ISBN: 978-3-95450-234-9 ISSN: 2673-5504 doi:10.18429/JACoW-SRF2023-WEIXA02

RESULTS OF THE R&D RF TESTING CAMPAIGN OF 1.3 GHz Nb/Cu CAVITIES

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Abstract

In the context of the R&D program on 1.3 GHz Nb/Cu carried out at CERN, a total of 25 tests have been performed since 2021. This talk will present these results. Three different manufacturing techniques have been used to produce the copper substrates, in order to investigate which is the most suitable in terms of quality and economy of scale. On one hand, the focus has been on optimizing the surface resistance at 4.2 K, as this will be the operating temperature of Future Circular Collider (FCC). The results at this temperature are encouraging, showing repeatable and optimized RF performance. On the other hand, RF tests have been done at 1.85 K too, aiming at deepening the knowledge of the mechanisms behind the Q slope. This is key to work on the mitigation of this phenomenon and ultimately to extend the application of this technology to high energy, high gradient accelerators. The influence of the thermal cycles has been thoroughly investigated. A systematic improvement has been observed of both the Q slope and the residual resistance with small thermal cycles.

INTRODUCTION

Historically, Nb has been the material of choice for Superconducting Radio Frequency (SRF) cavities. However, the development of niobium/copper (Nb/Cu) cavities introduced several advantages that made them an appealing alternative, such as improved thermal properties, easier fabrication and manufacturing and operation costs [1]. The latest is especially crucial for large-scale projects where the fabrication of numerous cavities is required. However, the degradation of performance at high fields, known as the Q-slope, has limited the use of Nb/Cu cavities to low-gradient machines such as LEP, LHC or HIE-ISOLDE [2].

Nb/Cu technology has been the selected baseline for the 400 MHz FCC SRF system [3]. However, there is a need of improvement to meet the stringent operational requirements imposed by the FCC project, which exceed the capabilities of the existing LHC SRF system. In response, CERN has undertaken significant efforts through an R&D campaign to address these challenges, focusing on advancements in various aspects such as substrate manufacturing, surface treatments prior to coating and deposition techniques [4]. The goal is to achieve high repeatability in terms of quality while maintaining cost-effectiveness on a large scale.

Furthermore, extensive efforts have been undertaken to comprehensively understand the underlying mechanisms behind the Q-slope phenomenon. It is crucial to demonstrate that this issue is not intrinsic to the Nb/Cu technology and can be effectively overcome for its application on SRF systems of future high-gradient accelerators [5].

As part of the R&D campaign, a total of 25 cavities have been tested since 2021 [6]. Results will be reported and discussed in the following sections.

METHODOLOGY

The steps followed for fabricating the cavities and preparing them for finally proceeding to the RF testing are described in the following section:

Cavity Preparation

The first step in the cavity preparation is the production of the substrate. Three different techniques have been investigated:

- Machining a bulk copper billet (BM): Four seamless substrates have been produced by machining copper billets. The cut-offs are welded at the irises level [7].
- Electroforming (L): Two substrates were produced by growing a copper substrate on an aluminum mandrel. It is important to note that this is the only method that avoids welds in the entire cavity structure [8].
- E-beam welded at the equator (W): Two spun half cells were welded at the equator and also at the cut-offs from the inside using a deflector to improve the quality of the welded surface exposed to the RF fields [9].

It is important to note that out of the three techniques, only one (W) involves a weld at the equator. This is due to the observation at HIE-ISOLDE that seamless substrates showed significant improvement in performance compared to welded ones [10, 11]. Currently, the baseline for substrate production in the FCC project is spinning, similar to the LHC, with a strong effort dedicated to the investigation on hydroforming [9, 12]. Nevertheless, there is ongoing interest in exploring methods to produce high-quality welds, such as in the case of substrate W.

Before the coating process, the substrate undergoes several important steps. First, it is degreased to remove any hydrocarbon based contamination. Then, it is electropolished to remove any surface imperfections and contaminants. This step helps to achieve a smoother and cleaner surface, which is crucial for optimal RF performance. After electropolishing, the substrate is passivated to protect it from oxidation.

Next, a layer of niobium (Nb) is deposited on the substrate using High Power Impulse Magnetron Sputtering (HiPIMS).

