BREAKDOWN MECHANISMS IN ELECTROSTATIC DEFLECTOR

M. Re, G. Cuttone, E. Zappalà, S. Passarello, INFN-Laboratori Nazionali del Sud,
44, Via S. Sofia, Catania, I-95123, Italy

Abstract

The Electrostatic Beam Deflectors for the K800 Superconducting Cyclotron are the most critical elements of the beam extraction system. It has been carried out an accurate investigation from the microscopic point of view, leading to a better comprehension of the complex phenomena taking part in the breakdown process. The environmental conditions are high electric field (up to 130 kV/cm), high magnetic field (up to 5 T) in addition with high energy (70 MeV/u) and high power ion beam. It has been found that all the materials constituent the electrostatic deflector, and not only the electrodes, give an important contribute to the mechanism of breakdown that occurs in two main ways: insulator metalization and enhanced electrodes electron emission. These two effects are involved in a positive feedback process which amplifies the effects leading to a fast breakdown. These phenomena are here shown and some possible solutions are at the moment under test using several bulk (Mo, Ti, Cu) and coating materials (TiN, Diamond Like Carbon).

1 INTRODUCTION AND EXPERIMENTAL

In this paper we present an extensive study on the electrostatic beam deflector for the K800 Superconducting Cyclotron in Catania (hereafter CS). This component is the most critical element of the Beam Extraction System, which consist on two moveable electrostatic deflectors and a series of eight magnetic deflectors. This study was carried out performing an accurate investigation from the microscopic point of view. The results shown here have lead to a better comprehension of the complex phenomena tacking part in the breakdown process. The environmental conditions of high electric field, high magnetic field, in addition with high energy and high power of the accelerated beam passing through the deflectors, make this component peculiar in his behaviour when the voltage is applied at the cathode. A cross-sectional view of the electrostatic deflector is shown in Fig. 1. Previous work has been carried out on shorted cathodes simulating the working conditions, it was found [1] that the dark current depends on the cathode material and its treatments. Present work has been carried out in the real operational conditions i.e. during irradiation and deflection of accelerated beams. It has been found that not only the cathode material plays an important role, but also all the materials constituent the whole electrostatic deflector give an important contribute to the breakdown mechanisms. In

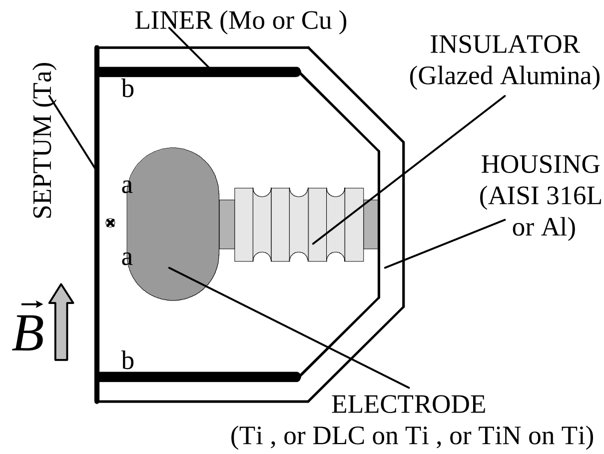

Figure 1: Cross Section of the Electrostatic Beam Deflector.

our experiments the cathodes were in Titanium alloy (6% Al, 4% V, Ti balance: $TiAl_6V_4$) or in $TiAl_6V_4$ coated with 6-7 µm of Ti rich Diamond Like Carbon (DLC), the liners were in Molybdenum or in oxygen free copper (Cu-OF), the insulators were in Alumina (99.5%) glazed with amorphous cristobalite, the septum was in Tantalum and the housing in Aluminium alloy or in stainless steel (AISI 316L). The alumina's glazing reduces surface outgassing, porosity and crystallographic defects which are responsible for the current leakage due to secondary electron avalanche emission [2]. The deflectors were tested during the normal operation of the CS, extracting a 62 MeV/u beam of H_2^+ by applying a voltage of –60kV to the cathodes, the gap between electrodes and septum was set at 5 mm, the vacuum environment was provided by the CS accelerator chamber (10^{-6} mbar) and the magnetic field was 3.5 T. After few hours in these working conditions several deflectors experience a higher absorption current, but the breakdown occurs only later, when this dark current continuously or suddenly increases above 500 µA, leading to a voltage limitation by the power supply. The experiments were performed using current-voltage analysis both in linear and in Fowler-Nordheim plots [3] to study the macroscopic effects of breakdown; Rutherford Back Scattering (RBS) [4] using a 1.7 MeV He^+ beam, X-Ray Fluorescence (XRF) using a 22.1 keV Cd source, for the surface investigation; Optical Microscopy and Secondary Electron Microscopy (SEM) for the surface morphology and 2D map by Energy Dispersion X-ray analysis (EDX) for the elements distribution on the surface.

