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FLUX TRAPPING IN NITROGEN-DOPED AND 120°C BAKED CAVITIES*

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Abstract

It is well known that external magnetic fields can cause higher residual resistance in superconducting RF cavities if the field is present during cooldown. However, the effect of cavity preparation and surface mean free path on the resulting residual resistance from magnetic field is less well studied. In this paper, we report on recent studies at Cornell in which two SRF cavities (one nitrogen-doped and one 120°C baked) were cooled through Tc in an applied uniform external magnetic field. Trapped flux and residual resistance were measured for a variety of cooldowns and applied magnetic fields. It was found that the residual resistance due to trapped flux in the nitrogen-doped cavity was three times larger than in the 120°C baked cavity.

INTRODUCTION

New light sources such as the proposed SLAC Linac Coherent Light Source II (LCLS-II) [1] and the Cornell Energy Recover Linac (ERL) require many SRF cavities operating at high intrinsic quality factor, Q_0. Ambient magnetic fields in the vicinity of the cavities can cause a degradation in Q if the cavity is cooled through T_c in this field. It is important to understand how a magnetic field will affect cavity performance so magnetic shielding for cryomodules can be properly designed. Until recently, it was believed that niobium cavities cooled in a magnetic field would see an increase in their residual resistance by 0.3 nΩ/mG of field [2]. This number was obtained using a simple theoretical model and is in rough agreement with experimental data for niobium cavities with clean RF surfaces. However, current state of the art SRF cavities preparation calls for baking in impurities into the RF surface layer to reduce BCS surface resistance, which as is presented in the following, has significant impact on residual resistance from trapped magnetic flux. In this paper, we discuss an experiment in which two cavities were tested in an applied external magnetic field. Both cavities were single-cell 1.3 GHz ILC shaped, the first one prepared with nitrogen-doping at Fermilab and the second prepared with EP and 120°C bake at Cornell. These measurements provide new insight into how cavity preparation affects a cavity's susceptibility to losses from trapped magnetic flux.

EXPERIMENTAL METHOD

Two single-cell 1.3 GHz ILC shaped cavities were prepared, one with nitrogen doping at FNAL (heat treatment at 800°C in vacuum followed by 20 minutes in 20 mTorr of nitrogen followed by an additional 30 minutes in vacuum) and one with EP and final 48 hour 120°C baking at Cornell. Each cavity was placed inside a Helmholtz coil that provided a uniform (within ±5%) magnetic field pointing parallel to the cavity symmetry axis. Temperature sensors were mounted on the top and bottom flanges and the equator to measure cool down rates and gradients over the cavities. A single-axis fluxgate magnetometer was placed on the top iris to measure both the applied field and the trapped flux after cooling. A picture of the experimental setup is shown in Fig. 1.

Figure 1: A picture of the experimental setup including Helmholtz coil, temperature sensors, and fluxgate magnetometer.

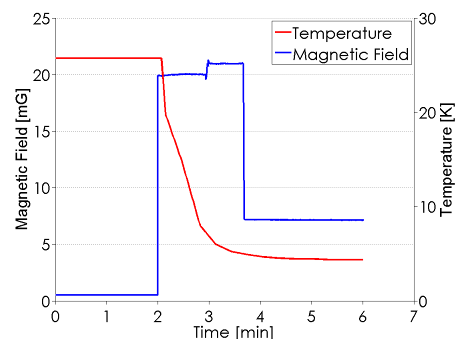

Figure 2: A schematic of an example cool down. The field is turned on and then the cavity is cooled. After going through T_c, the field is turned off but there is some residual field left. This is a result of some flux being trapped in the cavity.

For each cool down, the method was as follows:

1. Have cavity above T_c with the external field off.
2. Turn external field on and begin cooling
3. When cavity goes through T_c a jump occurs in the measured magnetic field due to flux expulsion.
4. Turn external field off. The remaining field measured on the fluxgate is the trapped flux - that is the amount of field that remains after the field is turned off.

A schematic of an example cool down in shown in Fig. 2. It can be seen that after cooling and turning the field off, the field does not drop to it's near-zero field value. This is due to some flux being trapped in the superconducting cavity walls.

