SURFACE CHARACTERIZATION OF VACUUM COMPONENTS EXTRACTED FROM LHC DIPOLE MAGNET

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Abstract

Vacuum components of a dipole magnet exposed to the proton beam in the LHC at CERN were extracted from the LHC ring during the technical stop 2016 – 2017. Chemical analysis as well as Secondary Electron Yield (SEY) measurements were performed on their surface after a month of air exposure, to study possible surface modifications induced by the electron cloud bombardment during operation. The study shows that surfaces exposed to the cloud exhibit a lower maximum SEY and a lower copper hydroxide contribution than the same surface, never exposed to the beam. In addition, carbon graphitization could be detected on one of the LHC extracted components. These three features were previously identified as main characteristics of a copper surface conditioned by electron irradiation. This demonstrates that the LHC extracted components were at least partially conditioned in the accelerator under the effect of electron cloud.

INTRODUCTION

In the last decades, conditioning of surfaces by electron bombardment has been extensively studied in the laboratory, in particular to understand and foreseen the behaviour of particle accelerators with respect to the electron cloud effect [1-3]. However, only few studies on surface modifications induced by electron irradiation could be directly performed on accelerator components [4-7], leading to a lack of understanding regarding the conditioning state of some accelerators [8].

During the extended year-end technical stop (EYETS) 2016-2017, a faulty dipole magnet was exchanged in the LHC ring at CERN. After warming up and venting of a full LHC sector, the magnet was removed from its position in the tunnel and brought to the surface. Two vacuum components exposed to the beam, namely a beam screen and a pumping slot shield, were extracted from the magnet and their surface was analysed in the laboratory by X-Ray Photoelectron Spectroscopy (XPS) and Secondary Electron Yield (SEY) measurements to investigate surface modifications induced by the electron cloud exposure inside the LHC. To interpret the observations, a laboratory study has been performed in parallel to understand the mechanisms and the characteristics of the conditioning process of copper, the material of the LHC beam screen which is exposed to the beams.

In this paper, the chemical surface analysis as well as SEY measurements performed on the LHC extracted components are reported and compared with results from the laboratory conditioning study.

EXPERIMENTS

Laboratory study

The experiments were carried out in a baked UHV system (base pressure 6 x 10^{-10} mbar) made out of µ-metal. The setup is equipped for XPS analysis at normal emission angle (monochromatic Al Kα source, hν = 1486.7 eV) and SEY measurement. An electron flood gun allows sample irradiation for the conditioning study. The SEY δ is defined as the ratio of the total number of emitted (true secondary and backscattered) electrons I_s and the number of impinging electrons I_p. SEY measurements were carried out at normal incidence, between 10 and 1800 eV electron landing energy. The primary current I_p was first measured applying a positive bias on the sample (V_{sa} = +40 V). The bias was then switched to negative value (V_{sa} = -40V) and the sample current $I_{sa} = I_p - I_s$ was measured. The SEY was then computed: $\delta = 1 - I_{sa}/I_p$. The primary current was kept below 2.5 nA to limit the sample conditioning during the SEY measurement (estimated corresponding dose: 4 x 10^{-7} C/mm²). The reproducibility of the SEY measurement is estimated to be ±0.05 for two subsequent measurements at the same position. Conditioning was carried out using a flood gun at E = 250 eV at normal incidence. The sample current during irradiation was about 150 µA (measured with V_{sa} = +32V) for an irradiated area estimated to 1000 mm². The samples used for the laboratory study were 15x20 mm² copper pieces cut in a spare LHC beam screen and were cleaned in a commercial detergent, following the procedure applied for cleaning the beam screens and pumping slot shields installed in the LHC.

