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SURFACE RESISTANCE MEASUREMENTS OF LHC DIPOLE BEAM SCREEN SAMPLES

F. Caspers, M. Morvillo, F. Ruggiero, J. Tan and H.Tsutsui

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Abstract

An estimate of the resistive losses in the LHC dipole beam screen is given from cold surface resistance measurements using the shielded pair technique. Several beam screen samples have been evaluated, with different copper coating methods, including a sample with ribbed surface envisaged to reduce electron cloud losses thanks to its low reflectivity. Experimental data, derived by a proper analysis of the measured Q-factors and including error estimates are compared with theoretical predictions of the anomalous skin effect.

1 INTRODUCTION

One of the undesirable phenomena that contribute to the thermal load on the cold LHC beam screen is the beam-induced resistive wall heating. The key element to this effect is the surface resistance which is frequency dependent and which is sensitive to the coating preparation technique, and in particular to the surface roughness. For that purpose a resonator was developed to measure the surface resistance in the range 150 – 2300 MHz at room temperature as well as in a cryostat. This device, however, is susceptible to a significant amount of technical parameters, which are discussed section 2. Improvements brought to the test stand [1] are described in a chronological sequence and the user will be given practical hints and guidelines for future measurement campaigns. The results of cold measurements (without magnetic field) performed with the latest version of the resonator are presented section 3. They agree with theoretical predictions in the anomalous skin effect regime, contrary to previous results obtained by an earlier version of the resonator [2].

2 TEST SET-UP

2.1 Measurement Principle

Two cylindrical inner conductors are placed in parallel inside a tube, which is the Device Under Test (DUT). The measurement principle consists in exciting even and odd Transverse Electromagnetic Modes (TEM) with a Vector Network Analyser (VNA) and in evaluating the corresponding Q-values. From these two parameters we derive the effective resistance of the DUT and of the inner conductors, assumed identical. As shown in [1], the phase-shift between the inner conductors, 0° (even mode) and 180° (odd mode), is obtained by an external hybrid circuit.

Basically in a coaxial resonator, the fundamental mode is determined by the length of the inner conductor, here 925 mm which is equal to $\lambda_0/2$ and gives a resonant frequency of $f_0 = c/\lambda_0 = 162$ MHz, if one neglects the influence of the end capacity of the rods. The following harmonics are given by $f_n = n \times f_0$ where n is an integer. Note that at half the resonator the electric field is zero for odd harmonic number, and maximum for even harmonic numbers.

The device is a 1.2 m long (length of the DUT) and 39.2 mm diameter cylindrical resonator with two copper-coated inner conductors of 16 mm diameter each. The coating technique of the DUT results from the co-lamination of a sheet of copper and a sheet of stainless steel (SS), which was then rolled and welded to form a tube. Details of the tube fabrication process are extensively described in Ref. [2].

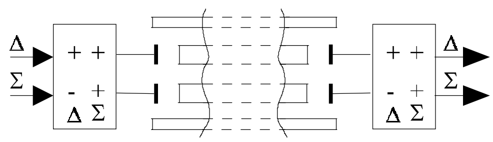

Figure 1: Schematic test set-up; port1=left; port2=right.

The technical choice for non-superconducting material for the inner conductors is motivated by

- the requirement to be tested in a high DC magnetic field,
- the absence of quench phenomena,
- its versatile handling,
- the capability to work on a wide temperature range,
- an acceptable price for the hardware.

The inner conductors are held by three identical internal teflon supports (ε' = 2, loss factor tan(δ) = 10^{-4}). Each disk-like support is fixed by two nylon pins which are inserted in the inner conductors. The two end side supports are placed 1 mm from the rods end side. The gap between the centre of the inner conductors is set to a = 19 mm. Finally the resonator is coupled to the VNA via two pairs 17 mm-long semi-rigid SMA cables, each one being terminated by a 3 mm-long antenna.

The cables are connected to the hybrid devices (Anzac H-9, range 2-2000 MHz) in a given excitation configuration, e. g. starting with the Δ-mode (see Fig. 1). A more detailed representation of the test stand in the odd mode is given in [1, 2]. Then S-parameters and loaded Q's are recorded from the fundamental frequency to the highest harmonic achievable, without running into wave-guide modes (Higher Order Modes = HOM). Thereafter the hybrids are connected from Δ to Σ excitation. All together the relevant S-parameters S_{11} (input reflection), S_{21} (transmission from port 1 to port 2) and S_{22} (output reflection) are recorded for the Σ- and Δ-modes.