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This technique has been chosen based on the results of a testing campaign using the quadrupole resonator (QPR), which demonstrated the best RF performance with HiPIMS-coated samples [13].

After the coating process, 100 bars high-pressure water rinsing is systematically performed to remove any residual particulates to ensure a clean surface before the cavity undergoes testing.

Once a cavity has been tested and evaluated, the coating is stripped, and the preparation process is restarted, beginning with the electropolishing step. This allows for repeated testing and refinement of the cavity's performance.

The notation used for identification of the cavities consists of a letter indicating the manufacturing technique, followed by a first number to identify each substrate, and a second number after a point to indicate the number of coatings applied. For example, considering the notation L1.3: The "L" indicates that the substrate was produced using the electroforming method. The number "1" identifies this particular substrate among others produced by the same method. The number "3" indicates that this is the third coating being applied to this specific substrate.

RF Testing

The RF tests are performed at the CERN Cryogenics Laboratory following standard testing procedures [14], where the cavities are inserted in a small vertical cryostat. To minimize measurement uncertainty, the reflected power is minimized by adjusting the inserted length of a mobile input coupler to maintain critical coupling during the measurements.

First, the Q_0 is measured as a function of the accelerating field (E_{acc}) while keeping the temperature of the helium bath constant. This is done at both 4.2 K and 1.85 K. The second measurement involves obtaining the Q_0 as a function of temperature while maintaining a fixed E_{acc}. The average surface resistance (Rs) is determined by dividing the geometrical factor of the cavity (G) by the measured Q_0, and is then fitted to the following formula:

$$R_s = R_{res} + \frac{A_{BCS}}{T} e^{-\frac{\Delta(0)}{k_B T}}; \qquad (1)$$

being R_{res} the residual resistance, A_{BCS} a parameter that depends on the purity of the material and $\Delta(0)$ the superconducting energy gap at $T = 0$ K.

A last scan is done to measure the shift in the resonance frequency when increasing the temperature above the transition temperature. The change in the resonance frequency Δf is related to the change in the penetration depth $\Delta\lambda$ using Slater's Theorem. This is then fitted as a function of the temperature using the following equation:

$$\lambda = \frac{\lambda(0)}{\sqrt{1 - \left(\frac{T}{T_c}\right)^4}} + c, \qquad (2)$$

where $\lambda(0)$ is the penetration depth at 0 K, T_c is the critical temperature, and c is the offset to obtain the measured $\Lambda\lambda$.

A thermal cycle is systematically performed after completing the initial set of measurements, which are then repeated. The main objective is to minimize the temperature gradient across the cavity during the cooling process, particularly when crossing the critical temperature from the normal to superconducting state. This is achieved by raising the cavity temperature slightly above its transition temperature (within the range of 12-30 K) and then restarting the cool-down from that point. It has been observed that employing this method can reduce temperature gradients across the cell by up to one order of magnitude compared to the initial cool-down from ambient temperature to 4.2 K without interrupting the helium transfer.

RF RESULTS

To give an idea of the repeatability of the results, the scans of Q_0 vs *Eacc* for all cavities are shown at 4.2 K and 1.85 K in Figs. 1 and 2, respectively. These results represent the best scans obtained for each coating.

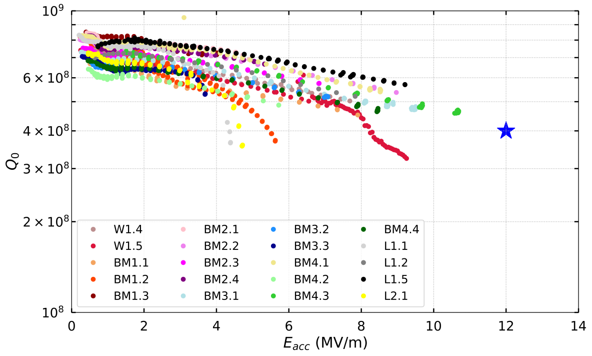

Figure 1: Quality factor (Q_0) vs accelerating field (E_{acc}) at 4.2 K of all tested cavities. Blue star indicates the scaled 400 MHz FCC requirements for 1.3 GHz cavities [15].

