

BREAKDOWN STUDIES FOR THE CLIC ACCELERATING STRUCTURES

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Abstract

Optimizing the design and the manufacturing of the CLIC RF accelerating structures for achieving the target value of breakdown rate at the nominal accelerating gradient of 100 MV/m requires a detailed understanding of all the steps involved in the mechanism of breakdown. These include surface modification under RF fields, electron emission and neutral evaporation in the vacuum, arc ignition and consequent surface modification due to plasma bombardment. Together with RF tests, experiments are conducted in a simple DC test set-up instrumented with electrical diagnostics and optical spectroscopy. The results are also used for validating simulations which are performed using a wide range of numerical tools (MD coupled to electrostatic codes, PIC plasma simulations) able to include all the above phenomena. Some recent results are presented in this paper.

INTRODUCTION

The development work for the CLIC linear collider has shown already at an early stage the need for a simple test setup, complementary to RF measurements, where studies of resistance of materials to high electric fields could be carried out with minimal investments and fast turn-around. Experiments have started in 2001 with a simple tip-to-plane device in UHV, where fields of several 100's of MV/m can easily be established with potentials of a few kV over gaps of a few 10's of μm [1]. The device allows measuring both Field Emission (FE) currents and breakdown (BD) events, tracking the voltage and current characteristics. It has also been progressively instrumented over the years, with the possibility of measuring optical spectra emitted during FE and BD, and performing quantitative residual gas analysis which is correlated with FE and BD. The purpose of the study is twofold. First is to study the resistance of materials to breakdown, spanning from the CLIC baseline material Cu to other possible candidates, which may be relevant for CLIC itself or for other future accelerators like the ILC or the Muon Collider, and the interplay of the breakdown field with surface treatments and the vacuum environment. On the other hand thanks to the good instrumentation, more fundamental studies on breakdown physics have started which serve also the purpose of benchmarking multiscale simulations of breakdown ignition and development by coupled MD and PIC computations [2], with the aim

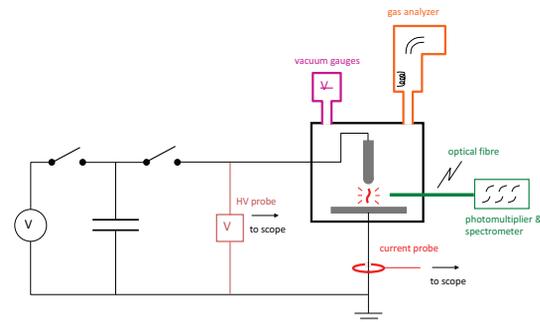


Figure 1: Schematic set-up of the spark-test devices.

of finally having a better insight on breakdown mitigation. In this paper we will briefly describe some new results obtained with cobalt, originated from a better insight on the material physics involved in the process.

EXPERIMENTAL RESULTS: COBALT

Two spark-test systems have actually been built and are in operation, having basically the same functionality. Their schematic set-up is illustrated in Fig. 1. A capacitor is charged at a given potential, and then connected to the spark gap where it may fully discharge in the event of a breakdown. During breakdown full traces of voltage and current are recorded, as well as optical spectra and vacuum pressure. Measurements of conditioning speeds, breakdown fields and breakdown rates of several metals and metallic alloys have already been presented [3]. Measurements of the field enhancement factor β after conditioning suggest also that the local breakdown field is constant for each breakdown [4], in agreement with previous measurements where the local breakdown field is claimed to be only dependent on the electrode material [5, 6]. With copper electrodes, the measured local breakdown field is around 10.8 GV/m [4].

The high breakdown field of titanium (780 MV/m) has motivated the choice of testing cobalt in the DC spark setup. Indeed, titanium is the only metal with a hexagonal crystal structure which had been tested so far, all other metals having a cubic structure. The purpose of the present experiment is to confirm that this particular crystal structure could have a positive influence on the breakdown field. Cobalt is a good candidate with the same structure, since it can be easily found on the market and has relatively good other properties. For example, its work function (5 eV) is higher than those of all other tested metals (between 4.3

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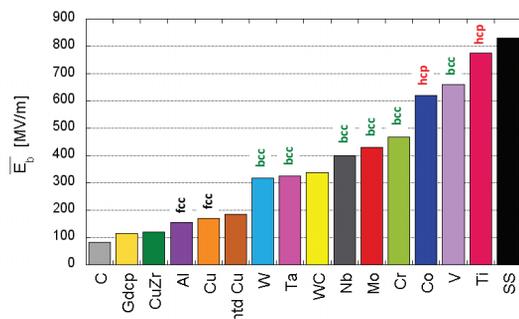


