TIME DOMAIN MEASUREMENTS OF THE SUB-THZ RESPONSE OF DIFFERENT COATINGS FOR BEAM PIPE WALLS

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Abstract

Modern accelerators and light sources often require special treatment of the vacuum chamber surface in order to avoid undesirable effects and maximize machine performance. Coatings with Non Evaporable Getter compounds and amorphous Carbon have been extensively tested and used with very effective results since they allow to reduce the secondary electron emission from pipe walls and therefore the relevant beam instability. An electromagnetic characterization of such coatings is therefore fundamental to build a reliable impedance model. We present here a method based on time domain measurements of an electromagnetic wave passing through a tailored waveguide, where the material under test is deposited on a planar slab. This configuration allows an easy measure of samples having a homogeneous coating thickness and a reasonable area, with parameters chosen in order to have a good signal-to-noise ratio, avoiding at the same time problems due to peel-off and blistering during deposition. The study on the electromagnetic response is performed in the frequency range from 0.1 to 0.3 THz, corresponding to the first transverse electric (TE) mode propagation inside the designed waveguide.

INTRODUCTION

One step for the optimization of the machine performance in modern accelerators and light sources is the special treatment of the vacuum chamber surface in order to avoid undesirable effects. In particular, in positron rings the electron cloud mechanism starts when the synchrotron radiation, emitted by the beam, creates a large number of photoelectrons at the wall surface of the beam vacuum chamber. These primary electrons may cause secondary emission or be elastically reflected [1]. If the value of the secondary electron yield (SEY) of the surface material is greater than unity, the number of electrons starts to grow exponentially and may lead to beam instabilities and many other side effects [2, 3]. The reduction of the SEY value in the pipe walls is one of the keypoint in order to avoid these problems. Coating materials, that are exploited for the SEY reduction but also for improvement of the pumping process or other purposes, change the surface impedance of the vacuum chamber. This variation may affect the electromagnetic interaction of the beam with the surrounding vacuum chamber and consequently result in beam instability limiting the machine performance. Therefore, an accurate electromagnetic characterization (EMC) of coating materials is required for building a reliable impedance model and for the characterization of performance limitations in modern particle accelerators and storage rings [4]. Non Evaporable Getter (NEG) coating is a mature and well-established technology currently exploited at CERN for ultra-high vacuum pumping. Coatings of amorphous Carbon (a-C) have been extensively tested [5] and used [6] at the CERN Super Proton Synchrotron (SPS) accelerator and other experiments [7] for SEY reduction with very effective results. There is therefore a demand for a full EMC characterisation of these novel materials.

The present study is in the framework of the Compact Linear Collider (CLIC) damping rings experiment that requires a thorough evaluation of the surface impedance at very high frequencies (i.e. millimeter waves and beyond). Usually, this is done by resorting to standard techniques in the frequency domain, which however show severe limits over 100 GHz in terms of accuracy, complexity and cost. An alternative approach for materials that require a strong wave-matter interaction is THz waveguide spectroscopy [8], where measurements are performed in time domain and information on the sample frequency response is retrieved by Fourier transform. This technique has been used in the past for characterizing thin samples deposited either on dielectric substrates or directly on the waveguide [9, 10].

In the following we first present the THz setup under use and its recent upgrade. Then, we summarize the experimental measurements, already reported in two different papers [11, 12], for the extraction of the electromagnetic properties of high quality NEG samples used to validate the method. Lastly, we describe the setup change and the analytical studies implemented in order to measure the response of a-C coatings overcoming the demanding thickness requirement.

The proposed method overcomes the inconveniences reported in a previous work on the EMC of NEG coatings in the frequency domain [13], like inhomogeneity, blistering and peel-off induced by the high temperature deposition on a standard rectangular waveguide with a complex geometry. We solve this by placing a calibrated waveguide with integrated horn antennas in the optical path of a THz spectrometer and separating the signal guiding system in two parts: a fixed (squared or triangular) waveguide, and a removable slab where the coating is deposited. This choice allows to measure with ease large area coatings deposited on

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metallic plates as in the case of accelerators, where averaged quantities are needed.

