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THE EFFECTS OF FIELD EMITTED ELECTRONS ON RF SURFACE

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Abstract

The ever-growing demand for higher RF gradients has considerably increased the risk of breakdown in accelerating structures. Field emission is the most common form of RF breakdown that generates free electrons capable of inflicting irreversible damages on the RF surface. This paper presents a systematic experimental and simulation programme to understand possible sources and their influence on RF cavity operation.

INTRODUCTION

Breakdown which occurs both in RF and DC systems, has been the centre of attention for many year without any general agreement on what triggers this phenomenon [1]. Field emission is the most common problem encountered in superconducting and normal cavities. Grain edges, surface distortions and debris from past breakdown events have been identified as possible emission sites [2, 3]. The presence of defects enhances the local electric field that accelerates emitted electrons. These secondary electrons can cause discontinuities in RF, generate noise, gas burst and damage metallic and insulator surfaces [4]. The heat and stresses exerted by these electrons bombarding the RF surface can lead to surface deformations, creating additional emitting sites [3]. Although breakdown initiates locally, its effects are global.

Currently, the majority of the models focus on surface defects as the only source of emission. In order to develop a better understanding of breakdown, it is vital to study what factors contribute to the formation of such sites, hence lowering the performance of the structure.

PROPOSED RESEARCH PROGRAM

This study is in close partnership with the MUCOOL collaboration at Fermilab. Their ultimate goal is to develop muon-cooling systems for Muon Colliders and Neutrino Factory [5]. A series of high power RF tests are performed on button shaped samples using an 805 MHz closed cell pillbox cavity. Further details regarding the MUCOOL Testing Area (MTA) are given in [5-7].

Experimental Study

As demonstrated in figure 3 of [5], tests at the MTA show a striking drop in the supported RF gradient in the 805 MHz cavity when the solenoidal field is applied. This is of high concern for the Neutrino Factory. The quality and condition of the RF surface plays an important role in determining the performance of the accelerating structure. The MTA has been focusing extensively on testing different materials and surface coatings to evaluate their

performance when operated within the solenoid field. However, surfaces can be damaged during production and assembly [3]. In order to understand cavity performance and thereby develop better means of production, one needs to look into how fabrication procedure defined the RF surface. This work is a systematic study proposed by the UKRF consortium (Imperial College London, Lancaster University, Cockcroft Institute) aiming to test copper samples fabricated using various techniques.

Experimental Setup

The design of the new button consists of a support mandrel and removable cap, allowing the use of a number of forming techniques. The cap sitting on top of the mandrel is the subject for high power testing. Currently, the cap is pressed from a flat oxygen free high thermal conductivity copper (OFHC) sheet.

It is vital to characterise the surface after each step right from material selection up to the end of production. The surface topology and chemical composition of the surface are studied by White light Interferometry and X-ray photo spectrometry (XPS). Scratches introduced during fabrication are removed in steps starting by hand polishing the surface with different grades of sand paper to eliminate larger scratches. A chemical etch followed by an ultrasonic bath would remove grease and larger particles. The surface becomes shiny through electro polishing (EP), using a standard 85% phosphoric acid and 15% butanol mix. Finally, the surface is cleared from any residuals through a high-pressure de-ionised water rinse.

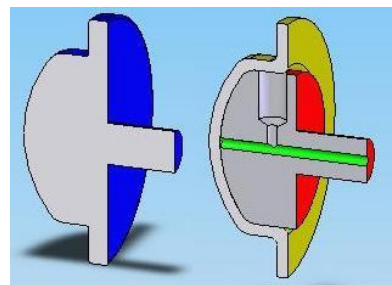


Figure 1: MTA buttons design (left) UKRF button design.

The removal of the damage layer would uncover the virgin copper, ensuring the exposure of the desirable surface to high electric field during testing. A final stage of surface characterisation is conducted once the sample has been tested. By studying the results from each stage of characterisation, it is possible to build a clear picture on how the surface has been changing throughout production. By comparing figures from various

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production methods, it would be possible to see which technique causes less damage, hence increasing the performance of the cavity.

