OPTIMAL NITROGEN DOPING LEVEL TO REACH HIGH Q_0*

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Abstract

New continuous wave (CW) accelerators such as LCLS-II at SLAC require many SRF cavities operating in the medium field region at unprecedented high Q_0. In order to achieve this demanding goal, nitrogen-doping of the SRF cavities will be used. Nitrogen-doping has been shown to affect the BCS resistance both by a lowering of R_{BCS} at low fields and by the introduction of an anti-Q slope which enables the Q_0 to continue increasing as the RF field is increased. The exact strength of this anti-Q slope is heavily dependent on the doping recipe and specifically the mean free path of the RF penetration layer of the doped cavities. In addition to its effect on R_{BCS}, the mean free path affects the amount of residual resistance obtained due to trapped magnetic flux. We have analyzed nine cavities prepared with different levels of nitrogen-doping to understand how BCS and residual resistance are affected by changes in the mean free path. Here we present a model based on these experimental results to predict the optimal doping level to reach the maximum Q at 16 MV/m[1] based on the ambient magnetic field conditions. We find that if the cavities can be cooled with small amounts of trapped flux, moderate nitrogen-doping is better, while if they will have large amounts of trapped flux, lighter dopings should be used.

INTRODUCTION

Nitrogen-doping has been shown to dramatically improve the intrinsic quality factor, Q_0, of SRF cavities in the medium field region [1]. This improvement in Q_0 is due to two effects: a lowering of the low field temperature dependent BCS resistance, R_{BCS}, by a lowering of the electron mean free path, and an introduction of an anti-Q slope which allows R_{BCS} to decrease further by resulting in a decreasing R_{BCS} as the electric field is increased [2]. These two effects have resulted in cavities repeatably reaching Q_0's higher than 4×10^{10} at 2.0 K and 16 MV/m compared with less than 2×10^{10} in cavities prepared with standard methods. In addition to these benefits on R_{BCS} however comes a higher sensitivity of residual resistance to trapped magnetic flux, $R_{res,B}/B_{trapped}$ [3]. That is the amount of residual resistance, R_{res}, that a cavity will have for a given amount of trapped magnetic flux in its walls.

Both of these effects, a lowering of R_{BCS}, and an increase in R_{res} from trapped flux are heavily dependent on the exact doping level of the cavity. This doping level can be quantified with the electron mean free path: nitrogen-doping directly leads to a lowering of the mean free path [2]. Here we summarize the experimental data measured on single-cell cavities at Cornell which represent a large spread in doping level in order to combine these two effects and find the optimal nitrogen-doping level to minimize the total surface resistance for a given amount of trapped magnetic flux.

CAVITIES TESTED

A total of nine single-cell cavities of varying levels of nitrogen-doping were tested. For each cavity the BCS resistance at low and high fields and $R_{res,B}/B_{trapped}$ were measured. The mean free path was also extracted for each cavity. For a full description of the experimental methods used to measure these properties and a table listing them see [2].

DEPENDENCE OF BCS RESISTANCE ON MEAN FREE PATH

The temperature dependent component of surface resistance is called the BCS resistance, denoted R_{BCS}. At low fields its behavior is well-explained by standard (non-field dependent) BCS theory [4]. At higher fields however there does not exist a theory that fully encompasses the parameter space. Nitrogen-doped cavities have been shown to possess an anti-Q slope which is a result of a decreasing R_{BCS} with increasing E_{acc}. A few theories have been proposed, aiming at explaining this anti-Q slope. A promising theory by Gurevich is discussed in comparison to experimental data in [5]. At low fields, R_{BCS} for nitrogen-doped cavities closely follows the mean free path dependence predicted by BCS theory [2]. At high fields however there is a deviation. This is shown in Fig. 1 which shows R_{BCS} at 16 MV/m and 2 K for the cavities tested. Also shown is the low field BCS prediction and an adjusted BCS prediction. This adjustment comes from assuming a logarithmically decreasing R_{BCS} with E_{acc} which has been shown to approximate the anti-Q slope well [2]. In addition to this logarithmic dependence on field, the strength of the anti-Q slope is heavily dependent on mean free path with larger anti-Q slopes corresponding to lower mean free paths [2]. It can be seen that this adjustment shows very good agreement with the experimental data suggesting that R_{BCS} at higher fields is still governed by BCS theory with a small correction. The Gurevich theory which provides this correction results in the same qualitative behavior. For full details see [5]. While low field BCS theory predicts a minimum in R_{BCS} at mean free paths of

