EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH
ORGANISATION EUROPÉENNE POUR LA RECHERCHE NUCLÉAIRE

CERN - TS Department

EDMS Nr: 473750
Group reference: TS-MME

TS-Note-2004-037
5 May 2004

MATERIAL STUDIES FOR CLIC RF CAVITIES

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Abstract

Following the EST/SM suggestion of replacing copper by molybdenum or tungsten for the construction of the RF cavity irises, different CLIC main beam accelerating structures were produced, extensively operated and disassembled for iris surface inspection.
The observed surface modifications were found to be very similar to those obtained by sparking in a dedicated laboratory set-up, showing the superior behaviour of both Mo and W with respect to Cu, in terms of surface erosion and conditioning.
The iris thermomechanical fatigue due to RF heating was simulated by high power pulsed laser irradiation. A CuZr alloy was found to be much more resistant than pure Cu. Measurements at higher pulse number will be performed on CuZr in order to extrapolate its fatigue behaviour up to the nominal CLIC duration.
Finally a possible future development of a hybrid probe beam acceleration structure will be presented.

Presented at the TS Workshop
Archamps, France, May 4 – May 6, 2004

1 INTRODUCTION

Since about three years the EST-SM group - now part of the TS-MME group - contributes to the selection, the analysis and developments of materials used in the high field regions of the main beam accelerating structure of CLIC (Compact Linear Collider) and is involved in the construction of prototypes through the assembly techniques (the latter topic not being discussed in the present article). Achieving TeV energy range with a new two-beams acceleration scheme is the main challenge of the future CLIC. Beyond any details of the accelerator system the length of the linear accelerator will be determined by the final energy and the maximum accelerating field that can be obtained, therefore in order to restrict the length to a conceivable size the field has been chosen as high as 150 MV/m. As a consequence the peak surface field in the RF cavities of the probe beam will range above 300 MV/m at the present level of the design optimization at 30 GHz and 120 ns pulses. Such high electric and hence magnetic RF field at the surface of the cavities will have two main consequences on the material surfaces. The high electric field regions are prone to breakdown with the effect of the modification of the cavity shape through loss of material by evaporation, as confirmed by the "post mortem" analyses performed on the accelerating copper structures tested in CTF2 (CLIC Test Facility 2) (Fig. 1). The high magnetic field regions are submitted to intense induced currents, which heat up abruptly the surface and induce thermo-mechanical stress because of the local thermal expansion. Such stress pulses at the nominal repetition rate (100-300 Hz) will lead to fatigue deterioration of the surface, which will on one hand worsen the surface conductivity for RF currents and increase power losses through surface heating and on the other hand it will initiate crack propagation leading to failure.

2 REGIONS OF HIGH ELECTRIC SURFACE FIELD: FROM COPPER TO TUNGSTEN

The copper irises of the RF cavities have shown their weakness with respect to breakdown in the tests performed in CTF2 (Fig. 1). A large test facility as CTF2 is, however, not flexible and adapted for quick testing of several materials, since each new material to be tested implies typically the construction of a 30 cells accelerating structure and the operation of a large infrastructure to drive the accelerator. For this reason EST-SM has developed in parallel starting in 2002 a laboratory spark-test device, which enables to submit materials to high electric field in dc mode. The aim of such a device is obviously to find a material, which can withstand the highest field without breakdown and does not suffer of major deterioration even when a breakdown event occurs.

The test device [1] consists of a plane sample surface in front of a rounded tip electrode to which a positive high voltage (up to 12 kV) is applied through a charged capacitor. The electrode system and a mechanical translator allowing for gap spacing regulation are placed under ultra high vacuum (10^{-9} mbar). After connecting to the electrode gap the charge of the capacitor decreases from its initial value either through field emission current from the surface or through a breakdown event in the gap. Monitoring the charge after a defined time enables one to detect breakdown events (capacitor completely discharged) and in the experiment the capacitor charge or charging voltage is increased stepwise until breakdown occurs. In this way the device allows the breakdown field E_{bl} and, by repeating the experiment, its evolution as a function of the number of breakdown events on the same surface site to be measured.

The results obtained in 2003 for the breakdown field measured on three materials, OFE Cu, Mo and W are shown in Fig. 2. The surfaces were prepared only by chemical cleaning. The choice of Mo and W as alternatives to Cu was motivated by physical properties of the refractory metals, namely their low vapour pressure. From the data in Fig. 2 it appears that after a series of sparks Mo and W can withstand larger fields than Cu and in particular larger than about 300 MV/m. Averaging over several sample sites we found an average breakdown field of 170 MV/m for Cu, 260 MV/m for Mo and 350 MV/m for W [2]. This already proves that the device is suitable to select materials with respect to their breakdown properties.