CP600, *Cyclotrons and Their Applications 2001, Sixteenth International Conference*, edited by F. Marti

2 OBSERVATION AND DISCUSSION

2.1 Macroscopic observations

Macroscopic effect of the breakdown is the electrode higher absorption current. By comparing several current-voltage curve shape in Fowler-Nordheim plots (Fig. 2) it has been found that different effects are involved in the breakdown mechanism. In Fig. 2 curve A is the case of a deflector with good performance showing only Field Electron Emission (FEE) form the electrode surface i.e. high slope and straight line. Curve B is the case of a deflector with enhanced FEE i.e. lower slope, quite straight line. Curve C is the case of FEE plus other mechanism of current adsorption (conduction on insulator surface) i.e. non-straight line.

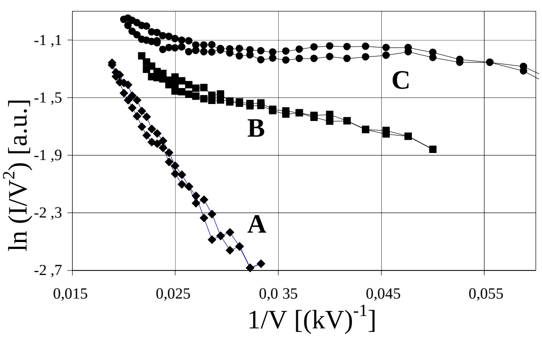

Figure 2: Fowler-Nordheim plot of three different deflectors behaviour. Curve B has been down shifted for a better representation. The used formula is $\ln\left(\frac{I}{V^2}\right) = K_1 \cdot \frac{1}{V} + K_2$ K_1 depends on temperature, work function, gap and increasing field factor. K_2 depends on K_1 and emitting area. This plot can put in evidence the FEE phenomenon.

2.2 Microscopic observations

In the operational condition, the trajectory of the electrons emitted by the electrode is strongly influenced by the presence of the magnetic field, from the calculations and the computer simulations [5] it turns out that they are emitted by the cathodes in correspondence to the highest curvature and the highest electric field (point '**a**' in Fig. 1), once emitted they are directed to the liner (point '**b**' in Fig. 1), the magnetic field not only drives the motion but also acts as focusing in their trajectory.

After the breakdown the liners on their surface exhibit a high density of spot reproducing the shape of the electrodes, this confirms the previous simulations. From the RBS and XRF analyses on the liners it turns out that these spots are re-solified material made of pure Mo or Cu (respectively in case of Mo or Cu-OF liners). This means that the focused electrons impinging on his surface are able to locally increase the temperature above its melting point (2896 K for Mo).

The electrodes exhibit a metallic halo on their surface, XRF analysis confirms that this is a thin Mo layer (in case of use with Mo liner).

The analyses performed on the insulators show that in many cases the breakdown occurs because of surface metalization, this is responsible for surface conduction. The RBS analyses performed on the insulators confirm that the metal on the surface is the same of liner material.

From these observation it is clear a first mechanism of breakdown. The electrodes emit electrons that the magnetic field focuses in the liner, this locally melts and evaporates depositing a metallic layer on electrodes and insulators, then insulators starts to conduct on the surface and the current increase above the power supply limit (typical current-voltage plot: Fig. 2 curve C).

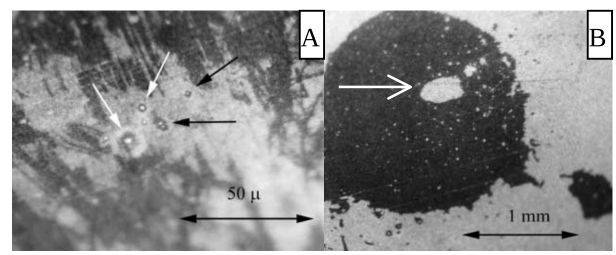

Figure 3: Optical microscopy of an DLC on Ti electrode used with Mo liners. Arrows in Fig. 3A indicate the metallic micro-tips on the surface, note that they exhibit free surface around them. The dark surface is DLC while the white is Mo. In Fig. 3B the arrow indicates the point in which is taken SEM and EDX picture of Fig. 4.

