FUNDAMENTAL STUDIES ON DOPED SRF CAVITIES*

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Abstract

Recently, doping with nitrogen has been demonstrated to help SRF cavities reach significantly higher intrinsic quality factors than with standard procedures. However, the quench fields of these cavities have also been shown to be frequently reduced. Here we report on fundamental studies of doped cavities, investigating the source of reduced quench field and exploring alternative dopants. We have focused on studying the quench of nitrogen-doped cavities with temperature mapping and measurements of the flux penetration field using pulsed power to investigate maximum fields in nitrogen doped cavities. We also report on studies of cavities doped with other gases such as helium. These studies have enabled us to shed light on the mechanisms behind the higher Q and lower quench fields that have been observed in cavities doped with impurities.

INTRODUCTION

Nitrogen-doping of SRF cavities has recently been developed as a new cavity preparation technique in order to reach higher intrinsic quality factors Q_0 than have been previously achievable with standard niobium cavities [1]. Nitrogen-doping consists of treating niobium cavities in a UHV furnace at high temperatures with a small amount of nitrogen gas. This treatment has been shown to cause an anti-Q slope in the medium field region (between 5 and 20 MV/m) opposite the usual medium field Q slope observed. However, this improvement is not without its trade offs: more often than not nitrogen-doped cavities quench at lower fields than undoped cavities. The cause of this lower field quench is not yet well understood.

In order to better understand the underlying mechanisms of the success and potential pitfalls of nitrogen-doped cavities (and cavities doped with other gases) a research program is ongoing at Cornell. Here we discuss our latest results specifically focusing on the development of a new nitrogen diffusion simulation, quench studies in both CW and pulsed mode, and doping a cavity with helium gas.

DOPING PROCESS STUDIES

The diffusion of nitrogen into niobium is well described in [2]. We have developed a code based on this model to accurately predict nitrogen concentration in niobium for a given set of treatment parameters (temperature, time, etc.). In addition to implementing the model in [2], we have added a calculation for how the nitrogen diffuses further into the niobium when the source is removed; i.e. when the niobium continues to "bake" in vacuum after the doping. By having a good understanding of how the treatment parameters affect material properties we can better predict a good "recipe" for doped cavities. Figure 1 shows an example run of our model. Shown is the nitrogen concentration in niobium as a function of depth for a treatment at 800°C for 20 minutes with nitrogen followed by 30 minutes in vacuum (anneal time). Also shown are results of secondary ion mass spectroscopy (SIMS) on a sample treated in this way. We can clearly see that in the bulk the simulation agrees with the SIMS data. This result is very promising: it shows that the model can accurately predict nitrogen concentration.

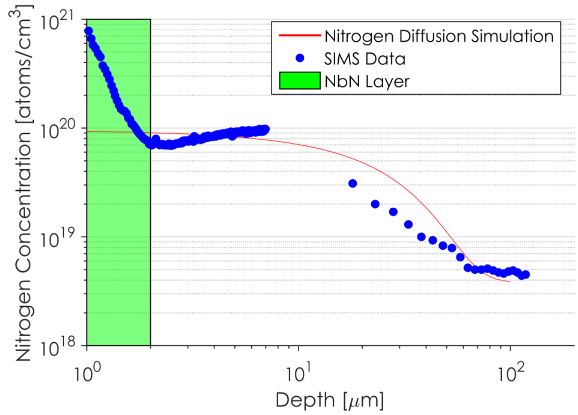

Figure 1: A plot of the N_2 concentration as predicted by the diffusion model compared with measurements on a nitrogen-doped niobium sample. Sample was treated with three cavities at 800°C for 3 hours in vacuum followed by 800°C in 60 mTorr of N_2 for 20 minutes followed by an additional 30 minutes in vacuum.