Breakdown events in vacuum are generally initiated by field emission currents between the electrodes and the spark-device is equipped also for this type of measurements. A characteristic parameter of the field emission current is the so called field enhancement factor β, which describes the local field E_{loc} as a function of the macroscopic applied field E as $E_{loc} = \beta * E$. The measured β depends on the geometry and in particular on the aspect ratio of possible asperities in the gap region and is also influenced by the surface chemistry. The evolution as a function of the number of sparks for the β value on Mo and W confirms the results obtained for the breakdown field. In contrast to the case of Cu, the evolution for W and Mo shows a decrease of β so that the local field provoking field emission and finally the breakdown is decreasing.

The energy stored in the capacitor is 1.4 J at 10 kV and if concentrated on a small area it is sufficient to provoke damages. Fig. 3 illustrates the aspect of the surface of Cu and W after the experiments related to Fig. 1. The damages are more extended for Cu than for W and Mo (not shown).

The motivations for the choice of Mo and W as alternatives to Cu seems to be correct. Indeed, in the case of Mo and W a single spark will not worsen the situation in an irreversible way, since a further conditioning can recover or improve the material performance (Fig. 2). The reason could be the comparatively low vapour pressure of the refractory metals at high temperature. Melting provokes a smoothing without major material loss or crater formation through catastrophic spark current enhancement due to the presence of the vapour. The smoothing is further favoured by the high surface energy of the refractory metals.

Finally, the test on CTF2 of two accelerating structures consisting of copper RF cavities but with Mo and W irises has demonstrated that higher fields can be reached by using refractory metals; the maximum RF breakdown field obtained after conditioning on the Cu structure was 250 MV/m compared to 350 MV/m for W and 420 MV/m for Mo [3]. This shows that the dc testing is relevant to predict the RF behaviour with respect to breakdown.

The next experiments will investigate the kinetics of the conditioning by modifying the apparatus to use less energy per breakdown event and the influence of different surface treatments of the materials. A further aspect which will be considered in view of the production of large series of components is the difficulty of machining of Mo and W at the necessary level of accuracy.

3 EXPERIMENTAL SIMULATION OF THE SURFACE INDUCED FATIGUE

The regions submitted to high currents will be heated by each pulse (order of 100 ns) of the RF accelerating field at a repetition rate of 100-300Hz during the lifetime of the accelerator. This adds up to about 1010-1011 heating pulses. Due to the tiny penetration depth of the RF in the metal (skin depth) the currents and hence heating are produced in a layer of the order of 300 nm thickness [4]. Material fatigue data are generally available only for about 108 cycles and for macroscopic stresses applied to the bulk of the material. In 2003 EST/SM has proposed to simulate the fatigue behaviour of the materials in a situation as close as possible to the CLIC application by using short UV laser pulses. The laser pulses can heat up the surface and induce mechanical stress in the same way as for the RF currents.

A XeCl excimer laser with 308 nm wavelength, about 50 ns pulsewidth and 25 mJ energy per pulse (after beam shaping) has been used to irradiate OFE copper and Cu-Zr C15000. The latter is a precipitation hardened alloy with 0.15 %wt content of Zr, which is expected to withstand better to fatigue and has an electrical conductivity only about 10 % worse than copper. The temperature profile for the laser pulse heating can be calculated and the depth of the induced temperature increase is of the order of 400 nm. The effect of irradiation is visible in Fig. 4, where two surfaces of Cu and Cu-Zr are compared after 60000 pulses at 0.2 J/cm^2 energy density. Both surfaces were initially diamond turned and did not show any visible roughness at the scale of the images, but after irradiation the OFE copper surface displays clear modifications due to the laser induced stress provoking material fatigue. By irradiating at larger number of pulses also the Cu-Zr surface shows modifications. The best method to quantify the modification induced by the laser irradiation was found to be the measurement of the increase in average roughness R_a. The data for Cu and Cu-Zr irradiated at various energy densities are shown in figure 5 and allow us to conclude that in order to obtain the same level of roughness or surface damages Cu-Zr must be irradiated with 50 times more pulses than OFE copper. The temperature increase at the surface, when submitted to pulses of 0.2 J/cm^2 is calculated to be about

120 K. This calculation of the temperature variation has been verified by increasing the energy up to the threshold of surface melting and indeed melting occurred at the predicted energy density.