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1 16 MV/m and 2 K were chosen to study due to this being chosen as the operating temperature and gradient for LCLS-II.

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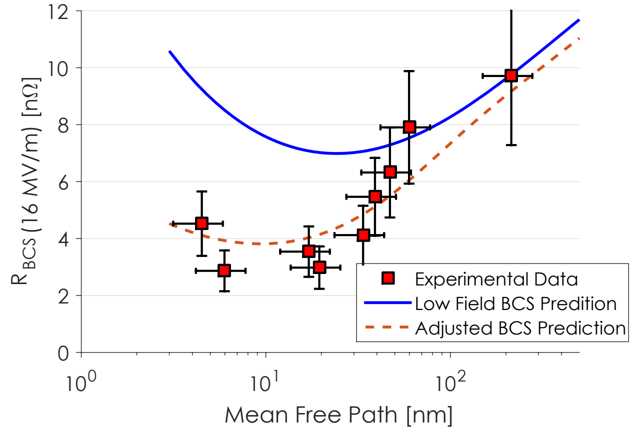

Figure 1: R_{BCS} at 16 MV/m and 2.0 K versus mean free path. Shown in red are the cavities tested. The blue line shows the low field BCS theory prediction and the red dotted line shows the low field prediction adjusted assuming a logarithmic dependence of R_{BCS} on E_{acc} as demonstrated in [2]. R_{BCS} at higher fields is well described by our empirical model assuming a logarithmic field dependence, whose strength is a function of mean free path.

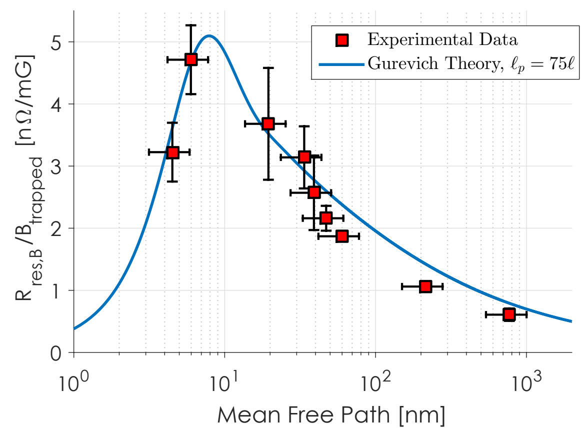

Figure 2: Sensitivity of residual resistance to trapped magnetic flux ($R_{res,B}/B_{trapped}$) versus mean free path for the cavities tested. Also shown is a fit to Gurevich's theory of vortex oscillations. For full details of the theoretical description and fitting see [3].

~20 nm, this minimum is shifted as the field is increased. At 16 MV/m, the minimum is at ~10 nm. This shows that stronger doping yields a lower R_{BCS} down to mean free paths of ~10 nm after which R_{BCS} increases slightly as mean free path is further lowered.