Preliminary Results

In order to assess how the surface topology is being altered, a series of measurements have been conducted on buttons and flat copper samples taken from the same batch used to form the buttons. These are shown below in table 1 where A, B, C and D refer to modal average of received, mechanical polished, chemical etched and electro polished sample respectively.

Table 1: Surface roughness using Interferometer, modal average taken over 5 samples each case.

	Flat Sample		Button	
	Ra (nm)	Rq (nm)	Ra (nm)	Rq (nm)
A	106	143	356	459
B	140	194	180	240
C	252	362	220	292
D	93	121	98	120

Ra and Rq are the average surface roughness and the RMS roughness. The further Ra is from Rq, the more pronounced the defects. The pressed cap has a much rougher surface when received compared to flat samples, even when no machining has been performed. This demonstrates the fact that working the metallic surface to create the desired shape alters the surface topology. Figure 2 shows interferometer images of the altering metallic surface in the first and last stages of the surface preparation procedure.

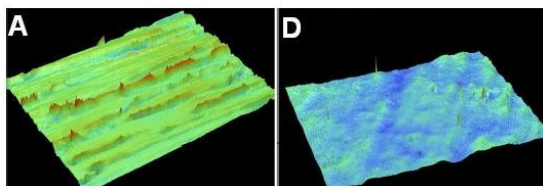


Figure 2: Interferometer images of OFHC copper [8].

The surface is levelled by the phosphoric acid present in the EP mix, while butanol is responsible for providing a greater control over the solution’s conductivity. It is known that electro polishing with an 85% phosphoric acid gives rise to oxygen formation. This leads to creation of sever etched pits on the surface [9]. Oxygen formation can be minimised by careful control over the EP current/voltage, maintaining the anode near the critical cusp point as illustrated in figure 3 [10]. It is essential to maintain this profile as steady as possible to minimise alterations in the final polish.

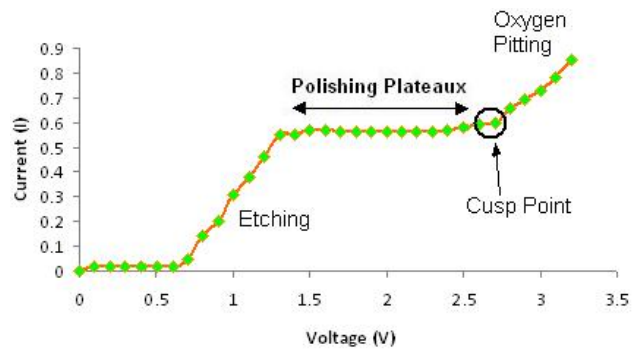


Figure 3: Characteristic plot for electro polishing.

The XPS investigations of figure 4 show fascinating changes in the chemical composition of Cu surface layers. We see a 96% reduction in carbon and oxygen contaminations after mechanical polishing followed by an additional drop of 50% through chemical etching. However, this process was reversed after EP with a 25 and 100 fold increases in carbon and oxygen respectively, due to the chemistry used. More interestingly is the addition of P impurities from EP, bonding in the surface layer to the Cu via 3S and 2P3/2.

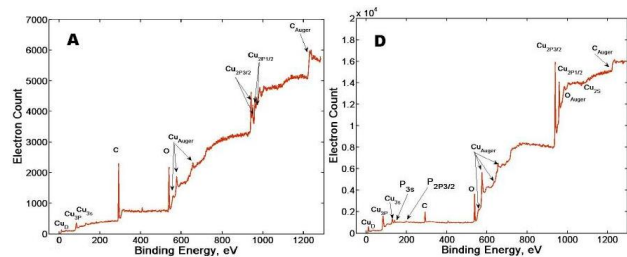


Figure 4: Binding energies of electrons released through XPS of OFHC copper sample [8].

