IMPURITY CONTENT OPTIMIZATION 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 trapped flux, depends on the mean free path. A systematic study of a variety of 1.3 GHz cavities with different surface treatments (EP, 120 °C bake and different N-doping) is carried out. 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 studied the trend of the BCS surface resistance contribution as a function of mean free path, showing that N-doped cavities follow close to the theoretical minimum. Adding these results together we show that the 2/6 N-doping treatment gives the highest Q-factor values at 2 K and 16 MV/m, as long as the magnetic field fully trapped during the cavity cooldown is lower than 10 mG.

INTRODUCTION

Recently, a new surface treatment implemented on superconducting cavities, called nitrogen-doping, shows unprecedented values of quality-factors ($Q_0 > 4 \cdot 10^{10}$) at medium values of accelerating field (E_{acc} = 16 MV/m) [1]. However, it was shown that whenever external magnetic is trapped in nitrogen-doped cavities, the Q_0 degradation is more severe than in standard-treated niobium cavities such as 120 °C baked and electro-polished (EP).

To understand this peculiar behavior, it is necessary to analyze the RF surface resistance, $R_s = G/Q_0$. R_s is given by two contributions, one temperature-dependent called BCS surface resistance (R_{BCS}), and one temperature-independent called residual resistance (R_{res}).

Surprisingly, in nitrogen-doped cavities R_{BCS} decreases with the increasing of the accelerating field. This results in an increasing of Q-factor with accelerating field called anti-Q-slope [1] .

The residual resistance term R_{res} is the one affected by trapped magnetic flux [2]. The amount of trapped flux depends on both the value of external magnetic field which surrounds the cavity during the SC transition, and on the cooldown details, which affects the magnetic flux trapping efficiency [3–5]. Fast cooldowns, with large thermal gradients along the cavity length, facilitate magnetic flux expulsion, while slow and homogeneous cooling through transition leads to full flux trapping.

In this paper both the trapped flux and the BCS surface resistance contributions are studied for cavities subject to different surface treatments: electro-polishing (EP), 120 °C baking, and N-doping with different time of nitrogen exposure and EP removal. Details on the N-doping treatment can be found elsewhere [1, 6].

The findings here reported allow a better understanding of which surface treatment is required to maximize the Q-factor for a certain RF field, taking into account the external DC magnetic field trapped during the cooldown. More details of this study may be found in Ref. [7].

EXPERIMENTAL PROCEDURE

All the cavities analyzed are single cell 1.3 GHz Tesla-type niobium cavities.

In order to estimate the trapped flux surface resistance, every cavity was RF tested, 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 applied.

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

A schematic of the instrumentation used to characterize the trapped flux surface resistance may be found in Fig. 1 of Ref. [8]. Helmholtz coils are used to adjust the magnetic field around the cavity, Bartington single axis fluxgate magnetometers to monitor the external magnetic field at the cavity equator, and thermometers to measure the temperature distribution during the cooldown.

The residual resistance may be considered as a sum between the trapped flux surface resistance, R_{fl}, and the "intrinsic" residual resistance, R_0, which does not depends on trapped flux.

At 1.5 K the BCS surface resistance contribution becomes negligible, therefore $R_{res} = G/Q(1.5K)$.

If during the cooldown the amount of trapped flux is successfully minimized, then: $R_{fl} \simeq 0$ and $R_{res} \simeq R_0$. 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. Alternatively, the measurement was done after a complete magnetic flux expulsion ($B_{SC}/B_{NC} \sim 1.74$ at the equator). We have observed that these two methods gave the same results within the mea-

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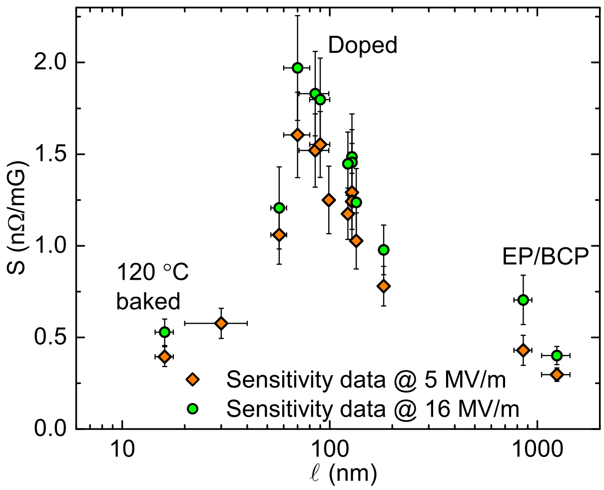