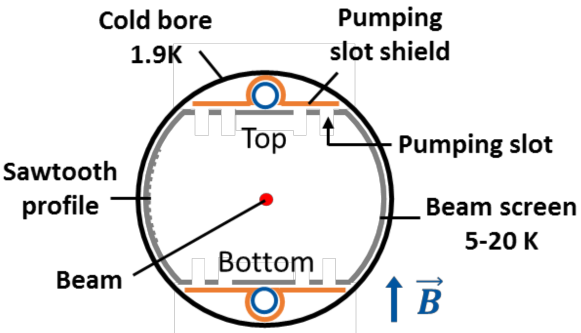

Figure 1: Schematic of the LHC beam vacuum system in the arcs

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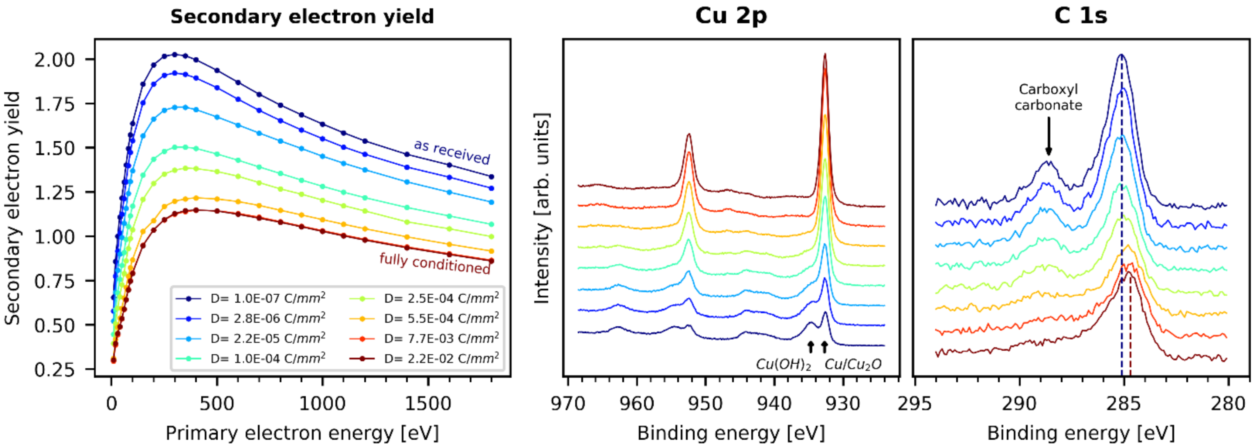

Figure 2: Laboratory conditioning of copper: secondary electron yield curves, Cu 2p and C 1s XPS lines

LHC extracted components

Two vacuum components exposed to the electron cloud during the LHC operation were removed from the LHC dipole magnet (see Figure 1).

A 16 m long beam screen made of colaminated copper (inner face) on stainless steel (outer face) was extracted from the cold bore and slices were cut at different positions along the magnet. For each slice, SEY curves and XPS spectra were acquired in different points with respect to the azimuthal position in the laboratory setup described above. Because of the confinement of the electron cloud by the dipole field, the two flat sides of the beam screen (normal to the field) are expected to receive most of the electron irradiation dose. On the external lateral side, a sawtooth profile is machined to absorb synchrotron radiation (see Figure 1).

The pumping slot shield, made of copper beryllium alloy (UNS C17200) passivated with chromic acid after detergent cleaning and located on top and bottom of the beam screen, was also analysed. In particular, longitudinal SEY profiles and XPS analysis were performed along the beam axis in order to investigate differences in conditioning states between areas which were exposed to the electron cloud through the beam screen pumping slots and areas which remained masked by the beam screen (see Figure 1).

For both components the analysis were performed after 1 to 2 months of air exposure, a venting of a full LHC sector being required to exchange the magnet. Thus, deconditioning of the surface and loss of the *in-situ* conditioning state are expected.