Surfaces, depending on band structure, density of states (DoS) and environmental conditions, are capable of emitting electrons. Secondary Electron yield (SEY) describes the number of electrons emitted from a surface due to the impact of an incident electron. To gain an insight into this behaviour we used the numerical package DMol to calculate variational self consistent solutions to the density functional theory (DFT) equations [11], expressed in a numerical atomic orbital basis, so that we could represent the bonding seen experimental of the P. The solutions to these equations gave the wave functions and electron densities that we used to study the effects of P bonding on the band structure and Dos. The results are shown in figure 5, where we represented the system as an infinite slab of Cu with P introduced into the surface layer. These simulations indicate that the P impurities increase the Dos and band structure, causing overlapping. This indicates a higher ability to stream electrons from the material surface, leading to unpredictable behaviour.

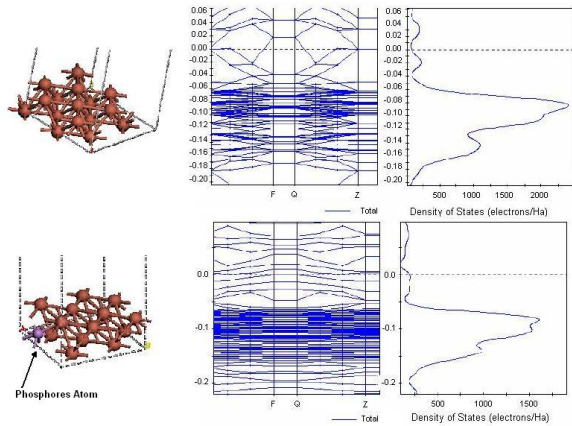


Figure 5: DFT simulations of copper with and without P impurity. Dos (left), band structure (right), dotted lines show the Fermi energy, units are in Hartrees [8].

Simulation Study

In addition to the above work, it is important to simulate how free electrons can initiate breakdown depending on the way surface defects alter the electric (E) and magnetic (B) field profile of a cavity.

We use Comsol Multiphysics to create a 3D profile of E and B fields of a cavity. A major advantage of working in 3D is the possibility to place various asperities with different shapes and orientations anywhere in the model. Figure 6 demonstrates a cross sectional view of the E field profile in an 805 MHz cavity. As expected, local field enhancements are observed around the defect.

The electrons behaviour is being studied using a homegrown particle tracking code that uses Matlab to extract the E and B fields from Comsol at any point in space. Being able to communicate directly with Comsol eliminates the need for pre-defined grid points. This allows precise extraction of parameters in order to track electrons from the emission site up to the point of impact.

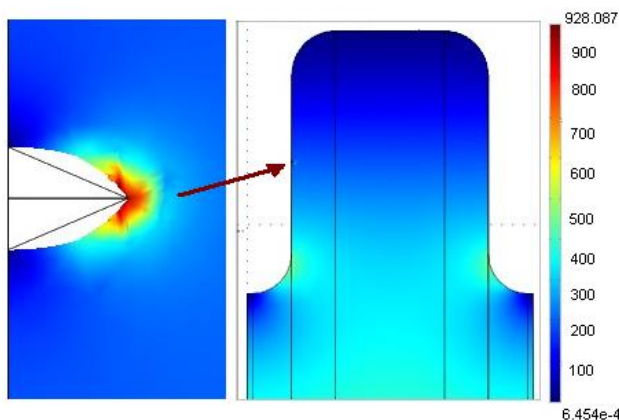


Figure 6: E field enhancement due to presence of defect on a flat surface in an 805 MHz cavity.

FUTURE PLAN

Although we are just beginning, we have some initial results showing how the manufacturing procedure affects the RF surface. This highlights the importance of the proposed study, which should provide vital information regarding manufacturing and assembly. This can lead to the development of more suitable and efficient techniques at later stages. We intend to expand this effort by looking at additional manufacturing techniques. Eventually, we aim to determine whether these electrons leave the systems or simply are trapped into the RF surface, causing secondary emissions. By examining various parameters at the point of impact, it would be possible to determine the level of heat and stresses generated.

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