

## A DEVICE TO MEASURE THE RESISTIVITY OF A COPPER CAVITY SURFACE AT LOW TEMPERATURE

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### Abstract

During the manufacture of the LEP superconducting thin niobium film copper cavities it turned out that, without any modification of the coating parameters, the second and further coatings resulted in better RF performance (lower RF losses) than the first one. The origin was supposed to be the copper substrate. A device was designed and tested that allowed the characterization of the copper substrate surface layer of several micron thickness by determining its residual resistivity from a measurement of its surface resistance at low temperatures. The experimental layout and the measurement results are presented.

### 1 INTRODUCTION

The LEP upgrade project is based mainly on superconducting (sc) niobium thin film accelerating cavities. It is a success, as is well demonstrated by electron positron beams colliding with more than 200 GeV centre of mass energy [1]. Nevertheless, several years ago, when the cavities were manufactured, there was a lower than expected acceptance rate for the first coating caused by larger RF losses [2]. Two important improvements resulted in an increase in the acceptance rate from 20 % to 70 % [3]. The thickness of the copper layer to be removed was doubled and the temperature during bake out and coating was decreased from initially 210 – 220 °C by about 40 - 50 °C.

This paper is based on a previous report [4]. The objective of the work was to understand the reason for the increase in success rate with the increasing number of layers of copper. The general idea at that time was that impurities in the niobium layer are the culprit for poorer RF performance. The hypothesis, which turned out to be false, was that the first niobium layer deposited became contaminated by interstitial impurities having diffused from the copper substrate into the niobium. For any further coating less impurities would be available, resulting in lower RF losses. The residual surface resistivity of the bare copper cavity was larger after

coating than before – in contradiction to the hypothesis. Hence lower RF losses of the niobium coating are achieved by increasing the resistivity of the copper substrate surface layer.

This result was not understood at that time. Nevertheless, it was already known that the copper substrate properties, such as the surface roughness, influence the RF losses of the niobium film [5].

In the present paper, we describe, for general interest, the method used to obtain this conclusion.

Since then, convincing evidence for this conclusion has been published elsewhere [6]: the nature of the substrate on which the film is grown is determinant in defining its properties. On average, films grown on oxide-free copper display larger values both of the mean residual resistance and of its rate of increase with the RF field amplitude.

### 2 EXPERIMENTAL

The general idea of the experiment is this: A copper cavity from the production process (#90) was processed in the routine way and the residual surface resistance (which is the surface resistance at low temperature) was measured in parallel after different steps of the production process.

#### 2.1 Design considerations

The experiment is based on the fact that the residual resistivity (which is the resistivity at low temperature) depends critically on the impurity content. The residual resistivity can in principle be determined from the residual surface resistance by RF methods.

In our specific case, the fundamental mode frequency of the cavity is 352 MHz, which is impractical for two reasons. Firstly, the RF penetration depth  $\delta$  is 3.4  $\mu\text{m}$  at room temperature and less than 1  $\mu\text{m}$  at 4.2 K. This depth determines the thickness within which the copper surface is probed. One  $\mu\text{m}$  is too small, because the roughness of the copper is typically of the same order of magnitude. Secondly, in this frequency range, the surface resistance becomes insensitive to the impurity content because of the anomalous skin effect. Therefore it was necessary to lower the frequency

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down into the domain of the normal skin effect, where the probed thickness becomes larger and the surface resistance depends on the impurity content.

## 2.2 Experimental layout

A solution was found by loading the cavity with a tube made of niobium sheet with a capacitor at its lower end (Fig.1), also machined from niobium sheet. This part is sc at low temperatures and hence should not contribute to the RF losses of the cavity. The tube has an external diameter of 16 mm and leaves enough room inside to be cooled by liquid helium. In addition, in order to increase the cool down speed, a copper tube inside the niobium tube guides the helium vapour above the heat screens of a vertical cryostat. A carbon resistor at the lower end of the niobium tube allows the measurement of the temperature there.

The capacitor is of a cylindrical type. It consists of an inner bulb with a diameter of 100 mm and a length of 190 mm, which is connected to the rod and also cooled by liquid helium. Its outer cylindrical part is brazed to the lower flange and is cooled by heat conduction from below. A Kapton® foil (0.2 mm) fills the gap of 0.3 mm width in between the bulb and the cylinder. The upper flange of the cavity is made from stainless steel and coated with copper (200 µm). The lower one is made from massive copper in order to minimize the RF losses still more. The niobium bulb has a distance of 10 mm from the lower flange in order to compensate for differential contractions during cool down. The RF input and output antennae are of the loop type to improve the coupling to the lowest mode at 2.2 MHz and are mounted on the upper and lower coupler ports.

