THE DEPENDENCE ON THE RF FREQUENCY OF THE FIELD DEPENDENT PART OF THE SURFACE RESISTANCE OF NIOBIUM SPUTTER COATED COPPER CAVITIES

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Abstract

The major part of the RF system for the now dismantled LEP electron positron collider consisted of 352 MHz four cell copper cavities sputter coated with a thin niobium film. The relation of the quality factor Q (E) versus the accelerating field E showed a slight slope – indicative of a surface resistance R that depends on the RF magnetic field H. The polynomial fit $R(H) = R_0 + a \cdot H + b \cdot H^2$ is applied for a subset of the LEP cavities manufactured and measured between 1991 and 1996 and compared with data from 1500 MHz cavities that were manufactured in a similar manner. A linear relation of the field dependent part of R with the RF frequency is confirmed.

1 INTRODUCTION

The major part of the RF system for the now dismantled LEP electron positron collider consisted of 352 MHz four cell copper cavities sputter coated with a thin niobium film (niobium film cavities). The relation of the quality factor Q versus the accelerating field E showed a slight slope – indicative of the field dependent part of the surface resistance R. This was tolerable for the nominal accelerating fields used for LEP (6 – 7 MV/m). For further applications of this technology at higher fields and different RF frequencies, however, the physical nature of the field dependent part of R should be better known. In an earlier paper [1], a linear relation with frequency of this field dependent part was found by comparing results obtained at 352 MHz (LEP cavities) and 1500 MHz [2] (manufactured in collaboration with Saclay), H being the peak surface magnetic field amplitude. In the meantime a much larger sample size has become available at 1500 MHz for cavities manufactured at CERN in a similar way to the LEP cavities [3]. The polynomial fit $R(H) = R_0 + a \cdot H + b \cdot H^2$ allowed a satisfactory fit of the data obtained. In the paper presented the same polynomial fit is applied for the LEP cavities manufactured and measured between 1991 and 1996. The frequency dependence of the field dependent part of $R_1(H) = a \cdot H + b \cdot H^2$ is determined from the two frequencies 1500 MHz and 352 MHz and compared with the previous results. Consequences with regard to the physical origin will be drawn.

2 CHOICE OF EXPERIMENTAL SETUP

The ideal experimental set-up would be a sufficiently small sample inside a host cavity exposed to a homogeneous RF magnetic field H at different RF frequencies. The RF losses would be measured indirectly from the Q-value of the host cavity or directly, after calibration, from the increase of the temperature of the sample when exposed to the RF field. To construct such a set-up is demanding in terms of precision and sensitivity, because one wants to measure the variation of R_1 with H, which is a second order effect. Attempts to construct such devices were successful but were not yet fully exploited for series measurements [4].

A second somewhat less ideal approach would be provided by a cavity that can be excited in different modes and whose resonant frequencies are sufficiently apart. However, as their field patterns are different, sensible conclusions can only be drawn under the supposition of a uniform R (H) all over the cavity surface. Such a supposition is often not justified.

A third approach could be realised by manufacturing RF cavities in large numbers of similar shape and methods but different size (or frequency). One might hope that by analysing such a large number of cavities random variations in RF performance will average out and the remaining variations are due to the different frequency. Such a possibility was offered at CERN by the manufacture of niobium film cavities for the LEP collider (352 MHz) and for fundamental research (1500 MHz). The initial results of the study on 1500 MHz cavities are published in ref. 3. They will serve as a basis for comparison with the results from the present analysis from the LEP niobium film cavities. Details of the manufacturing procedure can be consulted elsewhere [3, 5].

3 SELECTION CRITERIA, DATA ANALYSIS AND RESULTS

Data are available on all cavities manufactured between 1991 and 1996 by European firms, by both industry and CERN, and by CERN alone, with similar methods as applied in industry. These data were scrutinized as follows. The analysis was based on measurements of Q (E) automatically recorded during the reception tests in an assembly hall at CERN (SM18). These data were transformed into those of R (H) by the replacement $R = 280/Q$ and $H = 4 \cdot E$, R being measured in nΩ, H in mT, Q in 10^9, and E in MV/m. In order not to blur the results by taking into account data on cavities subject to fabrication flaws, all cavities that did not pass the reception criteria (Q (6 MV/m) $\geq 4\cdot10^9$) were rejected from the analysis. Further more only data on cavities tested under similar conditions were retained (cryostat in the SM18 hall with the cavity in vertical position, helium bath temperature 4.5 K, no active compensation for the ambient magnetic field B). The analysis was performed on all data up to E = 5 MV/m (H = 20 mT), which is low enough to avoid the field region where supplementary losses by electron emission occurred (uninteresting in the present context). Data that displayed Q (E) curves that were different depending on whether the RF field was raised or lowered (hysteresis) were identified and rejected, as explained later. In total 245 cavities were analysed as described. A polynomial fit of the surface resistance R (H), similar to the one used in ref. 3, $R(H) = R_0 + a\cdot H + b\cdot H^2$, with fitting coefficients a and b, and the field independent part R_0, represent the data in a satisfactory way (R is measured as before in nΩ and H in mT).

