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ANTI-Q-SLOPE ENHANCEMENT IN HIGH-FREQUENCY NIOBIUM CAVITIES

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Abstract

N-doped 1.3 GHz niobium cavities showed for the first time the so-called anti-Q-slope, i.e. the increasing of the Q-factor as a function of the accelerating field. It was verified that the anti-Q-slope is consequence of the decreasing of the temperature-dependent component of the surface resistance as a function of the field. This trend is opposite compared to the increasing of the surface resistance previously observed in 1.3 GHz standard (EP, BCP, 120 °C baked) niobium cavities. The effect of the different state-of-the-art surface treatments on the field dependence of the surface resistance is studied for 650 MHz, 1.3 GHz, 2.6 GHz and 3.9 Ghz cavities. This proceeding shows that the field dependence of the temperature-dependent component of the surface resistance has a strong frequency dependence and that the anti-Q-slope may appear even in clean niobium cavities if the resonant frequency is high enough, suggesting new routes toward the understanding of the anti-Q-slope effect.

INTRODUCTION

Superconducting Radio-Frequency (SRF) cavities are key components of modern particle accelerators. For continuous wave (CW) accelerators it is extremely important to maximize the cavity Q-factor in order to lower the power dissipated in the cavity walls and, therefore, the cryogenic cost. The so-called nitrogen-doping is a surface treatment capable to dramatically improve the SRF performance, increasing the Q-factor by a factor of three at medium values of accelerating field, i.e. around E_{acc} = 16 MV/m [1]. Peculiar signature of such a treatment is the increasing of the quality factor as a function of the accelerating field, called anti Q-slope to underline that the trend is opposite to the usual Q-slope observed at medium accelerating field, in standard treated niobium cavities.

The R&D of SRF cavities in the last decades has been particularly focused in studying 1.3 GHz cavities, therefore there are no much data on the surface resistance of state-of-the-art niobium cavities acquired at different frequencies. In 2017 [2] we showed for the first time the results of a systematic study of the field and frequency dependence of the micro-wave surface resistance. In this proceeding we are adding some data and some insights on the physics underneath the field-dependence variation of the surface resistance with the frequency.

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Table 1: Summary of the Frequency Studied for Each Surface Treatment

	650 MHz	1.3 GHz	2.6 GHz	3.9 GHz
EP	X		X	
BCP		X		X
120 C baking	X	X	X	X
2/6 N-doping	X	X	X	X

EXPERIMENTAL PROCEDURE

Some elliptical niobium cavities resonating at 650 MHz, 1.3, 2.6 and 3.9 GHz were processed with state-of-the-art surface treatments and RF measured between 2.0 and 1.4 K. A summary of the surface treatments performed on each cavity is show in Table 1. All the cavities after fabrication are chemically treated, usually via electro-polishing (EP), in order to remove about 120-150 μm from the inner surface, and then are degassed for about 3 hours at 800 or 900 °C in an ultra-high vacuum furnace. In case of 3.9 GHz cavities, buffer-chemical polishing (BCP) was performed instead of EP because of the easier applicability to such a small structure. The treatment indicated in Table 1 refers to the one performed after the degassing stage: in case BCP'ed cavities, about 40-50 μm are removed via BCP; in case of 120 °C baked cavities, they are fully assembled to be RF tested and then are baked at 120 °C for about 48 hours; in case of N-doped cavities, nitrogen is injected in the furnace at 800 °C with a partial pressure of p =25 mTorr, for 2 minutes, then they are left at the same temperature for other 6 minutes in ultra-high vacuum before being naturally cooled down. The doping procedure is always followed by 5 μm of EP removal.

The temperature-dependent components of the surface resistance (R_T), called also BCS surface resistance, and the residual resistance (R_{res}) have been calculated as a function of the RF field, for each cavity. Since the BCS surface resistance exponentially decreases as a function of the temperature, in case of low frequencies cavities, such as 650 MHz and 1.3 GHz, the R_T contribution at T = 1.5 K becomes negligible compared with the residual resistance R_{res}, therefore: $R_S(1.5K) \simeq R_{res}$, and: $R_T(2K) = R_S(2K) - R_{res}$.

