TRAPPED FLUX SURFACE RESISTANCE ANALYSIS FOR DIFFERENT SURFACE TREATMENTS*

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Abstract

The trapped flux surface resistance is one of the main contributions on cavity losses which appears when cavities are cooled in presence of external magnetic field. The study is focused on the understanding of the different parameters which determine the trapped flux surface resistance, and how this change as a function of different surface treatments. The study is performed on 1.3 GHz niobium cavities processed with different surface treatments after the 800 °C bake: electro-polishing (EP), 120 °C baking, and N-doping varying the time of the Nitrogen exposure. The trapped flux surface resistance normalized for the trapped magnetic flux is then analyzed as a function of the mean free path in order to find the surface treatment which minimized the trapped flux sensitivity.

INTRODUCTION

When type II superconductors are cooled below their critical temperature the material pass through the mixed stated before stabilizing in the Meissner state. While in the mixed state the magnetic field is free to penetrate the superconductor, in the Meissner state the superconductor behaves as a perfect diamagnet.

During the transition between these two states the Meissner effect guarantees the magnetic flux expulsion from the superconductor. However, whenever defects are present inside the superconductor, magnetic flux may be energetically favorable to stay pinned inside the material, and the Meissner effect would be incomplete [1].

Some studies [2, 3] highlighted the fact that when the cavity is cooled below its critical temperature, the amount of trapped magnetic field depends on the thermal gradients at the transition phase front. Large thermal gradients are usually achieved with fast cooldowns with starting temperature as higher as possible than the critical temperature. On the other hand, the amount of trapped flux increases when the cavity is cooled with slow cooldowns with starting temperature close to the critical one. In particular when the cooldown is done really slow all the external magnetic field is trapped into the cavity walls.

The magnetic field trapped into the superconductor causes additional losses which substantially lower the Q-factor of the accelerating cavity.

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This effect becomes particularly important in the case of N-doped cavities since they are more sensitive at the trapped flux compared to non doped cavities [4].

In this paper the trapped flux sensitivity is studied for cavities processed with different surface treatments after the baking at 800 °C: electro-polishing (EP), 120 °C baking, and various N-doping recipes.

The trapped flux sensitivity was found to be dependent on the mean free path l, and experimentally was observed the presence of a maximum of magnetic trapped flux sensibility around $l \simeq 50$ nm.

EXPERIMENTAL SET-UP

All the cavities analyzed are single cell 1.3 GHz Tesla-type niobium cavities. A scheme of the instrumentation of those cavities is shown in Fig. 1. They were instrumented with a pair of Helmholtz coils in order to adjust the magnetic field around the cavity as desired. Four Barlington single axis flux gate magnetometers (green rectangular in the figure) were placed equidistantly around the cavity equator in order to monitor the external magnetic field during the cavity cooldown. In order to supervise the cooldown details the cavity was also equipped with three thermometers (orange squares in the figure), one at the lower iris, one at the equator and one at the upper iris.

Every cavity was measured after both fast ans slow cooldowns:

1. Fast cooldown:
   - Compensating the magnetic field outside the cavity in order to minimize its value during the SC cavity transition
   - With Helmholtz coils switched off making sure that the magnetic expulsion was total
2. Slow cooldown with 10 mG of applied magnetic field

The detailed explanation of such procedures will be explained in the following sections.

All the RF tests performed were conducted at the vertical test facility (VTS) of Fermi National Accelerator Laboratory (FNAL).

ORIGIN OF TRAPPED MAGNETIC FLUX

As mentioned in the introduction, the magnetic flux can be trapped during the normal conducting (NC) - superconducting (SC) transition of the cavity.

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The amount of the magnetic flux trapped in or expelled from the cavity material can be estimated from the ratio between the magnetic field after (B_{SC}) and before (B_{NC}) the SC transition. Indeed, in case of parallel field to the beam axis, when the cavity fully expel all the external magnetic field this ratio is about 1.8 at the cavity equator [2]. On the other hand, when the cavity traps all the magnetic field there are no changes in the amount of magnetic field measured at the equator (or in other regions closed to the cavity surface).

Making a simple proportionality it is possible to estimate the percentage of trapped flux as follow:

$$B_{trap}(B_{NC}, \frac{B_{SC}}{B_{NC}}) = B_{NC}\left(1 - \frac{\frac{B_{SC}}{B_{NC}} - 1}{0.8}\right) \quad (1)$$

In Fig. 2 the ratio B_{SC}/B_{NC} is showed as a function of the thermal gradient between the equator and the upper iris of the cavity. This thermal gradient is calculated as the difference between the temperature measured in the upper iris of the cavity when the equator reached T_c and the critical temperature.