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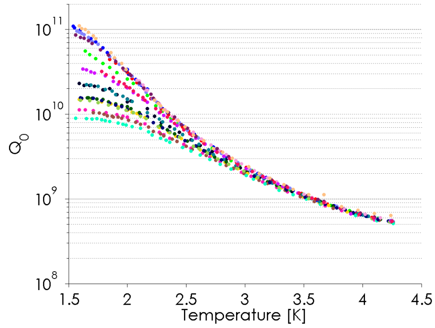


Figure 3: Q_0 vs T for 18 cool downs of the nitrogen-doped cavity in different applied magnetic fields and cool down rates.

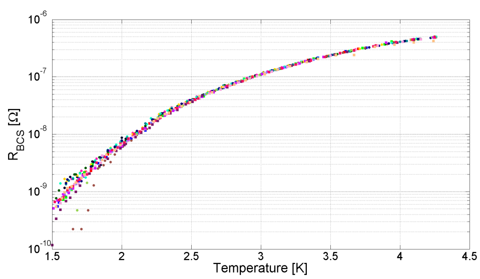


Figure 4: R_{BCS} vs T for 18 cool downs of the nitrogen-doped cavity.

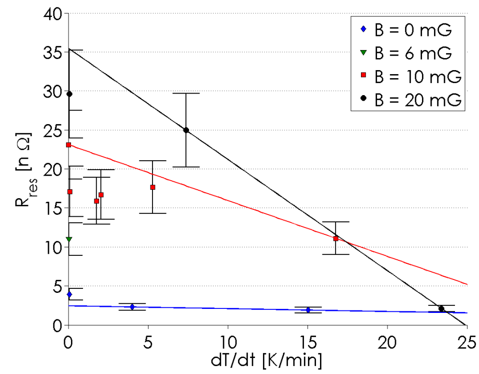
After turning the coil off and cooling completely, Q_0 vs temperature was measured at low RF field amplitude. From this measurement, residual resistance could be extracted by fitting using SRIMP [3]. These measurements were done for a variety of different applied external fields and cool down rates for each cavity.

Q_0 VS T

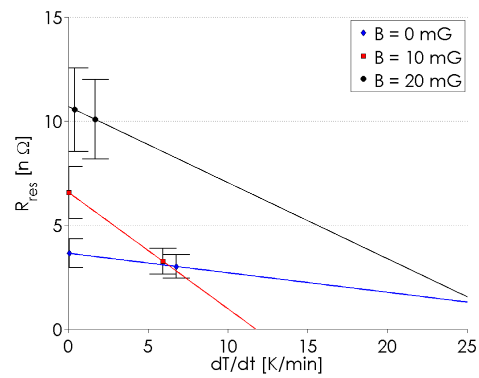
The applied magnetic field and cool down rate will cause a change in Q_0 vs T. An example of the 18 cool downs done for the nitrogen-doped cavity is shown in Fig. 3. It can be seen that at high temperatures, all cool downs have the same Q_0 vs T performance but at lower temperatures a spread occurs. This spread is a result of the external field and cool down rate affecting the residual resistance of the cavity. In fact, if we look at the BCS resistance versus temperature as in Fig. 4, we can see that R_{BCS} remains unchanged in all of the different cool downs. This means that the magnetic field is affecting only the residual resistance.

EFFECT OF COOL DOWN RATE

The cool down rate had a strong effect on the residual resistance of both cavities; see Fig. 5. It was found that the faster the cool down rate through Tc , the smaller the residual resistance in agreement with earlier observations [4]. Moreover, we can see that the slopes of R_{res} vs cool-down rate for the two cavities are similar and thus the effect of cool-down rate on R_{res} is similar for both cavities. In practice, this means that a cavity can achieve a low residual resistance



(a) R_{res} vs cool down rate for the nitrogen-doped cavity.



(b) R_{res} vs cool down rate for the 120°C baked cavity.

Figure 5: R_{res} vs cool down rate for the two cavities in different applied external fields. In both cases, faster cool down rate gives less residual resistance and higher applied external field gives higher residual resistance.

even if it is cooled in a large magnetic field as long as the cool down rate is fast enough. In Fig. 5 we can also see that the higher the applied magnetic field during cool down, the higher the residual resistance. However, at the same applied magnetic field and cool-down speed, the residual resistance is significantly higher for the nitrogen-doped cavity than for the 120°C baked cavity. This will be discussed more in the next section.

