RF LOSSES FROM TRAPPED FLUX IN SRF CAVITIES*

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Abstract

Previous measurements at Cornell have shown that the sensitivity of residual resistance to trapped magnetic field in SRF cavities is heavily dependent on the mean free path of the RF penetration layer of the niobium. Here we report on a systematic study of ten cavity preparations with different mean free paths and the effect of these preparations on sensitivity to trapped magnetic flux. In the clean limit, longer mean free path leads to a lower sensitivity to trapped magnetic flux while in the dirty limit the opposite is true, shorter mean free path leads to lower sensitivity. These results are also shown to be in good agreement with theoretical predictions of RF losses due to oscillations of vortex lines.

INTRODUCTION

Superconducting RF (SRF) cavities are the dominant driving force in today's modern accelerators. New machines such as LCLS-II at SLAC require the cavities to operate at high intrinsic quality factors, Q_0, in the medium field region [1]. Because Q_0 is inversely related to surface resistance, R_s, R_s must be minimized to reach optimal performance. This surface resistance can be broken up into two components: a temperature-dependent BCS resistance (R_{BCS}) and a temperature-independent residual resistance (R_{res}) [2]. R_{BCS} comes directly from the losses caused by oscillating electrons in an RF field and can be calculated from BCS theory [3]. R_{res} on the other hand has many contributions including losses from oxides, hydrides, and trapped magnetic flux [2]. Here we discuss an experiment to quantify how trapped magnetic flux leads to residual resistance for cavities of different preparation methods and how this behavior compares with expectations from theory.

THEORETICAL CONSIDERATIONS

In 2013 Gurevich and Ciovati developed a model to explain the additional residual resistance a cavity will have from trapped magnetic flux [4]. They studied the impact of normal conducting vortices on the surface resistance for fields perpendicular to the cavity surface by calculating the losses due to the oscillations of vortex lines under RF fields. The dissipated power from a single vortex line can be calculated as

$$P = \frac{H_p^2 \phi_0^2 \left(\sinh\sqrt{2\nu} - \sin\sqrt{2\nu}\right)\sqrt{\nu}}{2^{3/2}\eta \ell_p \left(\cosh\sqrt{2\nu} + \cos\sqrt{2\nu}\right)}, \tag{1}$$

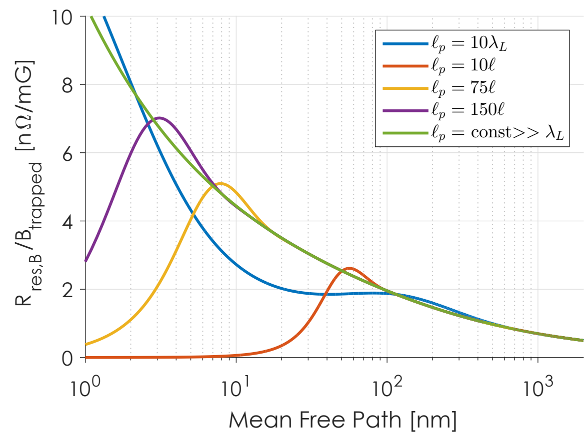

Figure 1: Residual resistance from trapped flux normalized to the amount of trapped flux as predicted by the Gurevich theory [4] for different interpretations of the mean spacing between pinning cites.

where H_p is the RF peak magnetic field, ϕ_0 is the flux quantum and ℓ_p is the mean spacing between pinning centers, with

$$\nu = \omega\eta\ell_p^2/\epsilon, \quad \epsilon = \frac{\phi_0^2 g}{4\pi\mu_0\lambda^2}, \tag{2}$$

$$\eta = \phi_0 B_{c2}/\rho_n, \quad g = \ln\kappa + \frac{1}{2}, \tag{3}$$

where κ is the GL parameter, B_{c2} is the upper critical field, ω is the resonance frequency, λ is the penetration depth, and ρ_n is the normal conducting resistivity (proportional to one over the mean free path with constant of proportionality 0.37×10^{-15} $\Omega\cdot$ m^2 [5]). From Equation 1, the additional residual resistance can be calculated for a given amount of trapped magnetic flux

$$R_{res,B} = \frac{2PB_{trapped}}{\phi H_p^2}. \tag{4}$$

It is then useful to normalize to the trapped field and define the sensitivity parameter, $R_{res,B}/B_{trapped}$. This sensitivity of residual resistance to trapped magnetic flux quantifies how much additional residual resistance to expect from a given amount of trapped magnetic flux.

