SENSITIVITY OF NIOBIUM SUPERCONDUCTING RF CAVITIES TO MAGNETIC FIELD*

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Abstract

One important characteristic of nitrogen-doped cavities is their very high sensitivity to increased residual surface resistance from trapped ambient magnetic flux. We have performed a systematic study on the losses by trapped flux, and their dependence on the mean-free-path (MFP) of the niobium RF penetration layer. Cavities with a wide range of MFP values were tested in uniform ambient magnetic fields to measure trapped magnetic flux and resulting increase in RF surface resistance. MFP values were determined from surface impedance measurements. It was found that larger mean free paths lead to lower sensitivity to trapped magnetic flux.

INTRODUCTION

With SRF cavities reaching ever high intrinsic quality factors and reaching new, unprecedented levels of efficiency, the impact of the magnetic field present in the vicinity of the cavities becomes ever more important. During cool down, part of the ambient magnetic field will get trapped in the superconductor. This trapped flux in the RF penetration layer then causes losses in RF fields, resulting in an increase in the residual resistance of the cavity. However, the exact material parameter dependence of the impact of trapped magnetic field on the cavity's residual resistance had yet to be studied systematically Here we present the results of an experiment at Cornell to study how the cavity preparation method impacts a cavity's sensitivity to the magnetic field trapped in its walls.

EXPERIMENTAL SETUP

A total of eight cavities were prepared with a variety of methods: 6 nitrogen-doped cavities with varying levels of doping and two cavities prepared in a more standard fashion, one electropolished and one electropolished followed by a 48 hour 120°C bake. Each cavity was then assembled on a vertical test stand and surrounded by a Helmholtz coil. This coil applied a uniform external magnetic field parallel to the cavity's axis. A fluxgate magnetometer was placed on the cavity's iris to measure both applied magnetic field and trapped magnetic flux. Three temperature sensors were also placed on the cavity, one on each flange, and one on the equator in order to measure cool down rates and spatial temperature gradients. A picture of the experimental setup is shown in Fig. 1.

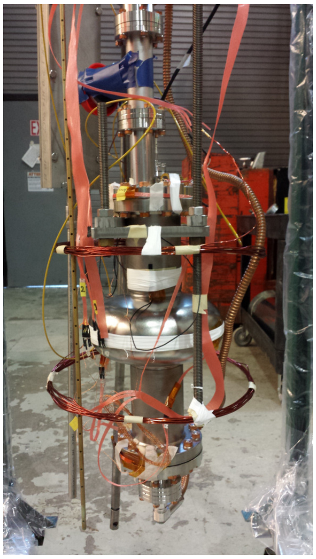

Figure 1: The experimental setup. A 1.3 GHz ILC shaped single-cell cavity was surrounded in a Helmholtz coil to induce a uniform external magnetic field parallel to the cavity axis.

Each cavity was cooled down in a variety of magnetic fields in order to trap different amounts of magnetic field in the cavity walls. Figure 2 shows a typical cool down. For each cool down, Q_0 versus temperature was measured, allowing us to extract residual resistance by BCS fitting using SRIMP [1] using the method described in [2]. Additionally, resonance frequency versus temperature was measured for each cavity to extract mean free path by converting to change in penetration depth versus temperature in order to extract mean free path.

EXPERIMENTAL RESULTS

The results of these measurements are shown in Fig. 3. The mangetic flux sensitivity is defined as

$$\text{Sensitivity} = \frac{dR_{\text{res}}}{dB_{\text{trapped}}}, \tag{1}$$

the slope shown in Fig. 3. We can see that there is a large spread in cavity sensitivity to trapped flux. The stronger doped cavities showed higher sensitivity and all nitrogen-doped cavities showed higher sensitivity than the EP and EP+120°C baked cavities. The EP cavity shows a sensitivity slightly larger than the EP+120°C baked cavity but still

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Table 1: Sensitivity of Cavities to Trapped Flux

Cavity	Preparation	Mean Free Path [nm]	Sensitivity to Trapped Flux [nΩ/mG]
TE1-2	N-Doping[1]+ 6 μm VEP	19 ± 6	3.7 ± 0.9
TE1-3	N-Doping[1]+ 12 μm VEP	34 ± 10	3.1 ± 0.5
TE1-1	N-Doping[1]+ 18 μm VEP	39 ± 12	2.5 ± 0.6
TE1-4	N-Doping[1]+ 24 μm VEP	47 ± 14	2.2 ± 0.2
TE1-5	N-Doping[1]+ 30 μm VEP	60 ± 18	1.87 ± 0.08
TE1-2	"Over-Doping"[2]	6 ± 1	4.7 ± 0.6
NR1-3	VEP	800 ± 100	0.6 ± 0.1
NR1-3	VEP + 48 hour 120°C Bake	120 ± 36[3]	0.84 ± 0.05

[1] 100 μm VEP, 800°C in vacuum for 3 hours, 800°C in 60 mTorr of N_2 for 20 minutes, 800°C in vacuum for 30 minutes.

[2] 100 μm EP, 800°C in vacuum for 3 hours, 900°C in 60 mTorr of N_2 for 20 minutes, 900°C in vacuum for 30 minutes, 18 μm EP.

[3] The 48 hour 120°C bake has been shown to affect only a fraction of the RF penetration layer. Because our method of mean free path extraction averages over this entire layer, the exact mean free path value is difficult to extract.

