

Field dependent surface resistance of niobium on copper cavities

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The surface resistance R_S of superconducting cavities prepared by sputter coating a niobium film on a copper substrate increases significantly stronger with the applied rf field compared to cavities of bulk material. A possible cause is that the thermal boundary resistance between the copper substrate and the niobium film induces heating of the inner cavity wall, resulting in a higher R_S . Introducing helium gas in the cavity, and measuring its pressure as a function of applied field allowed to conclude that the inner surface of the cavity is heated up by less than 120 mK when R_S increases with E_{acc} by 100 nΩ. This is more than one order of magnitude less than what one would expect from global heating. Additionally, the effects of cooldown speed and low temperature baking have been investigated in the framework of these experiments. It is shown that for the current state of the art niobium on copper cavities there is only a detrimental effect of low temperature baking. A fast cooldown results in a lowered R_S .

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I. INTRODUCTION

Superconducting cavities prepared by coating a micrometer thick niobium film on a copper substrate are currently used at CERN in the LHC and for the HIE-Isolde project [1]. The operation temperature here is 4.5 K, where this technology enables a lower surface resistance than cavities prepared from bulk material, caused by the lower residual resistance ratio (RRR). The Bardeen Cooper Schrieffer (BCS) surface resistance is minimal if the electron mean free path is approximately as long as the BCS coherence length [2]. This condition is met for a RRR of about 10 in case of niobium, a typical value obtained for films on cavities prepared by magnetron sputtering [3]. Other advantages of Nb/Cu cavities are lower material cost, no need for shielding the Earth's magnetic field, and enhanced thermal stability avoiding quenches [4]. For quarter-wave resonators, cryostat design is facilitated since these copper structures can be cooled by conduction [1].

Despite these advantages, the Nb/Cu technology is currently not considered for accelerators requiring highest accelerating gradient E_{acc} like the ILC, or lowest surface resistance R_S at temperatures of 2 K and below, especially for high duty cycle and continuous wave applications. The reason is that R_S increases strongly with E_{acc} . The origin of this field dependent surface resistance has been the subject of many studies in the past [3,5,6], but is still far from being fully understood. The film thickness of about 1.5 μm is

large compared to the London penetration depth λ_L of about 32 nm. Therefore differences in the performance (apart from thermal conductivity issues) should be largely due to the manufacturing procedure and the resulting surface structure. No single dominant source can be expected, thus several hypotheses need to be addressed individually to identify their origin and possibly reduce their extent. In this paper the effect of a potential temperature difference between the inner cavity surface and the helium bath, induced by rf heating, is investigated. The influence on the rf performance of the cooldown speed and low temperature baking are addressed.

An issue in superconducting cavities is the possibility that the thermal impedance of the cavity wall leads to an increased temperature of the inner surface exposed to the rf, resulting in an increased surface resistance [6]. For bulk niobium cavities it has been shown that this effect at least contributes to the field dependent surface resistance [7]. For Nb/Cu cavities the problem is even more complex, since the thermal impedance across the film/substrate interface is unknown and adds to the total thermal conductivity. Here a method previously tried in [6] to directly measure the inner surface temperature of a superconducting cavity is investigated in detail.

Thermal cycling has been studied in detail by several laboratories on bulk niobium [8,9] and also on nitrogen doped niobium cavities [9]. It is however still unclear, what the ideal cooldown procedure is and if it depends on the material treatment of the cavity. Another open question is how much magnetic flux created by thermal currents influences R_S , which could be the reason for differences observed between vertical and horizontal test results [8]. Studies on Nb/Cu cavities are not only useful to push their performance, but also to obtain further information about the mechanism of thermal cycling in general, since Nb/Cu

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cavities are a lot less sensitive to ambient magnetic fields [3]. At CERN such studies have been carried out using the Quadrupole Resonator [10,11] on a Nb/Cu sample prepared by electron cyclotron resonance (ECR) sputtering [12] and on HIE Isolde Nb/Cu quarter wave resonators [13]. In this paper the first study on elliptical Nb/Cu cavities is presented. Results will be compared with the references given above and an advice for a cooldown procedure of cryomodules equipped with Nb/Cu cavities will be given.

