RF Characterisation of Laser Treated Copper Surfaces for the Mitigation of Electron Cloud in Accelerators

Krkotić, P.; Calatroni, S.; Himmerlich, M.; Neupert, H.; Perez-Fontenla, A. T.; Wackerow, S.

Published in:
Journal of Physics: Conference Series

DOI:
10.1088/1742-6596/2687/8/082029

Publication date:
2024

Citation for published version (APA):
Krkotić, P., Calatroni, S., Himmerlich, M., Neupert, H., Perez-Fontenla, A. T., Wackerow, S., & Abdolvand, A. (2024). RF Characterisation of Laser Treated Copper Surfaces for the Mitigation of Electron Cloud in Accelerators. *Journal of Physics: Conference Series*, *2687*(8), Article 082029. https://doi.org/10.1088/1742-6596/2687/8/082029

Journal of Physics: Conference
Series

PAPER • **OPEN ACCESS**

RF Characterisation of Laser Treated Copper Surfaces for the Mitigation of Electron Cloud in Accelerators

To cite this article: P Krkotić *et al* 2024 *J. Phys.: Conf. Ser.* **2687** 082029

14th International Particle Accelerator Conference IOP Publishing
Journal of Physics: Conference Series **2687** (2024) 082029 doi:10.1088/1742-6596/2687/8/082029

RF Characterisation of Laser Treated Copper Surfaces for the Mitigation of Electron Cloud in Accelerators

P Krkotić[1], S Calatroni[1], M Himmerlich[1], H Neupert[1], A T Perez-Fontenla[1], S Wackerow[2] and A Abdolvand[2]

[1] CERN, 1211 Meyrin, Switzerland,School of Science
[2] Engineering, University of Dundee, DD1 4HN Dundee, Scotland

E-mail: `patrick.krkotic@cern.ch, sergio.calatroni@cern.ch`

Abstract. In accelerator beam chambers and RF waveguides, electron cloud and multipacting can be mitigated effectively by reducing the secondary electron yield (SEY). In recent years, it has been established that laser-engineered surface structuring is a very efficient method to create a copper surface with a SEY maximum close to or even below unity. Different laser pulse durations, from nanoseconds to picoseconds, can be used to change surface morphology. Conversely, the characteristics that minimise the SEY, such as the moderately deep grooves and the redeposited nanoparticles, might have unfavourable consequences, including increased RF surface resistance. In this study, we describe the techniques used to measure the surface resistance of laser-treated copper samples using an enhanced dielectric resonator with 12 cm diameter sample sizes operating in the GHz range. The quantification basis lies in a non-contact measurement of the high-frequency losses, focusing on understanding the variation of surface resistance levels depending on the specifics of the treatment and possible post-treatment cleaning procedures.

1. Introduction

Laser treatments on copper have triggered interest in methods to reduce the secondary electron yield (SEY) values while keeping good properties at microwave frequencies. Especially in circular proton accelerators, a low SEY is an essential requirement for guaranteeing beam stability at a high beam intensity [1]. Laser treatments may, conversely, increase the copper surface resistance, thus affecting beam-induced RF heating due to wake losses which, e.g., is of particular relevance for the HL-LHC cryogenic components [2]. Therefore, the critical role of such surface treatments as potential electron cloud mitigation in the HL-LHC motivates further experimental validation of their performance.

Several laser treatment methods have been explored in the past, including laser ablation surface engineering (LASE) [3], laser-induced periodic surface structures (LIPSS) [4], and laser-engineered surface structures (LESS) [5], which all use a different set of laser-treatment parameters. The independent measurements of these laser-structured surfaces at the mega- and gigahertz range at room and cryogenic temperature have shown that the surface resistance varies enormously depending on the relative orientation of the laser scan lines with respect to the RF surface currents, on the depth of the groves produced, and, more generally, on the overall topography. LESS, due to the peculiar production technique relying upon repetitive laser beam scanning in a linear pattern, might have a pronounced effect that not only depends on the grooves produced but also on the simultaneous redeposited nanoparticles left on the surface.