The Gurevich theory is heavily dependent on material parameters such as the mean free path and also the mean spacing between pinning sites, ℓ_p. There is however no good intuition for how ℓ_p should be calculated. Figure 1 shows $R_{res,B}/B_{trapped}$ versus mean free path (ℓ) calculated from Equation 4 for different interpretations of ℓ_p. Two

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distinct regions emerge. In the clean limit, $R_{\mathrm{res,B}}/B_{\mathrm{trapped}}$ decreases as $1/\sqrt{\ell}$. In the dirty limit however behavior is very different based on how ℓ_p is calculated. For constant ℓ_p, $R_{\mathrm{res,B}}/B_{\mathrm{trapped}}$ increases very quickly as $1/\ell^2$ as ℓ decreases. However, if one assumes a linear relationship between the mean free path and the mean spacing between pinning sites as

$$\ell_p = C\ell, \tag{5}$$

then a maximum $R_{\mathrm{res,B}}/B_{\mathrm{trapped}}$ is found. In the very dirty limit $R_{\mathrm{res,B}}/B_{\mathrm{trapped}}$ decreases as the mean free path is decreased. The exact position and height of this maximum is dependent on the constant of proportionality, C. This linear relationship is a reasonable assumption because it is likely that vortex lines will be pinned at defects, which are related to the mean free path.

EXPERIMENTAL APPARATUS

In order to study how $R_{\mathrm{res,B}}/B_{\mathrm{trapped}}$ is affected by cavity preparation, an experiment was carried out on 8 nitrogen-doped cavities [6] and two standard prepared cavities (EP and EP+48 hour 120°C heat treatment). Nitrogen-doping strongly affects the mean free path of the RF penetration layer and provides a useful knob to turn to study the effects of changing mean free path [7]. The nitrogen-dopings consisted of 6 cavities doped at 800°C in 60 mTorr of nitrogen for 20 minutes followed by a 30 minute anneal. After doping they were given different amounts of final vertical electropolish (VEP) [8]. The other two nitrogen-doped cavities were doped at higher temperatures, 900 and 990°C, respectively followed by small amounts of VEP. The ninth cavity was prepared with just a bulk VEP and the tenth with bulk VEP followed by a 48 hour 120°C heat treatment.

A picture of the experimental apparatus is shown in Fig. 2. The cavities were all 1.3 GHz ILC shaped single-cell cavities and were surrounded by a Helmholtz coil to apply a uniform external magnetic field parallel to the cavity axis. Temperature sensors were placed on the equator and both cavity flanges to measure cool down rates and gradients and a fluxgate magnetometer was placed on the iris to measure the applied and trapped magnetic field at that location. A full description of the methods used to extract magnetic flux is given in [9].

For each cavity, at least three cool downs were completed in different amounts of trapped magnetic flux. The residual resistance was extracted for each of these cool down and $R_{\mathrm{res,B}}/B_{\mathrm{trapped}}$ was found by applying a linear fit to the $\mathrm{R_{res}}$ versus trapped flux data. The mean free path, $\mathrm{T_c}$, and energy gap ($\Delta/\mathrm{k_B T_c}$) were also extracted for each cavity by fitting the change in $\mathrm{R_s}$ and penetration depth with temperature using BCS theory and the methods described in [9].