Sub-THz SYSTEM UPGRADE

Sub-THz measurements of NEG coatings have been carried out using a Time Domain Spectrometer (TDS) operating in transmission mode. The setup is based on a commercial THz-TDS system (TERA K15, MENLO Systems) customized for the specific coating characterization in the waveguide. The system is driven by a femtosecond fiber laser @1560 nm with an optical power < 100 mW and a pulse duration < 90 fs. In the standard configuration, the laser output is split into two beams in pump-probe mode. Fiber-coupled photoconductive antenna modules are utilized for both electric field signal emission and detection. A fast opto-mechanical line with a maximum scanning range of approximately 300 ps is used to control the time delay between the pump and the probe beam. Signal detection is performed by a lock-in amplifier that drives the pulse generation at about 90 KHz and integrate the output voltage over an interval of 100 ms. Pulse waveforms are sampled by 2048 data-points in 150 fs intervals of optical delay (step size $\sim 30\ \mu$m). Each scan requires about 10 min of measurement time.

The THz beam system includes a set of TPX (polymethylpentene) lenses, symmetrical with respect to the center line between the transmitter and the receiver, used to collimate the short $(1-2$ ps) linearly polarized pulse on the waveguide. This results in a Gaussian-like beam with a waist of approximately 8 mm in diameter and a quasi-plane wave phase front. The coupling efficiency between the free space signal and the input and output horns is then manually optimized by maximizing the signal transmitted through the waveguide. Under our experimental conditions, we can safely assume that the waveguide works in a single mode regime and mode conversion at the entrance of the horn antennas may be neglected. A sketch of the optical configuration is shown in Fig. 1.

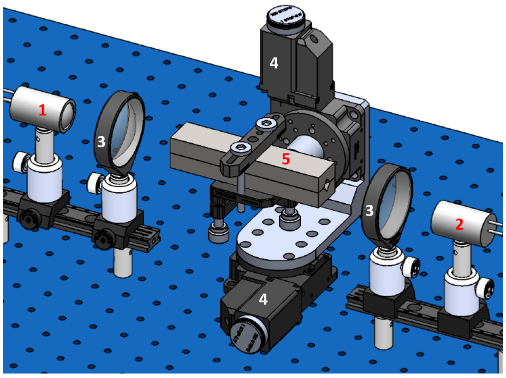

Figure 1: Sketch of the opto-mechanical setup utilized for the measurements: 1) Emitter, 2) Detector, 3) TPX collimating lenses, 4) Micrometric alignment systems, 5) waveguide with embedded horn antennas.

The waveguide is placed on a kinematic mount coupled with a micrometric goniometer in order to achieve an accurate control over the target positioning. The bottom of the waveguide is fixed onto the kinematic mount and the metal slabs can be replaced by removing the upper part of the structure only. The waveguide is firmly tightened with a rigid clamp for minimizing any possible air gap in between the top and the base plate. The area around the waveguide entrance is shielded with a metal sheet with an extrude cut at the center for blocking unwanted free space THz radiation from the emitter to the receiver antennas.

The upgrade of the system, performed last year, improved the spectral range from 3 THz up to 5 THz and the dynamic range from 70 dB up to 90 dB. By changing the optical delay unit, the scanning temporal range increased from 300 to 800 ps with a consequent improvement of the spectral resolution from 3.5 to 1.5 GHz.

A standard Fast Fourier Transform (FFT) algorithm is used to obtain frequency dependent transmission curves from the time domain signals. Figure 2 shows the THz spectrum of the free space signal obtained in air with the upgraded system.

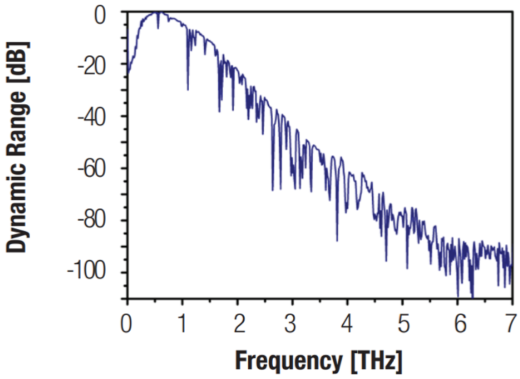

Figure 2: THz frequency domain spectrum of the free space signal for the upgraded system.

