DC BREAKDOWN EXPERIMENTS FOR CLIC

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Abstract

For the production of the Compact Linear Collider (CLIC) RF accelerating structures, a material capable of sustaining high electric field, with a low breakdown rate and showing low damages after breakdowns is needed. A DC breakdown study is underway at CERN in order to test candidate materials and surface preparations. The saturated breakdown fields of several metals and alloys have been measured, ranging from 100 MV/m for Al to 850 MV/m for stainless steel, being around 170 MV/m for Cu and 430 MV/m for Mo for example. The conditioning speed of Mo can be significantly improved by removing oxides at the surface with a vacuum heat treatment, typically at 875°C for 2 hours. DC breakdown rate measurements have been done with Cu and Mo electrodes, showing similar results as in RF experiments: the breakdown probability seems to exponentially increase with the applied field. Measurements of time delays before breakdown show two different populations of breakdowns, immediate and delayed breakdowns, indicating that two different mechanisms could exist. The repartition of these two populations depends on the electrodes material.

INTRODUCTION

The feasibility of the future 12 GHz multi-TeV e^+e^- Compact Linear Collider (CLIC) is under investigation at CERN. Collisions of lepton-antilepton in this energy range will be essential to explore further the new physics that will be possibly discovered by the Large Hadron Collider (LHC). In order to limit this linear collider to an acceptable length, extremely high accelerating gradients of the order of 100 MV/m are required. With such fields, RF breakdowns are likely to occur and to produce damages on the accelerating cavities. Therefore, a material capable of sustaining high electric fields and showing low damages after breakdowns is needed. Furthermore, in practical operation, breakdowns can also lead to the loss of the accelerated beam due to random kicks. Thus, each structure has to have a breakdown probability as low as possible, typically in the order of 10^{-7}.

In this context, a DC breakdown study is underway at CERN in order to test candidate materials and surface preparations, and also to have a better understanding of the breakdown mechanism [1, 2, 3, 4]. DC tests are faster and more flexible than high power RF tests, and can be performed with a much simpler setup. The results obtained with this experiment, run in parallel to RF structure tests [5, 6], are therefore useful to have additional inputs for the design and the choice of the future CLIC RF structures.

Measurements of breakdown field, conditioning speed, breakdown rate and time delays before breakdown are presented here, for different metals and alloys.

EXPERIMENTAL SETUP

Figure 1 shows a schematic view of the DC spark setup. The electrodes are made of the same material, in a point-to-plane configuration, and are located in a ultra-high vacuum (UHV) chamber at a typical pressure of $5{\cdot}10^{-10}$ mbar. The anode is a hemispherical rounded tip, 2 mm in diameter, and the cathode is a grounded plane surface. The gap is typically set to 20 μm. For the measurement of the breakdown field E_b, the 27 nF capacitor C is charged with a high voltage power supply *via* the relay $S1$, and then connected to the anode *via* the high current relay $S2$ during typically 2 seconds. If no breakdown occurs, the voltage is increased and the cycle is repeated until the breakdown field is reached. Sparks are repetitively produced in this way in order to condition the tested spots on the electrodes surfaces. For breakdown rate measurements, the capacitor is always charged at the same voltage and breakdowns are detected with a 500 MHz current transformer (CT) connected to a scope. Finally, the delay time between the voltage rise and a breakdown is measured with a 75 MHz high voltage probe, also connected to the scope. More details about the setup can be found in [1].

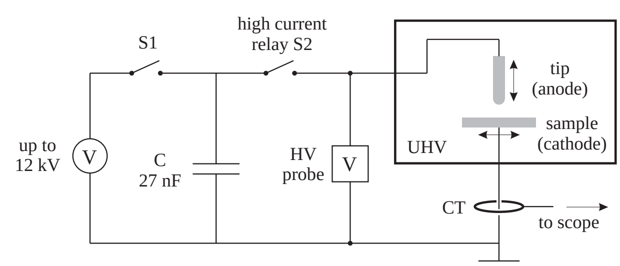

Figure 1: Schematic drawing of the experimental setup.

RESULTS AND DISCUSSION

Breakdown Field of Materials

A conditioning phase is generally observed, during which the breakdown field increases with the successive sparks until it reaches saturation. The saturated field $\overline{E_b}$ is calculated by taking the average of the breakdown fields

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after the conditioning phase. The number of sparks necessary to reach saturation depends on the material, but is typically between 20 and 100. Copper behaves differently as the other tested materials, since saturation is immediately reached ("immediate conditioning"). Figure 2 shows the saturated field of the various materials tested so far: C (graphite), Glidcop® (AL-15), copper-zirconium alloy (UNS C15000), Al, OFE Cu (UNS C10100), heated OFE Cu (2h at 815°C), W, Ta, tungsten carbide (10% Co, 0.8 μm grain size), Nb, Mo, Cr, V, Ti and stainless steel (316LN).