2.2 Data Analysis

In a two-port resonator, the loaded quality factor Q_{load} at resonance ω_0 is related to the dissipated power in the cavity walls P_{wall}, to the losses P_1 and P_2 in the coupling ports, and to the stored energy U_0 by the following equation:

$$\frac{1}{Q_{load}} = \frac{P_{wall} + P_1 + P_2}{\omega_0 U_0} = \frac{1}{Q_{wall}} + \frac{1}{Q_1} + \frac{1}{Q_2}\,. \quad (1)$$

With the so-called coupling factor β_i [$i=1,2$] defined as

$$\beta_i = \frac{Q_{wall}}{Q_i} = \frac{P_i}{P_{wall}}\,, \quad (2)$$

Eq. (1) turns into

$$\frac{Q_{wall}}{Q_{load}} = 1 + \beta_1 + \beta_2\,. \quad (3)$$

At resonance β_i is related to the reflection coefficient $|\rho_i|$ by

$$|\rho_i| = \frac{\left|1-\beta_i^{-1}\right|}{1+\beta_i^{-1}}\,. \quad (4)$$

RF quantities measured in a given mode at a given resonance frequency are Q_{load} , S_{11}, S_{22} and S_{21}. From S parameters one gets $|\rho_i|$. Deducing β_i 's gives Q_{wall}.

More explicitly, P_{wall} is the total power dissipated by the inner conductors and by the outer conductor. With respect to both excitation modes one obtains:

$$\frac{1}{Q_{wall,\Delta}} = \frac{1}{Q_{inner,\Delta}} + \frac{1}{Q_{outer,\Delta}} = \frac{R_{si}}{\Gamma_{i,\Delta}} + \frac{R_{so}}{\Gamma_{o,\Delta}} \quad (5)$$

$$\frac{1}{Q_{wall,\Sigma}} = \frac{1}{Q_{inner,\Sigma}} + \frac{1}{Q_{outer,\Sigma}} = \frac{R_{si}}{\Gamma_{i,\Sigma}} + \frac{R_{so}}{\Gamma_{o,\Sigma}} \quad (6)$$

where R_{si} and R_{so} are the surface resistances of the inner and of the outer conductors, $\Gamma_{i,\Delta}$, $\Gamma_{o,\Delta}$, $\Gamma_{i,\Sigma}$ and $\Gamma_{o,\Sigma}$ are geometrical factors. The last four quantities which are also frequency dependent have to be computed [3] to solve the system of two equations with two unknowns R_{si} and R_{so}, assuming that the two inner conductors have identical coating characteristics. The variation versus frequency of the surface resistance of both inner conductors and DUT is obtained by solving this system for each TEM mode. The function $R_{so}(\omega)$ is then used to calculate the parasitic power dissipation per unit length in a circular beam screen :

$$\frac{P}{L} = \frac{I_{av}^2 \cdot c^2}{M \cdot f_0 \cdot \pi}\int_0^\infty \left|\tilde{\lambda}(\omega)\right|^2 \cdot \frac{R_{so}(\omega)}{l}\cdot d\omega \quad \text{[W/m]}, \quad (7)$$

where I_{av} is the average beam current, M the number of bunches, f_0 the revolution frequency, c the velocity of light l the perimeter of the beam screen cross section and $\tilde{\lambda}(\omega)$ the bunch spectrum.

2.3 Sensitivity on Tolerances and Measurement Errors

The surface resistance is obtained by combination of the measured Q-values of the odd and the even modes with coefficients as a function of the geometrical parameters of pure TEM-modes. Sources of errors are the errors of the measured Q-values and the geometrical errors of the cross section. The accuracy in Q measurement for both the odd and the even mode is estimated to be 0.5% by taking into account the correction for external loading via S_{11} and S_{22}. The Q-value is lowered by the dielectric loss in the vinyl (nylon) screws, which tie the inner conductor to the teflon support [1]. To reduce the effect, the vinyl screws are positioned in regions of small electric field.

A very important source of problems was the mode coupling with the undesired TEM-like modes in the coupler region at either side, which lowers the Q-values and leads to ripples in the curves of Q vs. frequency [2]. We made the length of the coupler region shorter so that the resonant frequencies of the undesired modes are beyond our measurement frequency range. For the geometrical errors of the cross section, the error of the lateral spacing of the inner conductors is estimated to be 0.1 mm. From the analysis presented in Refs. [2-3], the resulting total error on the measured surface resistance is below 10%. The size of the inner conductors and their distance can be optimised from the error analysis. The optimised parameters may change if we assume significantly different surface resistances for inner and outer conducting surfaces [3].

3 MEASUREMENT RESULTS

The surface resistance measured for sample tubes with smooth and ribbed surface, at room temperature and at liquid helium temperature (without magnetic field) is shown in Figs. 2 and 3, respectively.

