

SHIELDED PAIR METHOD FOR CYLINDRICAL SURFACE RESISTANCE MEASUREMENT AT CRYOGENIC TEMPERATURE

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Abstract

The shielded pair resonator method was already used in the past at CERN to measure the surface resistance of the LHC beam screen both at room temperature and cryogenic temperature. We have refined and adapted the measurement to be able to measure other types of beam screens and also to operate in a strong dipolar magnetic field. This is necessary for testing the possible effects of coatings and surface treatments for e-cloud suppression for the HL-LHC project or the properties of HTS coated beam screens within the FCC-hh study. Several calibration runs were done at cryogenic temperatures (4.2 K) measuring the surface resistance of a copper pipe to identify the precision, stability, and reproducibility achievable using this method. This work describes the challenges of the measurement and ways to mitigate them.

INTRODUCTION

The surface resistance of the LHC beam screen plays an important role both from the point of view of beam stability and beam-induced resistive wall heating and as a general rule, it should be as low as possible. With new requirements on secondary electron yield of the beam screen, new ideas for novel surface treatments (such as amorphous carbon coating or laser surface structuring) are studied both for use in HL-LHC and later possible use in FCC-hh, for which also high-temperature superconductor (HTS) coatings are being considered. The goal of this project is to develop a measurement system that can easily be adapted to different geometries of beam screens and is able to measure surface resistance in the frequency range of 500-1 500 MHz, inside the FRESKA superconducting dipole magnet (9.5 T) and eventually in FRESKA2 (14.6 T) at temperatures ranging from 4.2 K up to room temperature.

To achieve this a shielded pair ("two-rods") measurement setup is being designed. In the past, this technique was used to measure the surface resistance of the LHC beam screen at cryogenic temperature and inside an LHC dipole magnet [1, 2]. The new setup has to fit inside the FRESKA dipole magnet and stay inside the uniform field region. This defines the maximum length of the setup and sets a lower limit to the frequency of the measurement (400 MHz). In this paper, we describe the results of our first test on a prototype system at liquid helium temperature. The goal of this test was to identify the challenges and uncertainties of the measurement using a copper tube as a known reference.

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MEASUREMENT METHOD

A resonator is constructed using a copper tube, two inner copper rods, and copper end caps. Teflon supports are used to center the inner rods, and hold them vertically in place. A sketch of the setup is visible in Fig. 1. There are 2 couplers on both ends of the resonator. This allows exciting and measuring of the resonant modes using a vector network analyzer (VNA). By measuring the transmitted and reflected power as a function of the exciting frequency we can identify the different resonant modes, as well as measure their quality factor (Q). The quality factor is defined as

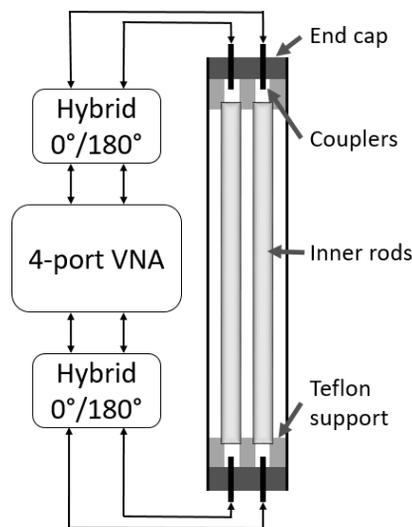


Figure 1: Sketch of the experimental layout. The hybrid junction has two inputs and two outputs. It either forwards "input A" to both outputs or sends "input B" and its opposite signal to the outputs.

$$Q = \frac{2\pi \text{ stored energy}}{\text{energy lost in one period}} = \frac{2\pi f \mu_0 \int_V |H|^2 dV}{\int_s |H|^2 R_s ds}, \quad (1)$$

where f is the frequency of the resonance, μ_0 is the vacuum permeability, H is the magnetic field strength, and R_s is the surface resistance of the cavity walls. In the case of a simple resonator with no dielectric material inside, and with homogeneous surface resistance of the walls R_s can be taken out of the integral and the equation simplifies to

$$Q = \frac{\Gamma}{R_s}, \quad (2)$$

where Γ is the geometry factor and it depends only on the resonator geometry. It can be calculated precisely from electromagnetic simulation.

The 2-rod resonator has 2 fundamental modes (even and odd modes seen in Fig. 2). Their frequencies are separated by 10 MHz. In the even mode, the inner rods are on equipotential and there is no field between the rods. In the odd mode, the electrical phase of one of the rods is shifted by 180° . There are two main ways to excite these modes separately. We can use a $0^\circ/180^\circ$ hybrid junction, or we can use the 4 port VNA in "balanced" (common, and differential) mode. The advantage of using balanced modes is that there are fewer components in the setup, so potentially fewer sources of errors. Calibrating the measurement together with the hybrids is a bit more time-consuming than without since we have to use 2 identical manual calibration kits and open/short/load both outputs of a hybrid at the same time. In the case of the balanced mode measurement, we can use an automatic 4-port calibration kit. We tried both measurement methods, and since they gave identical results, we decided on using the hybrids, to stay comparable to measurements done in the past.