The graph clearly shows that the larger is the thermal gradient, the more efficient is the magnetic flux expulsion. The trend differs for different cavities and not all the cavities analyzed reached the condition of full flux expulsion. More detailed studies on the expulsion behavior of different cavities is reported in [5].

Important for the purpose of this paper is that the amount of the trapped flux does not depends only on the amount of external magnetic field which surrounds the cavity during the SC transition, but also depends on the cooldown details which tweak the magnetic flux trapping efficiency and therefore determine the real amount of magnetic flux trapped at the cavity RF surface.

TRAPPED FLUX SURFACE RESISTANCE

When the magnetic field is trapped in the superconductor, the surface resistance can be defined as sum of three different terms: the BCS surface resistance R_{BCS}, the intrinsic residual resistance R_0 and the trapped flux surface resistance R_{fl}.

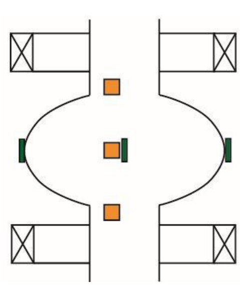

Figure 1: Scheme of the cavity instrumentation: four flux-gates magnetometer around the equator (green rectangles), three thermal sensor at the bottom iris, equator and upper iris (orange squares), pair of Helmholtz coils.

Since the trapped flux surface resistance does not depend on temperature, usually this term is associated with the residual resistance without distinguish the two different contributions. In this paper we separate the trapped flux surface resistance from the intrinsic cavity residual resistance:

$$R_s(T, B_{trap}) = R_{BCS}(T) + R_{fl}(B_{trap}) + R_0 \quad (2)$$

At low temperatures the BCS surface resistance contribution becomes negligible and the surface resistance can be approximated as:

$$R_s(B_{trap}) \simeq R_{fl}(B_{trap}) + R_0 \quad (3)$$

The trapped flux surface resistance can be calculated as the difference between the surface resistance measured at low temperature and the intrinsic residual resistance of the cavity:

$$R_{fl}(B_{trap}) = R_s(B_{trap}) - R_0 \quad (4)$$

The surface resistance values are experimentally determined from the Q-factor versus accelerating field RF measurements. In particular, the surface resistance $R_s(B_{trap})$ is obtained from the Q-factor measured at low temperature, usually about 1.5 K, and at fixed value of accelerating field, where $R_s = G/Q$.

In order to minimize the uncertainty of the trapped field estimation, the value of the surface resistance was calculated from the RF measurement after a slow cooldown in about 10 mG. In this way the value of the trapped flux surface resistance for the cavities studied was extracted after similar cooldown conditions.

The value of the intrinsic surface resistance R_0 is determined from the Q-factor measured after a cooldown with very low value of trapped magnetic field, so that $R_{fl} = 0$ and $R_s = R_0$. In order to obtain very low values of trapped magnetic flux the magnetic field outside the cavity was compensated to zero during the cooldown in order to obtain values on average lower than 1 mG at the equator. Alternatively, when possible, the measurement was done after a complete magnetic flux expulsion ($B_{SC}/B_{NC} = 1.8$ at the equator).

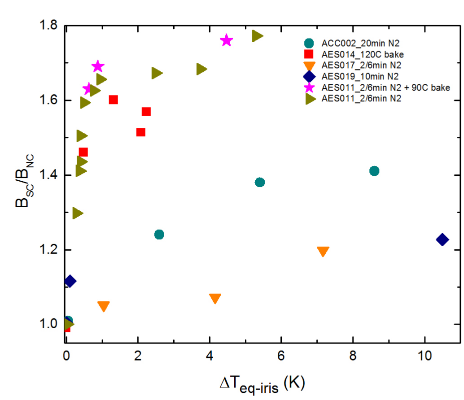

Figure 2: Ratio of the magnetic field after and before the SC transition as a function of the thermal-gradient between the equator and the upper iris of the cavity.

Table 1: Summary of the treatments done on the analyzed cavities with the estimated values of mean free path and trapped flux sensitivity.

Cavity Name	Surface Treatment	Mean Free Path (nm)	R_{fl}/B_{trap} (nΩ/mG)
TE1AES011	2/6min N2 + 2mm EP + 90C bake + 3mm EP	143	1.24
TE1AES017	2/6min N2 + 5mm EP	180	0.98
TE1AES018	30min He	270	0.71
TE1AES019	10min N2 + 5mm EP	168	1.24
TE1ACC002	20min N2 + 5mm EP	50	1.96
TE1AES014	120C bake	2	0.52

TRAPPED FLUX SENSITIVITY

The trapped flux sensitivity determines the amount of losses per unit of magnetic field trapped and can be defined as:

$$Sensitivity = \frac{R_{fl}}{B_{trap}} \quad (5)$$

Cavities with large trapped flux sensitivity will have lower Q-factors, i.e. higher surface resistance, respect to cavity with low sensitivity, per same amount of trapped flux.

