

# ORIGIN AND MITIGATION OF THE BEAM-INDUCED SURFACE MODIFICATIONS OF THE LHC BEAM SCREENS

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## Abstract

All over Run 2, the LHC beam-induced heat load on the cryogenic system exhibited a wide scattering along the ring. Studies ascribed the heat source to electron cloud build-up, indicating an unexpected high Secondary Electron Yield (SEY) of the beam screen surface in some LHC regions. The inner copper surface of high and low heat load beam screens, extracted during the Long Shutdown 2, was analysed. On the low heat load ones, the surface was covered with the native  $\text{Cu}_2\text{O}$  oxide, while on the high heat load ones  $\text{CuO}$  dominated at surface, and it exhibited a very low carbon coverage. Such chemical modifications increase the SEY and inhibit a proper conditioning of the affected surfaces. Following this characterisation, the mechanisms for  $\text{CuO}$  build-up in the LHC beam pipe were investigated on a newly commissioned cryogenic system allowing electron irradiation, surface chemical characterisation by X-ray Photoelectron Spectroscopy and SEY measurements on samples held below 15 K. In parallel, curative solutions against the presence of  $\text{CuO}$  in the LHC beam screens were explored, which could be implemented in-situ to recover a proper conditioning and lower the beam-induced heat load.

## INTRODUCTION

An unexpected high beam-induced heat load was measured in the beam screen cooling circuit of half of the eight LHC arcs all over Run 2 (2015-2018). This puzzling data was detected first after the Long Shutdown 1 (LS1), a period of maintenance and upgrade including the venting of the cryogenic beam vacuum system to air [1]. Surface analyses were performed on the copper layer of beam screens extracted from the accelerator during the LS2 (2019-2021). The measurements evidenced the presence of native  $\text{Cu}_2\text{O}$  oxide on the surface of the low heat load beam screens, while the high heat load ones were oxidized to non-native  $\text{CuO}$  oxide and showed an exceptionally low carbon coverage [2]. In addition, the Secondary Electron Yield (SEY) of the beam screens after extraction was found higher when  $\text{CuO}$  was present. Finally, the room temperature conditioning by electron irradiation of  $\text{CuO}$ -rich surfaces was observed to be moderate compared to the one of  $\text{Cu}_2\text{O}$ , but not completely inhibited, and  $\text{CuO}$  was observed to be partially reduced to  $\text{Cu}_2\text{O}$  [2]. This reduction could be hindered or slowed down in the operating conditions of the beam screens, namely between 5 and 20 K, leading to the survival of a high-SEY oxide in some LHC beam screens, to an intense electron cloud activity and to the related high beam-induced heat load. Here, the behaviour of  $\text{CuO}$  under

electron irradiation in cryogenic conditions and the origin of its build-up in some LHC beam screens are assessed. In addition, possible techniques for in-situ  $\text{CuO}$  reduction are reviewed.

## CONSEQUENCE AND ORIGIN OF $\text{CuO}$ BUILD-UP IN THE LHC

The cryo-conditioning tests performed in this work were carried out on a new system enabling X-ray photoelectron spectroscopy (XPS), electron irradiation and SEY measurement (part still under commissioning) of samples below 15 K. Irradiation was performed by 250 eV electrons.

### Cryo-conditioning of $\text{CuO}$

The fraction of  $\text{CuO}$  at the surface of beam screen samples was deduced from XPS measurements of the  $\text{Cu } 2p_{3/2}$  state [3].  $\text{CuO}$  fraction evolution during electron irradiation at 250 eV, both at room temperature and 15 K, is shown in Fig. 1.

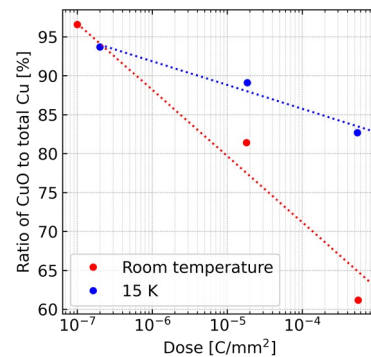


Figure 1: Effect of temperature on  $\text{CuO}$  reduction under electron irradiation at 250 eV (lines are guide to the eye).

$\text{CuO}$  reduction is significantly hindered at 15 K, possibly because of the reduced diffusivity of  $\text{Cu}$  and  $\text{O}$  ions in the oxide layer at cryogenic temperature. Therefore, the build-up and the stability of this high-SEY oxide at cryogenic temperature together with the low content of carbon, which limits the graphitic coverage essential for SEY decrease [4, 5], could be responsible for the high beam-induced heat load occurring in some regions of the LHC arcs.