Low temperature *in situ* baking is used for bulk niobium cavities to shift the so-called Q -drop (exponential increase of the surface resistance at high field) to larger values enabling economical high gradient operation [14]. In the medium field region above 10 MV/m Nb/Cu cavities also exhibit an exponential increase of R_S with E_{acc} . One might therefore argue that the origin for this is the same as for the Q -drop of bulk niobium cavities. To test this hypothesis the cavity used in this study was tested under the same conditions before and after a 150 °C bakeout.

II. EXPERIMENTAL SETUP AND PROCEDURE

A micrometer thick niobium film has been deposited by high-power impulse magnetron sputtering (HIPIMS) technology on the inner surface of an elliptical single-cell TESLA type [15] 1.3 GHz copper cavity produced by spinning and electropolishing. The important cavity parameters for the studies presented here are found in Table I. They relate the peak magnetic and electric fields to the accelerating gradient E_{acc} and the unloaded quality factor Q_0 to the surface resistance R_S . In the following always E_{acc} and R_S will be used. The HIPIMS sputtering technique for superconducting cavities is under investigation at CERN since 2010 [16]. Literature shows that better film morphology, denser and smoother films, can be achieved compared to standard dc magnetron sputtering (dcMS) coating technology [17]. The cavity analyzed here has been coated with a peak current of 200 A (current density of 2 A/cm²), a potential of 570 V, an average current of 2.6 A with a pulse width of 200 μ s and a frequency of 106 Hz [16]. Preceding sample studies have motivated these parameter choices [18]. A detailed description of the coating system as well as plasma and surface characterization is reported elsewhere [18]. So far the rf cavity results show systematically an increase of R_S with E_{acc} , similar to what has been observed in the past for cavities coated by dcMS [3].

TABLE I. Parameters of TESLA type cavities [15].

| | |
|--------------------|----------------|
| Geometry Factor G | 270 Ω |
| E_{peak}/E_{acc} | 2.0 |
| B_{peak}/E_{acc} | 4.26 mT/(MV/m) |

For the vertical cold tests the cavity has been equipped with an input coupler with a $Q_{ext} = 2 \times 10^9$ and a pick-up antenna with $Q_{pick-up} = 3 \times 10^{11}$. The external coupling Q_{ext} was chosen to obtain critical coupling at 1.8 K and $E_{acc} \approx 15$ MV/m. RF measurements were performed using the phase locked loop technique [19]. Temperature sensors were mounted above and below the cavity cell to measure the temperature and its gradient during the phase transition from the normal to the superconducting state. The vertical bath cryostat has been equipped with a mu-metal shield to reduce the ambient magnetic field to about 3 μ T. Helium was transferred using standard dewars, pressurized with helium gas. For the initial cooldown the gas overpressure was set to about 200 mbar. During this first helium transfer the dewar was emptied when the cavity temperature was about 50 K. This yielded a uniform cavity temperature. The temperature gradient at the phase transition was the lowest of all cooldowns performed, see Fig. 1.

In total the cavity was cooled down five times. Each cycle started with a measurement of R_S as a function of E_{acc} at 4.2 K. Then the cavity was further cooled down to 1.8 K by pumping the helium bath to 16.5 mbar. This process takes several hours, which is slow enough to take several measurements of R_S at $E_{acc} = 1$ MV/m. After the initial cooldown the cavity was warmed up twice above T_c and cooled down again. To ensure that the whole cavity was in the normal conducting state, before the helium transfer was restarted, the temperature on the top and the bottom of the cell were constantly monitored and recorded. Additionally the quality factor was measured with a network analyzer. The maximum temperature the cavity reached in these cycles never exceeded 20 K. For the first thermal cycle the

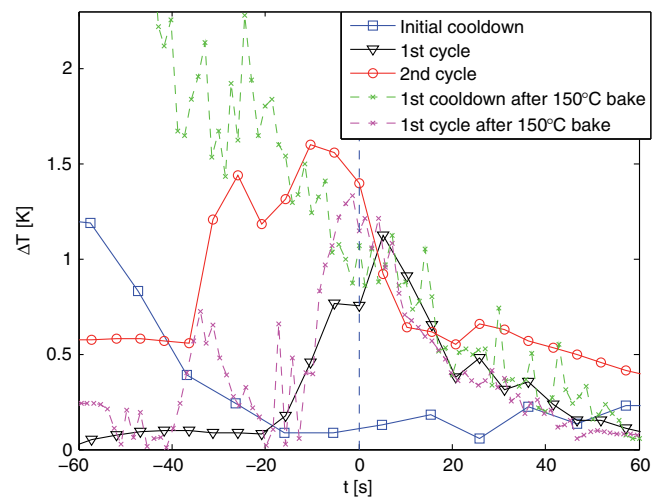


FIG. 1. Temperature gradient along the cell from one minute before until one minute after the phase transition for five cooldowns.