The model also can predict the drop in nitrogen pressure during the doping that we observe as cavities take nitrogen. The results of this simulation along with pressure drop data from a nitrogen-doping is shown in Fig. 2. We can see that the model accurately predicts the correct pressure drop for a given treatment. More importantly however, this confirms that the pressure of nitrogen during the doping does not affect the amount of nitrogen taken in by the niobium. The model described in [2] leads to a change in pressure that depends only on $\sqrt{t}$. This is a very important result that demonstrates that it is indeed feasible to reproduce similarly prepared cavities in different furnaces and at slightly different pressures. This is also consistent with measurements observed in which cavities that were prepared with almost the same parameters - except for differences in the nitrogen

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ISBN 978-3-95450-178-6

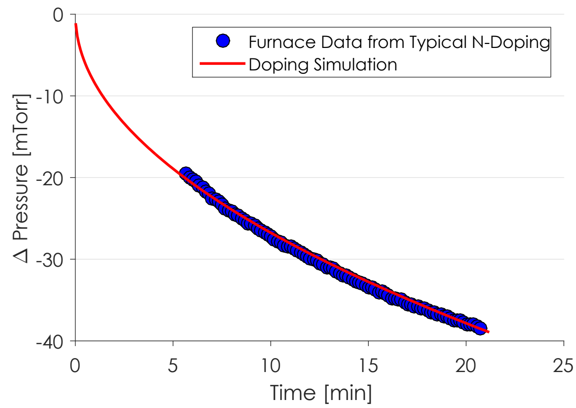

Figure 2: Predicted pressure drop in the UHV furnace from the diffusion model compared with the actual pressure drop. This shows that nitrogen uptake is not dependent on pressure as the change in pressure follows a $\sqrt{t}$ dependence.

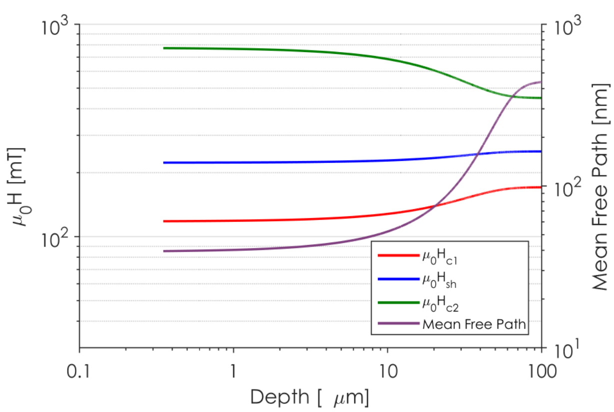

Figure 3: H_{sh}, H_{c1}, and H_{c2} predictions from the diffusion model. These results are for a nitrogen-doping at 800°C for 20 minutes with a 30 minute anneal time.

pressure resulted in very similar and consistent performance. These results indicate that the doping level in the niobium is limited not by the amount of nitrogen in the furnace but by the rate at which the niobium can take in nitrogen.

With the knowledge of the nitrogen-concentration from simulations (or SIMS data), we can also compute the critical fields H_{c1}, H_{c2}, and H_{sh} for the material. This is found by converting concentration into mean free path. For a given mean free path, the critical fields can then be calculated [3]. Figure 3 shows this conversion to critical fields as a function of depth for the same simulation. The knowledge of these critical fields will be invaluable to understanding the cause of low field quenches in nitrogen-doped cavities.

QUENCH STUDIES

A single-cell 1.3 GHz ILC shaped cavity was prepared with nitrogen-doping in such a way to strongly dope the material. It was degassed at 800°C for 3 hours and then doped with nitrogen at 900°C for 20 minutes in 60 mTorr of N_2 followed by an anneal at 900°C for 30 minutes in vacuum. The cavity then received an 18 μm vertical electropolish. The cavity quenched at 15 MV/m, a standard low field quench for strongly doped cavities.

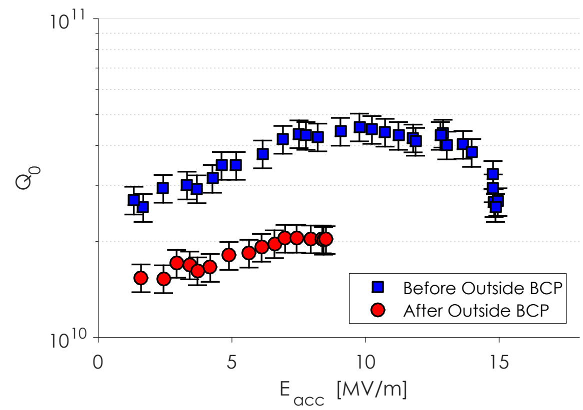

Figure 4: Q_0 vs E_{acc} at 2.0 K for a nitrogen-doped single-cell cavity before and after outside BCP. Outside BCP resulted in a decrease in Q_0 and quench field.