The sensitivity was calculated normalizing the trapped flux surface resistance respect with the amount of trapped magnetic field.

During a slow cooldown the magnetic flux is usually all trapped, but sometimes the cooldown dynamics allow some flux to be expelled. In order to take into account that, the trapped magnetic flux is calculated using Equation 1.

The values of sensitivity estimated for the cavities analyzed are shown in Fig. 3 and in Table 1.

All the cavities analyzed are baked at 800 °C for three hours followed by the treatment explained in Table 1. The $2/6min$ N-doping treatment corresponds to a nitrogen exposure of the cavity (25 mTorr) at 800 °C for 2 minutes, followed by an annealing step at 800 °C for 6 minutes. The heating is then stopped and the cavity let cooling to room temperature. The other N-doping recipes under study, $10min$ and $20min$, imply that the cavity is left at 800 °C for 10 or 20 minutes in presence of nitrogen (25 mTorr) and then cooled down to room temperature [6].

The cavity AES018 was treated with helium at 800 °C, since helium is a noble gas, it is not energetically favorable to diffuse into niobium via thermodynamic process such as gas-solid absorption. The performance of this cavity He-treated were indeed the same of an usual electropolished (EP) cavity.

From this data it appears clear that the trapped flux sensitivity depends on the surface treatments. In particular N-doped cavities have higher sensitivity than standard EP and 120 °C bake cavities. Anyway looking at the N-doped cavities, their sensitivity is not always the same but it depends on the doping recipe. Heavily doped cavities, as ACC002, show higher sensitivity than lightly doped cavities as AES017.

This is the first hint that the sensitivity depends on the cavity mean free path, which is determined by the surface treatment.

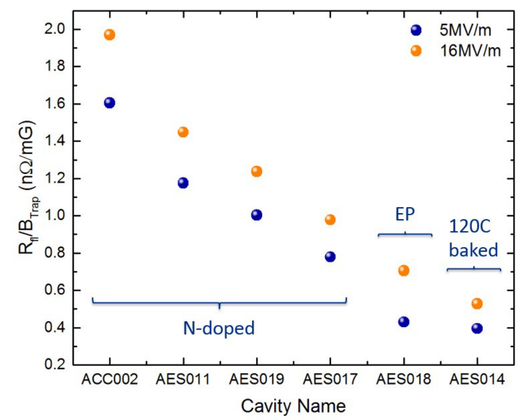

Figure 3: Trapped flux sensitivity values estimated at 5 and 16 MV/m for cavities with different surface treatments.

The mean free path of the cavities analyzed was estimated using a MATLAB® version of SRIMP [7] developed by Cornell [8, 9].

The cavity resonance frequency as a function of the temperature during the cavity warm up through the critical temperature was acquired in order to obtain the variation of the penetration depth with the temperature close to T_c. These measurements were done by using a network analyzer which fed the cavity with low power.

In addition, in order to obtain the variation of the surface resistance as a function of the temperature, for $T \leq T_c/2$ the Q factor as a function of the temperature was acquired at low field, 5 MV/m, from 2 K to 1.5 K. In order to maximize the range of data useful to obtain a good estimation of the superconducting energy gap Δ. Such measurement was always done after the cooldown with approximately no trapped magnetic flux at the cavity surface, so the residual resistance is minimized to the intrinsic one only.

The MATLAB®/SRIMP program is used to estimate the value of mean free path which minimize the uncertainty of the interpolation of both curves penetration depth versus temperature and surface resistance versus temperature [9]. The fixed parameters are: the critical temperature, T_c, the coherence length, ξ_0, the London penetration depth, λ_L. The parameters obtained from the program are: mean free path, l, reduced energy gap, $\frac{\Delta}{kT_c}$, penetration depth at $T = 0$ K, λ_0.

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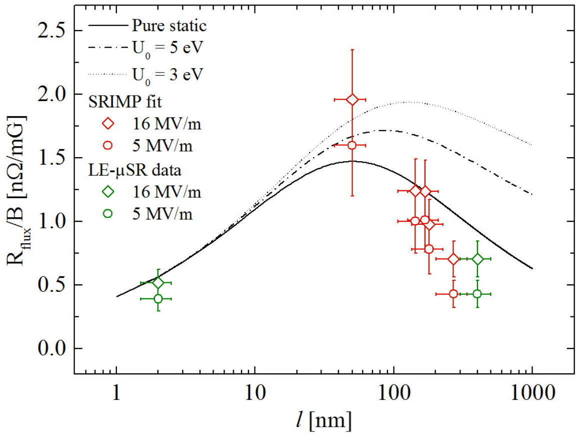

Figure 4: Trapped flux sensitivity calculated at 5 and 16 MV/m as a function of the mean free path. The red points' mean free path was estimated using SRIMP, the green points' ones were instead estimated from LE-μSR measurements. The black curves corresponds to the theoretical trend calculated in [11].

