CERN – EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

CLIC – Note – 875

DC BREAKDOWN EXPERIMENTS WITH COBALT ELECTRODES

A. Descoeudres
CERN, 1211 Geneva 23, Switzerland

F. Djurabekova and K. Nordlund
Helsinki Institute of Physics and Department of Physics,
P. O. Box 43, FIN-00014 University of Helsinki, Finland

Abstract

RF accelerating structures of the Compact Linear Collider (CLIC) require a material capable of sustaining high electric field with a low breakdown rate and low induced damage. Because of the similarity of many aspects of DC and RF breakdown, a DC breakdown study is underway at CERN in order to test candidate materials and surface preparations, and have a better understanding of the breakdown mechanism under ultra-high vacuum in a simple setup. The conditioning speed, breakdown field and field enhancement factor of cobalt have been measured. The average breakdown field after conditioning reaches 615 MV/m, which places cobalt amongst the best materials tested so far. By comparison with results and properties of other metals, the high breakdown field of Co could be due to its high work function and maybe also to its hexagonal crystal structure.

Geneva, Switzerland
(June 2009)

I. INTRODUCTION

The feasibility of the future 12 GHz multi-TeV $e^+ e^-$ Compact Linear Collider (CLIC) is under investigation at CERN [1-4]. 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 produce damage on the accelerating cavities. Therefore, a material capable of sustaining high electric fields with low breakdown rate (typically 10^{-7} breakdown per RF pulse) and with low damage after breakdowns is needed.

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 comprehension of the breakdown mechanism under ultra-high vacuum [5-9]. DC tests are fast, more flexible and are more easily instrumented 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, are therefore useful to get information about the physical quantities governing breakdown and electrode damage, and to have additional inputs for the design and the choice of materials for future high gradient accelerating structures.

Measurements of conditioning speeds, breakdown fields and breakdown rates of several metals and metallic alloys have already been presented [8]. Measurements of the field enhancement factor β after conditioning suggest also that the local breakdown field is constant for each breakdown [9], in agreement with previous measurements where the local breakdown field is claimed to be only dependent on the electrode material [10,11]. With copper electrodes, the local breakdown field is measured around 10.8 GV/m [9].

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 has been tested so far, all other metals having a cubic structure. It has been suggested [12] 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 and 4.65 eV), and it has also a good electrical conductivity ($1.8\cdot10^7\ \Omega^{-1}\mathrm{m}^{-1}$) similar to molybdenum. On the other hand, cobalt is ferromagnetic and its melting point is rather low for a metal (1495°C). Measurements of conditioning speed, breakdown field and field enhancement factor with Co electrodes are presented in this note.

II. EXPERIMENTAL SETUP

Figure 1 shows a schematic view of the DC spark setup. Both electrodes are made of cobalt, in a point-to-plane configuration. They are located in an ultra-high vacuum (UHV) chamber at a typical pressure of $8\cdot10^{-10}$ mbar. The anode is a hemispherical rounded tip, 2 mm in diameter, and the cathode (sample) is a grounded 10 mm x 50 mm rectangular plane surface, 2 mm in thickness. The sample is directly cut from a polycrystalline cold rolled sheet and the tip is obtained by turning the end of a cylindrical rod. The electrodes are cleaned according to the CERN standard procedure for UHV components prior to installation in the UHV chamber. The sample can be moved laterally inside the chamber in order to test several spots at its surface. The position of the tip, and therefore the gap distance, is controlled with a micro-positioning device combined with differential levers. The positioning accuracy of this system is around 1 μm, and the gap distance is set typically between 15 and 20 μm. Such small gaps are necessary to reach fields of several hundreds of MV/m with the available 15 kV power supply. The zero distance is found by bringing the electrodes into contact and measuring a short circuit.

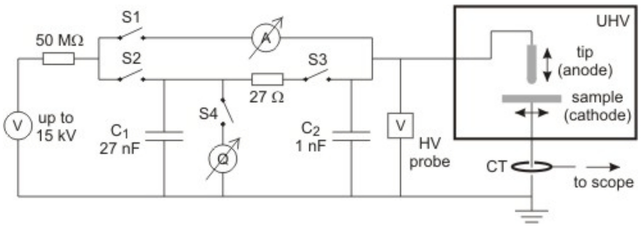

Fig. 1: Schematic drawing of the experimental setup.

Field Emission (FE) measurements between the electrodes can be performed by closing the S1 relay and by applying high voltage to the anode directly from the power supply. The FE current is read with a multimeter. From these current-voltage characteristics and the assumption that they follow a Fowler-Nordheim behaviour, the field enhancement factor β can be calculated [5]. The local microscopic electric field at the surface is then given by the macroscopic electric field multiplied by β. For the measurement of the breakdown field E_b, the 27 nF capacitor C_1 is charged with the power supply first to a low value via the relay S2, and then connected to the anode via the high current relay S3 for 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. The accuracy of the gap distance is checked before and several times during a conditioning experiment by re-establishing contact between the two electrodes. There is no evidence that this procedure significantly modifies the saturated breakdown field. Breakdowns are detected with a 500 MHz current transformer (CT) connected to a 1 GHz scope. The C_2 capacitor is used to damp voltage overshoots when the S3 switch is closed. In the present setup, the maximal energy available for the discharge is around 1 J and is chosen to be of the same order as in the RF experiments at 30 GHz conducted at CERN. More details about the setup can be found in [5].