overpressure was set relatively high to about 250 mbar on the helium supply dewar, while for the second cycle the overpressure was set to only 50 mbar to reduce the cooldown speed. Figure 1 displays the temperature difference ΔT between the upper and the lower sensor from one minute before until one minute after the lower sensor displayed a value below T_c . The upper sensor showed systematically higher values so $\Delta T = T_{\text{up}} - T_{\text{down}}$, where T_{up} and T_{down} are the temperature recorded from the upper and the lower sensor at the same time. Temperatures were recorded about every 4 s. The cooldown speed is defined as $T_{\text{down}}(t_{-1}) - T_{\text{down}}(t_1)/(T_1 - T_{-1})$, where t_1 and t_{-1} are the times just before and after the phase transition. The cooldown speed was measured to be about 70 mK/s for the initial cooldown and the second cycle and 230 mK/s for the first cycle.

After the initial cooldown several additional scans of R_S vs E_{acc} were performed just below and above the lambda point of helium at 2.17 K. During the warmup to room temperature the frequency shift was measured as a function of temperature to derive the penetration depth. For this, the liquid helium was almost completely evaporated, so that the whole cavity was only cooled by helium gas. A few liters left on the bottom of the cryostat allowed obtaining a constant temperature along the cavity by evaporating some of the liquid. For a precise measurement pressure control is extremely crucial. A PID-controlled butterfly valve was used to pump the bath pressure to 80 mbar. A stability better than 0.02 mbar was achieved during the whole measurement. The pressure was in fact so stable that no frequency change, within the 1 Hz resolution of the network analyzer, was detectable. The total frequency shift between 4 and 9 K was about 5 kHz. A source of a systematic error is the thermal expansion of copper. Using literature values from [20] it was calculated that the frequency shift due to thermal expansion in the temperature range between 4 and 9 K is about 70 Hz, two orders of magnitude smaller than the frequency shift caused by the penetration depth change. After complete warmup the cavity was *in situ* baked at 150°C for 50 h. In the following rf tests only one thermal cycle with a fast cooldown has been carried out. The speed was 110 mK/s for the initial cooldown and 330 mK/s for the thermal cycle, after which an additional measurement was performed. Helium gas was introduced in the cavity. At 1.8 K its pressure was $p_{\text{RT}} = 5 \times 10^{-5}$ mbar measured at the top flange connection of the cryostat, which corresponds, according to the thermal transpiration law

$$p_{\text{cav}} = p_{\text{RT}} \sqrt{\frac{T_{\text{cav}}}{T_{\text{RT}}}} \quad (1)$$

to a cavity pressure $p_{\text{cav}} = 4 \times 10^{-6}$ mbar, where T_{cav} and T_{RT} are the cavity and the room temperature,

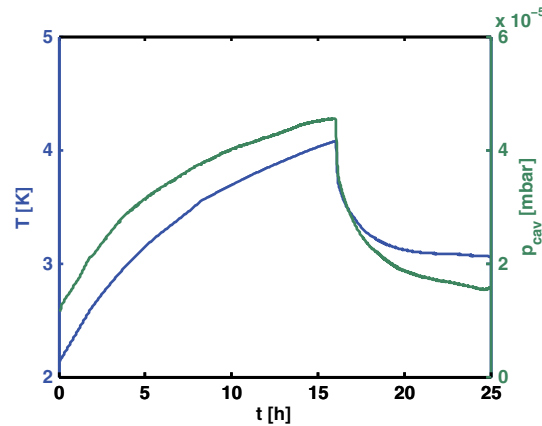


FIG. 2. Temperature and pressure in the cavity during warmup and following cooldown, measured as a function of time.

respectively. The surface resistance was once again measured as a function of E_{acc} , now with the helium gas inside the cavity. To test whether the temperature of the cavity's inner surface increases with E_{acc} the helium pressure was recorded. In order to calibrate the pressure to temperature values during the following warmup both quantities were recorded. A clear correlation was found, see Fig. 2. To verify that the pressure increase was not caused by a leak introducing just more helium gas with time the helium bath was pumped down again. Once more a clear correlation between p and T was found, see Fig. 2.

