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Resistivity Measurement of Metal Surfaces to Track Down Dislocations Caused by High Field

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Summary

We are developing a direct method to measure the surface resistivity of a metal that is being conditioned by inducing, in addition to HV DC pulses, a GHz RF current in an electrode system operated at cryogenic temperatures in vacuum. The changes in the Q-factor could indicate a formation of crystallographic defects under the surface, something that has been speculated as an important process behind the conditioning. We will present the modified design of the electrode system, based on the choke cavity design, simulations and experimental results regarding the characterization of this resonant system.

1 Introduction

The study of materials properties at microwave frequencies is an area of research in materials science, solid-state physics and electronic engineering, as well as in accelerator physics. The development of modern, high-speed, high power devices require better understanding of the properties of the materials in use, as well as novel materials which will replace the old ones. It is particularly challenging to measure the properties during operation or when the material is exposed to extreme conditions.

An example of this would be the high gradient operation of an accelerating structure in high energy particle accelerators, where the metal cavities have to sustain very high electromagnetic fields (250 MV/m) and to avoid electric breakdowns. Before the metal surface can accept such high field it has to undergo a conditioning process. The conditioning of a metal surface in a high-voltage system is the progressive development of resistance to vacuum arcing over the operational life of the system. In this way, the accepted electrical field can be increased by 4 to 5 times. The physics behind this process is still unknown. A possible explanation for this is that the high electrical fields create stresses inside the electrodes, resulting in creation of mobile dislocations that, with time, can move to the surface. Once they reach the surface, they create sharp features which amplify the local electrical field, resulting in an electrical breakdown.

So far, it was not possible to characterize the metal surface during the conditioning to test this hypothesis. One important parameter of the surface exposed to microwave field is its electrical resistivity, which is affected by the presence of the crystallographic defects like the dislocations. Investigating resistivity changes at cryogenic temperatures is advantageous because in cryogenic conditions, the resistivity is related only to the scattering of the electrons off the lattice defects, and not by the interaction between electrons and phonons.

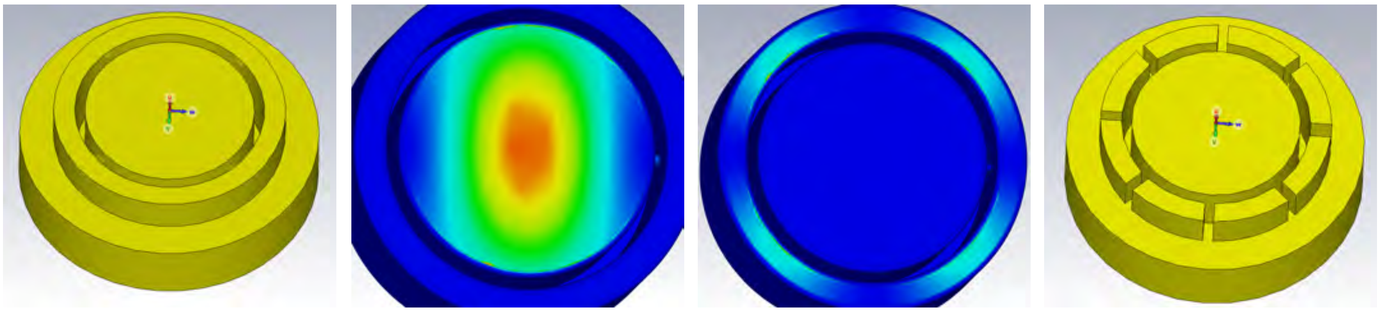
The dislocations are created only near the surface of the electrodes exposed to high frequency EM fields, a few micrometers deep. We are developing an RF-based resonant method, that is sensitive to only these regions and that ignores the bulk resistivity, which will be applied in the cryogenic discharge-system at FREIA laboratory. The cryogenic discharge-system at the FREIA laboratory consists of two parallel electrodes (diameter of 60 mm) separated by a fixed gap of 60 µm at cryogenic temperatures. The temperature can be varied from 4 K up to room temperature. The electrodes are conditioned by applying short (1 µs), high-voltage DC pulses with high repetition rate (few kHz). The work presented here describes a further development of the system and the modification of the electrodes to allow for the resistivity measurement during the conditioning. The detailed description of the set-up available in the FREIA laboratory can be found in [1] .