### Origin of $\text{CuO}$ build-up

Copper hydroxide  $\text{Cu}(\text{OH})_2$ , which spontaneously grows on air-exposed copper surfaces [6], has been proposed as a precursor for  $\text{CuO}$  build-up in the LHC [2]. However, room temperature conditioning of airborne  $\text{Cu}(\text{OH})_2$  layers led to their conversion to  $\text{Cu}_2\text{O}$ , i.e. a reduction to  $\text{Cu}^+$ , which has a sufficiently low SEY [5]. Nevertheless, also in this case, temperature is expected to play a major role in elec-

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tron irradiation-induced reactions by affecting diffusion kinetics. Another factor which influences the species formed or decomposed by electron irradiation is the presence of carbon on oxidized Cu surfaces. The absolute carbon coverage is known to influence the chemical transformation during electron bombardment [7] and could thus be decisive to determine the build-up or not of CuO.

The observed modifications of air-exposed copper samples during conditioning at room and cryogenic temperatures are reported in Fig. 2, and the ones for conditioning at 15 K of samples with different carbon coverages are shown in Fig. 3. In these figures, the evolution of the chemical state of copper during conditioning, as monitored by XPS, is followed for different doses through a Wagner-like plot [2, 3], where the usual Cu  $2p_{3/2}$  binding energy axis is replaced by the centre of gravity of this line, to account for the presence of multiple compounds [2]. The position of reference CuO, Cu(OH)<sub>2</sub>, Cu<sub>2</sub>O and Cu(0) samples is shown for comparison.

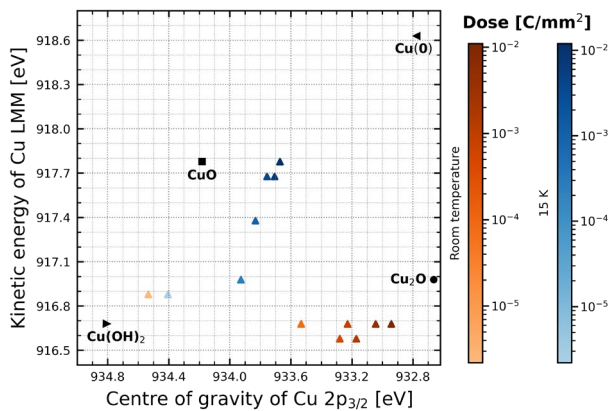


Figure 2: Conditioning of twin air-exposed copper samples at room temperature and 15 K.

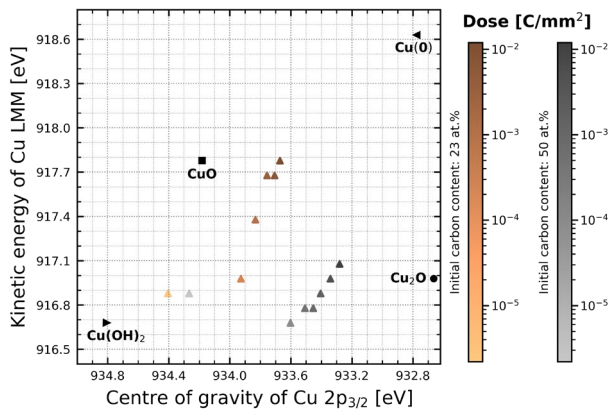


Figure 3: Conditioning at 15 K of air-exposed copper samples with different initial carbon coverages.

Figure 2 clearly shows the influence of temperature on the type of oxide dominating the surface after conditioning. While the conditioning at room temperature provokes the transformation of Cu(OH)<sub>2</sub> into Cu<sub>2</sub>O, the conditioning at 15 K of a twin sample deviates towards CuO. The formed CuO-like product is similar to the one observed in the

LHC-extracted beam screens, where the oxide observed after extraction was even closer to reference CuO in extreme cases [2].

Figure 3 shows the conditioning behaviour at 15 K of two copper samples with initially identical amount of copper hydroxide, but different carbon coverages (23 and 50 at.%). In the presence of high carbon coverage, conditioning leads to significant, but still incomplete, reduction of Cu(OH)<sub>2</sub> to Cu<sub>2</sub>O, i.e. the dehydration of Cu(OH)<sub>2</sub> to CuO is partially avoided. In addition, the carbon content drops to 35 at.%, as expected for a consumption of carbon species during the oxide reduction [7]. At low carbon coverage, Cu(OH)<sub>2</sub> is converted to CuO and the amount of carbon drops to 7.5 at.%, which is extremely low and is compatible with the amount of carbon found on the CuO-rich LHC-extracted beam screens [2].

To reproduce the Run 1 – LS1 – Run 2 LHC scheme and propose a scenario leading to CuO build-up only after LS1 in the accelerator, a copper sample exposed to air for more than a year and showing 40 at.% of carbon has been first conditioned at 15 K and then reconditioned at 15 K after 2.5 months of humid air exposure. The corresponding Wagner-like plot is given in Fig. 4.