RESULTS AND DISCUSSION

Laboratory conditioning of copper

The SEY curves as well as the Cu 2p and C 1s XPS core spectra acquired during the conditioning of a copper beam screen sample are shown in Figure 2. In the as received state, the sample exhibits a usual airborne contamination layer including copper hydroxide $Cu(OH)_2$ and carbon species. The maximum SEY of such a surface is about 2 and is found at a primary energy of 300 eV. During conditioning, two phenomena occur, leading to a global decrease of the SEY down to 1.15 at a primary energy of 400 eV for a dose of 10^{-2} C/mm^2. In the first stages of irradiation, a surface cleaning effect by electron stimulated desorption is observed through the vanishing of the $Cu(OH)_2$ and the carboxyl/carbonate components on the Cu 2p and C 1s lines respectively. For an electron dose greater than 2.5 x 10^{-4} C/mm^2, a shift of the C 1s line towards lower

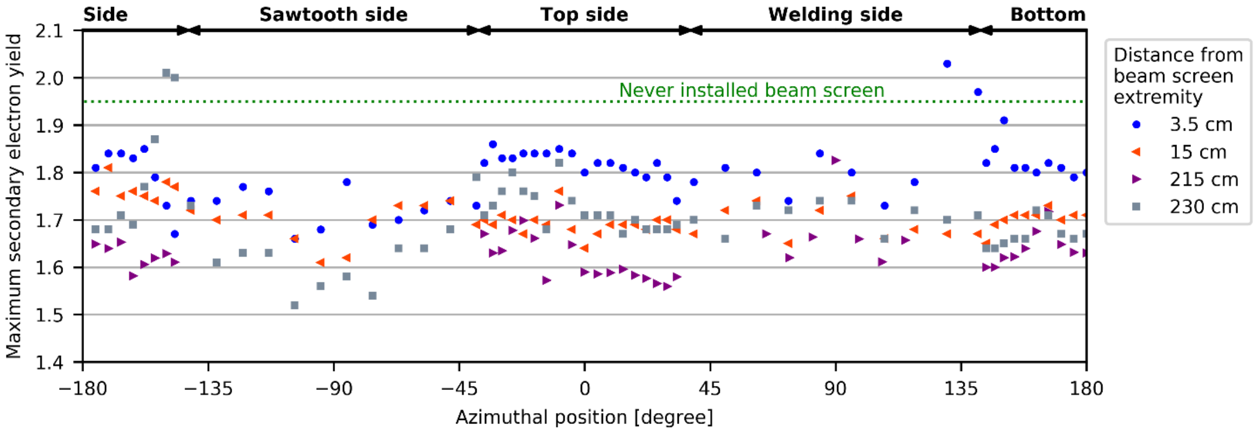

Figure 3: Maximum SEY with respect to azimuthal position for four slices cut in the LHC extracted beam screen

binding energies occurs, corresponding to graphitization of the adventitious carbon layer, as already reported [2].

LHC extracted components

Beam screen

Four slices of beam screen, cut at different positions along the magnet, were analysed. The maximum SEY with respect to the azimuthal position for the 4 slices is shown in Figure 3. Despite the electron confinement by the dipole field, no significant difference of maximum SEY is observed between the flat (top and bottom) sides and the welding side. The maximum SEY of those samples ranges from 1.5 to 1.85, which is well below the value of 1.95 measured on a beam screen never installed in the LHC. This observation is compatible with at least a partial conditioning state of the beam screen inside the LHC.

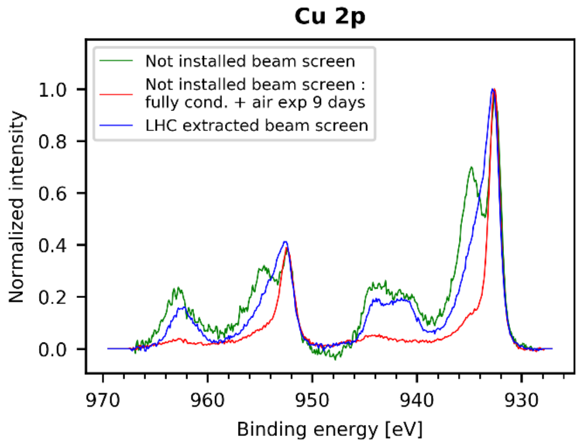

Figure 4: Cu 2p lines acquired on the bottom side of the LHC extracted sample located at 230 cm from beam screen extremity, on a never installed beam screen and on a never installed beam screen fully conditioned in the lab and stored for 9 days in air