Figure 2: Average breakdown field after conditioning of the materials previously tested in [3] and of Co. For pure metals, the crystal structure is indicated (fcc = face-centered cubic, bcc = body-centered cubic, hcp = hexagonal closed packed).

and 4.65 eV), and it has also a good electrical conductivity $1.8 \cdot 10^7 \Omega^{-1} \text{m}^{-1}$, similar to molybdenum. On the other hand, cobalt is ferromagnetic and its melting point is rather low for a metal (1495 °C). This latter point might lead one to expect a lower achievable surface field.

Compared to other metals [3], the conditioning speed of Co is slow. Saturation of the breakdown field is not reached before roughly 100 sparks. As titanium, cobalt shows significant gap distance instability, caused by strong erosion and material displacement after breakdowns, perhaps related to the low melting point. A decrease or an increase in the gap distance up to $\pm 30\%$ of the original gap distance can be observed after a few tens of sparks ($\pm 50\%$ for Ti). Gaps with Cu or Mo electrodes are more stable ($< \pm 10\%$ after 50 breakdowns).

The saturated field E_b is calculated by taking the average of the breakdown fields after the conditioning phase, where saturation occurs. It reaches 615 MV/m ($\pm 27\%$) in the case of Co. As it can be seen in Fig. 2, cobalt is amongst the best materials tested in term of saturated field.

The evolution of breakdown field E_b , β and the local breakdown field βE_b have also been measured. Although the breakdown field of Co is significantly higher than that of Cu, the β values of Co are so low that the local breakdown field of Co is also lower than that of Cu, around 8 GV/m. Measurements of local breakdown fields of several metals can be found in [6] and compared with our results, but data for Co are unfortunately lacking in this paper. These data compared to those of copper [4] are summarised in Table 1.

Table 1: Average Values After Conditioning of E_b , β and Local Breakdown Field for Cu and Co

	Cu	Co
Average E_b [MV/m]	159 \pm 51	615 \pm 166
Average β	77 \pm 28	12.5 \pm 4.5
Average βE_b [GV/m]	10.8 \pm 1.7	7.9 \pm 1.7

DISLOCATIONS BEHIND A BREAKDOWN PHENOMENON?

It is clear that many physical quantities must be taken into account to enable the explanation of performance of the different metal surfaces in sufficiently high electric fields with respect to the breakdown process. Such quantities as melting point, heat of fusion, thermal conductivity, electrical conductivity, vapour pressure, surface tension, and work function may appear probable to be related to the value of a critical field E_b . However, the ranking among the materials as it is shown in Fig. 2 indicates the necessity of complex approach to the problem, since none of the aforementioned quantities has been found to correlate well with the ranking.

Nevertheless, there is a parameter which might explain the observed order of the materials with respect to their performance. As a matter of fact, the crystal structure of the tested materials consistently underlies the observed order. The surfaces which showed the lowest performances had essentially face-centered cubic (fcc) structure (Al, Cu and Cu-alloys), moving on through the body-centered cubic (bcc) structure (W, Ta, Nb, Mo, Cr), and eventually the best performance was observed for hexagonal close packed (hcp) metals (Co and Ti). The only exception is the relative order of Co and V, however, the difference is small and can likely be due to an additional influence of other quantities, or their combination. Moreover, the ductility properties of even the same element may vary strongly depending on manufacturing technique [8]. In this respect, the crystal structure and relevant mechanisms of the evolution of defects and their migration should be taken into account. The long experience in the field of materials science dealing with metals under extreme conditions, for example materials designed for the use in fission and fusion reactors [8,9], shows the importance of the influence of surface imperfections and their evolution for prediction of surface behaviour.

It has been clearly shown that irradiation with neutrons of steels in fission reactors embrittles the irradiated surface [10, 11], increasing the probability of cracking of the materials, and causing the formation of voids and other extended defects which hinder the dislocation mobility in metals. The mobility of dislocations is strongly related to the concept of metal ductility. Some metals are known to be the most ductile, such as fcc metals, but others are less and some metals are fairly brittle. The decrease of ductility can be followed from fcc metals, where dislocation mobility is the highest to bcc metals and, eventually to hcp ones, which have the least dislocation slip systems [7, 12], also see [13].