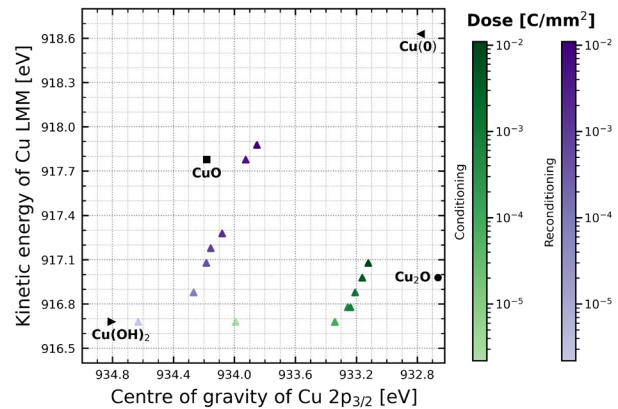


Figure 4: Conditioning and reconditioning at 15 K of an air-exposed copper sample.

Thanks to the initial carbon coverage, the transformation of Cu(OH)<sub>2</sub> into CuO is partially inhibited during the first conditioning. In parallel, the carbon content decreases and stabilizes to 31 at.% at the end of this conditioning. After 2.5 months of humid air exposure, Cu(OH)<sub>2</sub> coverage is significantly higher than for a non-conditioned sample stored in the same conditions. Indeed, in the current case, the formed layer is even similar to the one of a reference Cu(OH)<sub>2</sub> sample, pointing towards an increased surface reactivity after conditioning due to electron irradiation. Subsequently, the second conditioning leads to the transformation of Cu(OH)<sub>2</sub> to CuO. This difference of oxidation product formed under electron irradiation could be due to the higher amount of Cu(OH)<sub>2</sub> before the second irradiation, but also, as discussed before, to the lower amount of carbon, already partially depleted during the first conditioning. The carbon decrease had stabilized at the end of the first conditioning, but continued to decrease down to 13 at.% during the second irradiation, again compatible

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with carbon consumption by reaction with oxygen from the oxide or hydroxide [7]. In summary, this conditioning – air exposure – reconditioning sequence and the resulting surface modifications are compatible with the observed heat load increase in some arcs comparing LHC Runs 1 and 2.

## MITIGATION TECHNIQUES

In parallel to the investigations on the origin of CuO build-up in the LHC, in-situ curing methods have been explored. All of them are based on the removal of CuO from the surface by a reaction with a reducing gas promoted by various sources of energy. For this purpose, samples have been exposed to UV light and to atmospheric pressure plasma, both in 1 bar of N<sub>2</sub>-H<sub>2</sub> (95%-5%) mixture. Other samples were exposed to atomic hydrogen generated on a hot tungsten filament (H<sub>2</sub> pressure: 10<sup>-2</sup> mbar). The Cu 2p<sub>3/2</sub> spectra of a CuO reference sample before treatment, as well as the ones of three samples treated by the different techniques are shown in Fig. 5.

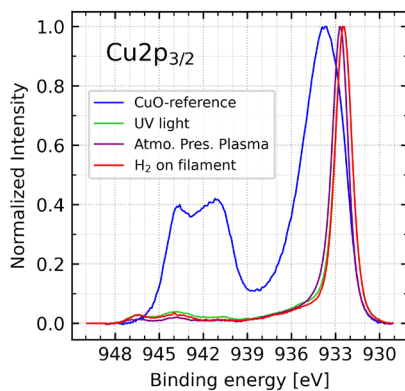


Figure 5: Cu 2p<sub>3/2</sub> spectra of CuO sample before and after various treatments.

In all cases, a complete CuO reduction is obtained, as witnessed by the complete disappearance of the CuO satellite between 939 eV and 945 eV. These techniques seem therefore promising for an in-situ deoxidation of the LHC beam screens.

## CONCLUSION

Thanks to a newly commissioned cryogenic system equipped for XPS analysis and electron irradiation, it is demonstrated that CuO is not reduced during conditioning by electron irradiation at 15 K. The build-up and the stability of this high-SEY oxide together with a low carbon coverage in some part of the LHC arcs can thus be responsible for high beam-induced heat load via intense electron cloud activity. In parallel, conditioning tests at 15 K of Cu(OH)<sub>2</sub>-covered copper surfaces with various amounts of carbon allowed to propose a scenario explaining the observed oxidation state and the associated high heat load of some LHC beam screens. The following sequence is proposed: at the start of LHC Run 1, the beam screens exhibited either

a low Cu(OH)<sub>2</sub> coverage and/or a large carbon content, which led to a normal (CuO-free) conditioning during Run 1, with possible start of carbon depletion → the high surface reactivity after electron irradiation during Run 1 enhanced hydroxide formation due to air-exposure during LS1, possibly influenced by the local ambient conditions → a local high Cu(OH)<sub>2</sub> and low carbon coverage then led to CuO build-up during Run 2. CuO-free beam screens could have resulted from conditioning of surfaces with low Cu(OH)<sub>2</sub> coverage or high carbon content at the end of LS1.

Techniques for in-situ deoxidation of the beam screens have been explored on a laboratory test bench and reduction of CuO is possible by exposure to reducing gas activated either by UV light or in an atmospheric pressure plasma, as well as by exposure to atomic hydrogen formed on a hot tungsten filament. The compatibility of these techniques with an in-situ implementation is under investigation and a further step is required to assess and avoid possible recurrence of CuO on the treated surfaces.

## ACKNOWLEDGEMENTS

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