DEPENDENCE OF RESIDUAL RESISTANCE ON MEAN FREE PATH

The temperature independent component of surface resistance, residual resistance, R_{res}, is made up of all losses that do not change with temperature. These are typically losses from oxides, hydrides, and trapped magnetic flux. In well-prepared cavities, R_{res} is overwhelmingly dominated by trapped magnetic flux. While the amount of trapped magnetic flux a cavity has is heavily dependent on the ambient magnetic field, flux expulsion efficiency of the material [6], and cool down conditions (large thermal temperature gradients during cool down resulting in better flux expulsion [7,8]), here we only consider the case once the magnetic field is trapped in the cavity's walls. The exact amount of R_{res} resulting from a given amount of trapped flux has been thoroughly studied in [3]. It was found that there was a strong dependence of $R_{res,B}/B_{trapped}$ on the cavity's mean free path: shorter mean free paths (stronger doping) resulted in larger $R_{res,B}/B_{trapped}$ down to mean free paths of ~10 nm after which $R_{res,B}/B_{trapped}$ decreased with further lowering of the mean free path. This behavior was well explained by Gurevich's theory of residual losses from vortex oscillations [9]. Figure 2 shows $R_{res,B}/B_{trapped}$ versus mean free path for the cavities tested along with a fit of Gurevich's theory to which $R_{res,B}/B_{trapped}$ is maximized. This maximum occurs at ℓ~10 nm. Unfortunately, this is very close to the mean free path at which R_{BCS} is minimized. Upon first inspection one may guess that very strongly doped cavities should be employed since they would have much lower $R_{res,B}/B_{trapped}$ however the region below $\ell \approx 10$ nm is typically plagued by low quench fields [2]. Therefore we will analyze the region only to the right of the maximum since modern CW accelerators require operation in the 15 to 25 MV/m range so mean free paths higher than 10 nm must be used to minimize the effects of quench field degradation.

FINDING AN OPTIMAL MEAN FREE PATH TO MINIMIZE TOTAL R_s

With a thorough understanding of how R_{BCS} and R_{res} are affected by mean free path, a total surface resistance can be calculated based on the mean free path. This will depend on the amount of trapped flux in the cavity walls which, as has been mentioned above, can be tuned by adjusting the flux expulsion efficiency of the material and cool down conditions of the cavity. In a cryomodule environment the amount of trapped flux achieved would be well understood from the cryomodule conditions and cooling scheme. Therefore we look at the total R_s obtained from different amounts of trapped flux. Figure 3 shows the sum of Fig. 1 and 2 for different amounts of trapped magnetic flux. It can be seen that there is a local maximum R_s roughly corresponding to the same maximum as observed in Fig. 2 at $\ell \approx 10$ nm. The region below 10 nm is plagued by low quench fields so we will disregard it. At low amounts of trapped magnetic flux, moderate dopings produce the lowest R_s while at high amounts of trapped flux, R_s is minimized by using lighter dopings.

A more illuminating look at the total R_s is given in Fig. 4. This is a contour plot of R_s versus trapped flux and mean free

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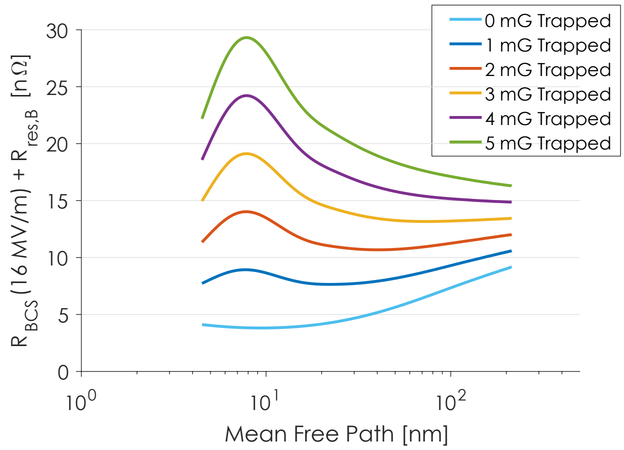

Figure 3: Total surface resistance computed from a sum of Fig. 1 and Fig. 2 for different amounts of trapped flux versus mean free path. At low amounts of trapped flux (below 2.5 mG), moderate to heavy doping gives the lowest R_s while at high amounts of trapped flux, the minimum R_s is outside the typical realm of nitrogen-doping. At mean free paths less than 10 nm, R_s can be further lowered, however this region is typically plagued by low quench fields.