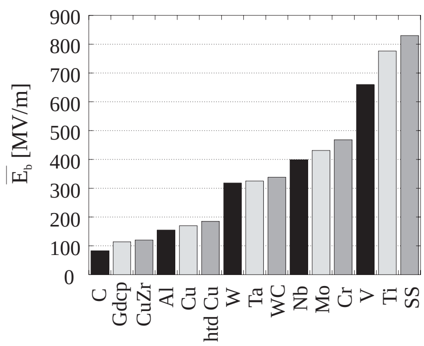

Figure 2: Saturated breakdown field $\overline{E_b}$ of tested materials.

Stainless steel has the highest saturated field (830 MV/m) and conditions after only 20 sparks, which makes it an interesting candidate. Bi-metallic structures Cu/SS could be considered, for example. Titanium has also a high saturated field but shows a strong material displacement after breakdowns (erosion or material transfer), while Cu (170 MV/m), Mo (430 MV/m) and stainless steel are more stable.

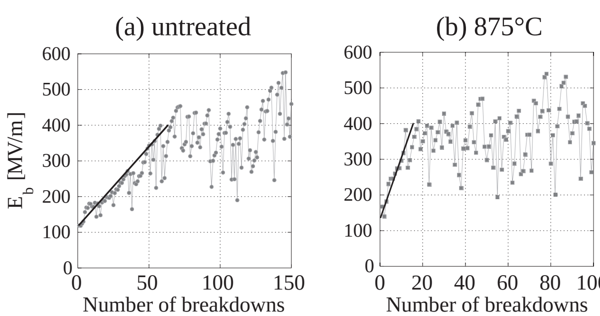

Figure 3: Improvements in conditioning speed of Mo after a heat treatment.

The conditioning speed of Mo can be much improved by a heat treatment, as shown in figure 3. The sample is heated during 2 hours *ex situ* in a UHV furnace at 875°C. While 60 sparks are necessary to reach 400 MV/m with untreated Mo (fig. 3a), only 15 sparks are needed with heated Mo (fig. 3b). Although the saturated field of Cu is slightly increased by 10% after 2 hours at 815°C (see fig. 2), the saturated field of Mo is not affected by the treatment. Surface analysis of the heat treated sample with X-ray photoelectron spectroscopy (XPS) shows a reduction of Mo oxides, which explains the improvement in the conditioning speed.

Treatments at 1000 and 1200°C can further reduce the conditioning speed down to 12 and 10 sparks respectively, but recrystallization occurs at these temperatures, as observed with hardness measurements (Vickers test). Since no recrystallization is observed at 875°C, this temperature is a good choice for Mo heat treatment.

Breakdown Rate of Cu and Mo

Whereas a high breakdown field is an important requirement for the material of CLIC structures, a low breakdown rate (BDR) at a given field is evenly important for a practical exploitation of the accelerator. DC BDR measurements are slow (typically 7 seconds per attempt) and therefore only possible at high breakdown probability ($> 10^{-4}$).

Figure 4a shows the evolution of the DC breakdown probability as a function of the applied field for Cu and Mo electrodes. Results of 30 GHz RF tests [5] are also plotted on the same figure, but against the surface field and not against the accelerating field. The surface field is indeed more comparable to the field seen by the electrodes in DC tests.

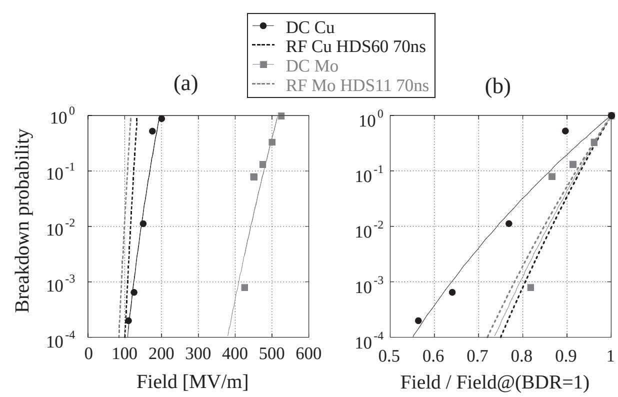

Figure 4: Breakdown probability of Cu and Mo in DC and in RF tests, (a) vs applied field, (b) vs normalized field.