RECENT RESULTS: NEG COATING

All results concerning the characterization of NEG coatings in the sub-THz region have been published in [11]. Here we resume the features of the specifically designed structure (see Fig. 3) that we used. It has a central copper slab 0.050 mm thick, where the material under test is deposited on both sides. This device consists of a cylindrical waveguide having radius 0.9 mm and length 42 mm, connected to two pyramidal horn antennas 39 mm long, with side width from 6 mm to $0.9\sqrt{2}$ mm (external to internal). The antennas are embedded in the device in order to enhance the electromagnetic signal collection and radiation [14]. The external shape of the structure is a parallelepiped having section $16 \times 12 \times 120\ \text{mm}^3$.

Regarding the NEG coating, its growth process was performed at the CERN deposition facilities (under the responsibility of the TE-VSC-SCC section) on both sides of two

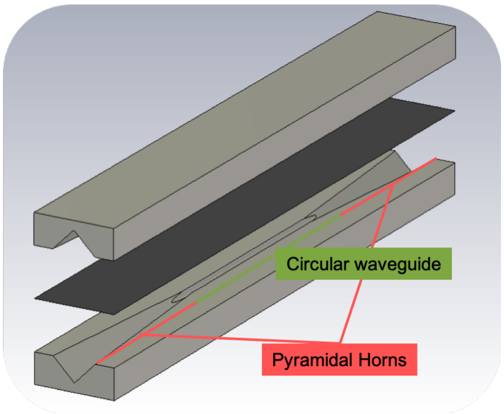

Figure 3: Model of the structure used for the measurements consisting of a circular waveguide and two pyramidal horns. The device is cut into two parts with the coated slab placed in-between.

different copper slabs by using a DC magnetron sputtering technique [5]. Measurements of thickness and composition along the waveguide axis were performed using X-Ray Fluorescence, confirming the good uniformity of the coating.

The d.c. conductivity value of the coated material was obtained from the comparison between the signal amplitude transmitted through the waveguide with the coated slab and the one obtained with an uncoated slab used as a reference. Knowing the coating thickness and resorting to the developed analytical tool, the surface impedance value has been inferred in the frequency range of a single mode transmission. In particular, assuming TE_{01} propagation in both the pyramidal transitions and in the circular waveguide, the overall usable frequency window was from 118 GHz to 283 GHz. For two different samples we found the same conductivity within the error given by the best-fitting procedure. Specific values were: $\sigma_{\mathrm{coat}} = (8.0 \pm 0.4) \times 10^5$ S/m and $\sigma_{\mathrm{coat}} = (8.2 \pm 0.6) \times 10^5$ S/m.

These results well agree with data already obtained with the frequency domain approach published in [13]. From the measured σ_{coat} values one can estimate the real part of the surface impedance as a function of frequency, which in turn can be used for modeling the resistive wall component of the beam impedance in modern accelerators.

FURTHER STEP: a-C COATING

The advantages of the setup employed for the NEG test, mainly (i) the possibility to characterize uniform samples and (ii) the re-usability of the structure for different coating materials, can be profitably exploited for the EMC of amorphous Carbon.

Attempts to make a-C coatings were first performed on copper squared samples 40×40 mm^2 having thickness of 50 μm. For the configuration shown in Fig. 3, in order to have a reasonable signal attenuation due to the coated slab a minimum a-C thickness t of 5 μm on both sides of copper is needed. It is important to highlight that the required thickness for EMC is one order of magnitude larger than usual values used for coating of vacuum chambers. Unfortunately, during the high temperature growth the a-C layer induces a residual stress on the copper substrate, producing slab bending (one side deposition) or even coating peel-off and blistering (two side deposition). These problems made impossible to obtain a-C coatings with both planarity and homogeneity suitable for THz characterisation, and led us to design a different test structure. To avoid any possible stress on the coated sample, we changed the measurement configuration depositing a-C on the single side of a bulk copper piece. This overcomes the above mentioned problems, however at the expense of reducing the relative weight of the sample under test in the overall losses of the test structure. Moreover, for the a-C characterization, we carried out an accurate analytical study for different shapes of the guiding device shapes. The first step was to estimate the relative attenuation produced by the coating in a structure having the same upper part as in the waveguide used for the NEG characterization. For the sake of clarity, figure 4 shows the front view of the studied device.