After manufacture, the niobium tube is mechanically brushed to remove the debris of the welding (TIG welding under protective gas in air). Subsequently the surface is cleaned by a brush, which has been immersed in the standard chemical polishing solution used for niobium.

In principle the frequency can be decreased to a very low value by sufficiently increasing the capacitance. The lowest RF mode (2.2 MHz) in this layout is a TEM coaxial mode, the electric energy of which is stored near the capacitor and the magnetic energy stored at the opposite end. The next highest mode is a TEM mode for which the length of the cavity corresponds to half a wavelength (66 MHz). The following modes are those for which the cavity length represents 2, 3, ... half wavelengths (130, 192, ... MHz).

The RF tests consist of measuring the S-parameters ( $S_{11}$ ,  $S_{21}$  and  $S_{22}$ ), and the bandwidth (or the loaded Q-value) with a Hewlett Packard HP70300 network analyzer.

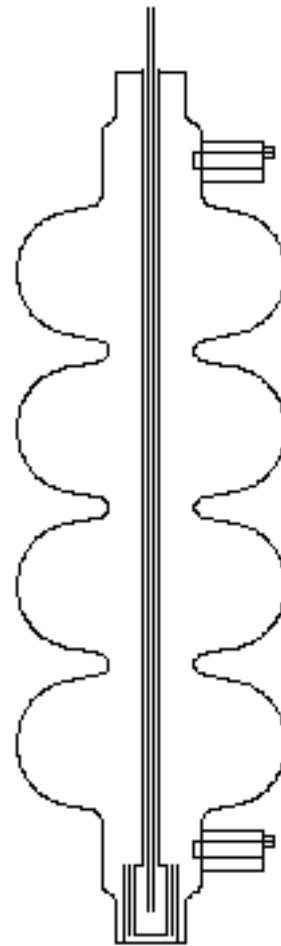


Figure 1: Schematic layout of cavity with sc niobium rod inside and niobium capacitor at lower end (with a Kapton® foil between the capacitor plates to increase its capacitance). A copper tube inside the niobium rod takes out the warm helium gas during the initial cool down and thus helps to increase the cool down speed.

## 2.3 RF measurements on a model cavity at room temperature

In order to determine the surface resistance one has to know the geometry factors of the different modes. They have been determined by extrapolation from a computer simulation.

For this purpose measurements on a copper cavity were performed and the results were compared with computer simulations. A copper wire of 2 mm diameter was stretched inside a copper cavity, which is available in the group's RF laboratory. One end of the wire was connected to the cavity body, the other end of the wire ended in a capacitor of 190 mm diameter and 1 mm plate distance filled with air. Its measured and calculated capacitance are 260 pF and 276 pF, respectively. The Q-values of the lowest modes were measured. In addition,

the Q-value in the fundamental mode, at 352 MHz of the bare cavity (without wire) was measured (Table 1).

Table 1: Computed and measured Q-values for bare copper cavity at room temperature (2 mm diameter copper wire)

| f (exp) [MHz]                                    | Q (exp) | Q (comp) |
|--------------------------------------------------|---------|----------|
| 6.1                                              | 277     | 290      |
| 63                                               | 972     | 882      |
| 124                                              | 1262    | 1225     |
| 183                                              | 1512    | 1520     |
| 352 <sup>1)</sup>                                | 53333   | 57479    |
| <sup>1)</sup> Measurement on cavity without wire |         |          |

The computation was performed with the computer codes SUPERFISH and URMEL. In order to increase the precision, the geometry used in the computation was slightly different from the real one (the wire diameter was 60 mm in the computation instead of 2 mm in the experiment and the gap distance was 15 mm instead of 1 mm).

The extrapolation of the Q-values obtained from the simulated geometry to the real geometry is described in the appendix. The numbers are listed in Table 1 (Q (comp)) and correspond to the measured values within 10 %. This fact gave us confidence in the validity of the extrapolation method.

Table 2: Partial geometry factors for copper surface with a 16 mm diameter tube inside (as in the experiment) and a capacitor gap slightly larger than in the experiment

| f [MHz]                                                                                            | URMEL | SUPERFISH |
|----------------------------------------------------------------------------------------------------|-------|-----------|
| 19                                                                                                 | 52    | 45        |
| 69                                                                                                 | 163   | 164       |
| 127                                                                                                | 276   | 298       |
| 184                                                                                                | 364   | 427       |
| A linear fit of the partial geometry factor is $G [\Omega] = (2.2 \pm 0.1) \cdot f [\text{MHz}]$ . |       |           |

As a next step we computed the RF losses for the cavity surface separately and the wire. Also here, for better precision, the computed geometry was slightly different from the real one (the capacitor gap was larger). This resulted in a larger frequency of the computed cavity shape (19 MHz) compared to the real one (2.2 MHz) (Table 2). Up till 200 MHz the results from the two programs differ by  $\pm 15$  %. The geometry factors were approximated with a linear fit,  $G [\Omega] = (2.2 \pm 0.1) \cdot f [\text{MHz}]$ . The error is given by the deviation of the slopes fitted to the results from the two computer codes. A linear fit is justified because the geometry factor is essentially proportional to the frequency and the volume to surface ratio. For the

modes under study this ratio is virtually constant. The partial geometry factor of the lowest measured mode at 2.2 MHz can therefore be obtained by extrapolation (4.8  $\Omega$ ).