For the cooldown lower pressures were measured for the same temperatures. Probably, by pumping on the helium bath the evaporated gas cooled down the upper flange of the cryostat to which the pressure sensor is connected. Now, T_{RT} is overestimated, yielding with Eq. (1) an underestimated p_{cav} . For the calibration of p_{cav} with respect to T only the values obtained during warmup were used. These have been recorded directly after the R_S and p_{cav} vs E_{ac} measurement. The goal of this calibration was to obtain an upper limit for the heating of the inner cavity surface by rf as a function of accelerating gradient. Taking the data obtained during the cooldown one would derive a lower temperature change for the same pressure change. Taking the data of the warmup is therefore better suited to define an upper limit. The cavity pressure p_{cav} as derived by Eq. (1) as a function of T and a linear fit to the data are displayed in Fig. 3. The physical mechanism, which is responsible for the pressure increase as a function of temperature involves temperature dependent adsorption on the cavity wall and expansion of the nonadsorbed gas with temperature. The pressure of about $p_{\text{cav}} = 4 \times 10^{-6}$ mbar was chosen to be high enough that the surface was saturated with helium and a temperature increase results mainly in an increase of the pressure of the nonabsorbed gas. Based on

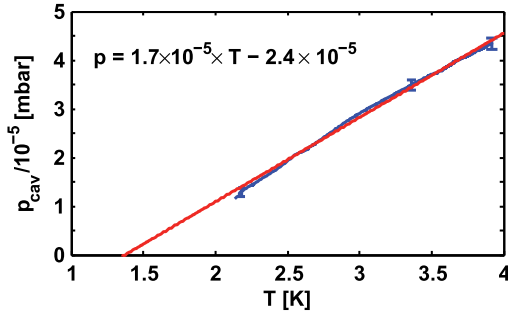


FIG. 3. Cavity pressure as a function of temperature measured during warmup. The blue curve represents measurements obtained every 10 s, while the red line shows a linear fit to the data.

data from [21] it can be estimated that at the pressure used, only a fraction of about 10% of the gas can be absorbed by the cold cavity surface. An even higher pressure has been tried, but resulted in strong discharging at a few MV/m making the measurement impossible. In case of a lower pressure no change of p with E_{acc} was detectable.

Having a saturated cold surface is important for comparing the pressure increase caused by warming of the helium bath for calibration to the pressure increase due to heating from rf. For example, if one would heat up by rf only the cavity cell releasing gas from its surface it could be adsorbed by the nonsaturated cutoff tubes remaining at bath temperature. In this case a warming of the cavity cell could mainly result in an increase of the adsorbed gas on the cutoff tube surfaces. The linear dependence measured between p and T (Fig. 3) suggests that the ideal gas equation is indeed applicable and the surfaces were well saturated.

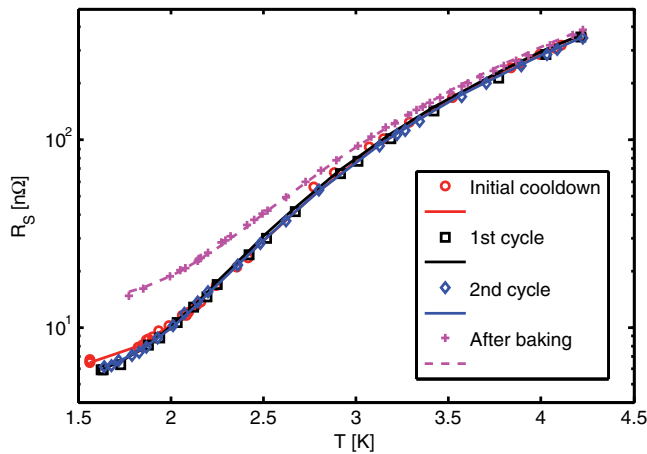


FIG. 4. Surface resistance R_S of a 1.3 GHz Nb/Cu cavity as a function of temperature measured after initial cooldown, two following thermal cycles above T_c and after baking.