III. RESULTS AND DISCUSSION

Figure 2 shows the evolution of the breakdown field E_b for Co. Compared to other metals [8], 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. A decrease or an increase in the gap distance up to ±30% of the original gap distance can be observed after a few tens of sparks (± 50% for Ti). Gaps with Cu or Mo electrodes are more stable (< ± 10% after 50 breakdowns).

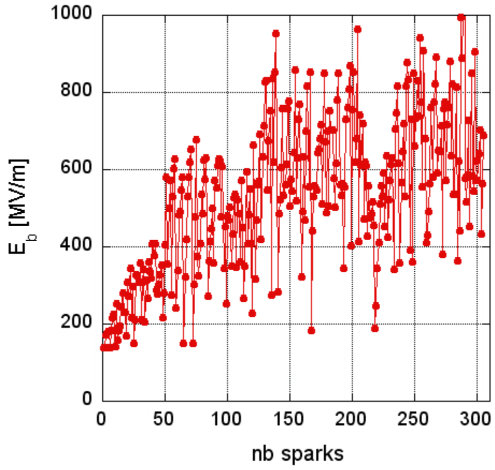

Fig. 2: Typical conditioning curve obtained with cobalt electrodes.

The saturated field $\bar{E}_b$ is calculated by taking the average of the breakdown fields after the conditioning phase, where saturation occurs. It reaches 615 MV/m (± 27%) in the case of Co. As it can be seen in figure 3, cobalt is amongst the best materials in term of saturated field. It is clear that many physical quantities are involved in the breakdown process (melting point, heat of fusion, thermal conductivity, electrical conductivity, vapour pressure, surface tension, work function, …), and that the ranking can not be explained by only one dominant material property. Nevertheless, it seems that a correlation between the crystal structure and the saturated field could exist. Figure 3 shows that metals with hexagonal structures perform globally better than metals with body-centered cubic structures, which perform better than metals with face-centered cubic structures. The high work function of cobalt (5 eV) is certainly also playing a significant role in its high saturated field.

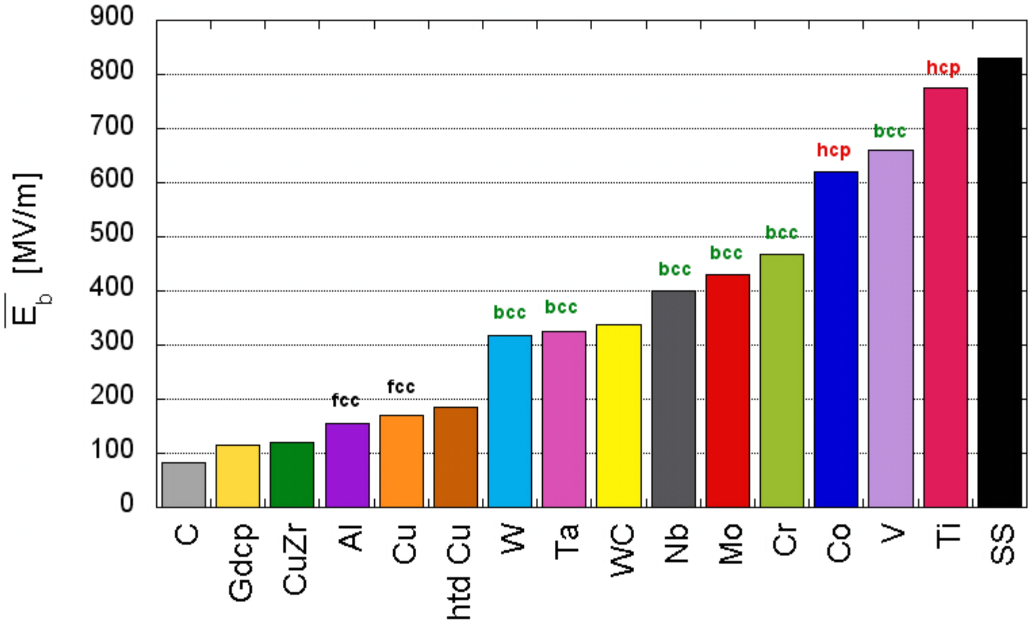

Fig. 3: Average breakdown fields after conditioning of the materials previously tested in [8] and of Co. For pure metals, the crystal structure is indicated (fcc = face-centered cubic, bcc = body-centered cubic, hcp = hexagonal closest packing).

The order of the crystal structures with respect to breakdown field suggests that there is a clear correlation with dislocation mobility and thus with the related concept of ductility. In general, pure fcc metals have the highest dislocation mobility and ductility, bcc metals somewhat lower, whereas hcp metals have least dislocation slip systems and are least ductile [13, 14].