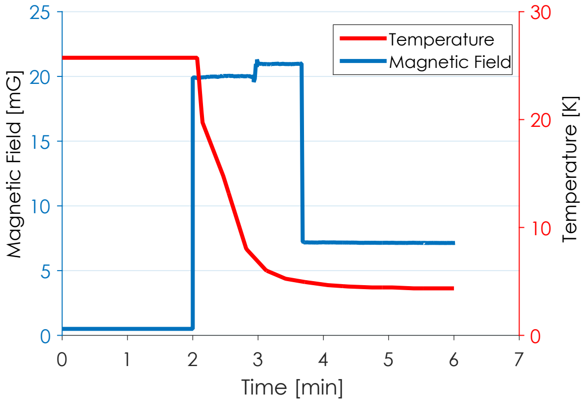

Figure 2: A schematic of a typical cool down. The cavity sits above T_c (at 25 K in this case) with the magnetic field off. The field is then turned on (to 20 mG in this case) and the cavity is cooled. There is a small jump in the magnetic field when the cavity becomes superconducting as flux is expelled. Once the cavity is cooled, the magnetic field is turned off and it drops to a higher value than before which represents the amount of magnetic field trapped in the cavity walls (trapped flux).

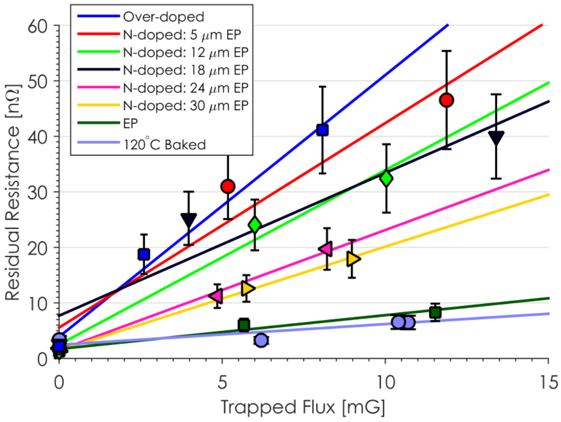

Figure 3: Residual resistance vs. trapped flux for all eight cavities. Cavities with higher levels of nitrogen-doping showed higher sensitivity. All nitrogen-doped cavities showed higher sensitivity than the two standard prepared cavities.

much lower than all the nitrogen-doped cavities. The exact sensitivities along with the extracted mean free paths for the cavities are shown in Table 1.

Nitrogen-doping also clearly lowers the mean free path of the material. This lower mean free path results in a higher sensitivities to trapped magnetic flux A plot of sensitivity to trapped flux (the slopes from Fig. 3) vs extracted mean free path is shown in Fig. 4. We can see that for dirty cavities, shorter mean free path leads to more susceptibility to trapped magnetic flux. This trend is in agreement with theoretical predictions that predict that shorter mean free path would result in higher sensitivity of residual resistance to trapped magnetic field [3].

CONCLUSIONS

We have shown that the exact sensitivity of a given SRF cavity to trapped magnetic flux depends very strongly on the cavity preparation. Nitrogen-doped cavities shown a stronger sensitivity than cavities prepared in a more standard way because they have a shorter mean free path than EP cavities. Ultimately this means that in order to achieve the high Q_0 values normally associated with nitrogen-doped cavities in practice, one must take action to cool down with large spatial temperature gradients for efficient flux expulsion [4] or improve magnetic shielding.

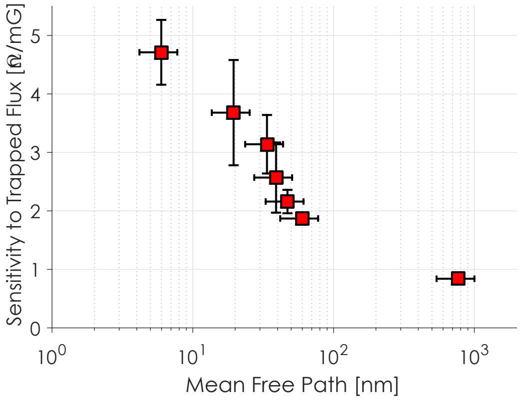

Figure 4: Sensitivity to trapped flux as a function of mean free path for the eight cavities. Larger mean free path results in less sensitivity to trapped flux.

REFERENCES

[1] J. Halbritter. FORTRAN-Program for the Computation of the Surface Impedance of Superconductors. *KAROLA - OA-Volltextserver des Forschungszentrums Karlsruhe [http://opac.fzk.de:81/oai/oai-2.0.cmp.S] (Germany)*, (3/70-6), 1970.

[2] D. Gonnella and M. Liepe. High Q0 studies at Cornell, September 2013.

[3] A. Gurevich and G. Ciovati. Dynamics of vortex penetration, jumpwise instabilities, and nonlinear surface resistance of type-II superconductors in strong rf fields. *Physical Review B*, 77(10):104501, 2008. PRB.

[4] D. Gonnella, R. Eichhorn, F. Furuta, M. Ge, D. Hall, V. Ho, G. Hoffstaetter, M. Liepe, T. O' Connell, S. Posen, P. Quigley, J. Sears, V. Veshcherevich, A. Grassellino, A. Romanenko, and D. A. Sergatskov. Nitrogen-doped 9-cell cavity performance in a test cryomodule for LCLS-II. *J. Appl. Phys.*, 117:023908, 2015.