Outside BCP

It is well understood that niobium doped with nitrogen and niobium nitride have worse thermal conductivity than pure niobium. Since the outside of a nitrogen-doped cavity has usually never been etched it is still covered in a nitrogen-doped layer. This layer has worse thermal conductivity than clean niobium and could cause poor cooling from the helium bath which would result in quenches at lower fields than standard niobium cavities. In order to test this theory we etched the single-cell cavity only on the outside to remove the NbN and nitrogen-doped layer. The Q_0 vs E performance at 2.0 K before and after outside BCP is shown in Fig. 4. Interestingly, the quench field did not increase after outside BCP, in fact it decreased from 15 MV/m to 8 MV/m! The Q_0 of the cavity also dropped significantly. The cause of these changes is currently under investigation.

Pulsed Testing

Before and after outside BCP, the cavity was tested on a high power insert in which 1 MW of power can be fed into it via a klystron. This measurement has been done on standard niobium and Nb3Sn to find the flux entry field as a function of temperature of a cavity [4]. These measurements provide a unique and powerful way of understanding the fundamental limits of a cavity (and more importantly, its preparation).

Figure 5 shows the results of this test before and after outside BCP. Plotted is the quench field as a function of $(T/T_c)^2$. Also shown is H_{sh} and H_{c1}, calculated from the mean free path of the cavity. The mean free path was extracted using the method described in [5]. The first thing to note is that the outside BCP had no impact on the maximum fields of the cavity in pulsed operation at all temperatures. Secondly, the pulsed mode quench field at 2.0 K is 50% higher than

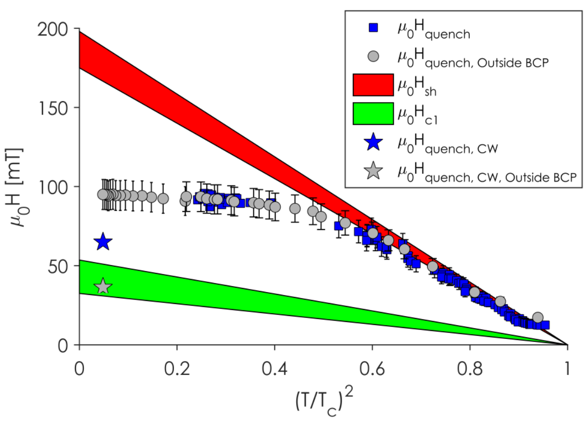

Figure 5: The high pulse power quench field for a single-cell cavity before and after outside BCP. Performance follows the superheating field at high temperatures and demonstrates behavior consistent with a defect and thermal quench at low temperatures.

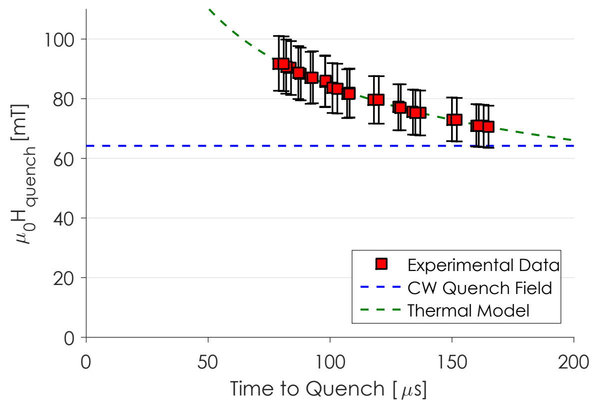

Figure 6: Quench field vs time to quench for the cavity. The dependence follows a simple thermal model, a clear indication that the quench is caused by a defect.

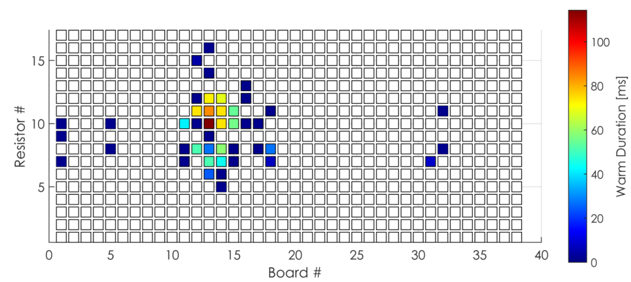

Figure 7: Quench location of the cavity using the Cornell single-cell temperature mapping system. Quench was centered at a single location, consistent with a defect.

the CW quench field before outside BCP. Thirdly, at high temperatures, the flux entry field very closely follows the superheating field, with a zero temperature value of 186 ± 12 mT, significantly lower than that of clean niobium and in agreement with theoretical predictions for dirty niobium with small mean free path. Fourthly, before outside BCP, the CW quench field was significantly higher than H_{c1} for the cavity. After outside BCP, the CW quench field was very close to H_{c1}. Finally, we can see that at low temperatures (T<~7 K), the quench field no longer follows the superheating field. This is a clear symptom of a defect taking over and leading to a thermal quench.