EXPERIMENTAL RESULTS

The extracted material parameters along with the measured $R_{\mathrm{res,B}}/B_{\mathrm{trapped}}$ for each of the ten cavities are shown in Table 1. Additionally, Fig. 3 shows $\mathrm{R_{res}}$ versus trapped

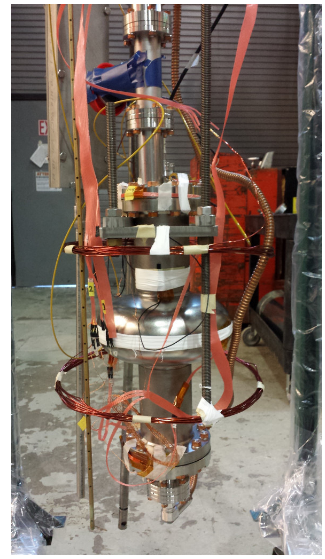

Figure 2: Experimental apparatus to measure the effects of trapped flux on cavity performance. A single-cell 1.3 GHz ILC shaped cavity was surrounded by a Helmholtz coil and dressed with fluxgate magnetometers on the iris and temperature sensors on the equator and both flanges.

flux for three specific cavities. There are several important points to take away from Table 1 and Fig. 3:

1. $\mathrm{R_{res}}$ increases linearly with trapped magnetic flux. This is expected from the Gurevich theory and from physical intuition in which each votex contributes a quantized amount of $\mathrm{R_{res}}$. The slope of this relationship is $R_{\mathrm{res,B}}/B_{\mathrm{trapped}}$.

2. There is not a strong correlation between $\mathrm{T_c}$ or $\Delta/\mathrm{k_B T_c}$ and $R_{\mathrm{res,B}}/B_{\mathrm{trapped}}$. There is however a strong correlation between ℓ and $R_{\mathrm{res,B}}/B_{\mathrm{trapped}}$.

3. There is a large spread in $R_{\mathrm{res,B}}/B_{\mathrm{trapped}}$ based on cavity preparation and mean free path.

4. All nitrogen-doped cavities measured showed a higher $R_{\mathrm{res,B}}/B_{\mathrm{trapped}}$ than the two cavities prepared with standard methods.

It is useful to compare the measured values of $R_{\mathrm{res,B}}/B_{\mathrm{trapped}}$ and mean free path with the predictions from the Gurevich theory. Figure 4 shows $R_{\mathrm{res,B}}/B_{\mathrm{trapped}}$ versus ℓ for the cavities tested (except for the 120°C treated cavity). Also shown is a fit to the data using the Gurevich theory. This fit was obtained with only one fit parameter, the constant of proportionality between the mean free path and the mean spacing between pinning sites. It is clear that there is very good agreement between the theoretical prediction and the experimental data. The maximum $R_{\mathrm{res,B}}/B_{\mathrm{trapped}}$ occurs at a mean free path of ~10 nm. Also shown is a $1/\sqrt{\ell}$ fit to the data in the clean limit showing that it very closely follows the predicted behavior in this limit.

Table 1: Extracted Properties of Cavities Tested

Cavity Name	Preparation	T_c [K]	Δ/k_BT_c	Mean Free Path [nm]	$R_{\mathrm{res,B}}/B_{\mathrm{trapped}}$ [nΩ/mG]
LT1-3	990°C N-Doping[1]+ 5 μm VEP	9.1 ± 0.1	2.05 ± 0.01	4 ± 1	3.2 ± 0.5
LT1-2	900°C N-Doping[2]+ 18 μm VEP	9.1 ± 0.1	2.00 ± 0.01	6 ± 1	4.7 ± 0.6
LT1-2	800°C N-Doping[3]+ 6 μm VEP	9.3 ± 0.1	1.88 ± 0.01	19 ± 6	3.7 ± 0.9
LT1-3	800°C N-Doping[3]+ 12 μm VEP	9.3 ± 0.1	1.91 ± 0.01	34 ± 10	3.1 ± 0.5
LT1-1	800°C N-Doping[3]+ 18 μm VEP	9.3 ± 0.1	1.88 ± 0.01	39 ± 12	2.5 ± 0.6
LT1-4	800°C N-Doping[3]+ 24 μm VEP	9.2 ± 0.1	1.89 ± 0.01	47 ± 14	2.2 ± 0.2
LT1-5	800°C N-Doping[3]+ 30 μm VEP	9.2 ± 0.1	1.88 ± 0.01	60 ± 18	1.87 ± 0.08
LT1-5	800°C N-Doping[3]+ 40 μm VEP	9.2 ± 0.1	1.94 ± 0.01	213 ± 64	1.06 ± 0.02
NR1-3	100 μm VEP	9.2 ± 0.1	1.81 ± 0.01	800 ± 100	0.6 ± 0.1
NR1-3	100 μm VEP + 48 hour 120°C Bake	9.2 ± 0.1	1.96 ± 0.01	120 ± 36[4]	0.88 ± 0.07