XPS analysis performed on the four slices revealed the presence of carbon, oxygen and nitrogen on top of copper, as well as traces of usual contaminants (S, Cl, Si). The Cu 2p line acquired on the bottom side of the slice located at 230 cm from the beam screen extremity is shown in Figure 4. For comparison, the Cu 2p lines acquired on a never installed beam screen before and after a full conditioning process in the lab followed by 9 days of air exposure are also shown. As expected from the laboratory study of copper conditioning reported above, the hydroxide contribution at 934.8 eV of the never installed beam screen is strongly decreased by the lab conditioning and remains low even after 9 days of air exposure. It is clear that the shape of the Cu 2p line of the LHC extracted sample is different from the never installed beam screen one, pointing again towards an electron cloud induced surface modification during LHC operation. No clear difference in the C 1s line is observed between LHC extracted and never installed (before conditioning) beam screens. The amount of carbon varies between 20 and 40% for all the points measured on the four slices and no correlation was found between the carbon concentration and the azimuthal position.

Pumping slot shield

A visual inspection of the pumping slot shield side facing the beam screen revealed the presence of dark traces corresponding exactly to the pumping slot shape and spacing, and thus to the areas exposed to the electron cloud in the LHC (see Figure 1). An air baking at 120°C for 26h enhanced the colour contrast as shown in Figure 5. The origin of the coloration is not yet understood and is currently under investigation.

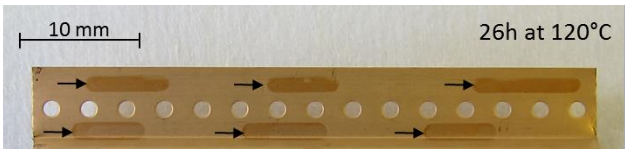

Figure 5: Dark traces corresponding to the pumping slots on the pumping slot shield side facing the beam screen

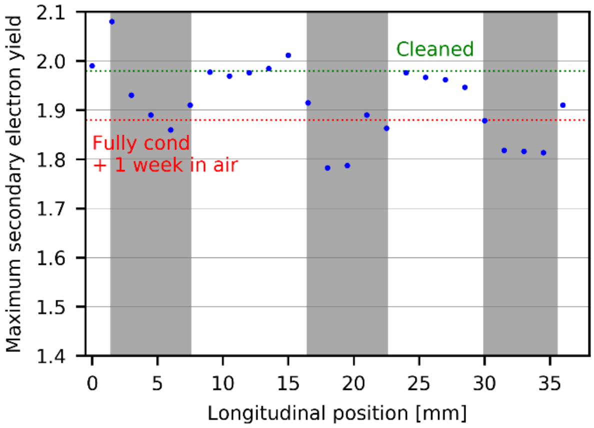

Figure 6: Maximum SEY with respect to longitudinal position for a LHC extracted pumping slot shield. The maximum SEY value for a cleaned (never installed) pumping slot shield before and after a full conditioning process in the lab followed by a week of air exposure

The SEY was measured on the sample as extracted (no baking in air) in different points along the beam axis and the corresponding maximum SEY profile is given in Figure 6 where the grey stripes represent the position of the dark traces. A clear and systematic step pattern is visible with low SEY regions corresponding to dark (irradiated) areas and high SEY regions in the non-irradiated areas. As for the beam screen, a reference sample (same component, but never installed in the LHC) was analysed for comparison. After the cleaning and passivation procedure, the never installed pumping slot shield exhibits a maximum SEY of about 2, corresponding to the value measured in the non-irradiated areas of the LHC extracted component. After full conditioning in the lab and 1 week of air storage, the maximum SEY of the never installed sample is below 1.9 and is compatible, within the experimental accuracy, with the maximum SEY observed in the irradiated areas.