In this paper, we report on validating the surface resistance of LESS-treated copper using a sapphire loaded closed Hakki-Coleman dielectric resonator [6] operating at 3.4 GHz from room to liquid nitrogen temperatures. Due to the temperature dependence of the electrical resistivity of copper, the RF skin depth varies between 1.3 µm and 0.3 µm without altering the resonance frequency significantly, which leads to the possibility of investigating the impact of the nanoparticles on the surface resistance. Repeated measurements of the same samples by removing particles gradually with different cleaning techniques are reported. In addition, we describe the measurement system and the sample preparation, followed by the experimental results and their possible implications for the HL-LHC.

2. Sapphire Dielectric Resonator

The closed Hakki-Coleman dielectric resonator (CHCDR) is the foundation for the measurement technique chosen for this characterisation [6; 7]. Our design, as presented in Fig. 1, is composed of a cylindrical copper cavity with a radius of 105 mm and a height of 20 mm, loaded with a c-oriented and low-loss tan(δ) sapphire (40 mm in diameter and 19.5 mm in height), and shielded axially by the test sample (120 mm in diameter). The dielectric is 0.5 mm smaller in height than the cavity to avoid any imprint of the single crystal onto the laser-treated samples. The structure sustains a TE$_{011}$ mode [8] at a resonance frequency of $f_0 = 3.4$ GHz in which the induced RF currents on the samples are solely azimuthal, as shown in Fig. 2. The absence of radial currents makes the resonator parameters sensitive to the properties of the tested materials, though insensitive to the electrical contact between the sample under test and the lateral walls. This device has successfully measured several types of surface treatments, including coatings on copper, such as TiZrV non-evaporable getter films and amorphous carbon films with titanium buffer layer [7].

The measurable resonator parameter, the unloaded quality factor Q_0, is related to the surface resistance R_S through [8]:

$$\frac{1}{Q_0} = \sum_k \frac{R_{S_k}}{G_k} + p \cdot \tan(\delta), \tag{1}$$

where, G_k refers to the geometrical factor of the k-th conductive surface of the cavity and p refers to the ratio of the energy stored in the dielectric to that stored in the entire cavity. Thus, the first term considers the losses of the different resistive surfaces in the resonator, and the

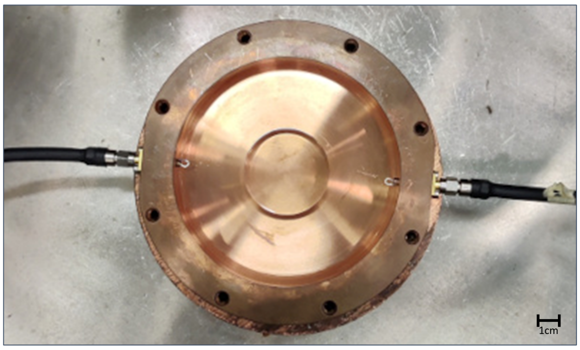


Figure 1: Photograph of the sapphire loaded CHCDR.

