ELECTROMAGNETIC CHARACTERIZATION OF MATERIALS FOR THE CLIC DAMPING RINGS

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Abstract

The performance of the Compact Linear Collider (CLIC) damping rings (DR) is likely to be limited by collective effects due to the unprecedented brilliance of the beams. Coating will be used in both electron (EDR) and positron damping rings (PDR) to suppress effects like electron cloud formation or ion instabilities. The impedance modeling of the chambers, necessary for the instabilities studies which will ensure safe operation under nominal conditions, must include the contribution from the coating materials applied for electron cloud mitigation and/or ultra-low vacuum pressure. This advocates for a correct characterization of this impedance in a high frequency range, which is still widely unexplored. The electrical conductivity of the materials in the frequency range of few GHz is determined with the waveguide method, based on a combination of experimental measurements of the complex transmission coefficient S_{21} and CST 3D electromagnetic (EM) simulations.

INTRODUCTION

The EM characterization of the material properties up to high frequencies is required for the impedance modeling of the CLIC DR components. Layers of coating materials such as amorphous carbon (aC) and Non-Evaporable Getter (NEG) are necessary for e-cloud mitigation and ultra-high vacuum. The waveguide method is used to characterize the properties of those coating materials in a range of frequencies of few GHz. The reliability of this method is tested in the range of 9-12 GHz using a standard X-band waveguide before trying to measure in the range of 325-500 GHz using a Y-band waveguide. The electrical conductivity of the material is obtained from the measured transmission coefficient S_{21} and 3D EM simulations with CST Microwave Studio®(CST MWS) [1].

WAVEGUIDE METHOD

An X-band copper (Cu) waveguide of 50 cm length and the same Cu waveguide coated with NEG are the devices under study during the experiment. Using a network analyzer, the transmission coefficient is measured over a frequency range from 9-12 GHz. The experimental method's setup is displayed in Fig. 1. The S_{21} coefficient is related to the attenuation due to the finite conductivity of the material.

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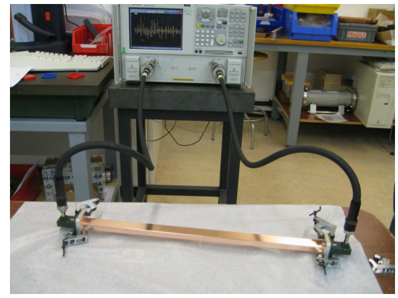

Figure 1: Measurements setup: using a network analyzer, the transmission coefficient S_{21} of an X-band waveguide is measured.

NEG Coating Procedure

NEG coating is necessary to suppress fast ion instabilities in the EDR. A Cu X-band waveguide is coated with a Ti-Zr-V thin film by magnetron sputtering using two cathodes, each of them made of elemental wires inter-twisted together [2]. The coating was targeted to be as thick as possible in order to increase the sensitivity of the measurements. From x-rays measurements, the thickness is assumed to be 9 μm. The real profile of the coating thickness will be implemented in the simulations as soon as more detailed profile measurements will be available.

SIMULATIONS WITH CST

The CST MWS is used to simulate a waveguide made from Cu and a NEG coated one with the same dimensions as the real ones (see Fig. 2). With the Transient Solver of CST, the experimental setup used for the measurements can be simulated in real time domain.

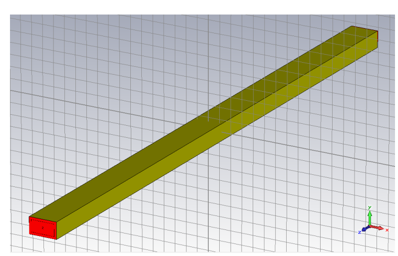

Figure 2: X-band Cu waveguide simulated with CST MWS of 50 cm length.

For each frequency from 9-12 GHz the output of the 3D EM simulations is the S_{21} parameter as a function of conductivity. The relative permittivity ε_r and permeability μ_r of the material are assumed to be equal to one while the conductivity σ is the unknown parameter which is scanned

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in simulations. For CST simulations, the coating thickness is assumed to be uniform and equal to 9 μm (expected thickness from x-rays) or infinite to simulate the case where the skin depth is much smaller than the thickness (upper limit for the NEG conductivity). The intersection at each frequency (see Fig. 3) of the measured S_{21} with the CST output obtained numerically, determines the unknown electrical conductivity as a function of frequency. Repeating this method for all the frequency range the material conductivity is obtained as a function of frequency.