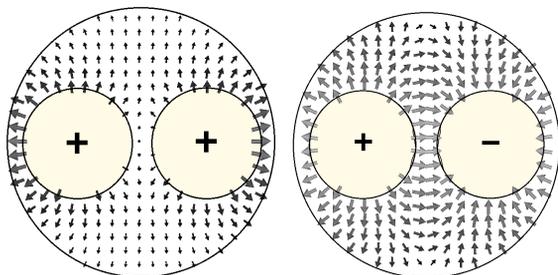


Figure 2: Even and odd mode electric field plots.

From the Q factors, we can calculate the surface resistance of the inner conductors and the outer wall. Using this method, we can avoid making any assumption on the surface resistance of the inner rods, except for being homogeneous on their surface. By replacing the outer tube with any future beam screen prototype, or coated beam screen we can measure the surface resistance of these beam screens directly, and we do not have to rely on flat sample measurements.

Since we are interested in the effect of the image currents arising in the LHC or particle accelerators with similar bunch length, we are interested in longitudinal currents with RF frequency up to 1.5 GHz. The requirement for longitudinal currents is satisfied, and for an inner rod length of 340 mm the fundamental even and odd modes have resonant frequencies of 416 MHz and 425 MHz respectively. We were able to measure the fundamental, the second, and the third harmonic modes since in the case of the fourth harmonic the coupling to the resonator became too strong. Thus we have 3 measurement points where we can compute the surface resistance (420 MHz, 840 MHz and 1 260 MHz).

The Teflon support has a slot for a centering pin and two grooves that ensure that the plane of the two rods is not twisted with respect to the plane of the couplers. Teflon was chosen

as the support material for its relatively low dielectric losses (G10 was also tested but it had introduced huge uncertainties into the Q measurement).

The cable assembly with the hybrid ensures that ports 1 and 2 of the VNA are coupled to the even mode of the resonator, while ports 3 and 4 are coupled to the odd mode. This way we can measure the transmission parameters S_{12} and S_{34} simultaneously. This enabled us to monitor the evolution of both the even and the odd modes during the cooldown of the setup. To take coupling losses into consideration we also measure S_{11} , S_{33} , S_{22} , S_{44} (two input reflections and two output reflections).

In our measurement setup, the hybrids and the VNA are at room temperature, while the resonator is inside a vertical cryostat cooled either directly with liquid helium, or cold helium gas (4.5 K). We were only able to calibrate the part of the assembly which is outside the cryostat. The effect of the 2 m long cable inside the cryostat, as well as the cryogenic feedthrough, can be eliminated using port extensions on the VNA. Uncalibrated electrical length, as well as frequency-dependent losses, can be subtracted from the signal during the measurement. This allowed us to measure precisely the power reflected from our device.

DATA ANALYSIS

From the VNA measurement, one can get the loaded quality factor (Q_{loaded}) to get the unloaded quality factor we have to subtract the contribution of the coupling losses:

$$Q_{unloaded} = Q_{loaded} (1 + \beta_1 + \beta_2), \quad (3)$$

where β_1 and β_2 are the coupling factors, and they can be calculated from the reflection coefficient $|\rho_i|$ as

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

The unloaded quality factors of the even and the odd mode (from now on signaled as Q_Σ and Q_Δ respectively), are related to the surface resistance of the inner rods and the outer tube as well as the dielectric losses of the Teflon as

$$\frac{1}{Q_\Sigma} = \frac{R_{s,i}}{\Gamma_{\Sigma,i}} + \frac{R_{s,o}}{\Gamma_{\Sigma,o}} + P_\Sigma \tan(\delta), \quad (5)$$

$$\frac{1}{Q_\Delta} = \frac{R_{s,i}}{\Gamma_{\Delta,i}} + \frac{R_{s,o}}{\Gamma_{\Delta,o}} + P_\Delta \tan(\delta), \quad (6)$$

where $R_{s,i}$ and $R_{s,o}$ are the inner and outer resistances, $\Gamma_{\Sigma/\Delta,i/o}$ are different geometrical factors (we can get them from simulation of the resonator), $P_{\Sigma/\Delta}$ are the electric energy filling factors for both modes, and $\tan(\delta)$ is the electrical loss tangent (material property). From simulations we can get the dielectric terms, and we can calculate corrected Q factors as

$$\frac{1}{Q_{\Sigma/\Delta,corr}} = \frac{1}{Q_{\Sigma/\Delta}} - P_{\Sigma/\Delta} \tan(\delta), \quad (7)$$

$$\frac{1}{Q_{\Sigma/\Delta,corr}} = \frac{R_{s,i}}{\Gamma_{\Sigma/\Delta,i}} + \frac{R_{s,o}}{\Gamma_{\Sigma/\Delta,o}}. \quad (8)$$

