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BROADBAND FREQUENCY ELECTROMAGNETIC CHARACTERISATION OF COATING MATERIALS

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Abstract

In the new generation of particle accelerators and storage rings, collective effects have to be carefully analyzed. In particular, the finite conductivity of the beam pipe walls is a major source of impedance and instabilities. A reliable electromagnetic (EM) characterisation of different coating materials is required up to hundreds of GHz due to very short bunches. We propose two different measurement techniques for an extended frequency characterization: (i) a THz time domain setup based on the signal transmission response of a tailored waveguide to infer the coating EM properties from 100 to 300 GHz or even further. This technique has been tested both on NEG and amorphous Carbon films. (ii) a resonant method, based on dielectric cavities, to evaluate the surface resistance Rs of thin conducting samples at low (GHz) frequencies. Due to its high sensitivity, Rs values can be obtained for very thin (nanometric) coatings or for copper samples with a laser treated surface, since they have an expected conductivity very close to bulk copper.

INTRODUCTION

Next generation of light sources and particle accelerators requires vacuum chamber treatments with sundry surface materials for both avoiding electron cloud (e-cloud) effects and enhancing the ultra-high vacuum condition, in order to prevent machine performance degradation and luminosity limitations. The reduction of Secondary Electron Yield (SEY) threshold value, for the mitigation of the e-cloud mechanism, has been a major subject of recent studies for finding the best candidate as pipe coating material. However, the use of a coating material unavoidably changes the overall machine surface impedance. Therefore, an accurate EM characterization is required.

In this work, three coating materials are the subject of our study: Non Evaporable Getter (NEG) alloys [1], that transform the vacuum chamber into an effective pump reducing the induced gas desorption and SEY; Amorphous Carbon (a-C), tested [2] at different CERN facilities with very effective results on SEY reduction; Laser-engineered surface structures (LESS) [3,4] produced on copper surfaces, considered as a possible alternative mostly to scale down the SEY threshold. Recently, we developed a time domain waveguide spectroscopy method by using a tailored guiding structure. The design allows to measure large area homogeneous coating deposited on removable metallic plates and to re-use the test system for different measurements. The EM characterization is performed by resorting to an ad-hoc analytical tool that is used for the experimental data interpolation. This technique has been successfully used to characterise NEG coatings deposited on both sides of thin copper slabs inserted in a waveguide. In the following, we summarize the EM characterization performed on NEG coating and already published [5,6]. We also report, for the first time, the preliminary results on the EM characterisation of a-C coating. Lastly, for the EM response of nanometric laser treated surface structures (with an estimated conductivity close to copper), we introduce a resonant technique approach, based on a dielectric cavity, in order to improve the overall sensitivity of the characterisation method.

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ELECTROMAGNETIC CHARACTERIZATION OF NEG AND a-C COATINGS

For the measurements, we used a tailored waveguide with a removable internal part where the coating is deposited. The guiding device is a $16 \times 12 \times 140$ mm^3 parallelepiped of gold plated brass. It consists of a central waveguide having a square section rotated by 45°, side 1.1 mm and length 62 mm, connected to two pyramidal horn antennas 39 mm long, with side width from 1.1 mm to 6 mm (see Fig. 1). This configuration has the advantage to optimise the free-space to waveguide transition, reducing spurious contributions and improving the EM signal transmitted through the structure [7].

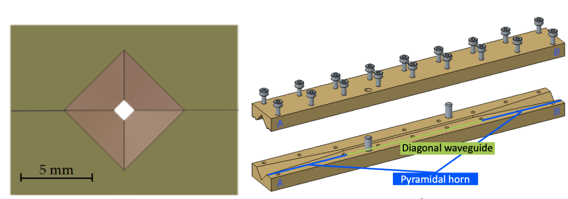

Figure 1: Device consisting of a waveguide with two pyramidal horn antennas. (a) Front view; (b) open view.

The single mode (sum of $TE_{1,0}$ and $TE_{0,1}$) frequency window ranges from 135 GHz to 300 GHz, limited by the second propagating mode [8]. Measurements are carried out using a Time Domain Spectrometer (TDS) operating in transmission mode, based on a commercial THz-TDS

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system (TERA K15 by Menlo Systems) customized for the characterization. The signal is recorded for each sample by averaging 1000 pulses for an overall acquisition time of 10 minutes. Frequency dependent transmission curves are obtained through the application of a standard FFT algorithm. In the experiment, the frequency resolution is about 8 GHz, determined by the scanning range of the delay line.

The conductivity value of the coated material is obtained from the comparison between the signal amplitude transmitted through the waveguide with and without coating, as reference. The relative attenuation along the entire structure has been analytically calculated as detailed in [6]. An analytical tool is used for the conductivity retrieval of the material under test.

