2022

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Original Publication Citation

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EFFECT OF DURATION OF 120 °C BAKING ON THE PERFORMANCE OF SUPERCONDUCTING RADIO FREQUENCY NIOBIUM CAVITIES∗

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Abstract

Over the last decade much attention was given in increasing the quality factor of superconducting radio frequency cavities by impurity doping. Prior to the era of doping, the final cavity processing technique to achieve the high accelerating gradient includes the “in-situ” low temperature baking of SRF cavities at temperature ∼ 120 °C for several hours. Here, we present the results of a series of measurements on 1.3 GHz TESLA shape single-cell cavities with successive low temperature baking at 120 °C up to 96 hours. The experimental data were analyzed with available theory of superconductivity to elucidate the effect of the duration of low temperature baking on the superconducting properties of cavity materials as well as the rf performance. In addition, the rf loss related to the trapping of residual magnetic field referred as flux trapping sensitivity was measured with respect to the duration of 120 °C bake.

INTRODUCTION

The performance of superconducting radio frequency (SRF) cavities are measured in terms of quality factor as a function of accelerating gradient. Higher quality factor with high accelerating gradient are desirable for operation of high energy future particle accelerators. Over the last decades, high quality factor at medium accelerating gradient (20 - 25 MV/m) was achieved by impurity doping with Ti or N [1–3]. The effect of low temperature baking in the presence of nitrogen also resulted increase in quality factor at medium accelerating gradient and it was extended to higher accelerating gradient over the baseline measurement [4, 5]. Most recently, the medium temperature heat treatment also resulted in the increase in quality factor likely due to the decomposition of surface oxide phase and oxygen diffusion within the rf penetration depth [6, 7].

The role of the low temperature baking (120 - 150 °C) on the performance of SRF cavities was studied extensively, mainly eliminating the high field Q-slope and few models were proposed in the past [8–12]. The oxygen diffusion model proposed by G. Ciovati [13], qualitatively explains the diffusion of oxygen in to the rf surface of SRF cavities. The same model also describes well to the diffusion of oxygen during the mid-T heat treatment (300 - 400 °C) [7]. Here, we present a systematic study on the performance of SRF cavities subjected to the low temperature baking to understand the effect of 120 °C baking duration. We extract the superconducting parameter from the temperature dependence of surface resistance and penetration depth.

CAVITY SURFACE PREPARATION AND RF MEASUREMENTS

Two TESLA-shaped 1.3 GHz single cell cavities (G = 277.85, Bp/Eacc = 4.23 mT/(MV/m)) were fabricated from high purity Nb. One of the single cells labeled TE1-05 was fabricated from fine-grain ASTM 5 Nb with RRR ∼ 400 and second cavity labeled TE1-06 was fabricated from a cold work niobium sheet. The cavities were processed with several heat treatment cycles in the range of 800 - 1000 °C followed by ∼ 25 µm electropolishing as the final surface preparation. The cavities were subjected to high pressure rinse, dried in clean room overnight and assembled with probes and pump-out port.

The cavities were loaded in the vertical Dewar to measure the flux expulsion when the cavity transitions to the superconducting state during cooldown. The details of flux expulsion technique are given in Refs. [14, 15]. Both cavities showed excellent flux expulsion when the temperature gradient across the irises is kept > 2.0 K. The baseline rf measurements were done with cavity cooldown in minimum residual magnetic field (< 1 mG) in Dewar with high temperature gradient (ΔT > 4K) across the cavity irises to ensure good flux expulsion of any residual magnetic field. The Q0 vs. the helium bath temperature (T) measurement was done from 4.3 to 1.6 K at Bp ∼ 15 mT. A representative plot for Rs(T) is shown in Fig.1 for cavity TE1-06 after electropolishing followed by 120 °C bake for 3 hours. At 2.0 K, the Q0 vs. Eacc measurement was carried out. The second set of measurements was done after warming the cavity above Tc and cooldown with ∼20 mG residual magnetic field in Dewar. The cavity was cooled with temperature gradient across the cavity < 0.1 K (Bsc/Bacc ∼ 1), ensuring that maximum ambient magnetic field was trapped during the cooldown. Again, the Q0 vs. T measurement was repeated from 4.3 to 1.6 K and at 2.0 K, the Q0 vs. Eacc measurement was done. This allows us to extract the flux trapping sensitivity, the increase in surface resistance due to the trapped residual magnetic field during cooldown.

The cavities were subjected to low temperature baking at 120 °C for several hours in the interval of (3, 6, 12, 24, and 48 hours) in a bake box. During the cavity baking process, the cavity was kept under vacuum (< 10−7 torr). The rf measurements of Q0 vs. T and Q0 vs. Eacc were repeated.
Figure 1: $R_s$ vs. $1/T$ for cavity TE1-06 after electropolishing followed by 120 °C/3hrs baking with < 1 mG and ∼ 20 mG trapped flux.

with different residual field trapped during the cooldown. The $R_s (G/Q_0)$ vs. ($1/T$) data were fitted as described in Ref. [16] using the following equation:

$$R_s(T) = A e^{-U/T_s} + R_i$$  \hspace{1cm} (1)

where $R_i$ refers to residual resistance due to the several intrinsic and extrinsic contributions such as trapped magnetic field during cooldown, non superconducting nano-precipitates, sub-oxide layer at the surface, broadening of the density of states, etc. The first term $A e^{-U/T_s}$ is due to the thermally activated quasi-particles in rf field. For weak rf field, the term is a good approximation of the Mattis-Bardeen expression for $R_{BCS}$, where $U$ represents the superconducting gap [17]. $T_s$ is the temperature of cavity’s rf surface. A summary of the $R_s(T)$ fits for cavities cooldown with < 1 mG is shown in Fig. 2. The fits were also repeated for cavities with ∼ 20 mG trapped residual field with no significant change in A and U, however the residual resistance $R_i$ increases. The flux trapping sensitivity $S(\mu \Omega/mG)$ was calculated as:

$$S = \frac{R_{i,20mG} - R_{i,0mG}}{20}$$  \hspace{1cm} (2)

Figure 3 shows the flux trapping sensitivity for two different cavities after successive 120 °C baking. Figure 4 shows the $Q_0$ vs. $E_{acc}$ for cavities after electropolishing and additional 120 °C baking for 3 hours. The electropolished cavities were limited by high field Q-slope. Surprisingly, the high field Q-slope was eliminated just after 3 hours baking at 120 °C. Similar improvement was observed in large grain cavities treated with buffered chemical polishing followed by 120 °C in-situ baking for 3 hours [18]. While increasing the baking time to as high as 96 hours, no significant change in quenched gradient was observed.

In order to obtain information about the mean free path near the surface, we measured the resonant frequency and quality factor while warming up the cavities from ∼ 4.3 K to higher than transition temperature (> 9.3 K) using vector-network analyzer, from which $R_s(T)$ and the change in resonant frequency was extracted. The frequency shift can be translated into a change in penetration depth according to

$$\Delta \lambda = \frac{G}{\pi \mu_0 f^2 \Delta f}$$  \hspace{1cm} (3)
with G being the geometric factor of the cavity, f is the resonant frequency. The data in the superconducting state were fitted using the numerical solution of M-B theory. The mean free path decreases with the increase in 120 °C baking time. A more detailed analysis of the temperature dependence of penetration depth will be presented in a future publication.

ACKNOWLEDGEMENTS

We would like to acknowledge Dr. Gianluigi Ciovati for Jefferson Lab technical staff members for cavity fabrication, processing and cryogenic support during rf test.

REFERENCES