A similar trend is observed both in RF and DC tests: the breakdown probability seem to increase exponentially with the applied field. But data points are preferentially fitted with power curves here (BDR $\sim E^k$, see [7]) rather than with exponential curves (BDR $\sim e^{kE}$), because BDR $\neq 0$ at $E = 0$ with the latter. Since breakdowns occur at a much higher field with Mo than with Cu in DC tests, it is easier to compare the different curves against a normalized field, as shown in figure 4b. For each set of data, the field is normalized with the value at which the breakdown probability is equal to 1. While the Cu slope is slightly steeper than the Mo slope in the RF data, the opposite is observed in DC. The slope of Mo in DC is similar to those of the RF curves. To get a more detailed interpretation of these results, measurements with better statistics and with other materials are needed.

Delays Before Breakdown

The time delay between the application of the high voltage and a breakdown is probably correlated with the breakdown mechanism. The study of these delays can therefore give some information about it. Histograms of delays measured with Mo electrodes are presented in figure 5. Two populations of delays are clearly visible, which could indicate two different breakdown mechanisms. The first, in black, has an average of 129 ns ($\sigma = 16$ ns). Since the rising time of the voltage has been measured around 100 ns, breakdowns of this first population are "immediate". The second population of delays, in grey, has an average of 1.17 ms ($\sigma = 0.33$ ms). These breakdowns will be called "delayed breakdowns", since the voltage holds constant for a certain amount of time before. These long delays have probably no equivalent in RF tests, since the typical timescale of one RF pulse is 240 ns.

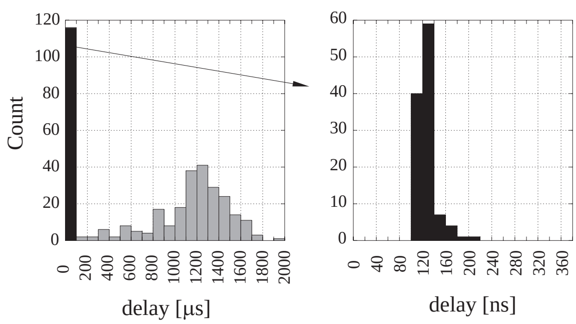

Figure 5: Histograms of delays with Mo electrodes.

Breakdowns of both populations occur at every field, but immediate breakdowns dominate in number during the conditioning phase (82%) and delayed breakdowns dominate after conditioning (76%). This could indicate that immediate breakdowns are rather present when the electrodes have still some contamination on their surfaces or desorb gases, whereas delayed ones are more likely to occur once the surfaces have been cleaned by the conditioning process.

The numeric repartition between immediate and delayed breakdowns depends on the material, as shown in figure 6. The materials are ranked in this figure according to their saturated field. The fraction of delayed breakdowns R (excluding the conditioning phase) for the different materials is given in table 1. It is observed that R increases with the saturated field, but no clear explanation of this fact can be given yet.

Table 1: Fraction of delayed breakdowns R

	Cu	Ta	Mo	St. Steel
$\overline{E_b}$ [MV/m]	170	300	430	830
R	0.07	0.29	0.76	0.83

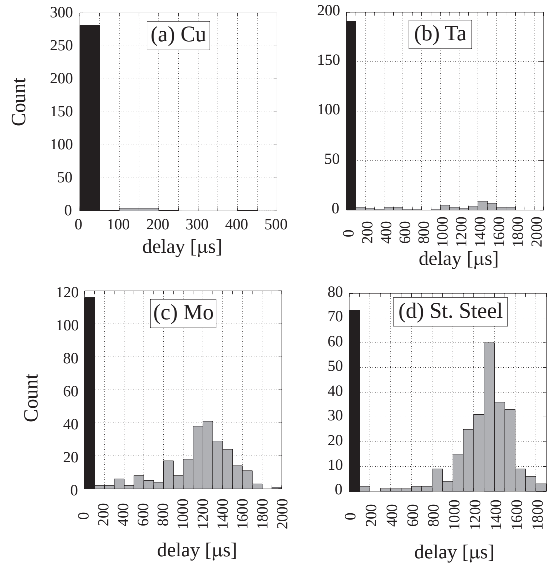

Figure 6: Histograms of delays for different materials.

CONCLUSIONS

DC breakdown experiments can easily provide measurements of quantities which are relevant in RF tests, such as breakdown fields and breakdown rates for example. Therefore, these experiments could help to select the best material for the production of CLIC accelerating structures. Stainless steel shows some interesting properties, with a very high saturated field. A careful surface preparation is also of importance, as demonstrated with heat treatments of Mo. Breakdown rate experiments can be conducted in DC as well, but a comprehensive interpretation of the results is delicate. Finally, the study of time delays before breakdown seems to indicate that the breakdown mechanism could be different during and after the conditioning phase. Such DC experiments will continue in parallel to the RF structures testing, and will hopefully add further understanding about the breakdown mechanism.

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