## 2.4 RF measurements on the "real" cavity

The sequence of RF tests and the results are summarized in Table 3. The response of the cavity to a frequency swept excitation signal was measured in reflection and transmission mode both from the input and output antennae. The set of quantities to be determined was the reflection factors  $\rho$  (from a polar plot of the reflection factor) and the insertion loss  $P_{\text{out}}/P_{\text{in}}$  in resonance and the bandwidth  $\Delta f$  by using the averaging option. The HP network analyzer allows a direct measurement of the loaded Q-value, too. In the usual way the coupling factors  $\beta'_{\text{in}}$  and  $\beta'_{\text{out}}$  were determined from the reflection factor  $\rho$ , as

$$\beta' = \begin{cases} \frac{1-\rho}{1+\rho}; & \text{undercoupled} \\ \frac{1+\rho}{1-\rho}; & \text{overcoupled} \end{cases} \quad (1)$$

by supplying power to the cavity by the input antenna ( $\beta'_{\text{in}}$ ) and by the output antenna ( $\beta'_{\text{out}}$ ). The prime takes note of the fact that this definition of coupling factor includes the transmitted power leaving the cavity (which is somewhat different from the usual definition of  $\beta$ ). The unloaded Q-value is determined by two independent methods. First, it follows from the loaded Q-value  $Q_L$  and the coupling factors as

$$\frac{1}{Q_0} = \frac{1}{Q_L} \cdot \frac{1 - \beta'_{\text{in}} \cdot \beta'_{\text{out}}}{(1 + \beta'_{\text{in}}) \cdot (1 + \beta'_{\text{out}})}, \quad (2)$$

which we call "reflection method".

Secondly, it can be determined from the insertion loss  $P_{\text{out}}/P_{\text{in}}$  and the external Q-values,

$$Q_{\text{ext}}^{\text{in}} = Q_L \cdot (1 + \beta'^{-1}_{\text{in}}), \quad (3)$$

$$Q_{\text{ext}}^{\text{out}} = Q_L \cdot (1 + \beta'^{-1}_{\text{out}}), \quad (4)$$

which we call "transmission method". The unloaded Q-value is then

$$\frac{1}{Q_0} = 2 \cdot \sqrt{\frac{P_{\text{in}}}{P_{\text{out}} \cdot Q_{\text{ext}}^{\text{in}} \cdot Q_{\text{ext}}^{\text{out}}}} - \frac{1}{Q_{\text{ext}}^{\text{in}}} - \frac{1}{Q_{\text{ext}}^{\text{out}}} \quad (5)$$

The unloaded Q-values obtained by these two methods are given in columns 3 and 4 of Table 3, and their weighted average in the next column.

Table 3: RF tests of bare copper cavities with niobium rod inside at 4.2 K and 2.2 MHz.

| Cavity name and test # | Treatment                                                     | $Q_0$ [10 <sup>3</sup> ] | $Q_0$ [10 <sup>3</sup> ] (Ins.loss) | $Q_0$ [10 <sup>3</sup> ] average | $R_s(\text{Cu})$ [ $\mu\Omega$ ] | $\rho$ [n $\Omega$ cm] | $\delta$ [ $\mu$ m] |
|------------------------|---------------------------------------------------------------|--------------------------|-------------------------------------|----------------------------------|----------------------------------|------------------------|---------------------|
| 90.0.a                 | Half cells electropolished (120 $\mu$ m) and cavity assembled | 25.9                     | 25.5                                | 25.8                             | 21 $\pm$ 3                       | 4.8 $\pm$ 1.3          | 2.4 $\pm$ 0.3       |
| 90.1.a                 | Cavity chemically polished and coated                         | 29.0                     | 29.0                                | 29.0                             | Cavity coated with niobium       | -                      | -                   |
| 90.1.b                 | Cavity stripped and chemically polished                       | 24.0                     | 24.4                                | 24.1                             | 34 $\pm$ 3                       | 13.1 $\pm$ 3.7         | 3.9 $\pm$ 0.4       |