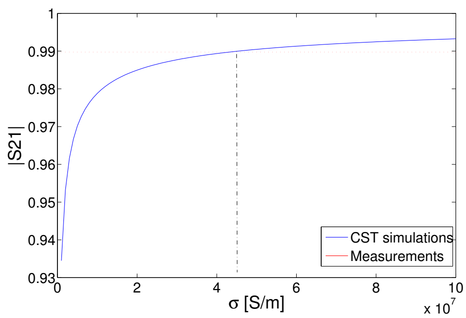

Figure 3: Example at 10 GHz: intersection of S_{21} from CST simulations with the measured value.

Conductivity Measurement of a Pure Cu X-band Waveguide

As a first step, a pure Cu waveguide is used to measure the S_{21} coefficient and test the feasibility of the method. The results from the experiment are shown in Fig. 4.

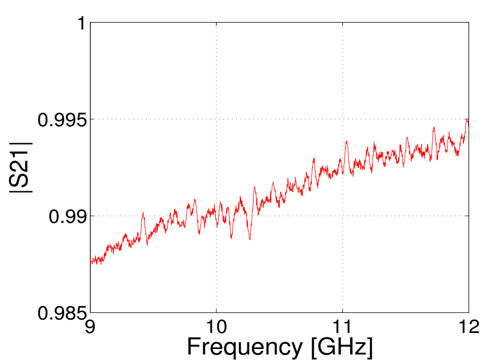

Figure 4: Measured S_{21} as a function of frequency for a pure Cu X-band waveguide.

A Cu waveguide is then simulated with CST MWS assuming conductivity equal to 5.8×10^7 S/m at 20 °C. The intersection of the measurements with the CST simulations show that the conductivity of Cu was estimated within the same order of magnitude with the known value (see Fig. 5). From the measurement, the average value of σ_{Cu} is equal to 5.91×10^7 S/m, which is in a very good agreement with the known one.

For the Cu waveguide measurements, the attenuation is very sensitive to the errors because of the small losses in Cu. Despite this fact, the results obtained were considered

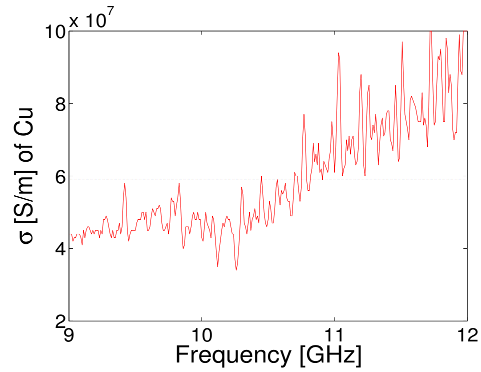

Figure 5: Copper conductivity as a function of frequency.

to be encouraging to continue with the NEG coated waveguide measurement. However, in the future it is foreseen to benchmark CST MWS and the reliability of the experimental method by using a stainless steel waveguide which will be less sensitive to the errors due to its lower conductivity. This future step will be another important benchmark of the method.

Conductivity Measurement of a NEG Coated X-band Waveguide

The same experimental method is used for the NEG coated waveguide in order to measure the S_{21} coefficient. In Fig. 6 the comparison of S_{21} between the pure Cu and the same waveguide coated with NEG is shown.

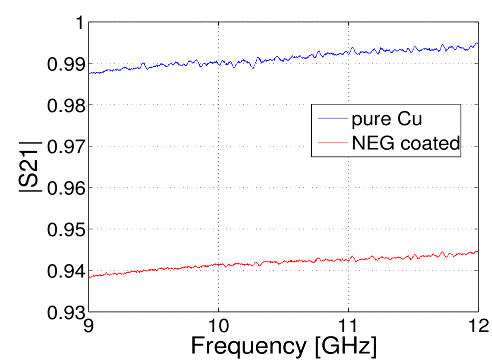

Figure 6: Measured S_{21} as a function of frequency for a Cu and a NEG coated waveguide.

Despite the unknown NEG coating thickness, the measured S_{21} coefficient indicates that the skin depth is small enough compared to the thickness allowing the EM interaction with NEG. Two possible scenarios exist; the skin depth is much smaller than the coating thickness, therefore the EM interaction is only with NEG and indeed the σ defined corresponds to σ_{NEG}. Second case is the skin depth to be comparable to the thickness and the EM interaction is with NEG and Cu. In the second case, the measured conductivity corresponds to a combination of NEG and Cu.

From the intersection of measured data with CST MWS results, the conductivity is plotted as a function of freductivity corresponds to a combination of NEG and Cu.