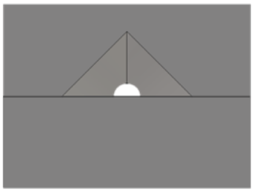

Figure 4: Front view of the structure (horn antenna + waveguide) with half-circular section.

A parametric study was performed for different thicknesses and assuming a coating conductivity $\sigma_{\mathrm{coat}} = 10^4$ S/m. The amorphous carbon conductivity is chosen by considering the worst case scenario, using values obtained by d.c. measurements on the same material [15]. Formulas used for the evaluation are reported in [11]. Corresponding values for the relative attenuation (difference between losses with and without the coating on top of the copper bulk piece) are plotted in Fig. 5 as a function of frequency for three different a-C thicknesses. Maximum thickness was chosen to be 3 μm because of the technological constraints given by the deposition process. Results show that in all cases the evaluated relative attenuation is lower than 1 dB, too low for a reliable detection by using the available measurement system.

Therefore, we modified the waveguide geometry with the aim to increase, for the same thickness, the relative weight of the test material coating on the overall attenuation. The new structure presents the half-square section rotated by 45°, that is a triangular section (see Figure 6) with side 1.1 mm and length 62 mm, that maximizes the losses of the planar coating with respect to the copper walls. This configuration has also the advantage to minimise the sharp transition from the two pyramidal horn antennas and the central sector, further reducing spurious contributions to losses and improving the signal transmitted through the structure.

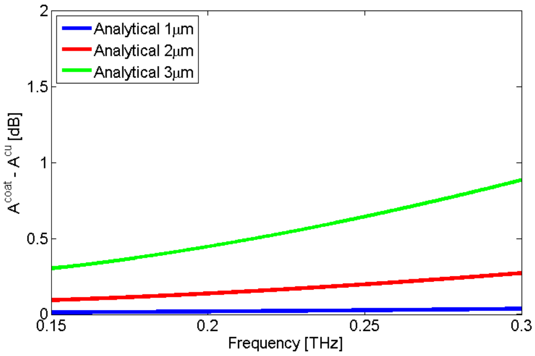

Figure 5: Test structure with half-circular waveguide: analytical evaluation of the relative attenuation on the slab vs frequency for the TE_{01} propagating mode, assuming different coating thicknesses and $\sigma_{\text{coat}} = 10^4$ S/m.

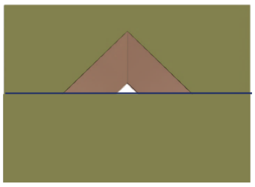

Figure 6: Front view of the structure (horn antenna + waveguide) with triangular section.

Figure 7 shows an exploded view of the new configuration. The relative attenuation is analytically evaluated [11] and results are shown in Fig. 8 as a function of frequency, for the same thicknesses and conductivity values considered before.

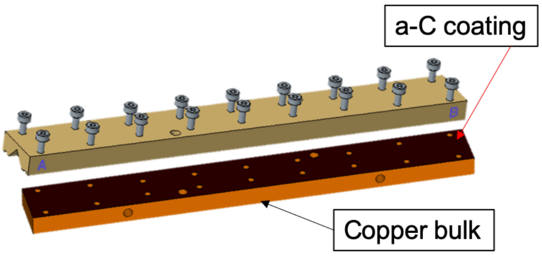

Figure 7: Exploded view of the newly designed configuration. The test structure is cut into two pieces: the upper part is a triangular waveguide with two half pyramidal horns, the lower part is a copper bulk slab on which the a-C coating is deposited.