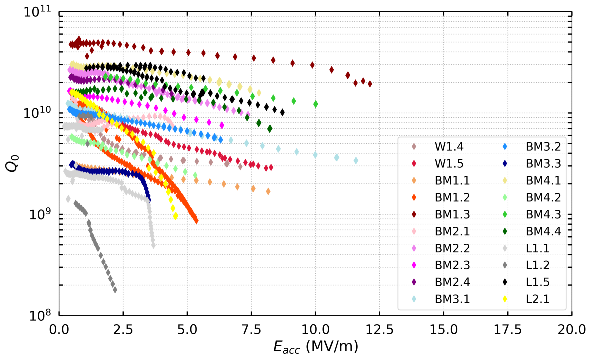

Figure 2: Quality factor (Q_0) vs accelerating field (E_{acc}) at 1.85 K of all tested cavities.

In order to analyze the maximum performance achievable with a specific substrate production method, such as the bulk machined series, the results for each of the four substrates are presented individually in Fig. 3.

It is worth noting that despite using the same coating deposition method and parameters, varying levels of performance were achieved.

The superconducting parameters that characterize the coating can be obtained from the Q_0 vs T and frequency vs T scans. Figure. 4 lists the average values and standard deviations of these parameters for all tested cavities, providing insight into the repeatability of the coating characteristics.

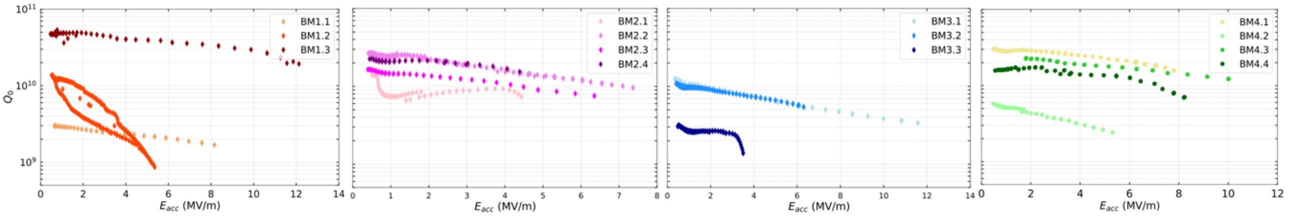

Figure 3: Quality factor (Q_0) vs accelerating field (E_{acc}) at 1.85 K for the BM series.

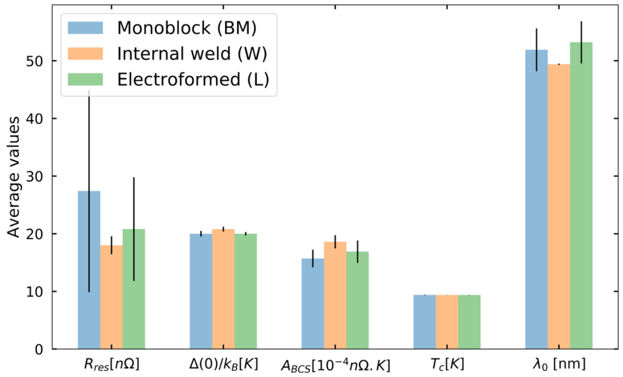

Figure 4: Superconducting parameters: Average and standard deviation for all tested cavities, separated by substrate manufacturing technique.

Thermal Cycles

As stated previously, a thermal cycle is systematically carried out in all the cavities with the goal of minimizing temperature gradients during the cool-down process. Figure 5 displays the performance at 1.85 K of cavity BM4.3 after undergoing various thermal cycles, each peaking at a different temperature. This enables the evaluation of the repeatability of the results across a wide range of initial temperatures.

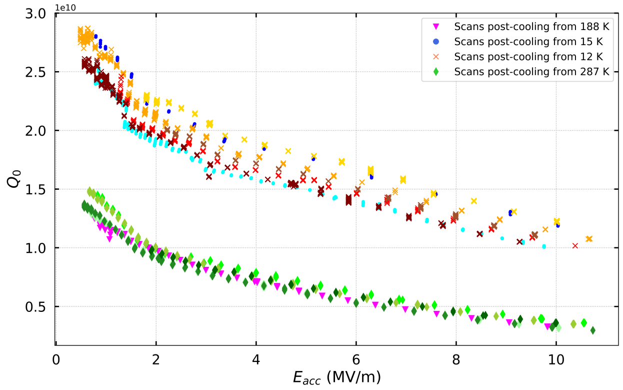

Figure 5: Q_0 vs E_{acc} scans at 1.85 K in cavity BM4.3 following cool-down cycles, initiated at four different starting temperatures.