The rolling process to form the tubes has an influence on the RRR. From cold measurements, the initial RRR of flat sheets decreased from 150 to 80 after forming. The fit curves (in the anomalous regime) of the surface resistance for the smooth tube are in good agreement with theory assuming the DC value of the electrical resistivity (1.7 10^{-8} Ωm).

The forming process of the ribbed structures (with corrugation depth of 30 microns and 0.5 mm period) increases the DC-resistivity to 2.15 10^{-8} Ωm. Impurities or inclusions contained in the mandrel may have degraded the copper layer. This rolled tube exhibits a RRR similar to the previous one, i.e. 90 (deduced from the anomalous regime). It does not seem to be sensitive to the saw-tooth structures. Owing to magneto-resistance, the resistivity is described by the Kohler law [2]. Using the physical parameters of the ribbed tube and setting B = 8.386T, one finds ρ(B,T) = 7.69 10^{-10} Ωm. With nominal LHC beam parameters [2] the RF losses amount to 104 mW/m for each circulating beam.

The data from the inner conductors are amazingly reproducible. With a resistivity of 1.7 10^{-8} Ωm the RRR found is 35. This fits once again with the interpolation formula in the anomalous regime [2].

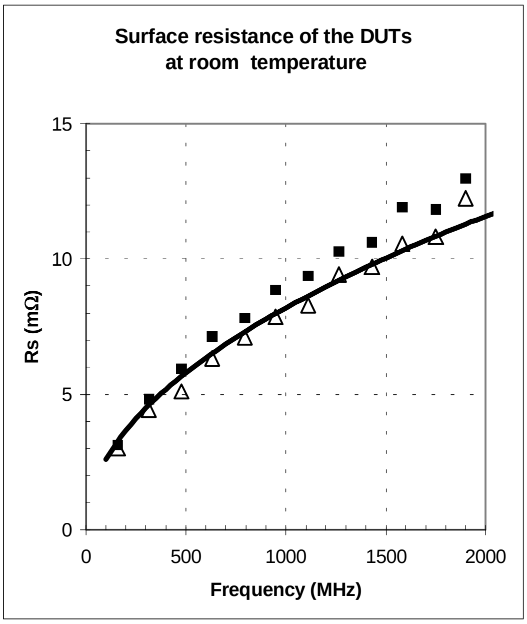

Figure 2: Surface resistance measured at room temperature for a sample tube with smooth (Δ) and another with ribbed (■) surface. The solid line gives the surface resistance calculated in the classical regime with resistivity ρ(300K)=1.7 10^{-8} Ωm.

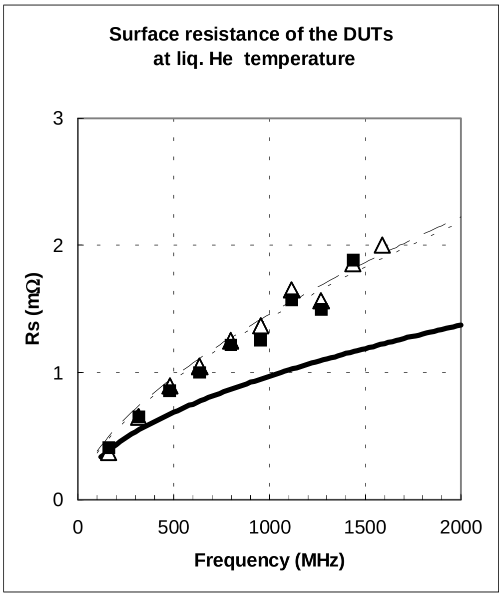

Figure 3: Surface resistance measured at 2K for a sample with smooth (Δ) and another with ribbed (■) surface.
Solid line:RRR=90 from ρ(300K)=2.15 10^{-8} Ωm,classical
Long dashed:RRR=90, ρ(300K)=2.15 10^{-8} Ωm, anomal.
Dashed line:RRR=80, ρ(300K)=1.7 10^{-8} Ωm, anomalous.

4 CONCLUSION

It has been demonstrated that the two-wire coaxial resonator technique is a reliable, yet not very easy tool to handle for measurements of the surface resistance of a long tube in a cryogenic environment. The results obtained show a remarkable reproducibility on the measured surface resistance of the inner (=resonator) rods and gave also a clear indication that the production process has a strong impact on the final performance and the effective RRR value measured in situ. It turned out that the ribbed surface structure required to minimise multiple reflections of the LHC synchrotron light are not of significant influence to the RF losses up to 1.5 GHz. Extrapolating from the measured surface resistance values at liquid helium temperatures without magnetic field, we can expect conduction losses of about 100 mW/m per beam at 8.4T.

5 REFERENCES

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