This calculation assumes that the frequency of the even and odd modes are close enough to each other so that $R_s(f_\Sigma) \approx R_s(f_\Delta)$. In our system, the frequency separation is 9 MHz, 11 MHz, and 16 MHz for the fundamental, second, and third harmonic modes respectively. Thus the surface resistance is slightly different for the two modes. This can be taken into account with another transformation of one of the quality factors. We used the assumption that the surface resistance increases with the square root of the frequency. This is true for conductors at room temperature. In the anomalous skin effect (ASE) regime the power of frequency changes slowly towards $2/3$. However, we use this estimation for every measurement, since at our measurement frequencies we are still not in full ASE regime. This correction accounts for 1%, 0.65%, and 0.63% change in the unloaded quality factors.

Finally, all that remains is to solve the linear system of equation connecting $Q_{\Sigma,corr}$ and $Q_{\Delta,corr}$ to $R_{s,i}$ and $R_{s,o}$. Because of the correction mentioned above, the results are corresponding to the surface resistances at the frequency of the odd mode.

Uncertainties

Potential sources of uncertainty of the final value of surface resistance are the following:

- Measurement of the quality factor from the S_{12} signal $\Delta Q_{loaded}/Q_{loaded} \approx 0.5\%$.
- Measurement error of the coupling factors $\Delta \beta/\beta \approx 2\%$. This includes possible calibration errors as well.
- Manufacturing errors can lead to incorrect geometry factors. We estimate that the relative errors of these factors are $\Delta \Gamma/\Gamma < 1\%$.
- There can be slight twists, and displacement of the parts. This could also cause a change in the geometry factors. The reproducibility of the results has been checked at room temperature. After a full disassembly and reassembly, the measured surface resistances are within the error-range of each other.

Using these assumptions we are able to use uncertainty propagation to estimate the relative uncertainty of the resulting surface resistances. They differ for every resonance, and surface, but remain between 3% and 7%.

MEASUREMENT RESULTS

First, before the measurement of the surface resistance, we had to conduct a measurement of the residual resistivity ratio (RRR). For this, we cut out samples of the tube and rod and measured their resistivity (DC) at room temperature and 4.2 K. The RRR of both the rods and tube was 42. This lets us evaluate the theoretical surface resistance of the samples. At cryogenic temperature and frequencies of a few hundred MHz, the anomalous skin effect accounts for an increase of the surface resistance of more than 10%. The

continuous green line in Fig. 3 is showing the theoretical surface resistance of copper with RRR 42 as a result of a Mathematica script [3]. The green region represents 10% relative error of the theoretical value.

The results of the measurement are visible in Fig. 3. The dashed blue line and the dotted orange line show the surface resistance of the inner rods and the outer tube respectively. The error bars are the result of the uncertainty estimation described in the last section.

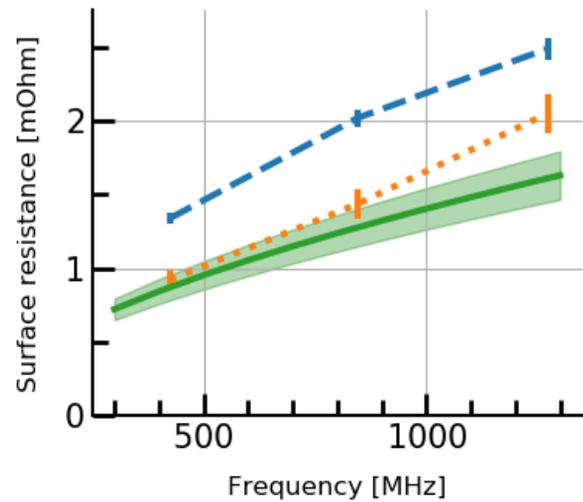


Figure 3: Result of the measurement. The blue dashed line and orange dotted line corresponds to the surface resistance of the inner rods, and outer tube respectively. The green continuous line is the surface resistance of copper at 4.2 K calculated with anomalous skin effect in mind. A 10% uncertainty range is shown around the theoretical curve.

As seen in the figure, there is a significant difference between the measured surface resistance of the rods and the tube. This can be caused by manufacturing introducing surface effects in the material, or possible twist of the rods. Further study is necessary to identify the source of this discrepancy.

CONCLUSION

The two-rod resonator method can be used to measure the surface resistance of tube-shaped objects. The measurement uncertainties limit us in how precisely we can determine the surface resistance. However, in the case of a copper tube as the device under test we were able to get results in accordance with theoretical values at cryogenic temperature. Results were gathered at three frequency points. In the future, we will be working on building and testing a measurement setup, which can also apply a strong dipole magnetic field to the sample, as well as vary the temperature of the whole resonator between 4.2 K and 50 K. We are also planning to test a tube made of six long stainless steel plates coated with HTS tape. This could be a first impedance measurement on an HTS coated beam screen prototype.

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