The observation 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].

The evolution of E_b, β and the local breakdown field during a part of the conditioning experiment of figure 2 is given in figure 4. The average values for Cu [9] and Co are summarized in table I. As for Cu but to a lesser extent (statistics are made only on a small number of breakdowns), one can see that the values of the local breakdown field of Co are less dispersed than those of E_b and β. This supports the conclusion that $\beta \cdot E_b$ is roughly constant in these experiments and depends only on the material. 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 [11] and compared with our results, but data for Co are unfortunately lacking in this paper.

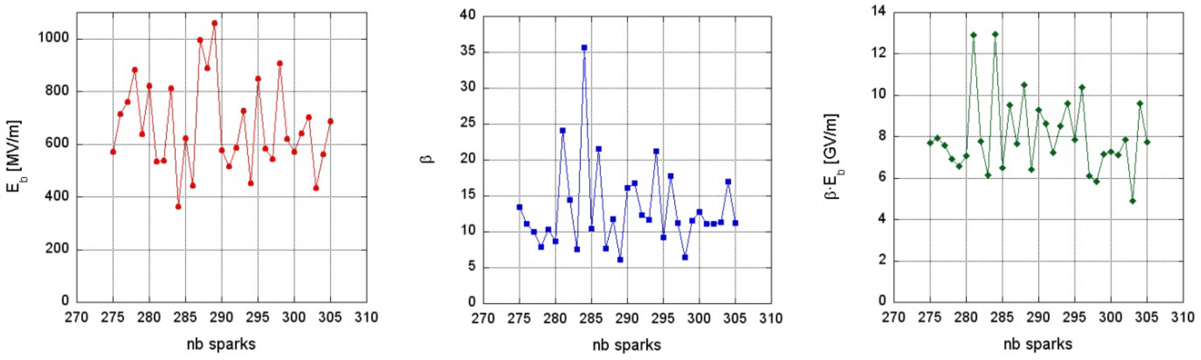

Fig. 4: Evolution of E_b, β and local breakdown field during a part of the conditioning experiment shown in figure 2.

Table I: Average values after conditioning of E_b, β and local breakdown field for Cu and Co.

	Cu	Co
average E_b [MV/m]	159 (± 32%)	665 (± 24%)
average β	77 (± 36%)	12.5 (± 36%)
average $\beta \cdot E_b$ [GV/m]	10.8 (± 16%)	7.9 (± 21%)

IV. CONCLUSION

Although cobalt has a slow conditioning speed and a poor gap stability, its average breakdown field is nevertheless amongst the highest measured so far, around 615 MV/m. In addition to its high work function, its hexagonal crystal structure could be at the origin of this high breakdown field. Indeed, the experimental data collected with several metals seem to indicate that a correlation between the crystal structure and the saturated field could exist.

REFERENCES

[1] J.-P. Delahaye, in *Proceedings of PAC99* (New York, USA, 1999), p. 250.

[2] G. Guignard *et al.*, *A 3 TeV e^+e^- Linear Collider Based on CLIC Technology* (CERN Report No. CERN-2000-008, 2000).

[3] W. Wuensch, in *Proceedings of APAC07* (Indore, India, 2007), p. 544.

[4] W. Wuensch, in *Proceedings of EPAC08* (Genoa, Italy, 2008), p. 2922.

[5] M. Kildemo, Nucl. Instrum. Methods Phys. Res. A **530**, 596 (2004).

[6] M. Kildemo, S. Calatroni, and M. Taborelli, Phys. Rev. ST Accel. Beams **7**, 092003 (2004).

[7] T. Ramsvik, S. Calatroni, A. Reginelli, and M. Taborelli, Phys. Rev. ST Accel. Beams **10**, 042001 (2007).

[8] A. Descoeudres, T. Ramsvik, S. Calatroni, M. Taborelli and W. Wuensch, Phys. Rev. ST Accel. Beams **12**, 032001 (2009).

[9] A. Descoeudres, Y. Levinsen, S. Calatroni, M. Taborelli and W. Wuensch, submitted to Phys. Rev. ST Accel. Beams.

[10] D. Alpert, D. Lee, E. Lyman, and H. Tomaschke, J. Vac. Sci. Technol. **1**, 35 (1964).

[11] P. Kranjec and L. Ruby, J. Vac. Sci. Technol. **4**, 94 (1967).

[12] F. Djurabekova, CLIC meeting, 27th February 2009, (http://indico.cern.ch/conferenceDisplay.py?confId=52729).

[13] W. D. Callister, Jr., Materials Science and Engineering, An Introduction (Wiley, New York, third edition, 1993).

[14] J. P. Hirth and J. Lothe, Theory of dislocations (Krieger, Malabar, Florida, 2nd edition, 1992).

[15] D. Terentyev, M. Klimenkov, and L. Malerba, Journal of Nuclear Materials 393 (2009) 30