Figure 1: Trapped flux sensitivity calculated at 5 (orange diamonds) and 16 MV/m (green circles) as a function of the mean free path.

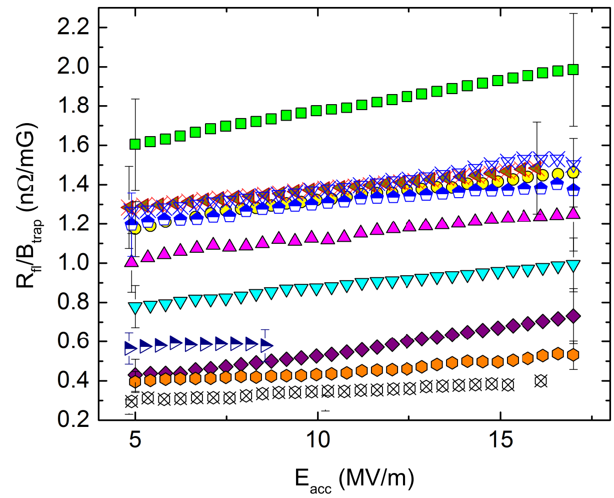

Figure 2: Sensitivity versus accelerating field of some of the cavities analyzed.

surements uncertainties. On the other hand, after the cavity trapped some external field: $R_{res}(B_{trap}) = R_{fl}(B_{trap}) + R_0$, where B_{trap} is the trapped field. $R_{res}(B_{trap})$ was always calculated from the RF measurements after slow cooldowns so that the amount of trapped flux approaches to the amount of external magnetic field imposed with the coil when the cavity is in the normal-conducting state, B_{NC}: $B_{trap} \simeq B_{NC}$.

The trapped flux sensitivity S 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 during each cooldown:

$$S = \frac{R_{fl}}{B_{trap}} . \quad (1)$$

The values 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:

$$R_{BCS} = R_s(2K) - R_s(1.5K) . \quad (2)$$

The electronic mean free path was estimated for all the cavities studied. Usually the estimation was done by means of a $C++$ translated version of SRIMP [9] implemented in the OriginLab data analysis program, as explained is Ref. [7].

RESULTS AND DISCUSSION

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

The sensitivity is minimized for both very small (120 °C bake cavities) and very large (EP and BCP cavities) mean free paths, and it is maximized around $l \simeq 70$ nm. Taking into account optimal N-doped cavities, when over-doped they show the highest sensitivity (l between 70 and 100 nm), while the 2/6 treatment gives the lowest sensitivity (l around $120 - 180$ nm).

Differences in terms of pinning force and dimensions or position of pinning center between the studied cavities may introduce some scattering on the dependence of sensitivity versus mean free path.

The vortex dissipation may be due to two contributions: i) static due to the normal-conducting core of the vortex [2] and ii) dynamic due to the vortex oscillation driven by the Lorentz force in presence of the RF field [10, 11]. The bell-shaped dependence of sensitivity as function of mean free path (Fig. 1) may be found considering simply the static contribution [12], however a better agreement with the data appears considering dynamic dissipation.

In Fig. 2 it can be seen that the trapped flux surface resistance, and therefore the sensitivity, increases with the RF field. A possible explanation to this phenomenon might be the progressive depinning of vortexes from their pinning center, driven by the increasing of the field, as hypothesized in Ref. [13].

We have also investigated the BCS surface resistance 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.