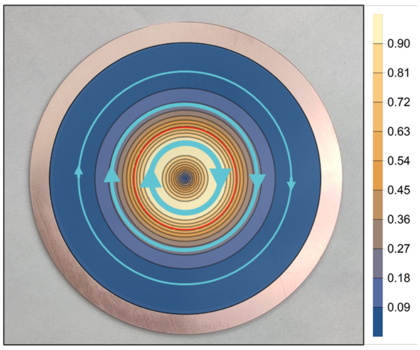


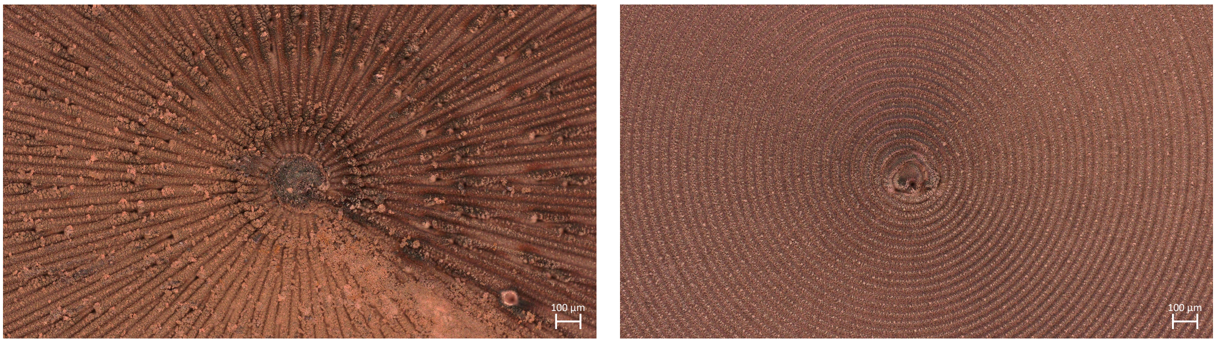
Figure 2: Induced azimuthal surface current density distribution on the sample surface for the TE$_{011}$ mode. The red circle indicates the edge of the dielectric puck.

second term takes into account losses of the dielectric body. How these values can be extracted numerically, experimentally and analytically is explained in detail in [7; 9].

3. Sample Treatment and Cleaning

A linearly polarised 10 ps pulsed laser with a wavelength of 532 nm operating at a repetition rate of 200 kHz was used to perform the laser surface structuring, as detailed in [10]. A lens system focused the laser beam onto the surface through a nitrogen nozzle. The laser was driven at maximum power with a Gaussian intensity profile (4σ spot diameter of 52 µm), resulting in an average fluence of about $0.9\,\mathrm{J/cm^2}$ upon the copper surface, corresponding to an average equivalent power of 4 W. To lessen surface oxidation, a laminar flow of nitrogen was directed toward the contact zone.

Employing the above-mentioned laser beam parameters, two solid OFE copper discs were laser structured at a scanning speed of 15 mm/s. One disc was treated with a radial pattern (LESS-I), while the second disc was treated in an azimuthal direction (LESS-II), as visible in the magnified optical micrographs in Fig. 3. The structures were created using a line pattern with about 45 µm spacing between each set of consecutive lines. The deep grooves created by the laser scanning, with an average relative depth per groove of about 20-30 µm, and the fine copper nanoparticles redeposited onto the surface, which result from the ablation process, are recognisable. For LESS-I, the groves were inscribed almost radially, forming triangle sectors. In this arrangement, the RF currents will cross orthogonally to the lines etched by the laser beam. Conversely, for LESS-II, the lines were etched in a single spiral pattern starting from the inner circle towards the outside of the disc. In this case, the RF surface currents are induced along with the groove lining.



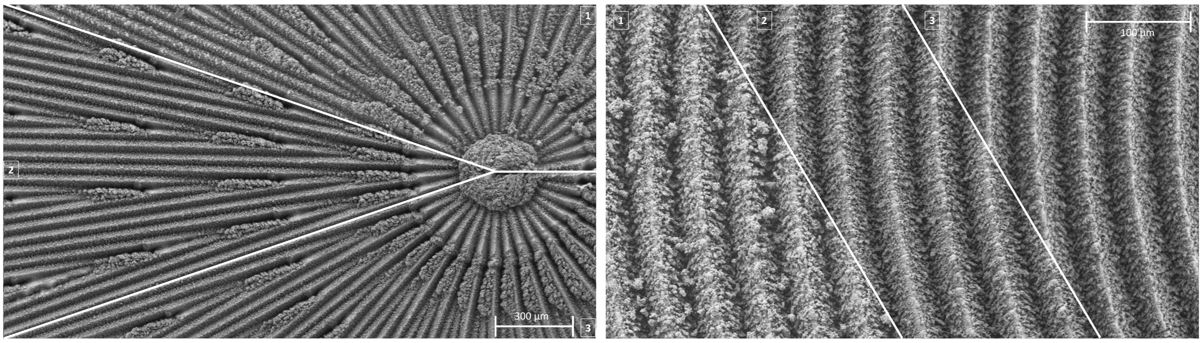
(a) Radial LESS structure (b) Azimuthal LESS structure