NEG Coating Results

Two Ti-Zr-V NEG samples, grown at the CERN deposition facilities [2], with 3.8 µm and 4.3 µm thickness, have been deposited on both sides of a thin copper slab, same length of the guiding device (140 mm) and 0.050 mm thick, that has been placed in the center of the device.

In Fig. 2, the experimental relative attenuation (with respect to a bare copper slab used as a reference) for both NEG coatings are shown. Data below 200 GHz have been discarded to avoid artifacts in the spectrum due to group and phase velocity dispersion.

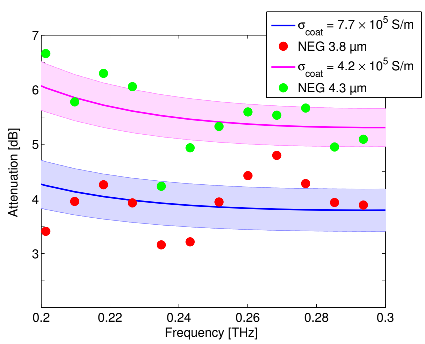

Figure 2: Experimental relative attenuation of 3.8 µm and 4.3 µm NEG coated slabs (red and green dots respectively) and best fit curves (blue and magenta lines respectively).

Magenta and blue continuous lines are the best fit curves that interpolate the experimental data resorting to the developed analytical model, the 95% confidence interval is displayed as shaded area. From this comparison values of $\sigma_{\mathrm{NEG}} = (7.7 \pm 1.1) \times 10^5$ S/m for the 3.8 µm sample, and $\sigma_{\mathrm{NEG}} = (4.2 \pm 0.5) \times 10^5$ S/m for the 4.3 µm sample, are yielded. These results have been published in [6] and fairly agree with data obtained on different NEG samples using the circular waveguide [5] and values extracted using the frequency domain approach [9].

a-C Coating Results

a-C coatings are grown at the CERN deposition facilities, with an average thickness of 3 µm. The EM characterization is performed by resorting to the same analytical tool [6] and guiding device used for NEG, with the lower part replaced by a bulk copper piece where the coating is deposited. The reason is that during the high temperature growth of the a-C layer, it was seen a residual stress on the copper substrate producing slab bending and coating peel-off. In this case therefore the signal is transmitted through a triangular waveguide having same width and length but half the section of the square waveguide. The amplitude spectra are presented in Fig. 3 for two samples in comparison with the bare copper.

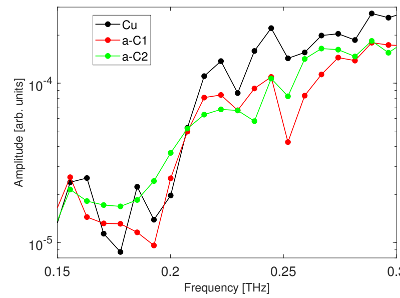

Figure 3: Amplitude transmission data through the waveguide with copper (black curve), with 1st a-C sample (red curve) and 2nd a-C sample (green curve).

The amplitude difference with respect to bare copper starts from approximately 220 GHz. The scattering between the two measurements and the fickle attenuation point out that we are working close to the sensitivity limit. In Figs. 4 and 5, the relative attenuation due to the first and second a-C coatings with respect to the copper reference are shown.

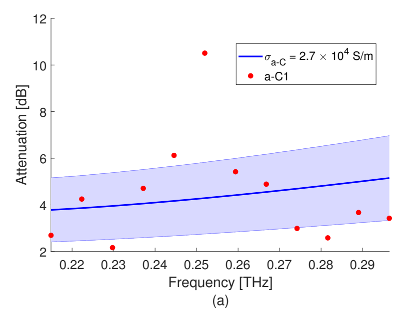

Figure 4: Experimental relative attenuation on the 1st a-C coated sample (red dots) and best fit curve (blue line).

Data below 220 GHz have been discarded to avoid artifacts in the spectrum especially pronounced near the cut off frequency. The blue continuous lines show the attenuation interpolated with analytical best fit curve for the two estimated conductivities, with the 95% confidence interval displayed as shaded area. We yield $\sigma_{\mathrm{a\text{-}C}} = (2.7 \pm 1.0) \times 10^4$ S/m for the first sample, and $\sigma_{\mathrm{a\text{-}C}} = (2.3 \pm 1.1) \times 10^4$ S/m for the second one. Although the measure relative error is quite high, about 40%, results fairly agree with data previously obtained on different a-C samples using DC measurements [10]. For future measurements, in order to have a higher signal-to-noise ratio, the coating thickness should be higher than 3 µm.