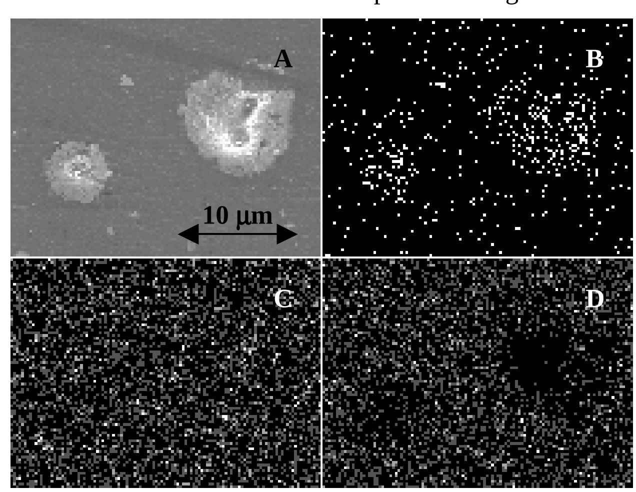

Figure 4: SEM (A) and EDX (B,C,D) analyses on the DLC on Ti electrode in the point indicated by the arrow in Fig. 3B. Fig. 4B is the surface Mo distribution taken from the characteristic Mo Lα line. The Fig. 4C is the Ti distribution from the Ti Kα line. The Fig. 4D is the Carbon distribution from the C Kα line. The tips here shown, are made of Mo evaporated from the liner.

In some cases the typical current-voltage curve was quite a straight line, similar to that in Fig. 2 curve B, which is more related to a stronger FEE (higher increasing field factor) than to an insulator surface conduction. In these cases the optical microscopy and the RBS analyses performed on the insulator surface did not show any evidence of metallic conductive layer on their surface.

In Fig. 3A and 3B are reported two observed optical microscopy of a DLC on Ti electrode surface. These analyses had put in evidence on the electrodes surface the presence of a metallic layer and a dense distribution of metallic micro-tips and micro-craters. In Fig. 4 B,C and D are reported the EDX analyses from which is possible to see the elements distribution. The craters are made of Mo (Fig. 4B), the Ti of the substrate is uniformly distributed (Fig. 4C), and the carbon of the DLC is covered by the Mo in correspondence of the craters (Fig. 4D).

2.3 Discussion

From the observation we can conclude that there is more than one phenomenon taking part in the breakdown mechanism. One is related to the insulator surface metalization, but there is at least an other one concerning the electrodes, in which the evaporated liner material forms high density of clusters (micro-tips). These are responsible for the enhanced FEE caused by the increasing field factor in proximity of the micro-tips. In this context the first effect is the electrons emitted by the electrodes. These electrons are able to melt locally the liner, which evaporates metalizing the insulators and the electrodes. Then insulators starts to conduct through the surface, this increase the temperature that enhance the FEE. This results in an amplification of the first effect. By other hand the liner material evaporate also onto the electrodes, here it forms clusters in which the electric field is increased by a factor depending on their size. This enhance the electron emission from the electrodes resulting again in an amplification of the first effect. A further evidence of this phenomenon is given to the fact that around the tips the surface is free of Molybdenum, in fact the temperature around the tip increases because of the FEE, this enhance the surface mobility of the Mo around the tips, therefore Mo cluster or atoms are able to migrate and to coalesce together or to ripen into bigger cluster [6]. All these effects acting in synergy lead to a fast breakdown of the electrostatic deflector. The question now is: in which condition the metal evaporated onto the electrodes forms clusters. One possible reason is the surface tension 'γ', i.e. the energy spent to create a surface. From a microscopic point of view, this is related to the energy of the dandling bonds of the atoms at the surface. In general a material with a lower γ try to uniformly cover another one with higher γ. In the opposite case this will forms clusters in order to reduce the total energy. In table 1 are reported some γ values: Mo has the highest γ value also compared with other metal (by exception of Ru, Ir, Os, W, Re) i.e. it will easily forms tips on other materials. Table 1 suggests that Cu from Cu-OF liner on Ti electrodes does not forms tips. Recent optical microscopy confirms these consideration.

Table 1: Surface Tension γ for some materials [6]

Material	γ [$mJ \cdot m^{-2}$]
Mo	~2300
Ti	~1700
Cu	~1400

3 CONCLUTIONS

The Electrode should be made by a material with a low primary and secondary electron emission in order to reduce the FEE: like DLC or TiN, in alternative is possible to take in consideration materials with moderate electron emission but high γ value, i.e. Ti, Pt, Mo or Re, used also as coating materials.

The liner should have high melting point, high thermal conductivity and low γ value compared to electrode material, i.e. Cu, Ti, Au (or Mo in case of Re electrodes).

The insulator should be glazed and have high thermal conductivity, i.e. BeO or AlN.

We also are testing the effects of a glow discharge treatment in presence of O_2 , it seems that O_2 is able to sputter the surfaces reducing the number of micro-tips and the surface conduction. This is also a reactive sputtering which should be able to oxidise the metalizations in order to produce a non-conductive material. These materials are at the moment under study and test; further investigation is needed to increase the deflector performances.

4 ACKNOLEDGEMENTS

We fully acknowledge for their help and suggestions: A. Grmek for mechanical design of the new deflector, C. Marchetta for the optical microscopy, F.P. Romano for the XRF spectra, from LNS. E. Viscuso and A. La Mantia for the SEM and EDX analyses from the company ST-Microelectronics in Catania.

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