2 Simulation and Experimental Results

We propose to modify only one electrode with a design based on choke cavity idea by T. Shintake [2] . A circular groove with a height equal to $\lambda/4$ will be machined in the surface of the electrode a few mm away from its edge, like it is shown in fig. 1a. This grove acts as a perfect magnetic wall and electromagnetic modes can be excited in the area delimited by the grove. The S-parameters, the electric and magnetic fields have been obtained from CST Studio Suite 3D simulations. Fig. 1b shows the magnetic field distribution of the fundamental mode, TM110, with a frequency of 3.7 GHz. But parasitic modes, which are very

[1] M. Jacewicz *et al.*, *Phys. Rev. Applied* **14**, 061002 (2020).
[2] T. Shintake, *Japanese Journal of Applied Physics* **31**, L1567, (`https://dx.doi.org/10.1143/JJAP.31.L1567`) (Nov. 1992).

close in frequency to the mode of interest, can be excited. This would cause problems in the fitting process, which is necessary to obtain the Q-factor. In order to avoid having parasitic modes contained outside the area delimited by the choke, like the one shown in fig. 1c, it is necessary to cut the current lines by machining eight notches in the outside surface of the electrode, like in fig. 1d. The quality factor of the fundamental mode of this cavity, obtained from simulation results, is $Q_0 = 39$ at room temperature and $Q_0 = 580$ at cryogenic temperatures where we expect the bulk resistivity to increase by a factor of 100.



(a) The initial simplified design of the electrode **(b)** H-field of the fundamental mode **(c)** H-field of the parasitic mode **(d)** The final design of the electrode

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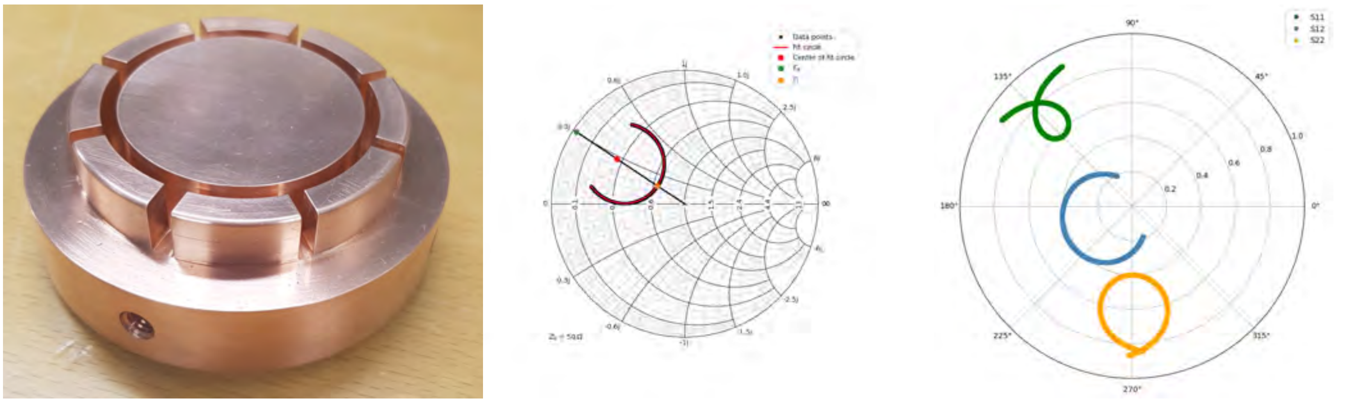
Figure 1. The initial and the final design of the electrodes, along with the magnetic field distributions of the fundamental and of the parasitic mode

This design has been tested on a prototype manufactured in the Uppsala University's workshop, shown in 2a. The quality factor of the fundamental mode of the system was measured to be around 75 and the coupling factor is between 0.2 and 0.6, depending on the position of the antenna. The experimental quality factor is higher than the simulated one because of the larger gap size used in the experiment. In fig. 2b, the resonance curve, measured in reflection geometry, is plotted in Smith chart format, along with the fit made using the QFIT7 algorithm, described in [3] . Transmission measurements were also made, using two antennas, placed at 90° and at 180°. As expected for this mode, due to its field distribution, there was little transmitted signal at 90°, while at 180°, we had significant transmission, as it can be seen in fig. 2c.



(a) The prototype of the modified electrode **(b)** Reflection resonance curve **(c)** Transmission resonance curve (antennas are placed 180° apart)

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Figure 2. The prototype of the modified electrode and the resonance curves plotted for the reflection and for the transmission geometries

3 Conclusions and Outlook

The experimental results obtained with the prototype electrode show that, with this design, it is possible to excite a mode between the electrodes separated by 60 um and to measure its quality factor, inside the cryogenic conditioning system. We are able to resolve small changes (0.3%) in quality factor, which encodes information about the metal resistivity near the electrode surface, with high repeatability. The observation of the relative changes in the resistivity on this order or higher would be a first proof of the formation of defects under the surface during conditioning.

[3] A. P. Gregory, NPL Report 10.47120/npl.MAT58, (`http://eprintspublications.npl.co.uk/9304/`).