The temperature rise for each pulse is directly related to the stress level induced in the surface layer during the pulse and therefore ideally one should apply laser shots to get the same temperature variation as the theoretical safety limit selected for CLIC, namely 56 K. However, such a low temperature rise is supposed to induce surface modifications only after a huge number of pulses and with the available repetition rate of lasers it is not possible to perform measurements up to 1010 cycles in useful times. The idea in the present study is to perform the same type of roughness measurement as a function of pulse number with various energy densities below 0.2 J/cm2. This series of data should indicate a trend for the minimum number of pulses necessary to get a defined level of damages as a function of the temperature rise per pulse. Finally this should enable an extrapolation to lower temperature variations down to a limit where the number of pulses necessary to induce damages exceeds the CLIC lifetime. This will give an experimentally defined safety limit for the material.

4 CONCLUSIONS AND PROSPECTS

In the previous sections we already presented some of the experiments, which are planned for 2004. As a consequence of the successful tests on W and Mo the CLIC study team has envisaged to build a hybrid accelerating structure composed of a copper alloy and a refractory metal part for the regions of high currents and high electric field, respectively. The fabrication method for a prototype of such a hybrid structure will be investigated by the MME group in order to meet the necessary dimensional accuracy and suitable surface- , vacuum- and breakdown properties together with the proper metrology control.

5 ACKNOWLEDGMENTS

The work described in this article has been performed by a close collaboration between many members of TS-MME. In particular I would like to mention Morten Kildemo for the development and measurements on the spark test device, Sergio Calatroni and Holger Neupert for the laser irradiation experiments and related calculations, Gonzalo Arnau-Izquierdo, Gudrun Jesse and Jean-Michel Dalin for the electron microscopy imaging and Ahmed Cherif for the surface roughness measurements.

6 REFERENCES

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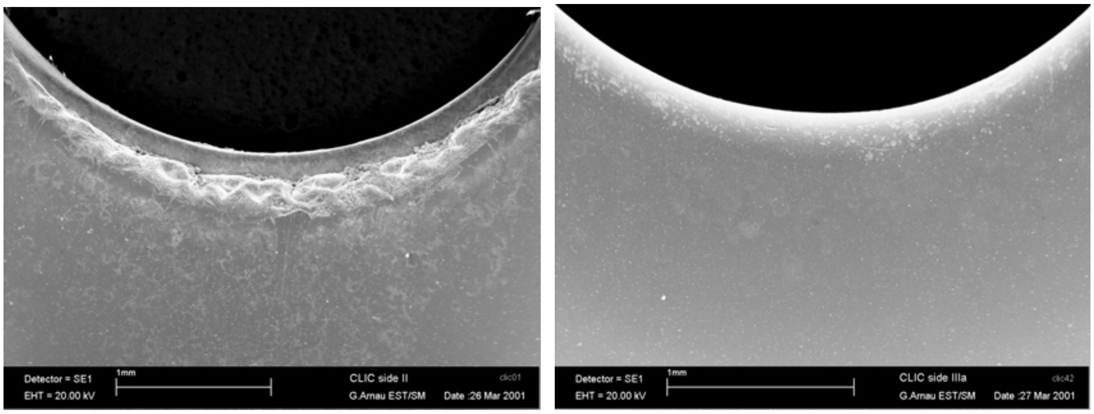

Fig. 1: Secondary electron microscope images of the effect of operation in CTF2 on a copper iris of the accelerating structure: the left image shows the modifications induced in the region submitted to the highest surface electric field of the first iris of the structure, whereas the right image shows an almost undamaged iris along the structure.(scale bar is 1 mm)

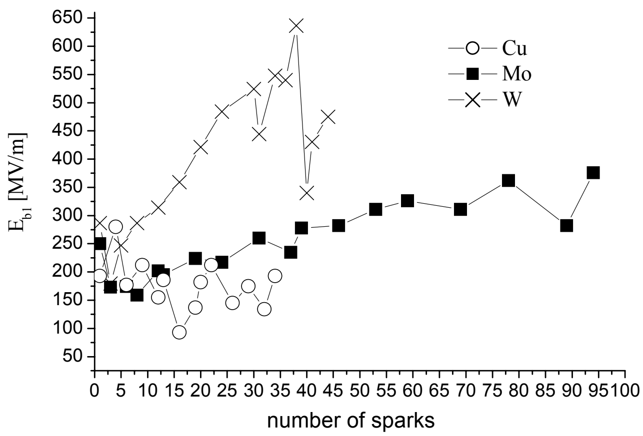

Fig. 2: Breakdown field measured with the DC spark-system for Cu (empty diamonds), Mo (black squares) and W (crosses) as a function of the number of sparks

