Broadband Frequency Electromagnetic Characterisation of Coating Materials

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Coatings at high frequency

Layers of coating materials significantly increase the resistive wall impedance at **high frequency**

- Low conductivity, thin layer coatings (NEG, a-C)
- Rough surfaces (LESS)

**Surface impedance** of the beam pipe depends on electromagnetic properties of *coatings*

Electromagnetic characterization of “coating materials” is fundamental to evaluate accelerator **performance limitations** and build up a machine impedance model.
Two different methods

Electromagnetic characterization of Coating materials

**Dielectric resonator**
- high sensitivity

**Sub-THz waveguide**
- small skin-depth

**NEG** (Non-Evaporable Getter)
- homogeneous coating

**LESS** (Laser engineered surface structures)
- conductivity compared with copper
- small samples

**a-C** (Amorphous carbon)
- coating thickness issues
First method

Sub-THz waveguide attenuation
The proposed method

Evaluation of the **signal attenuation** inside a DUT with coating deposited.

Electromagnetic characterization of coating material.
The Device Under Test

<table>
<thead>
<tr>
<th>Dimension in mm</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Material</td>
<td>Iron</td>
</tr>
<tr>
<td>Waveguide</td>
<td>Circular</td>
</tr>
<tr>
<td>Length</td>
<td>42</td>
</tr>
<tr>
<td>Radius</td>
<td>0.9</td>
</tr>
<tr>
<td>Horns</td>
<td>Pyramidal</td>
</tr>
<tr>
<td>Length</td>
<td>39</td>
</tr>
<tr>
<td>External side</td>
<td>6</td>
</tr>
<tr>
<td>Total Length</td>
<td>120</td>
</tr>
</tbody>
</table>
The Device Under Test

Methodology advantages: 1) Homogeneous deposition 2) System reusability 3) Large area coating
Analytical evaluations

Attenuation along the foil

Waveguide of length $l_g$ (TE$_{1,1}$ mode) + pyramidal transitions of length $l_t$ (TE$_{1,0}$, TE$_{0,1}$ modes)

$$A_{DUT} = \alpha l_g + 2 \int_0^{l_t} \alpha(z) \, dz = \frac{1}{2} Re(Z_S) \int_0^{l_t} \frac{|n \times H_{1,1}|^2}{Z_{1,1}|I_{1,1}|^2} \, dl + \int_0^{l_t} Re(Z_S) \int_0^{l_t} \frac{|n \times (H_{1,0} + H_{0,1})|^2}{Z_{1,0}|I_{1,0}|^2 + Z_{0,1}|I_{0,1}|^2} \, dl \, dz$$

Transmission line method

$$Z_S = Z_{coat} \frac{Z_{Cu} + jZ_{coat}tg(k_{coat}d)}{Z_{coat} + jZ_{Cu}tg(k_{coat}d)}$$
Analytical evaluations – comparison with numerical solver

Copper conductivity: $\sigma_{\text{cu}} = 6 \cdot 10^7$ S/m
NEG conductivity: $\sigma_{\text{NEG}} = 3.5 \cdot 10^5$ S/m*

Cylindrical waveguide + Pyramidal transition

Reliable analytical tool

First set of measurements on NEG coated foil

$$\sigma_{\text{coat}} = (8.0 \pm 0.4) \times 10^5 \text{ S/m}$$

$$\sigma_{\text{coat}} = (8.2 \pm 0.6) \times 10^5 \text{ S/m}$$

Novel measurement technique for the electromagnetic characterization of coating materials in the sub-THz frequency range.

Andrea Passarelli, Hannes Bartosik, Giovanni Rumolo, Vittorio Giorgio Vaccaro, Maria Rosaria Masullo, Can Koral, Gian Paolo Papari, Antonello Andreone, and Oliver Boine-Frankenheim

Measurement system upgrade

System specifications:
• Spectral Range: > 3 THz
• Dynamic Range > 70 dB
• Scanning Range ~ 300 ps
• Spectral Resolution < 3.5 GHz

Upgrade:
• > 5 THz
• > 90 dB
• ~ 850 ps
• < 1.5 GHz

More accurate guiding system manufacturing

Sub-THz Waveguide Spectroscopy of Coating Materials for Particle Accelerators

by Andrea Passarelli, Can Koral, Maria Rosaria Masullo, Wilhemus Vollenberg, Lucia Lain Amador, and Antonello Andreoni

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Measurement results on a-C

Two samples with 3 μm of Amorphous carbon on copper bulk

Andrea Passarelli

Mechanical stress a-C coating on Cu slab

\[ \sigma_{a-C} = 2.7 \times 10^4 \text{ S/m} \]
Second method

Resonant structure methodology
Resonant structure methodology

Dielectric resonator: Resonant structure methodology *improves the sensitivity* for the electromagnetic characterization of very thin laser surface treated structures and conductivity close to copper one.
Resonant structure methodology

The maximum Q-factor percentage difference is obtained with a minimum distance between the DUT and the sapphire.

Copper vs. molybdenum coated DUT

The graph illustrates the percentage change in Q-factor $(Q_{\text{ref}} - Q_{\text{coat}})/Q_{\text{ref}}$ for different distances $\Delta h$ and sapphire radii $R$. The maximum percentage change is observed at a specific $\Delta h$ for each radius.
The sapphire with larger radius (3.5 mm) will be used, because of its higher sensitivity in EM characterization of coating materials (LESS).
Conclusion & next steps

Electromagnetic characterization of coating materials

- Sub-THz waveguide attenuation
  - **Reliable analytical model** for the conductivity retrieval. Good agreement with CST solver.
  - **Successful measurement campaign**: reliable and handy method to evaluate the electromagnetic properties of samples under test.
  - Published results on NEG and novels on a-C coatings.

- Resonant structure methodology
  - **Improves the sensitivity**, useful for electromagnetic characterization of very thin laser surface treated structures (i.e. LESS)