In this same cavity, multiple Q_0 vs T cycles at different fixed accelerating fields were performed for two of the thermal cycles shown in the Fig. 5. The resulting curves corresponding to the cycle starting at 287 K are shown in Fig. 6. The same study was performed after cooling from 12 K. The objective was to obtain the superconducting parameters, in particular $R_{residual}$ as a function of E_{acc} and determine if this relationship differed between the two thermal cycles. The results are depicted in Fig. 7.

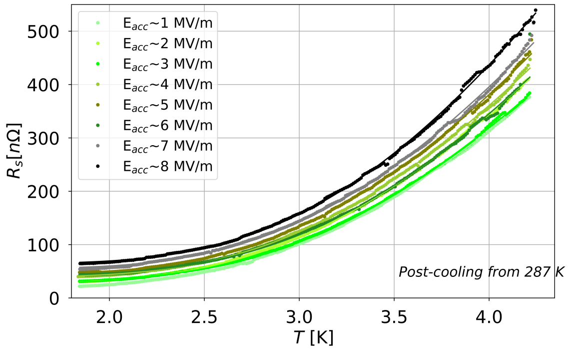

Figure 6: Surface resistance (R_s) vs temperature of BM4.3 cavity obtained at different fixed accelerating fields (E_{acc}) after cooling down from 287 K.

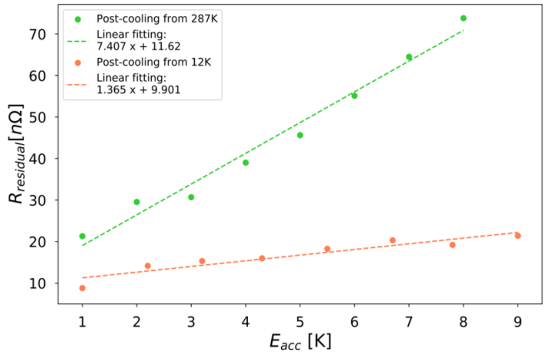

Figure 7: Residual resistance ($R_{residual}$)vs accelerating field (E_{acc}) obtained in BM4.3 after cool-down from 287 K and 12 K, leading to high and low thermal gradients at transition from normal to superconducting state respectively.

Additional Treatments

Various treatments were implemented in the same cavity BM4.3 to investigate if any extrinsic factors could enhance its performance. One approach involved modifying the external surface state of the cavity to improve the cooling with liquid helium [16]. This was motivated by observations of cooler areas in the cell of a cavity, detected during RF tests using a thermal mapping system, which likely indicated the occurrence of bubble formation in that regions [17]. Hence, to enhance the convection coefficient and promote the transition from natural convection to nucleate boiling, the surface roughness of BM4.3 was intentionally increased. This was done in two steps: first, the surface was deoxidized, and then it was sandblasted. Between each of these steps, the cavity had to be dismounted from the insert and undergo High Pressure Water Rinsing (HPWR). Additionally, the effect of a bake-out on the RF performance of the cavity was assessed. In this case, without dismounting the cavity from the insert or undergoing HPWR, the cavity was heated up to 75 °C for a duration of 30 hours. The obtained results can be found in Fig. 8.

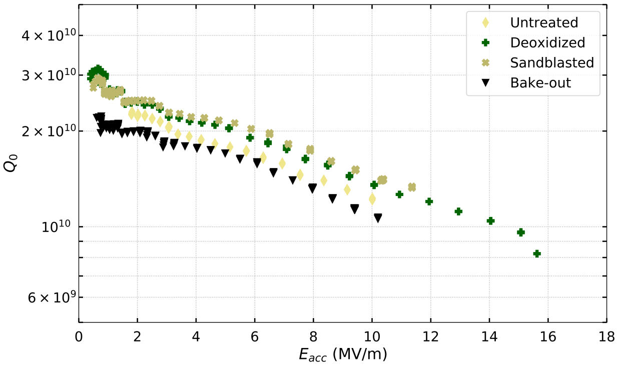

Figure 8: Comparison of the quality factor (Q_0) vs accelerating field (E_{acc}) at 1.85 K for the BM4.3 cavity with different external treatments.