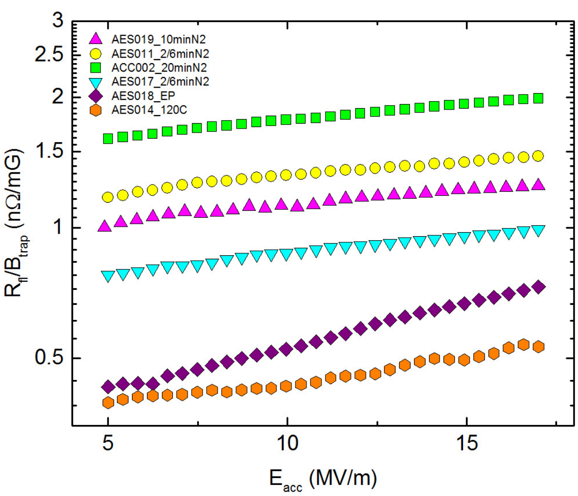

Figure 5: Trapped flux sensitivity as a function of the accelerating field.

The critical temperature was estimated from the measurement of the resonance frequency as a function of the temperature. Indeed the resonance frequency of the cavity drops during the transition through the normal conducting state, and stabilizes once the cavity becomes normal conducting. The critical temperature is then calculated as the average between the temperature of the last point of the cavity in the SC state and the first point of the cavity in the NC state.

The London penetration depth was instead fixed to λ_L = 39 nm, and the coherence length to ξ_0 = 38 nm.

This method for the estimation of the mean free path was used for the N-doped cavities and for the EP cavity but not for the 120 °C bake cavity.

The reason of this choice starts with the fact that we are interested at the values of the mean free path within the penetration depth at low temperature. The 120 °C bake treatment modifies the mean free path on the very surface of the cavity. For temperatures close to T_c the penetration depth becomes larger than the modified layer, probing a zone which is not representative of the mean free path in the interested region [10].

This technique is instead suitable in case of EP or N-doped cavities because in such cases the material properties are practically unchanged for several microns.

For this reason in Table 1 the value reported of the mean free path is the one estimated from LE-μSR measurements for a 120 °C bake cavity [10].

The data of trapped flux sensitivity as a function of the mean free path are shown in Fig. 4. For each cavity the sensitivity is calculated both at 5 and 16 MV/m. This graph is the experimental proof that the sensitivity has a maximum around 50 nm of mean free path, in agreement with theoretical model indicated with the black lines [11].

The mean free path of ACC002 (50 nm) causes its sensitivity to fall at the maximum of this curve, lightly doped cavities have instead larger values of mean free path, around 180 nm, so their sensitivity is lower and closer to the sensitivity of EP cavities.

Interesting is that 120 °C bake and EP cavities have very different values of mean free path, but they are both far from the maximum of the curve, allowing lower sensitivity.

In addition, the trapped flux sensitivity shows a dependence on the accelerating field (Fig. 5). In particular it increases linearly with the field, in agreement with what already found for the trapped flux surface resistance studies done on thin film cavities [12].

In Fig. 5 the curves of sensitivity as a function of the accelerating field are shown for the cavity analyzed. The slope of this curves appears to be almost the same for all the N-doped cavities studied, to be lower than the slope of non doped cavities. In particular, the EP cavity show the larger slope of the sensitivity versus accelerating field curve.

This means that the accelerating field dependence of N-doped cavities is lower than EP cavities. Therefore, their sensitivity will converge to the EP cavities' one at higher field.

CONCLUSIONS

The trapped flux sensitivity depends strongly on the cavity surface treatment, i.e. on the mean free path.

We experimentally found that the sensitivity is low for very small values of mean free path (as for 120 °C bake cavities), it increases reaching a maximum around l = 50 nm (over doped cavities), and decreases reaching again low values for large mean free path (as EP cavities).

It is therefore possible to tune the mean free path of N-doped cavities in order to optimize the value of magnetic flux sensitivity. Indeed from this study appears that lightly doped cavities have reasonable values of sensitivity, less than 1 nΩ/mG at low field.

In addition it was found that the sensitivity always increases with the accelerating field, and this effect is more important for EP cavities than N-doped cavities. As results the sensitivity of N-doped cavities may become the same of EP cavities at high accelerating field.

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