For high frequency cavities R_T at T = 1.5 K cannot be neglected, and in this case R_{res} has to be calculated by fitting $R_S(T)$ at different values of accelerating gradients. Since R_{res} is temperature-independent, $R_S(T)$ acquired during the cavity cooldown, within a data range between 2 K and 1.5 K, can be interpolated using the following formula: $R_S(T) = \frac{A\omega^2}{T} e^{-\frac{\Delta}{kT}} + R_{res}$, where A depends on

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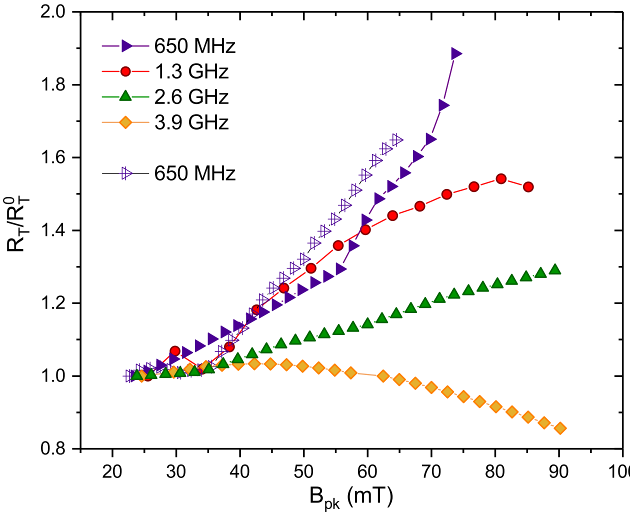

Figure 1: Normalized data R_T/R_T^0 as a function of the peak surface field for 120 C baked cavities.

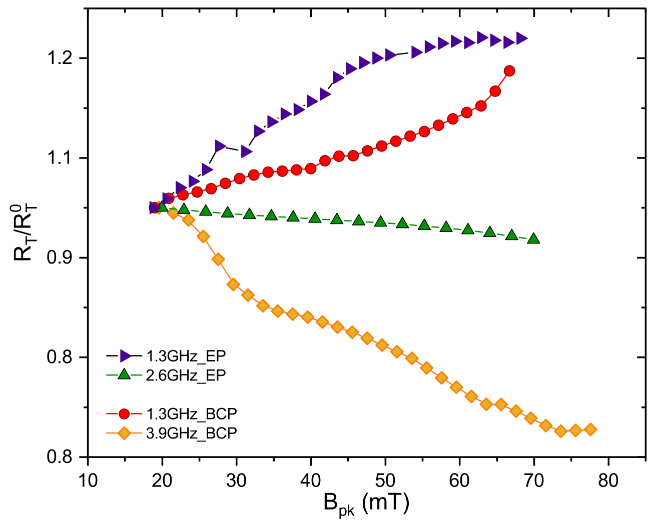

Figure 2: Normalized data R_T/R_T^0 as a function of the surface peak magnetic field for BCP and EP cavities.

many material parameters. The $R_S(T)$ curves are acquired at different values of accelerating field so that it is possible to extrapolate the whole curve of residual resistance as a function of the field. The accelerating field is then converted into surface peak magnetic field B_{pk} in order to allow for a better comparison of the field dependence of cavities with slightly different geometry.

RESULTS AND DISCUSSION

In order to compare the effect of each surface treatment on the BCS surface resistance, the data has been normalized for the R_T value at low field (usually around 20 mT).