The activated motion of dislocations can lead to the significant topological changes on the surface. Recently by using the molecular dynamics (MD) technique we have simulated one of the possible sources for the emission of dislocations at the perfect Cu(110) surface. As a source of dislocations we used a void near the surface with the differ-

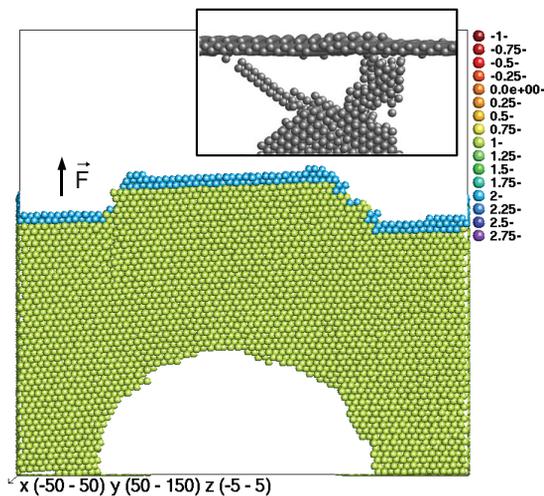


Figure 3: Snapshot of the asperity growth on Cu(110) surface in the presence of near-to-surface void. The constant force is exerted to all surface atoms to mimic the effect of electric field. The emission of a dislocation is shown in the inset, the imaging was done according to the potential energy. The atoms with the potential energy higher than the equilibrium value appear in the figure.

ent sizes between 4-10 nm in diameter. The (110) surface was chosen as this is the easiest glide direction for edge dislocations. In the simulation we tried to mimic the experimental DC setup, where the electric field between the electrodes exert significant force on the metal surfaces straining it upwards. Due to the short accessible time span of MD simulations, we exaggerated the exerted forces up to values which allowed seeing during simulation the emission of a dislocation from the void, and as a result mass transport towards the surface. The set of simulations has clearly shown that the bigger the void, the deeper it can be buried into the surface layers, while still triggering the growth of an asperity on the surface for the same tensile stress on the surface (Fig. 3). The inset of Fig. 3 shows the result of the simulation with the atoms of equilibrium potential energy filtered out, which shows the presence of dislocations emitted from the void. The mechanism involves the set of partial dislocation reactions, which bring extra atomic layers to the surface. The simulation we carried out for Co matrix (hcp) under the same condition as for Cu, did not show any dislocation activity even for forces 1.4 times higher (the ratio corresponds to the one between the Co and Cu bulk moduli).

We plan to combine these simulations to the hybrid ED-MD (*Electrodynamic-Molecular Dynamic*) code [14] to obtain a more realistic effect. This code was designed to obtain the dynamic charge rearrangement on the surface atoms following the surface topology, which leads also to the redistribution of the electric forces exerted on the surface atoms when the asperity starts to grow. The final result will give a better understanding of the ongoing processes, providing the additional information on the behaviour of

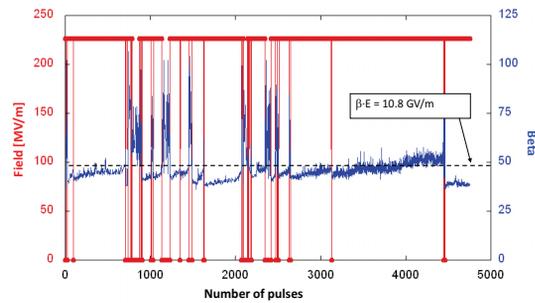


Figure 4: Evolution of β during breakdown rate measurements on Cu at 225 MV/m (From [4]). The electric field is in red, β in blue. The electric field is plotted at zero if a breakdown occurs, at the working value otherwise

metals under sufficiently high electric fields.

Another significant observation in Fig. 2 must be discussed separately. The fact that stainless steel has clearly the highest breakdown field, even though steels have the fcc or bcc crystal structure, is also consistent with low dislocation mobility. Stainless steels always contain a high proportion of Cr as an alloying element, and recent studies show that the presence of Cr strongly reduced dislocation mobility in steels, see e.g. [15].

This idea originated from the analysis of the results of BDR experiments on copper (see Fig. 4), where the evolution of β under repeated application of voltage pulses clearly suggested that the surface is being modified.

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