Additionally, at 4.2 K, quench field vs time to quench was measured by adjusting the forward power of the klystron. These results are shown in Fig. 6. Also shown is the prediction by a simple thermal model. We can see that the quench field is well described by the thermal model, again lending evidence to the conclusion that the quench is caused by a defect and is a thermal quench. The exact nature of the defect is under investigation, and could include lossy NbN or areas of poor surface quality (e.g. surface roughness) with premature flux entry.

Quench Location Detection

The Cornell single-cell temperature mapping system can be used for quench detection [6]. By measuring the time that a given resistor gets warm during a quench, one can determine the center of a quench. This result on the cavity discussed above is shown in Fig. 7. We can see that the quench was centered in one location near the equator, consistent with our pulsed measurements that suggest that a defect is causing the quench.

HELIUM DOPING

A single-cell 1.3 GHz cavity was doped with helium: 800°C in vacuum for 3 hours followed by 400°C in 40 mTorr of He gas for 2 minutes. The cavity was then immediately tested with no additional material removal and showed a strong Q slope. This Q slope was present even from low fields and at every temperature tested. The Q_0 vs E performance is shown in Fig. 8. Analysis of this data shows that this strong Q slope is coming purely from the temperature independent residual resistance. This residual resistance vs E is also shown in Fig. 8.

CONCLUSIONS

Recent studies at Cornell have shed new light onto the complicated subject of doped SRF cavities. We have developed a model that can accurately predict nitrogen concentration for a given doping. We have shown that how much nitrogen is taken in by cavities is not determined by the pressure in the furnace, easing requirements for producing consistency among nitrogen-doped cavities. We have conducted extensive studies on the frequently reduced quench seen in nitrogen-doped cavities. Specifically, we have found that the low field (15 MV/m) quench in a cavity was associated with a defect and was a thermal quench. The superheating field of a nitrogen-doped cavity was measured and found to be lower than that of standard niobium, in agreement with theoretical predictions. The CW quench field was shown to

ISBN 978-3-95450-178-6

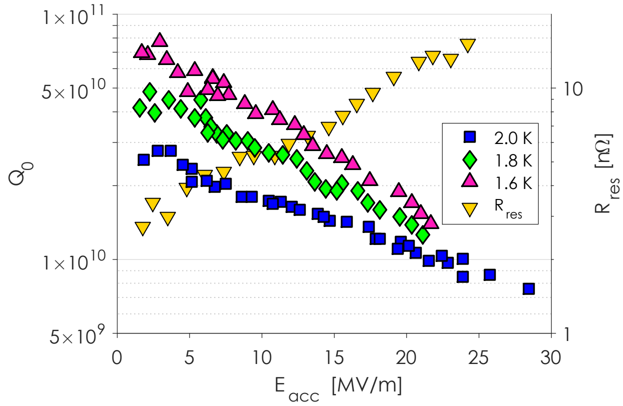

Figure 8: Q_0 vs E_{acc} performance for the helium doped cavity. Also shown is the residual resistance vs E_{acc}.

be higher than H_{c1} for the cavity but lower than the maximum fields in pulsed operation. Interestingly, outside BCP resulted in a severe degradation of both quench field and Q_0 but no change in the maximum field in pulsed operation or its temperature dependence. Finally, we've shown that helium doping results in a strong Q slope caused by an increasing residual resistance with increasing accelerating field.

The results presented here represent a step forward towards understanding the mechanisms behind doped cavities. Future work will focus on more studies of quenches in nitrogen-doped cavities, specifically with temperature mapping and more pulsed measurements. We will also apply our diffusion model to dope more cavities and work towards finding a good "recipe" that maximizes both Q_0 and quench field.

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