The losses of the body of the copper cavity are determined before the coating (test # 90.0.a) and before the second coating (after the niobium layer has been stripped off and the cavity has been chemically polished, test # 90.1.b). The measurement in between with the cavity body coated with a niobium layer (test # 90.1.a) is necessary in order to determine the parasitic losses from the flanges, the capacitor, etc. The assumption is made that the losses from the niobium parts (the bulb, the rod and the cavity body) are negligible. That this assumption is correct can be concluded from the relatively low Q-value under these conditions. The losses in the body of the copper cavity are given by the difference of the losses of the uncoated cavity and the coated one. The corresponding Q-values are named as  $Q_0$  and  $Q_{0,\text{Nb}}$ , respectively. Hence the Q-value  $Q_{0,\text{Cu}}$ , attributed to the losses of the body of the copper cavity,

$$\frac{1}{Q_{0,\text{Cu}}} = \frac{1}{Q_0} - \frac{1}{Q_{0,\text{Nb}}} . \quad (6)$$

The surface resistance is

$$R_s = \frac{G}{Q_{0,\text{Cu}}} . \quad (7)$$

The physically relevant parameters resistivity  $\rho$  and skin depth  $\delta$  are determined as

$$\delta = \frac{R_s}{\pi f \mu_0}; \quad \rho = \frac{R_s^2}{\pi f \mu_0}, \quad (8)$$

which are shown in the last columns of Table 3.

## 3 RESULTS AND DISCUSSION

### 3.1 Anomalous skin effect

The first item to be looked at is whether the experiment is governed by the normal skin effect. Otherwise the surface resistance would be insensitive to surface impurities (anomalous skin effect). From measurements on a 500 MHz copper cavity (made of OFHC copper, as is the one under test) it is known that the lower limit of the surface resistance in the normal skin effect amounts to 0.9 m $\Omega$  [7]. As it scales with the frequency as  $\omega^{2/3}$ , the corresponding lower limit for the cavity under test (with a resonant frequency 2.2 MHz) is 24  $\mu\Omega$  with an estimated error of  $\pm 10\%$ . The first data point for the surface resistance is just below and the second data point is well above that limit (Table 3, test # 90.0.a and 90.1.b, respectively). This is sufficient to conclude that the surface resistance and hence the resistivity of the copper surface layer have increased after the coating with a niobium film.

### 3.2 Measurement error

The error of the measurement was determined from the errors of the individual voltages  $V_i$ ,  $V_r$  "seen" on the input line ( $\pm 1\%$ ), the corresponding ones on the output line ( $\pm 1\%$ ), the loaded Q-value ( $\pm 2\%$ ), and the insertion loss ( $\pm 0.1$  dB). The relative error of the unloaded Q-values measured in the reflection mode is about  $\pm 2\%$ , and  $\pm 8\%$  when measured in the transmission mode. The surface resistance of the body of the cavity made of copper is given by the difference of the average surface resistances of the uncoated cavities and the coated one. Its error is between  $\pm 9\%$  and  $\pm 14\%$  (Table 3).

## 4 CONCLUSION

A method which allows the measurement by RF methods of the residual resistivity and hence the impurity content in a surface layer of a bare copper cavity has been described.

The thickness of the surface layer probed by RF is between 2.3 and 4.0  $\mu\text{m}$ .

The lower limit of the residual surface resistance in the regime of the normal skin effect is 24  $\mu\Omega$  at the frequency of 2.2 MHz.

The first data point is just below. Nevertheless, after coating the copper cavity with a thin niobium film, then stripping off that film and chemically polishing the copper cavity again, the residual surface resistance of the bare copper substrate surface layer is well above this limit.

Hence a more resistive copper substrate surface layer results in lower RF losses of the niobium coating on top.

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## 6 APPENDIX

**How to extrapolate the Q-values from the computed geometry to that of the model copper cavity (cf. Chapter 2.3):**

The resonant frequency of the lowest computed mode was 22 MHz. The current on the rod represents by far the largest contribution to the inductance. The inductance is derived from the spatial average of this current and the stored energy (1.3  $\mu\text{H}$ ). For the measured mode at 6.1 MHz the capacitor represents by far the largest capacitance compared to the stray capacitance of the wire. Hence from the measured resonant frequency the inductance can be derived (2.5  $\mu\text{H}$ ). Hence the inductances for the experimental layout and the one used in the model computation differ by the factor (2.5/1.3). The same is true for the stored energies (looking only at the magnetic part of the stored energy). This applies to all modes under investigation. Hence for the higher modes the computed

stored energy is multiplied with this same factor, which results in the stored energy of the experimentally measured mode. In addition, the losses on the wire are multiplied by the ratio of the radii (30), and the surface resistance  $R_s$  is adjusted according to the equation

$$R_s = \sqrt{\pi f \mu_0 \rho} , \quad (9)$$

$f$  being the frequency,  $\rho$  the resistivity of the metal the wire is made of.

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