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From the intersection of measured data with CST MWS results, the conductivity is plotted as a function of frequency. The plot displayed in Fig. 7 shows an upper limit for the NEG conductivity assuming that the NEG thickness is infinite in the simulation. The case of 9 μm thickness is also plotted in the same figure.

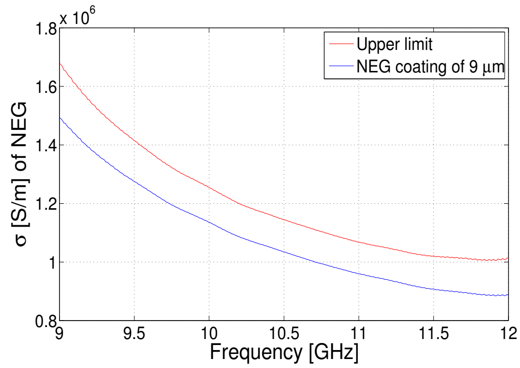

Figure 7: Conductivity of NEG as a function of frequency for infinite and 9 μm coating thickness.

Error Analysis with CST MWS

In order to check the reliability of CST MWS results on a coated waveguide, two tests are done. For the first one, different values of NEG thickness on a Cu waveguide are simulated varying from 1-20 μm. NEG conductivity is assumed to be equal to 2×10^6 S/m. The results are illustrated in Fig. 8.

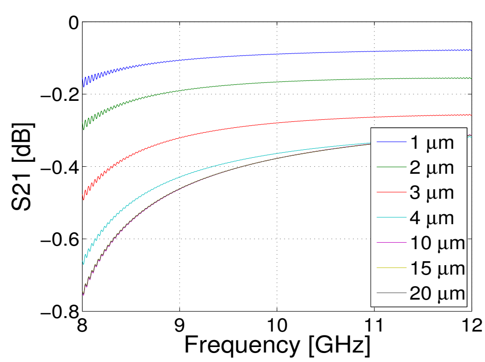

Figure 8: S_{21} results obtained from CST MWS for different values of NEG thickness.

For the lower values between 1-4 μm, the skin depth is larger or comparable to the thickness, therefore the EM fields interact with NEG and Cu. The skin depth can be estimated from Eq. 1:

$$\delta = \sqrt{\frac{2}{\mu\omega\sigma}} \approx 503\sqrt{\frac{1}{\mu_r f \sigma}} \qquad (1)$$

where δ is the skin depth in m, μ the permeability of the medium, μ_r the relative permeability, σ the conductivity in S/m and f the frequency in Hz [3]. For the range of frequencies simulated, 8-12 GHz, the skin depth varies from 3.9-3.2 μm respectively. At a certain frequency, as thickness increases, the interaction with Cu is reduced till the point where the skin depth is much smaller than the coating allowing only the interaction with NEG (thickness from 10-20 μm). CST MWS results are in agreement with the theoretical expectations.

As a second test, a waveguide with the properties of NEG (the assumption is made that the conductivity is equal to 2×10^6 S/m) is compared with a Cu waveguide coated with NEG of 100 μm thickness. Such thick coating results in the EM interaction only with NEG since the skin depth is much smaller than the thickness. Therefore the results of those two simulations should be identical. The comparison is illustrated in Fig. 9. The results are similar between those two cases as expected from theory.

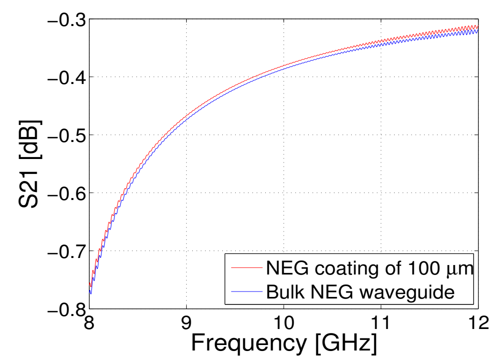

Figure 9: Comparison of S_{21} results obtained from CST MWS between a 100 μm NEG coated waveguide and a waveguide with the properties of NEG.

SUMMARY

The waveguide method combined with CST 3D EM simulations is used to determine the conductivity of NEG in a range of frequencies from 9-12 GHz. An upper limit for its value is obtained and first tests of the simulations reliability are done. In the future it is planned to benchmark in detail the CST MWS coating simulations, proceed with stainless steel waveguide measurements and conductivity measurements at higher frequencies in the range of 325-500 GHz.

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