DISCUSSION

In the following section, the results of the previously presented tests will be discussed, highlighting the main conclusions that have been obtained.

Reproducibility of the Coatings at 4.2 K

The analysis of the data obtained at 4.2 K holds significant importance in the context of the FCC project, where the SRF system is designed to operate at a similar temperature of 4.5 K. Achieving the required RF performance and ensuring high repeatability are crucial due to the large scale of the project, involving the fabrication of numerous cavities.

The RF tests conducted at 4.2 K have demonstrated the feasibility of meeting the requirements imposed by the FCC project, as illustrated in Fig. 1, where the blue star represents the scaled requirements at 1.3 GHz, as stated in the latest Conceptual Design Report. It is important to highlight that the tests on the cavities were stopped at an accelerating gradient lower than their actual operational limit due to restrictions at the Cryogenics laboratory related to the generation of radiation.

Besides, the RF performance of the cavities at 4.2 K exhibits repeatability within a reasonable range, with the quality factor values concentrated between 6 and 9.10^9 at low fields.

Furthermore, it is worth noting that the spread in the superconducting parameters, as obtained from the fitting of the Q vs T curves for all the cavities, is relatively low (see Fig. 4). Except for the residual resistance which exhibits more variability due to its sensitivity to even minor defects, the variation in the other parameters is limited. This indicates that the coating process is well under control.

In conclusion, the obtained results are highly encouraging and suggest that the current fabrication recipe for the cavities has the potential to meet the performance requirements of the FCC project. This is a significant milestone, as it indicates that the fabrication process is ready to be scaled up for the production of the final 400 MHz cavities for the FCC SRF system.

Influence of Substrate Preparation on RF Performance

Considerable efforts were dedicated to improving the coating process through a series of tests using the Quadrupole resonator [18]. Various samples were coated using different techniques, with HiPIMS demonstrating the most promising results [13]. Consequently, this was selected as the preferred technique and systematically employed for coating all the cavities.

However, the copper substrate also plays a critical role in the RF performance. This was clearly highlighted during the series of coatings performed on the BM1 substrate, as depicted in Fig. 3, where the performance was gradually improved from the first coating to the latest one. This is due to differences in the preparation of the substrate prior to coating. For instance, BM1.1 corresponds to the substrate coated immediately after machining, with the damaged layer caused by the diamond tooling still present, negatively affecting the RF performance. Subsequently, after removing the coating, a SUBU was applied to remove this damage layer, leading to improved performance as observed in BM1.2. However, the most significant improvement was achieved after performing an electropolishing (EP) prior to coating, resulting in the best achieved RF performance. Consequently, it was concluded that EP should be systematically performed in all the substrates prior to coating.

Furthermore, as shown in Fig. 3, it can be observed that the RF performance appears to reach a maximum value for each substrate. However, the exact reasons for these variations are not yet fully understood. Although the manufacturing technique was consistent, the use of different original copper billets may have contributed to the differences in performance. Further investigation is needed to identify the specific characteristics of the copper billets that affect the final RF performance.

Improved Performance with Thermal Cycles

Although historically Nb/Cu cavities were believed to be less sensitive to trapped flux compared to bulk Nb cavities, the notable improvements observed systematically after controlled cool-down cycles suggest that this effect cannot be ignored [19]. The presence of both Nb and Cu metals in contact, subjected to temperature gradients, may generate thermoelectric currents. Minimizing its effect is crucial to prevent trapped flux on the superconductor, which can significantly impact the overall performance of the cavity. As a result of carefully managing the cooling process and minimizing the temperature gradient, a systematic reduction in residual resistance has been observed in all the cavities, reaching up to a 60% decrease in some cases.

In addition, the thermal cycle also affects the Q slope of the cavities, as illustrated in Fig. 5. Other interesting observation that can be extracted from this plot is the tendency of the results to cluster into two distinct Q values based on the initial temperature, demonstrating the influence of the starting conditions on the performance of the cavity across a wide range of starting temperatures and the repeatability of the results.