EFFECT OF EXTERNAL FIELD

We've just shown that by cooling faster, one can reduce the residual resistance of a cavity. Not surprisingly, reducing the external magnetic field also will lower the residual resistance. It is useful to know how much residual resistance a cavity will have for a given amount of trapped flux. Figure 6 shows a plot of the additional residual resistance from the external field (total residual resistance minus the residual resistance of the cavity with no applied field) as a function of trapped flux (the reading of the fluxgate magnetometer after cooling and turning the applied field off) for both cavities. We can very clearly see that the nitrogen-doped cavity is much more susceptible to losses from trapped flux than the 120°C baked cavity. The nitrogen-doped cavity showed

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Table 1: Summary of Extracted Material Properties

Property	Nitrogen-Doped	120°C Baked
T_c [K]	9.2 ± 0.2	9.2 ± 0.2
Δ/k_bT_c	2.05 ± 0.02	1.95 ± 0.02
Mean Free Path [nm]	9 ± 3	23 ± 7
R_{res} from Trapped Flux [nΩ/mG]	2.9 ± 0.2	0.8 ± 0.03
R_{res} from Applied Field [nΩ/mG]	1.13	0.37

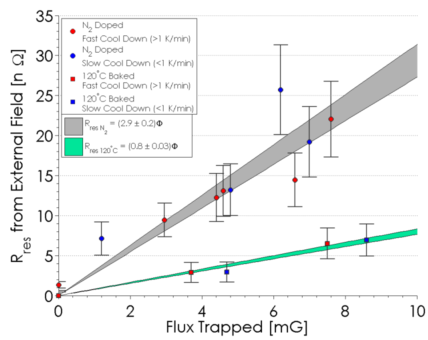

Figure 6: Residual resistance from the external field as a function of trapped flux for the two cavities. Losses are 3.6 times higher for the nitrogen-doped cavity than the 120°C baked cavity.

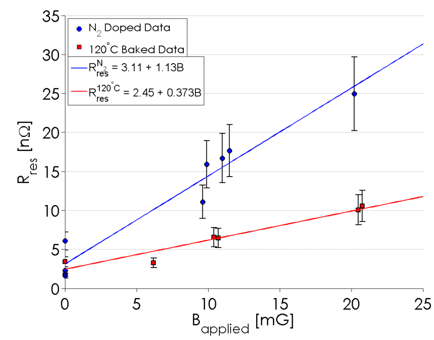

Figure 7: The residual resistance as a function of applied magnetic field for both cavities under fast (1 K/min < dT/dt < 20 K/min) cool downs.

2.9±0.2 nΩ/mG trapped and the 120°C baked cavity showed 0.8 ± 0.03 nΩ/mG trapped. The effective residual resistance from a given amount of trapped flux is 3.6 times higher for the nitrogen-doped cavity than the 120°C baked cavity!

The amount of flux that a cavity traps will depend both on the external field and the cool down rate. By cooling faster, the residual resistance can be decreased (by decreasing the fraction of the ambient field trapped in the cavity walls). If we look at just fast cool downs (1 K/min < dT/dt < 20 K/min), we can see how the two cavities' residual resistances are affected by just the applied magnetic field under fast cool down conditions. Figure 7 shows the residual resistance as a function of the applied magnetic field for both cavities for only the fast cool downs. The residual resistance is again significantly (about 3 times) higher for the nitrogen-doped cavity than the 120°C baked cavity for a given applied magnetic field. The nitrogen-doped cavity showed 1.13 nΩ/mG applied and the 120°C baked cavity showed 0.37 nΩ/mG applied. It is important to note that the number found for the 120°C baked cavity is very similar to the prediction from [2].

SUMMARY OF MATERIAL PROPERTIES

Material properties such as mean free path, energy gap, T_c, and residual resistance can be extracted from f vs T and Q vs T data using SRIMP [3]. A summary of these properties for the two cavities is shown in Table 1. We can see that the nitrogen-doped cavity has a significantly smaller mean free path than the 120°C baked cavity. We propose that this difference in mean free paths causes the difference in susceptibility to residual losses from trapped flux between the two cavities.

CONCLUSION

A nitrogen-doped cavity and 120°C baked cavity were cooled in a uniform ambient magnetic field and their residual resistances were measured for a variety of different applied external fields and cool down rates. It was found that the nitrogen-doped cavity was 3.6 times more susceptible to residual losses from trapped flux than the 120°C baked cavity. Therefore, under fast cool downs, the nitrogen-doped cavity showed three times higher residual surface resistance at a given ambient field than the 120°C baked cavity. These differences can be attributed to the difference in mean free paths of the two cavities with the nitrogen-doped cavity having a significantly smaller mean free path than the 120°C baked cavity.

ACKNOWLEDGMENTS

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