Table 1: Results of data analysis on the original data at T = 4.5 K and B = 33.8 μT and after modification for T = 4.2 K and B = 1 μT

	T = 4.5 K, B = 33.8 μT	**T = 4.2 K, B = 1 μT**
⟨a⟩	(0.39±0.19) nΩ/mT	(0.26±0.16) nΩ/mT
⟨b⟩	(0.033±0.005) nΩ/(mT)^2	(0.033±0.006) nΩ/(mT)^2
Correlation	b=-(0.020±0.003)·a+(0.040±0.002)	b=-(0.030±0.005)·a+(0.040±0.001)
Comments on errors	The errors are of statistical nature.	The errors include the statistical errors of both the averaging procedure and of the modification

The individual fitting coefficients a and b as well as the chi-square merit factor χ^2 were obtained by running the software package Mathematica on a Macintosh PowerBook G4 computer. The average values ⟨a⟩ and ⟨b⟩ of the individual fitting coefficients a and b, respectively, as well as their standard errors ⟨Δa⟩ and ⟨Δb⟩ were then determined on a subset of fitting results for sufficiently small χ^2 as described in the following. The individual fitting coefficients a and b were sorted with increasing χ^2. Then their average values and standard errors ⟨Δa⟩ and ⟨Δb⟩ were determined from the individual fitting coefficients a and b, running from the smallest χ^2 up till a maximum χ^2_{max}, which resulted in minimum standard errors. The existence of this minimum can be explained by the combination of two counteracting effects, the decrease of the standard errors when the number of measurements is becoming larger, and their increase, when the fit becomes worse (larger χ^2). It turned out that, as expected, the data showing a hysteresis were always associated with $\chi^2 > \chi^2_{max}$ and hence, by supposition, excluded. The individual fitting coefficients a and b were not independent but were correlated. In total, subject to the preceding analysis, 34 fits were taken into account for obtaining the final result for the average fitting coefficients ⟨a⟩ and ⟨b⟩ (Table 1), as well as the average field independent part of the surface resistance $\langle R_0\rangle = (37.7 \pm 3.0)$ nΩ that corresponds to a low field Q–value of $Q_0 = (7.3 \pm 0.6)\cdot10^9$.

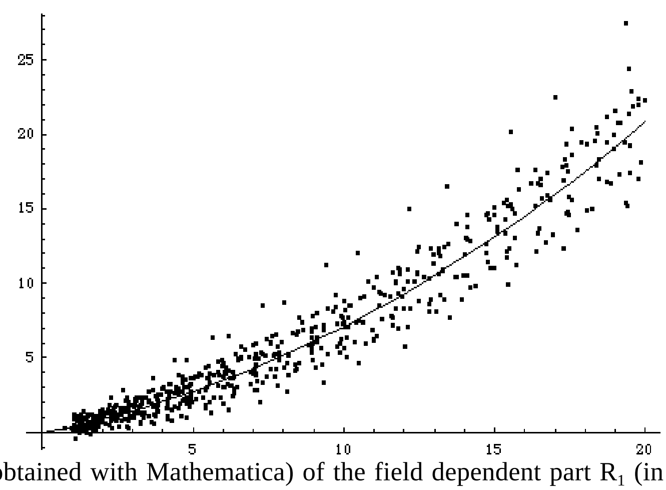

Fig. 1: Summary plot (obtained with Mathematica) of the field dependent part R_1 (in nΩ) of the surface resistance vs. the RF magnetic field amplitude H (in mT) measured at an ambient magnetic field of 33.8 μT and a temperature of the helium bath of 4.5 K. It was obtained by subtracting the field independent part R_0 from the original data of the surface resistance. The solid line indicates the least square quadratic fit to the data shown in this plot, $R_1 = a\cdot H + b\cdot H^2$. The fitting coefficient a and b are the same as the average fitting coefficients ⟨a⟩ and ⟨b⟩ given in Table 1.

To check this analysis all individual data on R_1 belonging to the remaining 34 fits (obtained after subtraction of the individual field independent part R_0) were put together and subject to the same fitting procedure as for the individual measurements. The fitting coefficients a and b that came out were the same as the average fitting coefficients $\langle a \rangle$ and $\langle b \rangle$ shown in Table 1. The summary plot is displayed in Fig.1.