From the results presented in Fig. 7, it can be concluded that the residual resistance depends linearly on the accelerating gradient. A similar study was conducted in HIE-ISOLDE SRF cavities and similar conclusions were drawn [20]. Besides, it is remarkable the discernible difference in the dependence observed after the thermal cycle. This is a crucial finding, as thermoelectric currents are indeed confirmed as one of the underlying causes of the observed Q slope in Nb/Cu cavities. To gain understanding of this phenomenon, investigations are ongoing, including the implementation of an intermediate oxide layer between Nb and Cu that acts as an insulator to potentially mitigate the generation of thermoelectric currents [21].

Influence of External Treatments

As shown in Fig. 8, the performance of the cavity exhibited a slight improvement following the deoxidation treatment of the external surface. However, the most significant accomplishment was the ability to reach an accelerating field of nearly 16 MV/m without triggering the radiation alarm, which is the highest value to date. At present, it remains unclear whether this improvement is attributable to the deoxidation process or to the longer duration of the high-pressure water rinsing performed. Nevertheless, following this positive outcome, it was decided to systematically apply longer HPWR to the next cavities.

The sandblasted cavity showed similar performance to the deoxidized version at low field, but it exhibited slightly better performance at higher fields with a reduction in the Q slope. This improvement could be attributed to better cool-down dynamics thanks to increasing the roughness of the external surface of the cavity. However, the overall improvement was not significant enough to justify the systematic application of this treatment. Nonetheless, further investigation in this direction will be done as the results indicate potential for further improvement. It is important to note that even with another round of HPWR, the achieved accelerating gradient was lower, suggesting that the effect of HPWR on RF performance may not be consistent or deterministic.

Finally, the RF test conducted after the bake-out process revealed a deterioration in performance. The exact reasons behind this are not yet clear. However, it is evident that conducting a bake-out at 75 °C is not beneficial and does not yield improved results. In future investigations, it may be worthwhile to explore different bake-out cycles to understand their effects on cavity performance. However, at the moment, the decision has been made not to perform further bake-out cycles due to the observed deterioration in performance.

CONCLUSIONS

The primary objective of the 1.3 GHz cavities R&D program is to develop a production recipe for 400 MHz cavities that meet the requirements of the FCC SRF system. Additionally, the program aims to better comprehend the mechanisms underlying the Q slope phenomenon. Understanding the factors contributing to this undesirable effect can lead to the development of strategies to mitigate or eliminate it, thereby expanding the applicability of Nb/Cu technology in high-energy, high-gradient accelerators.

Significant progress has been made in optimizing the performance of the cavities at 4.2 K, resulting in the successful development of a recipe that meets the requirements of the FCC project's SRF system. Besides, the achieved performances at this temperature demonstrate a high level of repeatability, indicating the robustness and reliability of the recipe. This is a strong indicator that this technology is ready for scaling up to the 400 MHz as part of the FCC project. However, achieving repeatability at the lower temperature of 1.85 K remains a challenge, as indicated by recent tests. Further investigations and improvements are necessary to understand and address the factors affecting performance consistency at this temperature.

Thermal cycles that minimize temperature gradients during the transition from normal to superconducting state have proven to enhance the overall performance of the cavities, improving both the residual resistance and the Q slope. This phenomena is believed to be associated with the generation of thermoelectric currents resulting from the contact between the two different metals (Nb and Cu) under temperature gradients. If these currents become trapped in the superconductor, they will cause losses during RF operation. To mitigate this effect, apart from the management of the cooling cycles, the possibility of isolating the two metals by introducing oxide layers between them will be explored in the future.

Regarding the engineering of the external surface of the cavity to enhance cooling, initial results indicate a slight improvement in performance. However, further investigations are required to refine this approach as the current improvement does not justify the systematic application of sandblasting to increase surface roughness. Nonetheless, there is potential for further improvement in this approach.

ACKNOWLEDGEMENTS

The authors would like to thank G. Pechaud, J. Bastard, A. Gogez, and S. Forel for the technical support with the preparation of the cavities and measurement setup, and A. Vacca, T. Koettig, S. Prunet and L. Dufay-Chanat for providing the cryogenic infrastructure and technical help.

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