III. RESULTS

A. Low field surface resistance

For each cooldown cycle the surface resistance was measured as a function of temperature at $E_{\text{acc}} = 1$ MV/m, see Fig. 4. The data has been fitted to BCS theory using the WinSuperFit software based on calculations from Halbritter [22]. As input parameters the critical temperature $T_c = 9.41$ K, the London penetration depth for infinite mean free path $\lambda_L = 32$ nm and the BCS coherence length $\xi_0 = 39$ nm were used. The former quantity was obtained from frequency shift measurements (see below), while the latter two were taken from the literature [2]. The critical temperature is higher than literature values for bulk niobium, which is typically found for niobium on copper films and can be related to stress in the film [3]. Three parameters were varied in a least squares fit, see Table II. The smallest residual resistance R_{res} was obtained for the fastest cooldown. The effect is however relatively small. The low temperature bakeout yielded an increase of R_{res} by several nΩ. The mean free path could not be accurately determined from R_S vs T , because it was not known whether the mean free path is larger or shorter than the coherence length. For thin film cavities this is not obvious, especially not after low temperature baking. From a measurement of the frequency shift, see Fig. 5, however, one can determine l independently even though it has to be noted that here the information depth is different (several 100 nm) than for the R_S vs T measurement (about 50 nm). From a least squares fit to the Gorter-Casimir expression [23]

$$\lambda(T) = \frac{\lambda_0}{\sqrt{1 - \left(\frac{T}{T_c}\right)^4}} \quad (2)$$

λ_0 and T_c are derived. From λ_0 the electron mean free path l can be obtained from an expression found by Pippard [24]:

TABLE II. Fit parameters obtained from low field surface resistance and penetration depth change measurement.

| | initial cooldown | 1st cycle | 2nd cycle | after baking |
|-----------------------------------|---------------------|-----------------|-----------------|-----------------|
| $\Delta/(k_b T_c)$ | 1.96 ± 0.03 | 1.90 ± 0.05 | 1.93 ± 0.01 | 1.89 ± 0.01 |
| R_{res} in nΩ | 6.1 ± 0.2 | 5.2 ± 0.2 | 5.5 ± 0.2 | 13.7 ± 0.4 |
| l in nm from R vs T | 85 ± 40 | 25 ± 120 | 25 ± 120 | 27 ± 130 |
| λ_0 in nm | | | 46 ± 4 | 78 ± 1 |
| l in nm from $\Delta\lambda$ | | | 58 ± 4 | 12 ± 1 |
| T_c | - | - | 9.41 ± 0.05 | 9.41 ± 0.02 |

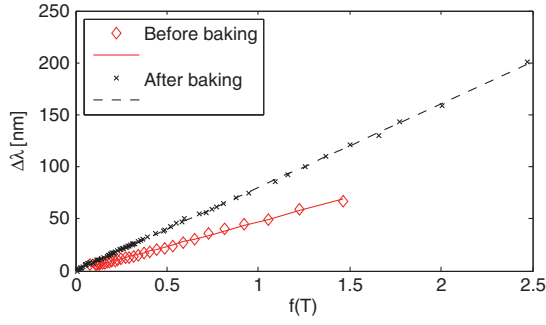


FIG. 5. Penetration depth change as a function of $f(T) = 1/\sqrt{1 - (T/T_c)^4} - 1$ before and after baking.

$$\lambda(l) = \lambda(l \rightarrow \infty) \sqrt{1 + \frac{\pi \xi_0}{2l}}. \quad (3)$$

The London penetration depth $\lambda_L = 32$ nm and the BCS coherence length $\xi_0 = 39$ nm were taken once more from literature [2]. This measurement shows that the low temperature baking significantly decreases l , see Table II. The BCS surface resistance is only slightly altered because it has its minimum at $l = \xi_0$ [2].