[1] 100 μm VEP, 800°C in vacuum for 3 hours, 990°C in 30 mTorr of N_2 for 5 minutes.
[2] 100 μm VEP, 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.
[3] 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.
[4] The 48 hour 120°C bake has been shown to affect only the mean free path in a fraction of the RF penetration layer [10]. Because our method of mean free path extraction averages over this entire layer, the exact mean free path value is difficult to extract.

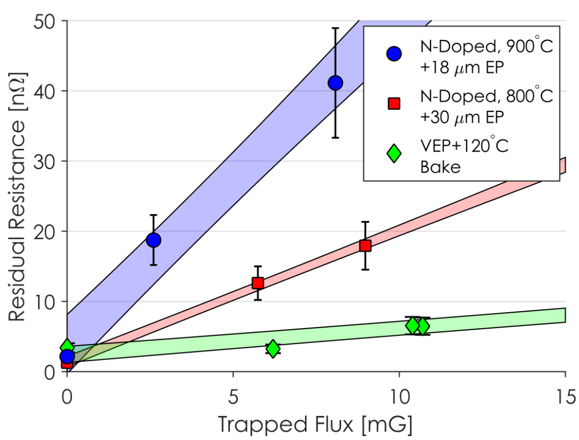

Figure 3: Residual resistance versus trapped magnetic flux for three of the cavities tested. R_{res} increases linearly with trapped flux and there is a large spread in slopes.

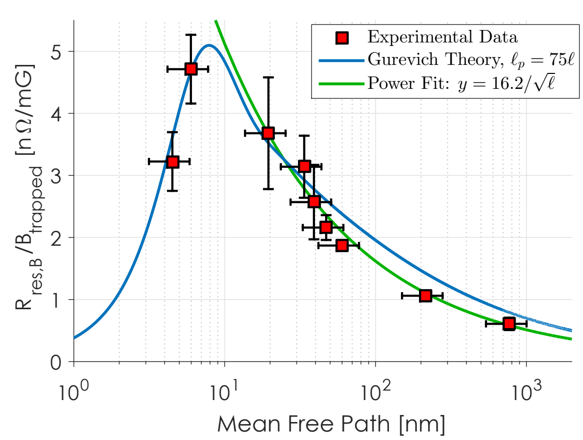

Figure 4: Sensitivity of residual resistance to trapped magnetic flux ($R_{\mathrm{res,B}}/B_{\mathrm{trapped}}$) versus mean free path for the cavities tested. Also shown in a fit to the Gurevich theory assuming a linear relationship between mean free path and mean spacing between pinning sites. The only fit parameter is the constant of proportionality between these quantities.

CONCLUSIONS

The method of cavity preparation has been shown to have a very strong impact on the sensitivity of residual resistance to trapped magnetic flux. Changing mean free path of the RF penetration layer directly leads to changes in $R_{\mathrm{res,B}}/B_{\mathrm{trapped}}$. In the clean limit, shorter mean free paths lead to larger $R_{\mathrm{res,B}}/B_{\mathrm{trapped}}$ while in the dirty limit shorter mean free paths lead to lower $R_{\mathrm{res,B}}/B_{\mathrm{trapped}}$. These measurements on ten individual SRF cavities of different preparations are in very good agreement with Gurevich's theory of vortex oscillations. This leads to a maximum sensitivity of residual resistance to trapped magnetic flux at a mean free path of approximately 10 nm.

The measurements discussed here provide insight into how best to minimize the contributions to residual resistance by trapped magnetic flux. Due to the lowering of the mean free path, nitrogen-doping inherently leads to larger $R_{\mathrm{res,B}}/B_{\mathrm{trapped}}$ than cavities prepared with standard methods. This effect however can be mitigated with improved magnetic shielding, making the benefits of nitrogen-doping outweigh the impact of worse sensitivity of residual resistance to trapped magnetic flux.

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