For this modified structure, the expected relative attenuation for a 3 μm thick a-C coating having $\sigma_{\text{coat}} = 10^4$ S/m is higher than 1 dB, ideally large enough to be detected using the measurement system available in our laboratory.

Nevertheless, because of the many unknown variables that may largely affect the quality of the deposited layer, we performed a parametric study of the relative attenuation as a function of frequency keeping the coating thickness constant (3 μm) and assuming different values of the conductivity. This is shown in Fig. 9 in different curves, where σ_{coat} is varied from 10^4 S/m to 5×10^5 S/m. Since we are testing a bilayered system (a-C coating and bulk copper), as far as conductivity decreases the material skin depth δ increases, and the EM field penetrates more and more in the bulk copper. From the plot, one can see that the relative attenuation increases with σ_{coat}, reaches its maximum for a value $\sigma_{\text{coat}} = 10^5$ S/m, where the skin depth is comparable with the coating thickness, then starts again to decrease because the field penetrates only in the coating layer. The frequency evolution changes also varying the value of σ_{coat}, since it depends on the ratio t/δ. This behavior needs to be realistically taken into account during measurements.

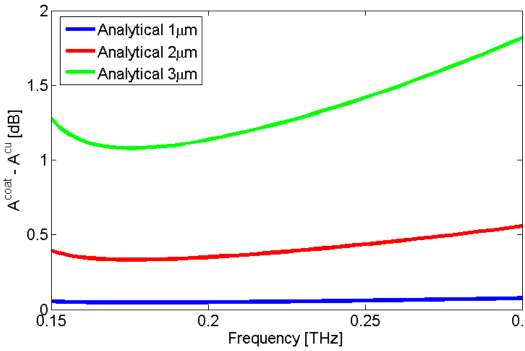

Figure 8: Test structure with triangular waveguide: analytical evaluation of the relative attenuation on the slab vs frequency for the TE_{01} propagating mode, assuming different coating thicknesses and $\sigma_{\text{coat}} = 10^4$ S/m.

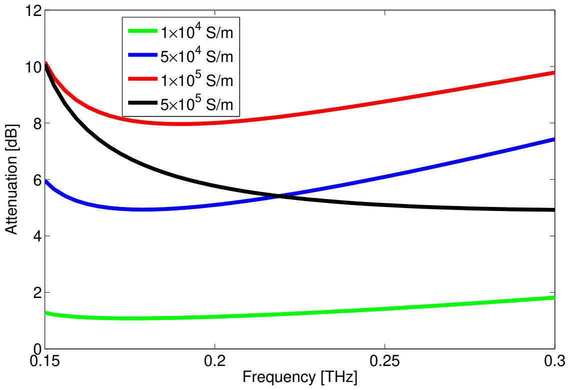

Figure 9: Test structure with triangular waveguide: analytical evaluation of the relative attenuation on the slab vs frequency for the TE_{01} propagating mode, assuming different conductivity values and coating thickness $t = 3$ μm.

Following this preliminary study, samples of 3 μm amorphous carbon coating on bulk copper have been prepared (i.e. after the MCBI2019 workshop in Zermatt) using DC magnetron sputtering at CERN deposition facilities (see Fig. 10). EM characterisation measurements on the first a-C sample are planned in a very near future.

Figure 10: 3 μm a-C coating deposited on a copper slab.

CONCLUSION

We developed a reliable, handy and affordable technique for the time domain evaluation of the electromagnetic properties of coatings for beam pipe walls. The method is based on the measurements of the signal transmitted through a tailored waveguide operating in single mode propagation in the sub-THz region. In comparison to previous techniques, the main advantages of this novel approach are:

- an inherently simplified approach for handling different coating materials;
- the possibility to test samples having a uniform deposition on copper or other wall constituents;
- the ability to extend the EM characterisation to larger area coatings and at higher frequencies.

Measurements performed on different NEG samples well agree with previous data obtained with a frequency domain approach and confirm the high potential of the proposed method.

For the test of a-C coatings, the setup was upgraded and the guiding system structure implemented, in order to overcome the demanding thickness requirement in amorphous carbon deposition. EMC on first samples will start very soon.

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