B. Field dependent surface resistance

Figure 6 shows R_S as a function of E_{acc} at 1.8 K for five cooldown cycles, including two after baking. At low field the surface resistance differs only by a few n Ω as one can also see from Fig. 4. At larger values of E_{acc} the differences in R_S become more pronounced. The lowest value is obtained for the fastest cooldown (1st cycle) before baking. Baking increases R_S significantly, especially at higher field. After baking R_S is again reduced by

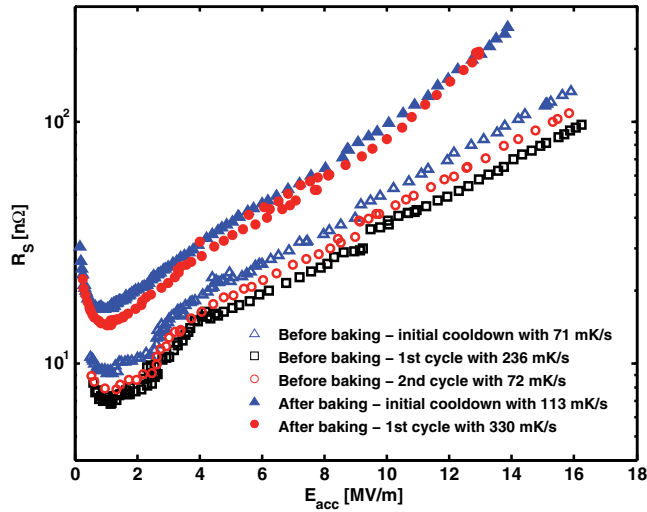


FIG. 6. Surface resistance R_S of a 1.3 GHz Nb/Cu cavity measured at 1.8 K before (open symbols) and after baking (closed symbols) for initial cooldown and several thermal cycles above T_c .

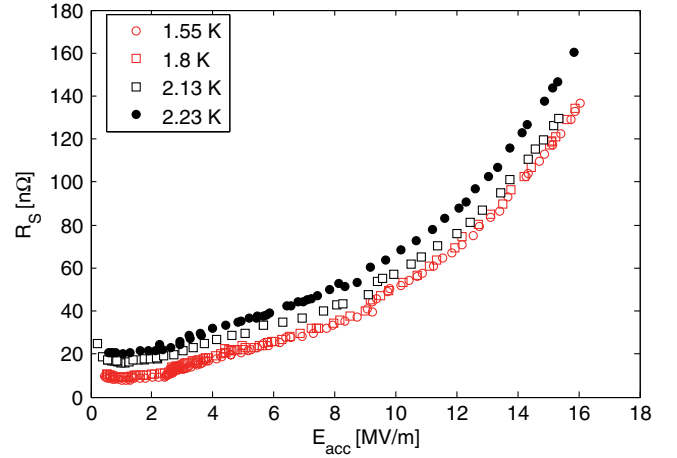


FIG. 7. Surface resistance R_S of a 1.3 GHz Nb/Cu cavity measured at four different temperatures. At low field R_S is similar for the four temperatures. At higher field R_S increases more strongly if data is taken at temperatures above the lambda point, compare Table III.

fast cooldown, even though the effect is less pronounced as before.

After the initial cooldown R_S was additionally measured as a function of E_{acc} for several temperatures, including one just above and one just below the lambda point of helium at 2.17 K, see Fig. 7. One can see that at low field R_S varies only slightly for the different temperatures, which can be entirely correlated to low field BCS losses, compare with Fig. 4. For higher accelerating gradients R_S increases stronger with E_{acc} for 2.23 K compared to the three other curves. This is the only curve measured in a normal fluid helium bath. Table III displays the increase of R_S between 1 and 15 MV/m for the four temperatures. Individual points were obtained by linear interpolation between the two data points closest to the fields of 1 and 15 MV/m, respectively.

After baking and the following thermal cycle the cavity was filled with helium gas. Then R_S vs E_{acc} was measured again, and also the helium pressure was recorded, see Fig. 8. In the range used the 2-digit pressure sensor had a resolution of 0.1×10^{-6} mbar. Using the calibration obtained during the following warmup (Fig. 3) this corresponds to a minimal detectable temperature increase of 60 mK. Above 10 MV/m a pressure increase by 0.1×10^{-6} mbar was detected, corresponding to a maximal temperature increase of 120 mK within experimental error margins.