Figure 3: Optical micrographs of the centre of the laser-engineered surface structured copper discs.

After the laser treatment, the discs were directly characterised. Furthermore, they were iteratively examined after consecutive cleaning steps:

- blowing with 5 bar N_2 followed by 15 min rinsing with ultra-pure water and subsequent rinsing with ultra-pure alcohol followed by N_2 dry-blowing
- ultrasonication in deionized water at 150 W for 10 min followed by spraying with ethanol and dry-blowing with filtered compressed air

Figure 4 presents the microscopic examination via SEM images of the disc surfaces. The findings suggest that in the direct comparison (approximately at the same location) the first cleaning step resulted in the removal of agglomerated dust and particles, while the remaining nanoparticles are attached stronger to the surface [10]. Thus, after the second cleaning the density of nanoparticles attached to the surface remains similar as before the ultrasonic cleaning.



(a) Azimuthal LESS structure (b) Radial LESS structure

Figure 4: SEM images of gradually cleaned laser treated copper surface. 1 as received, 2 low pressure cleaning, and 3 ultrasonic cleaning.

4. Characterisation of Samples

We conducted direct R_S measurements on samples with different LESS treatment structures. The treated copper samples are divided into two sets with three measurements following the cleaning procedure as described in the previous section; 1) as received, 2) low-pressure cleaning, and 3) ultrasonic cleaning. Figure 5 presents the results as the relative change of surface resistance compared to degreased OFE copper as a function of temperature. Two main features are observed: R_S increases with the orientation angle of the surface currents versus groove direction, and R_S reduces when the laser-treated surface is cleaned from nanoparticles. Generally, both sets follow the same pattern. The 'cleaner' the surface, which a lower density of nanoparticles, the smaller the overall roughness. Interestingly, as can be seen in the insets of

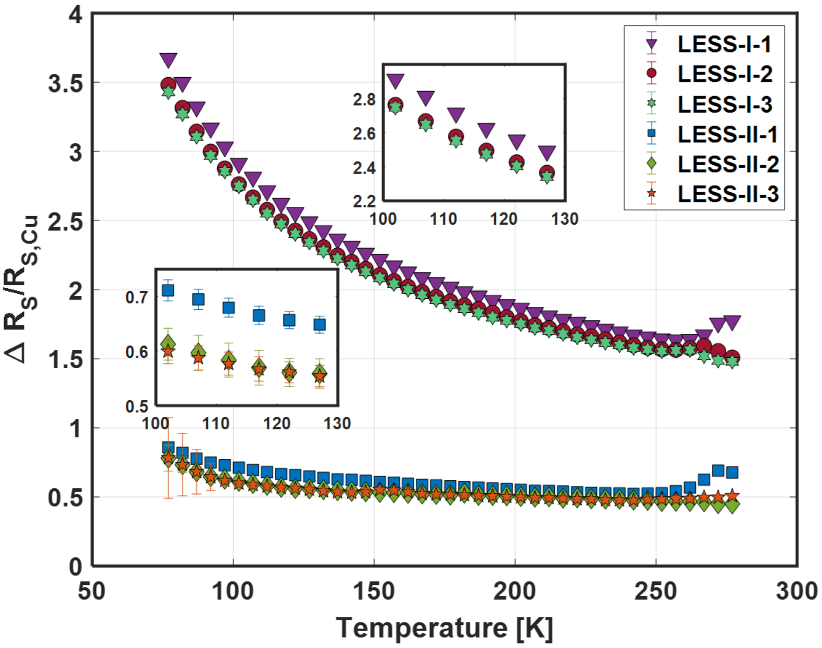


Figure 5: Measured surface resistance as a function of temperature for LESS-I radial and LESS-II azimuthal treated copper samples before and after cleaning procedures.