The results of the normalized data R_T/R_T^0 for 120 °C baked cavities are shown as a function of the peak magnetic field B_{pk} in Figure 1. From the graph it appears that at low field the trend is very similar, but for field grater than 40 mT, the field dependence starts to deviate depending on the cavity resonance frequency. Looking at the data of 650 MHz cavities, the increasing of R_T with the field results very steep for field higher than 60 mT, more than the one usually observed for the case of 1.3 GHz cavities with the same treatment. On the other hand, looking at the case of 2.6 GHz the trend seems to be more moderate, and in the case of 3.9 GHz the trend is almost reversed, showing a slight decreasing of R_T with the field. These findings are suggesting that the field dependence of the BCS surface resistance is strongly affected by the frequency: higher frequencies are favorable to decrease the R_T contribution at medium field.

Analogously, the normalized data R_T/R_T^0 for BCP and EP cavities are shown in Figure 2. In this case the comparison is only between 1.3 and 2.6 GHz for EP cavities and between 1.3 and 3.9 GHz for BCP cavities. However, it is clear how the frequency plays a major role in the R_T field dependence: differently than what happen at 1.3 GHz, at 2.6 and 3.9 GHz R_T decreases as a function of the field. This is a clear proof that the BCS surface resistance can decrease as a function of the field even in non-doped cavities.

In addition, looking at the curve of Q-factor as a function of the surface peak magnetic field of such EP 2.6 GHz and BCP 3.9 GHz cavities, we can clearly recognize the peculiar anti Q-slope, that had been previously observed only in N-doped cavities (see Fig. 3). Important implication of this new findings is that high frequency cavities might be useful for high field applications. For example, we have found that the 120 °C baked 2.6 GHz cavity shows Q-factors that approaches the one of a 1.3 GHz cavity processed with same treatment between 35 and 40 MV/m [2]. Comparing R_T/R_T^0 for N-doped cavities (made with exact same doping recipe)

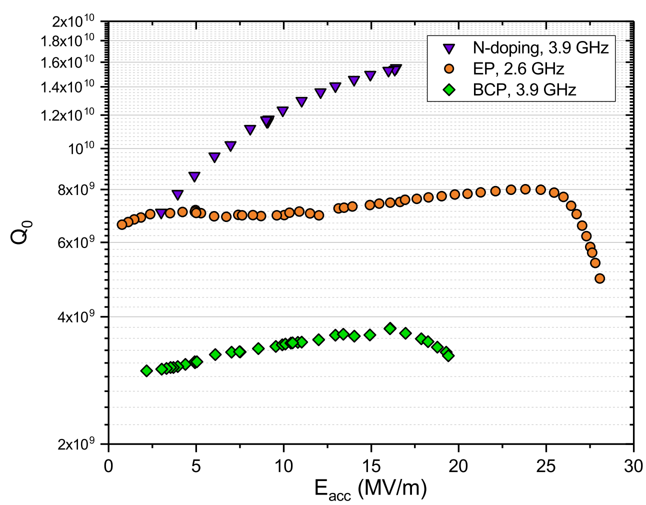

Figure 3: Q-factor versus accelerating field curves of: N-doped 3.9 GHz, EP 2.6 GHz and EP 3.9 GHz cavities.As pointed out in the text these measurements underline that the anti-Q-slope may appear even in clean (EP and BCP) niobium cavities when the frequency is high enough.

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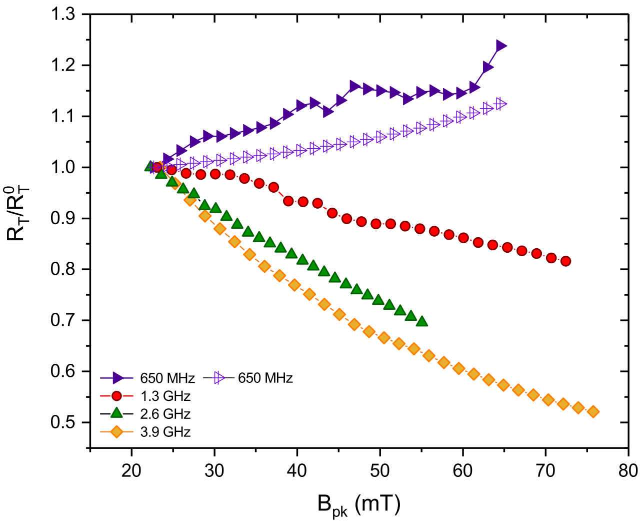

