TAILORING SURFACE IMPURITY CONTENT TO MAXIMIZE Q-FACTORS OF SUPERCONDUCTING RESONATORS *

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Abstract

Quality factor of superconducting radio-frequency (SRF) cavities is degraded whenever magnetic flux is trapped in the cavity walls during the cooldown. In this contribution we study how the trapped flux sensitivity, defined as the trapped flux surface resistance normalized for the amount of flux trapped, depends on the mean free path. A variety of 1.3 GHz cavities with different surface treatments (EP, 120 °C bake and different N-doping) were studied in order to cover the largest range of mean free path possible, from few to thousands of nanometers. A bell shaped trend appears for the range of mean free path studied. Over doped cavities fall at the maximum of this curve defining the largest values of sensitivity. In addition, we have also studied the trend of the BCS surface resistance contribution as a function of mean free path, revealing that N-doped cavities follow close to the theoretical minimum of the BCS surface resistance as a function of the mean free path. Adding these results together we show that optimal N-doping treatment allows to maximize Q-factor at 2 K and 16 MV/m as long as the magnetic field fully trapped during the cavity cooldown stays below 10 mG.

INTRODUCTION

When a type II superconductor is cooled below its critical temperature in presence of magnetic field, the superconductor passes through the mixed stated before stabilizing in the Meissner state. During the transition between these two states the Meissner effect guarantees the magnetic flux expulsion from the superconductor. However, whenever defects are present, the magnetic flux may be energetically favorable to stay pinned inside the material, and the Meissner effect would be incomplete. This trapped magnetic flux contributes to radio-frequency (RF) surface resistance (R_s), increasing the residual resistance contribution [1].

Recent studies [2–4] have shown that performing fast cooldowns, with large thermal gradients along the cavity length, it is possible to obtain efficient magnetic flux expulsion. On the other hand, slow and homogeneous cooling through transition leads to full flux trapping.

The amount of trapped flux does not depends only on the amount of external magnetic field which surrounds the cavity during the superconducting (SC) transition, but also 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.

In this paper the trapped flux sensitivity and the BCS surface resistance are studied for cavities subject to different surface treatments after the baking at 800 °C: electropolishing (EP), 120 °C baking, and N-doping with different time of nitrogen exposure and EP removal.

EXPERIMENTAL PROCEDURE

All the cavities analyzed are single cell 1.3 GHz Tesla-type Niobium cavities. A scheme of the instrumentation used for such characterization is shown in Fig. 1 in previous work [5]. A Helmontz coil was used in order to provide the desired the magnetic field around the cavity. Three or four Barlington single axis fluxgate magnetometers were placed equidistantly around the cavity equator in order to monitor the external magnetic field during the cavity SC transition. The cavity was also equipped with three thermometers, one at the lower iris, one at the equator and one at the upper iris in order to monitor the cooldown details.

In order to estimate the trapped flux surface resistance, every cavity was measured, at least, after two different cooldowns: i) compensating the magnetic field outside the cavity in order to minimize its value during the SC cavity transition, ii) cooling slowly the cavity with about 10 mG of external magnetic field.

After each of these cooldowns, the cavities were tested at the Vertical Test Facility (VTS) at Fermilab. Curves of Q-factor versus accelerating field were always acquired at both 2 and 1.5 K.

When the magnetic field is trapped in the superconductor, the surface resistance can be defined as sum between the BCS surface resistance, $R_{BCS}(T)$, and the residual resistance, R_{res}. Since the trapped flux surface resistance does not depend on temperature, this term is usually associated with the residual resistance without discriminate between these different contributions. In this paper we distinguish from the trapped flux surface resistance, R_{fl}, and the "intrinsic" residual resistance, R_0.

At 1.5 K the BCS surface resistance contribution becomes negligible and the trapped flux surface resistance can be calculated as:

$$R_{fl}(B_{trap}) = R_s(B_{trap}) - R_0 \qquad (1)$$

Where $R_s(B_{trap})$ is the value of the surface resistance calculated from the RF measurement after slow cooldowns in about $10-20$ mG. In this way $B_{trap} \simeq B_{NC}$ and the

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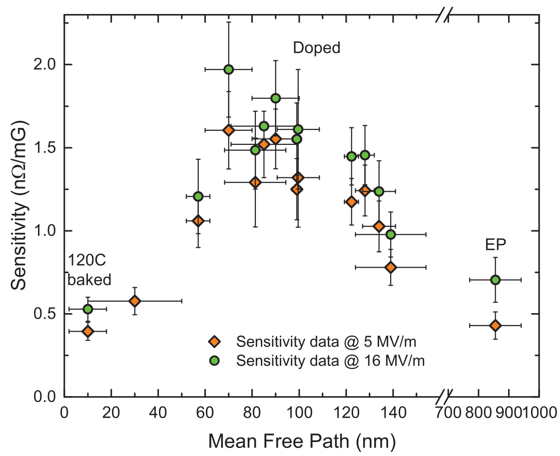

Figure 1: Trapped flux sensitivity calculated at 5 (orange diamonds) and 16 MV/m (green circles) as a function of the mean free path.