Fig. 5 of each set, the removal of nanoparticles results in the same impact of reducing the relative change in surface resistance by 10% independent of the groove orientation. Additionally, the ultrasonic cleaning shows no major improvement consistent with the microscopic examination in Fig 4. The fact that there is a relative increase of R_S compared to degreased OFE copper of about 50 to 90% for the azimuthal treated sample and 150 to 350% increase for the radial treated sample implies and proves that at frequencies relevant for accelerators as HL-LHC the groove shape and depth are the primary driving factor for the surface resistance, while for accelerators with short bunch lengths, the opposite might be the case. These findings are complementary to those of a previous study [5] performed at liquid helium temperature in a lower frequency range (0.4-1.2 GHz).

5. CONCLUSION

We describe the use of a sapphire-loaded dielectric resonator for the characterisation of the surface resistance in laser-engineered surface structured copper plates with periodic surface structures under working conditions that approach those found on high-energy proton colliders. We show that the removal of particulates can lower the surface resistance compared to non-post-processed laser-treated copper.

Acknowledgments

The authors would like to acknowledge the support of Catarina Serafim for providing optical images for this study. We also thank Gabriel Pechaud and Guillaume Rosaz for the low pressure cleaning as well as Louise Viezzi for the ultrasonic cleaning of the samples. The authors would like to acknowledge the support from the Science & Technology Facilities Council (STFC) of the United Kingdom (Grant No. ST/T001887/1).

References

[1] Zimmermann F 2004 *Phys. Rev. ST Accel. Beams* **7**(12) 124801

[2] Metral E 2021 *Journal of Instrumentation* **16** P10009

[3] Hannah A, Krkotić P, Valizadeh R, Malyshev O, Mutch J, Whitehead D, Pont M, O'Callaghan J and Dhanak V 2021 *Vacuum* **189** 110210 ISSN 0042-207X

[4] Nivas J, Valadan M, Salvatore M, Fittipaldi R, Himmerlich M, Rimoldi M, Passarelli A, Allahyari E, Oscurato S, Vecchione A, Altucci C, Amoruso S, Andreone A, Calatroni S and Masullo M 2021 *Surfaces and Interfaces* **25** 101179 ISSN 2468-0230

[5] Calatroni S, Arzeo M, Aull S, Himmerlich M, Costa Pinto P, Vollenberg W, Di Girolamo B, Cruikshank P, Chiggiato P, Bajek D, Wackerow S and Abdolvand A 2019 *Phys. Rev. Accel. Beams* **22**(6) 063101

[6] Hakki B and Coleman P 1960 *IRE Transactions on Microwave Theory and Techniques* **8** 402–410

[7] Brunner K, Krkotić P, Costa Pinto P, Gibbons E, Pfeiffer S, Vollenberg W and Calatroni S 2023 *PRAB* Submitted for publication

[8] Kajfez D and Guillon P 1998 *Dielectric Resonators* Artech House microwave library (Noble Publishing Corporation) ISBN 9781884932052

[9] Krkotić P, Aguasca A and O'Callaghan J M 2018 *2018 48th European Microwave Conference (EuMC)* pp 882–885

[10] Himmerlich M, Zanin D A, Taborelli M, Granadeiro Costa A R, Costa Pinto P, Lain Amador L, Vollenberg W, Baris A, Garcia-Tabares Valdivieso E, Perez Fontenla A T, Wackerow S and Abdolvand A 2023 *Advanced Materials Interfaces* **10** 2201671