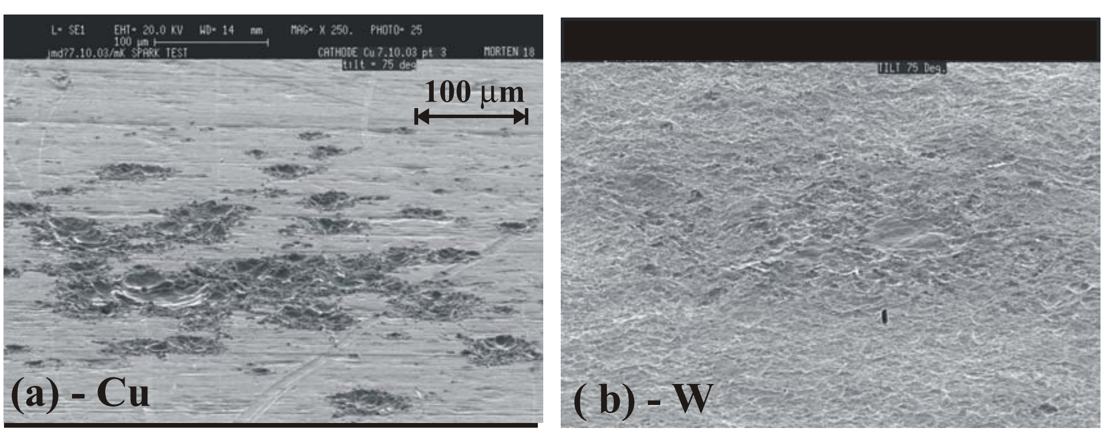

Fig. 3: Comparison of the surface damages after the breakdown measurements on Cu and on W. The scale is the same for both SEM images.

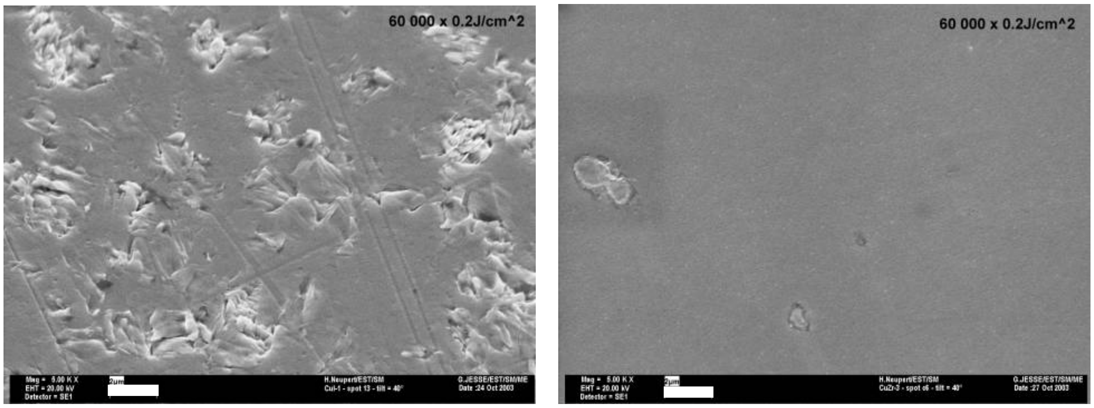

Fig. 4: Effect of laser irradiation on the surface of OFE copper (left image) and Cu-Zr alloy (right image) after 60000 pulses at 0.2 J/cm^2 . The white scale bar at the bottom of the figures corresponds to 2 μm.

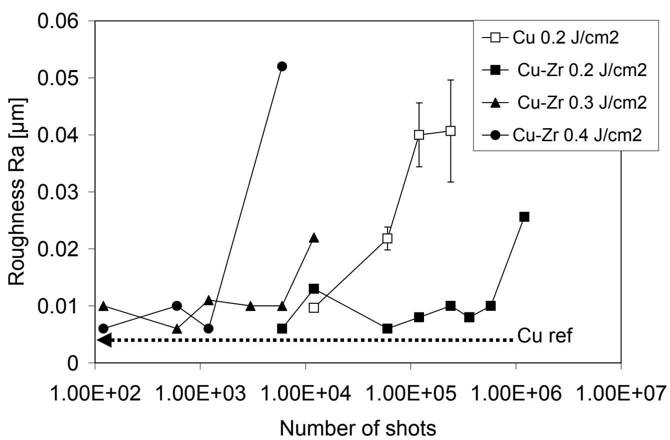

Fig. 5: Average roughness induced by laser irradiation on OFE Cu and Cu-Zr as a function of number of shots and for various energy densities. Error bars represent the standard deviation between roughness measurements within the irradiated area.