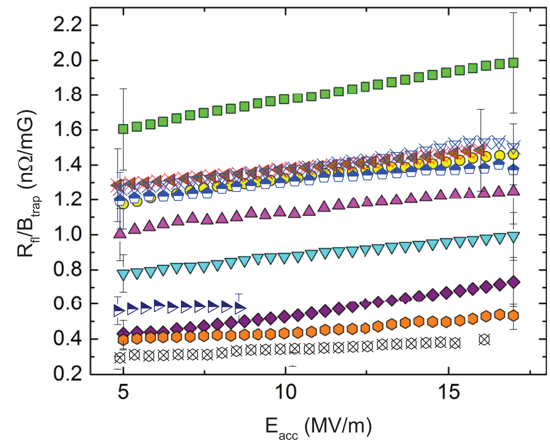

Figure 2: Sensitivity versus accelerating field of some of the cavities analyzed.

trapped flux surface resistances of different cavities are estimated after similar cooldown conditions. The intrinsic surface resistance R_0 is instead estimated from the Q-factor measured after cooldown with very low value of trapped flux, so that $R_{fl} \simeq 0$ and $R_s \simeq R_0$. In order to obtain very low value of trapped flux, the magnetic field outside the cavity was compensated during the cooldown through the SC transition. The average value of magnetic field measured at the cavity equator was always lower than 1 mG. Alternatively, when possible, the measurement was done after a complete magnetic flux expulsion ($B_{SC}/B_{NC} \sim 1.8$ at the equator). We have observed that these two methods gave the same results within the measurements uncertainties.

The trapped flux sensitivity determines the amount of cavity losses per unit of trapped flux and can be estimated by normalizing the trapped flux surface resistance for the amount of magnetic field trapped (B_{trap}) during each cooldown:

$$Sensitivity = \frac{R_{fl}}{B_{trap}} \tag{2}$$

The value of BCS surface resistance are instead estimated simply by subtracting the surface resistance measured at 2 K with the one measured at 1.5 K:

$$R_{BCS} = R_s(2K) - R_s(1.5K) \tag{3}$$

RESULTS AND DISCUSSION

All the cavities analyzed are baked at 800 °C for three hours followed by different surface treatments as: N-doping with different recipes, 120 °C bake and EP. In this way we had the possibility to study cavities within a wide range of mean free path at the cavity surface.

The mean free path of the cavities analyzed was estimated by means of a $C++$ translated version of SRIMP [6] implemented in the OriginLab data analysis program.

The cavity resonance frequency as a function of the temperature during the cavity warm up was acquired in order to obtain the variation of the penetration depth with the temperature close to T_c [7]. These measurements were done by using a network analyzer which fed the cavity with low power.

Then the variation of the penetration depth with the temperature is interpolated using SRIMP and fixing the following parameters: critical temperature (T_c), coherence length ($\xi_0 = 38$ nm), London penetration depth ($\lambda_L = 39$ nm). The parameters obtained from the code are: mean free path (l), reduced energy gap ($\frac{\Delta}{kT_c}$), penetration depth at $T = 0$ K (λ_0), residual resistance (R_0).

This method of estimation of the mean free path was used for the N-doped and EP cavities but not for 120 °C bake cavity. Indeed the 120 °C bake treatment modifies the mean free path at the very surface of the cavity and for temperatures close to T_c the penetration depth becomes larger than the modified layer, probing a region which is not representative of the mean free path in the interested region. For this reason for such cavity we used the mean free path directly measured with LE-μSR in a representative 120 °C bake cavity cut-out [8].

The results obtained for the sensitivity as a function of mean free path are depicted in Fig. 1. With this graph a clear bell-shaped trend appears for the trapped flux sensitivity as a function of the mean free path.

Looking at the surface treatment, N-doped cavities have higher sensitivity than standard EP and 120 °C bake cavities. The sensitivity also varies depending on the doping treatment, heavily doped cavities follows at the maximum of the curve while lightly doped cavities show the lower values of sensitivity for N-doped cavities.

Interesting is that standard treated niobium cavities as 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 low values of sensitivity.