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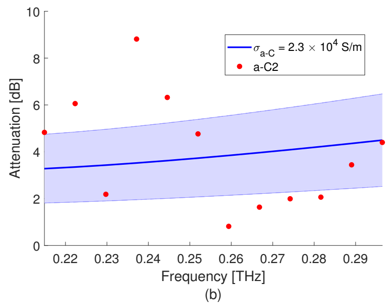

Figure 5: Experimental relative attenuation on the 2nd a-C coated sample (red dots) and best fit curve (blue line).

RESONANT STRUCTURE METHODOLOGY

For the EM characterization of very thin laser surface treated structures (i.e. LESS) with expected conductivity close to copper, we performed a numerical study on dielectrically loaded resonant structures [11]. The device is a closed copper cylindrical cavity (height 20 mm, radius 10.5 mm) loaded with a low loss dielectric puck. Two different sapphires (ε = 9.9) have been used as dielectric: the first with radius = 2.7 mm, height = 2.7 mm, and the second with radius = 3.5 mm, height = 3.5 mm; both placed on a hollow quartz support (ε = 3.75). A copper plate 10 × 10 × 1 mm^3, on which the coating/treatment is performed, is posed on the top. Efficient input and output coupling is ensured via small loop antennas asymmetrically (with respect to the longitudinal axis) placed, in close proximity with the sapphire puck (see Fig. 6).

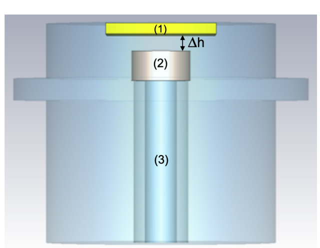

Figure 6: 3D model inside view of the dielectric resonator: 1) copper plate, 2) sapphire puck, 3) quartz hollow holder.

The operating mode (TE$_{011}$) is chosen to maximize the electric field and therefore the surface currents on the copper plate. For both sapphires, in order to investigate the technique sensitivity we performed CST Eigenmode simulations by varying the distance Δh, between the dielectric upper surface and the copper plate. For the investigated Δh, the resonance frequency spans from 16.5 to 18 GHz for the first sapphire, while for the second one it spans from 13 to 14 GHz. In Fig. 7 is depicted the relative difference of Q-factor for the copper plate coated with molybdenum with respect to the copper plate, used as reference.

The maximum percentage difference of the Q-factor is obtained with a minimum distance between the copper plate

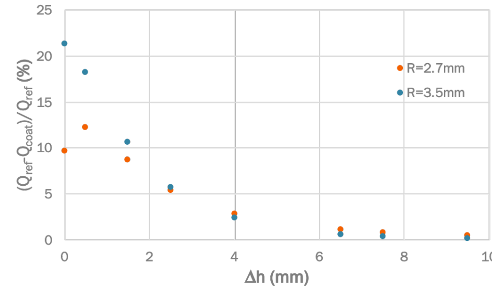

Figure 7: Numerical evaluation of Q-factor relative difference of molybdenum coated copper w.r.t. copper plate (reference) for several distances between dielectric and copper (Δh) for two sapphires.

and the dielectric, indicating that the dielectric focuses the electric field and increases the losses on the coating.

Q-factor has been numerically evaluated for different coating material resistivities on the copper plate. The variation of the Q-factor normalized to the copper one is shown in Fig. 8. The curve is well reproduced by a simple fitting curve with an inverse proportionality to the square root of the resistivity ratio of measured and reference materials ($\sqrt{\rho/\rho_{\mathrm{ref}}}$).

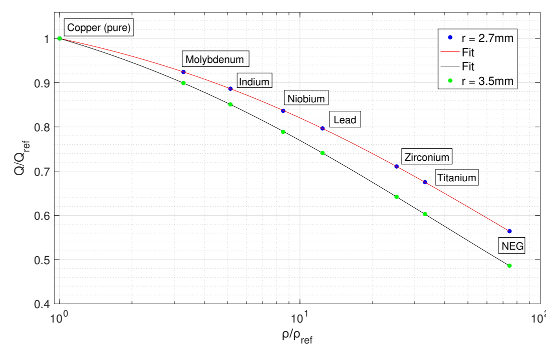

Figure 8: Numerical evaluation of Q-factor variation versus resistivity, normalized to copper for two sapphires.

From these curves, the unknown resistivity of materials can be obtained from the Q-factor variation with respect to reference material. From Fig. 8, it is clear that the sapphire with larger radius (3.5 mm) is the best candidate, because of its higher sensitivity, for the EM characterization of materials with a expected conductivity close to copper, as in the LESS case.

CONCLUSION

We studied two different methods in order to reliably evaluate the electrical conductivity of a coating material for accelerating structures under different operating conditions. These procedures are extremely useful for the evaluation of the surface impedance as a function of frequency, that is currently used for computing the resistive wall component of the coupling impedance, resorting on numerical and analytical tools, for beam dynamics studies in modern accelerators.

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