XPS spectra were acquired in both irradiated and non-irradiated areas of the LHC extracted pumping slot shield. In addition to the elements found on the LHC extracted beam screen, beryllium and chromium could be detected on this component. The Cu 2p and C 1s lines are shown in Figure 7. As expected from the laboratory study reported above, the $Cu(OH)_2$ contribution is strongly decreased in the irradiated areas with respect to the non-irradiated ones. In addition, in the irradiated zones, the C 1s line is shifted to lower binding energy demonstrating a graphitization of the adventitious carbon layer. These two observations are compatible with a conditioning of the dark areas induced by the electron cloud. It is worth mentioning that no difference of carbon concentration is observed whether the material was irradiated or not, contrary to analysis performed on components extracted from the SPS at CERN [9].

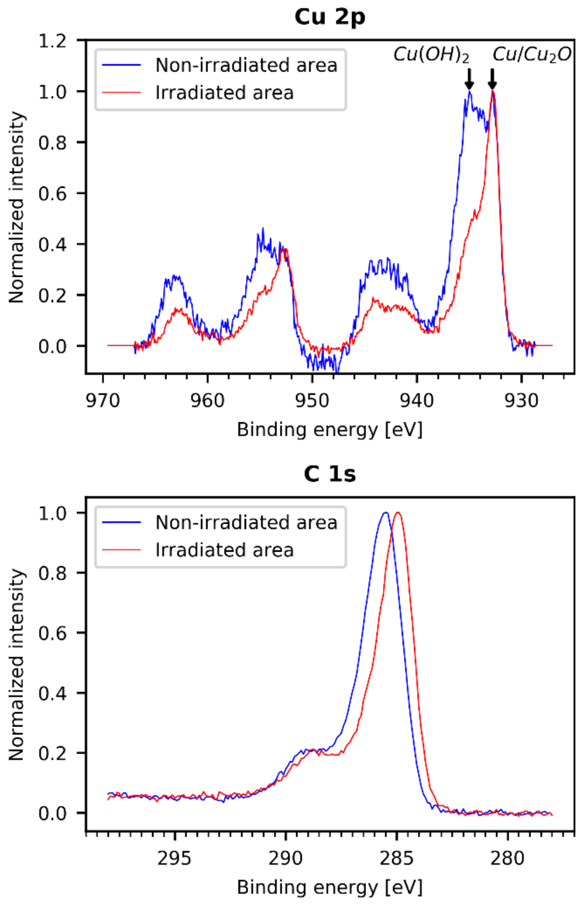

Figure 7: Cu 2p and C 1s lines acquired on the LHC extracted pumping slot shield, in irradiated and non-irradiated areas

CONCLUSION

A laboratory study allowed the identification of different features of the copper conditioning process. During electron irradiation, a decrease of the SEY induced by the cleaning of the surface ($Cu(OH)_2$ and carboxyls/carbonates removal) and carbon graphitization is observed.

In a second time, a beam screen and a pumping slot shield exposed to the beam in the LHC and extracted during the EYETS 2016-2017 were analysed after 1 to 2 months of air exposure. The beam screen as well as the pumping slot shield, in its irradiated areas, exhibit a lower SEY as well as a lower $Cu(OH)_2$ signal than the reference component which was never installed in the LHC. In addition, carbon in a graphitic form is observed in the irradiated areas of the LHC extracted pumping slot shield. These observations, identified in the laboratory study as characteristic features of the conditioning, prove that the LHC extracted components were at least partially conditioned by the electron cloud in the LHC. However, due to venting induced deconditioning, this study does not allow to deduce the conditioning level in terms of SEY of the components during the machine operation.

Furthermore, no carbon growth was observed for the LHC extracted components contrary to previous observations on SPS extracted components, proving that the conditioning does not rely on carbon growth.

More investigations are ongoing to understand the mechanisms of deconditioning in order to prepare the analysis of new components to be extracted from the LHC during the Long Shutdown 2.

ACKNOWLEDGEMENTS

The authors would like to thank all members of the TE-VSC group of CERN involved in this study.

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