ISBN 978-3-95450-147-2

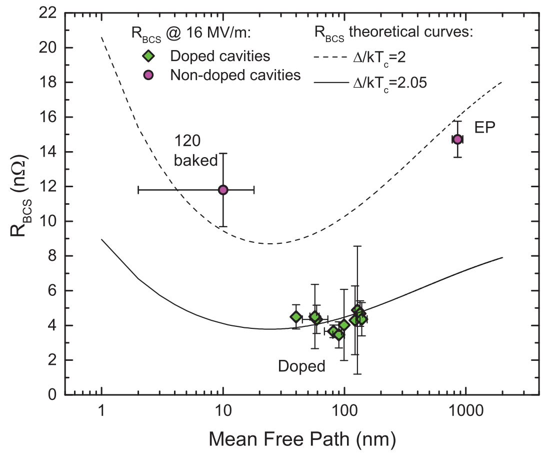

Figure 3: BCS surface resistance at 2 K and 16 MV/m as a function of mean free path.

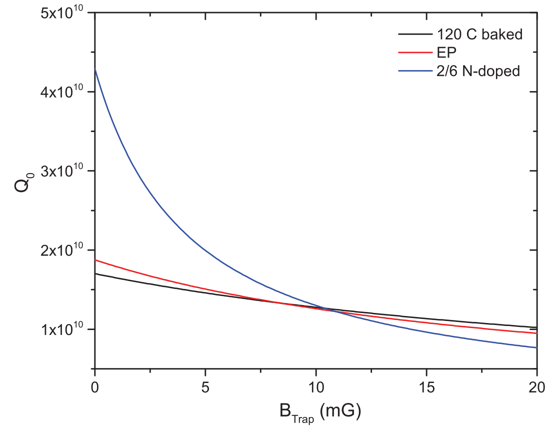

Figure 4: Extrapolation of Q-factor at 2 K and 16 MV/m as a function of the trapped field for 120 °C bake, EP and 2/6 N-doped cavities.

We have also found that the trapped flux surface resistance, and so the sensitivity, usually increases with the accelerating field, as can be seen from Fig. 2. This trend was reported also elsewhere [9, 10] but its nature is still unclear.

We have also investigated the BCS surface resistance contribution as a function of mean free path in order to fully characterize the surface resistance of SRF cavities. The BCS surface resistance contribution measured at 16 MV/m as a function of the mean free path is shown in Fig. 3. The green diamonds represent the doped cavities, while the pink circles are Niobium cavities with different standard treatments (120 °C bake, EP). The black curves are theoretical curves of R_{BCS} versus mean free path estimated for different reduced energy gap values.

It is clear that the BCS surface resistance is lowered with the introduction of interstitial impurities, which move the BCS toward its theoretical minimum which is about 20-30 nm of mean free path. Also, looking at the theoretical BCS curves, the values of R_{BCS} obtained for all the cavities analyzed cannot be interpolated with one single theoretical curve, suggesting that the mean free path is not the only parameter changing with the introduction of impurities. Following this hypothesis, one of the other parameters on which the BCS surface resistance depends on (λ_L, ξ_0, Δ, T_C) is changing as well. One possible explanation might be the difference of the reduced energy gap which seems to be higher in case of N-doped cavities.

Considering both the BCS and the trapped flux surface resistance trend as a function of the mean free path, it is possible to understand which treatment gives the high Q-factors depending on the amount of trapped magnetic field. For example, in Fig. 4 a simulation of the Q-factor as a function of the trapped field for 120 °C bake, EP and 2/6 N-doped cavities is shown. Detail of N-doping treatments may be found elsewhere [11, 12]. The simulation was done considering an intrinsic residual resistance of $R_0 = 4$ nΩ for 120 °C bake cavity and $R_0 = 2$ nΩ for all the other cavities. The 2/6 N-doped cavity considered for the simulation show $l = 122$ nm and $Sensitivity = 1.44$ nΩ/mg. From this graph it is possible to see that till about 10 mG of trapped flux the 2/6 N-doping cavity shows higher Q-factor than the other standard treated cavities. Above 10 mG of trapped flux the Q-factor is instead maximize for the 120 °C bake cavity which starts to take advantage from its lower trapped flux sensitivity.

CONCLUSIONS

In this paper we have shown that the trapped flux sensitivity depends strongly on the cavity surface treatment, and in particular it has a bell-shaped trend as a function of the mean free path. The sensitivity is low for very small values of mean free path (as for 120 °C bake cavities), than it increases reaching the maximum around $l = 70$ nm (as over doped cavities). Moving towards higher mean free path values the sensitivity decreases reaching again low value for large mean free path (as EP cavities). Using these results we can conclude that it is possible to tune the mean free path of N-doped cavities in order to optimize the value of magnetic flux sensitivity. We can also conclude that the 2/6 N-doping recipe provides the highest Q-factor achievable at 2 K at 16 MV/m as long as the magnetic field trapped during the cavity cool-down is lower than 10 mG.

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ISBN 978-3-95450-147-2