TABLE III. Surface resistance increase for four different temperatures.

| T [K] | 1.55 | 1.8 | 2.13 | 2.23 |
|--|-------|-------|-------|-------|
| $R_S(15 \text{ MV/m}) - R_S(1 \text{ MV/m})$ [n Ω] | 107.2 | 106.1 | 105.5 | 119.7 |

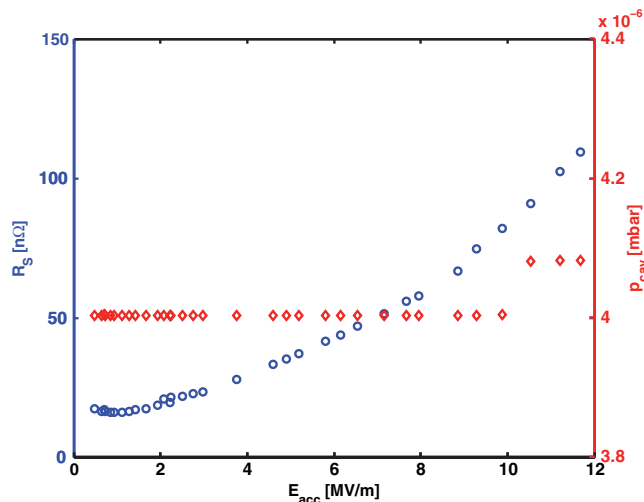


FIG. 8. Primary y-axis: Surface resistance R_S of a 1.3 GHz Nb/Cu cavity measured at 1.8 K. Secondary y-axis: Helium pressure p inside the cavity as a function of E_{acc} .

IV. DISCUSSION

A. Thermal cycling

It was shown that fast cooling can reduce the surface resistance of elliptical Nb/Cu cavities by about 20% at $E_{\text{acc}} = 15$ MV/m in a vertical test cryostat. Thermal cycling changes the low field residual resistance only slightly by fractions of a nΩ. The benefit is only at higher accelerating gradients, similar to what has been observed in [9] for low temperature baked 9-cell bulk niobium cavities. However, for the Nb/Cu cavity investigated here, this effect was reduced by baking. Furthermore, it has to be noted that the cooldown speed was at maximum 30 mK/s in [9], which is not even half as fast as the lowest cooldown speed of 70 mK/s obtained in the experiments here. In [8] it took at least one minute between the transition from the coldest to the warmest part of the cavity, here this was at maximum a few seconds. In [12] it was found by measurements using the CERN Quadrupole Resonator on a Nb/Cu sample prepared by electron cyclotron resonance (ECR) sputtering that a fast cooldown decreases R_S . The cooldown speed obtained in this experiment was comparable to what has been reported here. However it was found in contradiction to the results presented here that mainly the low field R_S is affected, while the influence on the field dependence is rather small. The results presented here suggest that the thermal gradient does not affect R_S but the cooldown speed is of importance, which is in contradiction to what has been measured on Nb/Cu quarter wave resonators in vertical tests [13]. To conclude, it can be said that the cooldown speed and the thermal gradient play an important role for minimizing losses in superconducting cavities. Comparing results from different publications is difficult because it is still unclear whether flux trapping

from ambient fields or thermal currents are more relevant. Another open question is whether cavities of different geometry and/or different materials/treatments need specific cooldown procedures. Based on the results presented here and taking into account that thermal currents might be more relevant in horizontal cryomodules than in vertical test cryostats the following procedure for horizontal SRF cryomodules equipped with Nb/Cu cavities is advised: (i) After the initial cooldown, a warmup just above T_c , (ii) Give the cavity time to thermalize to minimize thermal currents, (iii) Cooldown the cavity as fast as possible through T_c . This procedure is consistent with all experimental results on Nb/Cu cavities. In [8] it was suggested to either thermalize the cavity above T_c during the first cooldown or perform a thermal cycle. The former option is not advised for Nb/Cu cavities. The thermalized cavity in the first initial cooldown gave an even worse result than for the slowest cycle afterwards.