Figure 4: Normalized data R_T/R_T^0 as a function of the surface peak magnetic field for N-doped cavities.

at 650 MHz, 1.3 GHz, 2.6 GHz and 3.9 GHz (Figure 4), it is possible to notice similar results. At 650 MHz the BCS surface resistance of N-doped cavities slightly increase with the field, in contrast with the typical decreasing observed at 1.3 GHz. On the other hand, at 2.6 and 3.9 GHz, the effect of the reversal of $R_{\mathrm{T}}(B_{\mathrm{pk}})$ is enhanced. At 3.9 GHz, in particular, we can noticed that the BCS surface resistance is substantially decreased at around 70 mT, reaching half of his value at low field.

Also these findings reveal very important consequences. Thanks to such substantial decreasing of the BCS surface resistance, we observed unprecedented high value of Q-factors at medium field with the N-doped 3.9 GHz cavity, that reached $Q_0 \sim 1.5 \cdot 10^{10}$ at about 20 MV/m, as can be seen from Figure 3.

Summarizing, we have two major findings regarding the decreasing of the BCS surface resistance, origin of the anti Q-slope in 1.3 GHz N-doped cavities: i) it is more pronounced in high frequency cavities and, on the other hand, it is suppressed by low frequency; ii) it can be observed even in non-doped cavities, if the frequency is high enough.

These findings cannot be easily explained with the existing theory [3], indeed a recent effort on extrapolating the frequency dependence from this theory, taking into account the different level of quasiparticles overheating at different frequencies [4], has shown contradictory results compared to our experimental findings.

The results suggest that the peculiar decrease in the surface resistance as a function of the field strength is a consequence of a non-equilibrium distribution of QPs after their interaction with the RF field. This finding implies that non-equilibrium effects are visible in high-frequency clean niobium cavities and that when the cavities are N-doped, it is possible to observe such a nonequilibrium effect at lower frequencies. The real part of the conductivity, σ_1, which determines the RF losses in the superconductor, is directly proportional to the probability of absorbing a photon with energy $\hbar\omega$, which strongly depends on $f(E)-f(E+\hbar\omega)$.The term $f(E)-f(E+\hbar\omega)$ is smaller for the non-equilibrium scenario, allowing for a reduction in the surface resistance. One hypothesis that may explain these observations is that the presence of impurities modifies the relaxation and recombination times of QPs, τ_{eq} and τ_r, respectively, promoting the visibility of nonequilibrium effects at lower frequencies. Decreasing either τ_{eq} and τ_r for QPs indeed facilitates meeting the nonequilibrium conditions $\nu_{RF} > 1/\tau_r$,$1/\tau_{ep}$. Future studies will be focused on verifying this hypothesis.

CONCLUSIONS

The study here reported shows how the BCS contribution at the surface resistance varies as a function of: field, resonant frequency and surface treatment.

Differently from what expected based on the study of 1.3 GHz cavities, we have shown that $R_{\mathrm{T}}(E_{\mathrm{acc}})$ does not always decrease for N-doped cavities and, on the other hand, not always increase for non-doped cavities. The trend is instead intimately related to both the resonant frequency and the type of impurities. Based on this results appear that high RF frequency in general promotes the effect of the decreasing of the BCS surface resistance at medium field. This effect enables the observation of the anti Q-slope effect in both 2.6 GHz EP'ed and 3.9 GHz BCP'ed cavities and to reach record value of high Q-factor in 3.9 GHz N-doped cavities. Such unexpected results may promote the employment of high frequency cavities in future particle accelerators.

In addition, the frequency dependence of the surface resistance suggests that a non-equilibrium distribution of quasiparticles may be responsible for the anti Q-slope in SRF cavities.

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