4 COMPARISON WITH DATA PUBLISHED PREVIOUSLY AT 1500 MHZ

As already mentioned, the data were obtained at a temperature of the helium bath of 4.5 K, and the cavity was cooled down in a vertical position in a cryostat without compensating for the ambient magnetic field B = 33.5 µT (15 µT horizontally and 30 µT vertically). For convenience, the present results (352 MHz) are transformed to a bath temperature of 4.2 K and an ambient magnetic field B = 1 µT, in order to facilitate the comparison with those published in ref. 3 (1500 MHz). This modification is obtained from tests of a LEP type cavity at different temperatures*, and of another one† exposed to different static magnetic fields B perpendicular to the cavity axis. The results of these tests are summarized in Table 2. Taking these results, the average fitting coefficients $\langle a \rangle$ and $\langle b \rangle$ and the correlation between the individual a and b are thus modified for T = 4.2 K and B = 1 µT, as indicated in Table 1, column 3.

Table 2: Results of cavity tests used for the modification of the original data

$\Delta a/\Delta B$ [$n\Omega/(mT)^2$]*)	4±1*)
$\Delta b/\Delta B$ [$n\Omega/(mT)^3$]*)	0.08±0.03*)
$\Delta a/\Delta T$ [nΩ/mT/K]	0.9±0.3
$\Delta b/\Delta T$ [$n\Omega/(mT)^2/K$]	$(3\pm12)\cdot10^{-3}$
*) B was perpendicular to the cavity axis. The sensitivity for the external magnetic field directed longitudinally to the cavity axis is estimated to be the same as when directed perpendicularly.	

The final result of the field dependent part of the surface resistance R_1 is displayed by the solid line in Fig. 2, $R_1 = \langle a \rangle \cdot H + \langle b \rangle \cdot H^2$, using the modified $\langle a \rangle$ and $\langle b \rangle$.

The total errors $\langle \Delta a \rangle$ and $\langle \Delta b \rangle$ of the final result for R_1 at 4.2 K and 1 µT are obtained by the mean square root of all statistical errors. These are the statistical errors of the averaging procedure, the one of the correlation between a and b, and the one of the modification of the data to 4.2 K and 1 µT. The resulting errors marked in Table 1, third column. The error margins are the extremes of R_1 by taking into account these errors (solid lines in Fig. 2).

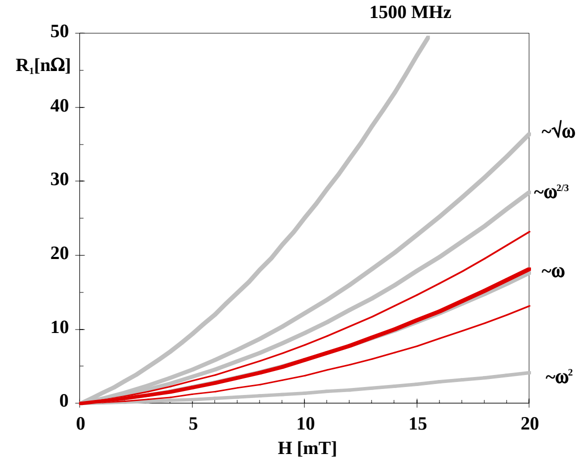

Fig. 2: The field dependent part R_1 of the surface resistance, measured at 352 MHz, and modified for a bath temperature of 4.2 K and an external magnetic field of 1 µT (strong solid line). The (thinner solid) lines above and below the strong one indicate the standard error margin derived from the present data analysis. The grey line at the top displays the surface resistance measured for 1500 MHz and otherwise similar conditions (4.2 K, 1 µT). The lower grey lines show the surface resistance at 352 MHz as derived from the one at 1500 MHz under different hypotheses with regard to its frequency dependence (symbols ~ $\sqrt{\omega}$, ~ $\omega^{2/3}$, ~ ω, ~ ω^2). Only a linear dependence is compatible with the present data.

5 DISCUSSION AND CONCLUSION

The surface resistance R of a superconductor is normally constant with increasing RF field amplitude H. It consists of the two contributions: the BCS part depends strongly on the temperature and goes with the square of the RF frequency ω, and the residual part which is independent of the temperature and has a frequency dependence that is not well known. Any field dependence of R, $R(H) = R_0 + R_1(H)$, indicates that a small fraction of the superconducting surface that is increasing with H behaves differently and gives rise to RF losses described by $R_1(H)$. The knowledge of the frequency dependence induced in that small surface fraction may hint at its physical origin. Possible loss mechanisms and their typical frequency dependence (in brackets) are the normal skin effect ($\omega^{1/2}$), the anomalous skin effect ($\omega^{2/3}$), flux penetration (ω), or BCS losses (ω^2). The inspection of Fig. 1 shows that a linear relation with the RF frequency ω of the field dependent surface resistance R_1 is the only one compatible with the data presented. This result corroborates the one already obtained in ref. 1.

* CERN name: 220.1

† CERN name: 323.1

This fact may indicate two characteristics. First, a single physical process can explain the field dependent losses in niobium film cavities. Secondly, these losses are constant per RF cycle, which in a straightforward way explains the linear dependence on frequency. The only loss mechanism the author is aware of that is compatible with this observation is flux penetration as described by Bean [6].

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