B. Low temperature baking

In situ baking of the cavity yielded a higher low field residual resistance and an enhanced field dependent surface resistance, while the temperature dependent BCS surface resistance R_{BCS} was almost unaffected. The former two effects have also been observed for bulk niobium cavities [14]. For bulk niobium cavities R_{BCS} is lowered by baking, which can be correlated to a decreased mean free path l . An unbaked bulk niobium cavity has $l \gg \xi_0$. Baking pushes l closer to ξ_0 . For Nb/Cu cavities baking also reduced l , but since these cavities already have $l \approx \xi_0$ before baking there is no reduction of R_{BCS} . For bulk niobium the low temperature bake is beneficial because it shifts the exponential increase of the surface resistance referred to as Q -Drop to higher fields. Since the baking did not have any similar effect for the Nb/Cu cavity it can be concluded that the origin of the field dependent surface resistance here is a different one than for the Q -drop of bulk niobium cavities. Currently there is no benefit from *in situ* baking of Nb/Cu cavities. However, it might become useful if the medium field Q -slope could be understood and cured and the Q -drop as observed for bulk niobium cavities would become the limitation of this technology.

C. Thermal resistance

Measurements of R_S as a function of E_{acc} just below and above 2.17 K the lambda point of helium have shown that the thermal resistance plays a role for the losses in Nb/Cu cavities cooled by helium-I. At 15 MV/m the surface resistance is about 20 nΩ higher if the cavity is only cooled by helium-I. In helium-II however the contribution to the overall field dependent surface resistance seems to be rather low. The increase of the inner surface temperature was measured to be at maximum 120 mK within experimental error margins. It has to be noted that for the calibration of the gas pressure with respect to the temperature the whole

cavity, including a part of the pumping line, was warmed up and for the rf measurement only the part of the cell with high surface magnetic field. The ratio of these surface areas is roughly two. Taking this into account, the heating of the inner surface can at maximum account for an additional R_S of 6 n Ω assuming low field BCS losses. On the other hand, an increase of 100 n Ω was measured between low field and 15 MV/m. It can be concluded that the thermal resistance can play an important role in minimizing the losses of superconducting cavities at high field. The thermal boundary resistance between the Nb film and the copper substrate is however not the main contribution for the field dependent losses of Nb/Cu cavities. In fact, the thermal resistance should play a more important role for bulk niobium cavities. In [6] it has been reported that the overall thermal conductance of a niobium film on a copper substrate is still four times higher than of electropolished niobium. Even for bulk niobium cavities operated in helium-I it had been concluded by thermal modeling that heating of the inner surface only plays an insignificant role [25].

The method to measure the gas pressure as a function of the accelerating gradient allowed to derive the inner surface temperature and to calculate an upper estimate of how much the heating of the inner surface accounts for the field dependent surface resistance. The experiments presented here were limited by the resolution of the two digit pressure sensor and therefore only allowed to conclude that global heating is not the main contributor to the field dependent surface resistance of Nb/Cu cavities. Further experiments, with enhanced resolution and also on bulk niobium cavities, are planned to study this effect in more detail. The method has already been tested on an LHC crab cavity and a significant pressure increase was detected. These results will be presented elsewhere. The method might also be used to obtain the quality factor Q_0 in horizontal cryomodule tests equipped with strongly coupled input antennas. In this case one could first measure Q_0 vs E_{acc} and p in a vertical test cryostat. After installation in the cryomodule one could insert gas in the cavity again and measure E_{acc} and p again and then obtain Q_0 by comparison with the results from the vertical test. This could serve as an independent method to the usual approach of obtaining Q_0 from the liquid helium consumption. It, however, has to be noted that the strong dependence of the pressure measurement on the experimental setup and the temperature distribution in the periphery need to be taken into account. Since the periphery changes entirely when moving from vertical to horizontal tests, the pressure values obtained are hard to compare. Application of this method to cryomodule testing would require a detailed study, taking into account the different volumes of the cavity with periphery in the different test setups. However, a quick uncalibrated check can always be made during helium processing, for which similar gas pressures are used.

V. CONCLUSION

It has been shown that a fast cooldown can significantly reduce the surface resistance of Nb/Cu cavities. There is currently no benefit from low temperature baking for this technology. The thermal resistance plays only a minor role for the field dependent losses if the cavity is cooled by helium-II. It can be concluded that the field dependent surface resistance of Nb/Cu is mainly limited by effects intrinsic in the film, which need to be investigated in detail if the current limitations shall be overcome.

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