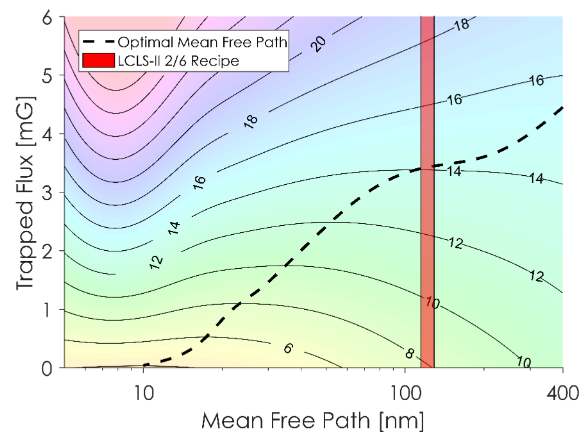

Figure 4: Total R_s versus mean free path and amount of magnetic field trapped computed by combining Fig. 1 and 2. Also shown is the "optimal doping" for a given amount of trapped flux, that is the doping level one should pick based on the amount of trapped flux to expect. Higher amounts of trapped flux require weaker dopings to minimize R_s. In red is the approximate mean free path of the cavities being used in LCLS-II which employ a 2/6 nitrogen-doping recipe.

path. The dashed line represents the minimum R_s curve for a given trapped flux - that is the mean free path that optimizes R_s for a given amount of trapped magnetic flux. In red is shown the approximate mean free path for the cavities prepared with the 2/6 recipe[2] used for LCLS-II production. LCLS-II is operating at a mean free path which is optimized for approximately 3 mG of trapped flux. If less trapped flux can be achieved in the cavities then stronger doping would still have produced lower R_s. Figure 4 gives a similar conclusion as Fig. 3, that is that at larger amounts of trapped magnetic flux, lighter nitrogen-doping is better. This bodes well for the LCLS-II project which has implemented fast cooling to improve flux expulsion to the order of 50% in the cryomodules with ambient magnetic fields <5 mG. At trapped flux values higher than ~5 mG, the optimal mean free path is larger than even lightly doped cavities. This suggests that if the trapped flux gets too high nitrogen-doping should not be used as a preparation method since the benefits of lower R_{BCS} will be completely outweighed by a large R_{res}.

CONCLUSIONS

The work presented above provides a guideline for choosing a cavity preparation method based on the magnetic field conditions that can be achieved in a cryomodule. As SRF cavities move into the High Q realm such as for LCLS-II, the most important parameter for choosing a preparation method will be the amount of trapped flux that the cavities will have when cooled in a realistic accelerator environment. In the region typically operated in (not considering the realm of heavily-doped cavities which is plagued by low quench fields), stronger nitrogen-doping leads to a lower R_{BCS} but a higher sensitivity of residual resistance to trapped magnetic flux. If trapped flux could be completely removed, moderate to strong doping would produce cavities with the lowest R_s and thus highest Q_0. However in reality there will always be some amount of trapped magnetic flux in the cavity walls. The exact amount will heavily depend on the ambient magnetic field near the cavity, the flux expulsion efficiency of the material, and the cool down conditions. This work (specifically Fig. 4) provides an estimate of the doping that cavities should be prepared with in order to minimize R_s based on the expected amounts of trapped magnetic flux achievable.

While nitrogen-doping can provide a means of reaching previously unreachable high Q_0's, it is not without drawbacks. Extensive care is required to minimize the amount of trapped flux that a cavity will see in order to minimize the effects of larger sensitivity of residual resistance to trapped magnetic flux. If this care is taken however, nitrogen-doping will allow new accelerators to operate at unprecedented levels of efficiency.

[2] Nitrogen-doping at 800°C in 25 mTorr of N_2 for 2 minutes followed by a 6 minute anneal and a final light EP of 7 μm.

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