The BCS surface resistance is lowered with the introduction of interstitial impurities. The presence of interstitial nitrogen indeed assets the BCS values close to the theoretical minimum that follows around 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

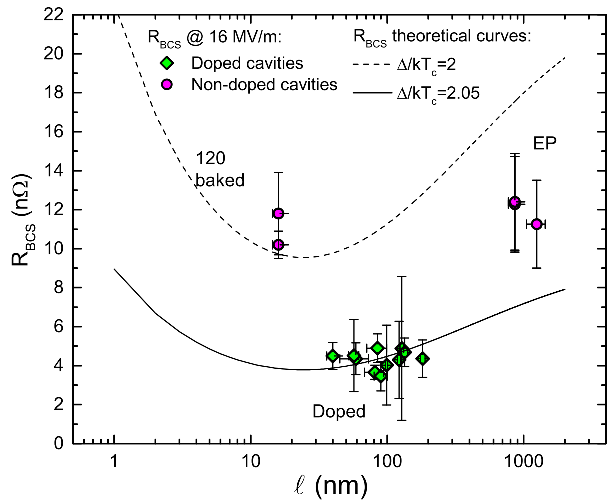

Figure 3: BCS surface resistance at 2 K and 16 MV/m as a function of mean free path.

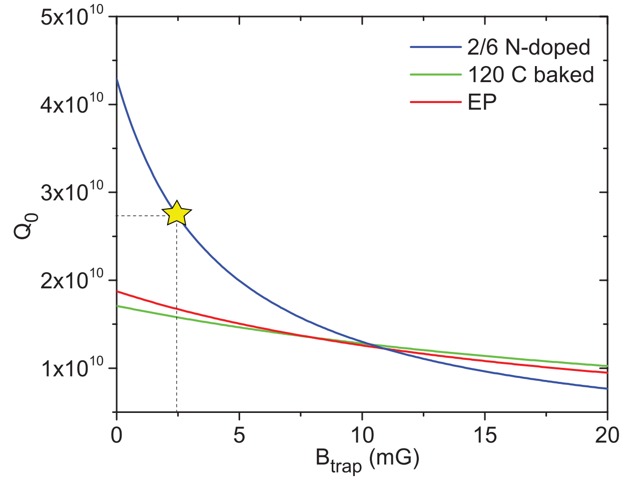

Figure 4: Extrapolation of Q-factor at 2 K and 16 MV/m as a function of the trapped field for 120 °C bake, EP and 2/6 N-doped cavities. The yellow star indicates LCLS-II specification.

depends on $(\lambda_L, \xi_0, \Delta, T_C)$ is changing as well. One possible explanation might be the increasing of the reduced energy gap Δ/kT_c in N-doped cavities.

Considering both the BCS and the trapped flux surface resistance as a function of the mean free path, it is possible to understand which treatment gives the highest Q-factors for a given amount of trapped magnetic field.

In order to visualize that, we calculate for each treatments among EP, 120 °C baking and N-doping, the Q-factor as follows:

$$Q_0 = G/(R_{BCS} + S \cdot B_{trap} + R_0)\,, \qquad (3)$$

where the values of B_{trap} ranges from 0 to 20 mG, R_0 = 4 nΩ for 120 °C bake cavity and R_0 = 2 nΩ for all the other cavities. For the N-doped cavities we chose the 2/6 N-doping treatment, which is the one of greatest interest for high-Q application, since it shows the best compromise between R_{BCS} and sensitivity values exploited so far. The 2/6 N-doped cavity considered for this calculation show ℓ = 122 nm and S = 1.44 nΩ/mg.

In Fig. 4 the Q-factor, at 2 K and 16 MV/m, as a function of trapped field for the different surface treatment is shown. From the graph it is clear that the 2/6 N-doping treatment shows higher Q-factor than the other treatments, as long as the trapped field is lower than 10 mG. Above 10 mG of trapped flux, the Q-factor is maximize for the 120 °C bake cavity which starts to take advantage from its lower trapped flux sensitivity.

The yellow star in Fig. 4 indicates the LCLS-II Q-factor specification. From this graph it is possible to see that for the 2/6 N-doping recipe, LCLS-II specification can be reached even if 2.5 mG of external magnetic field are fully trapped in the cavity.

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 dependence 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), then 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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