, a field-dependent decrease in surface resistance. Theoretical work has offered a mechanism for this behavior, and work at Cornell has developed an empirical model that links the theory to observations of the mean free path; in short, cavities with shorter mean free paths exhibit stronger anti-Q-slopes, due to the impact of the mean free path on the overheating of quasiparticles in the RF surface.

Recent exciting research into low-temperature-doped niobium cavities reveals similar anti-Q-slope behavior, and our work has shown that this behavior is consistent with that of high-temperature-doped cavities in its agreement with the theory and with our model of overheating as a function of mean free path.

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