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BEAM-INDUCED SURFACE MODIFICATION OF THE LHC BEAM SCREENS: THE REASON FOR THE HIGH HEAT LOAD IN SOME LHC ARCS?

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Abstract

All along the second run of the Large Hadron Collider (LHC), the beam induced heat loads in its cryogenic arcs exhibited strong scattering, with some arcs being close to their cooling capacity. Studies related the heat source to electron cloud, incriminating the surface properties of the arc beam screens, in particular their Secondary Electron Yield (SEY). To verify this hypothesis and as a first step in solving this critical issue in view of High Luminosity LHC, the beam screens from a low and a high heat load dipole were extracted from the accelerator during the Long Shutdown 2. Their inner copper surface has been analysed in the laboratory. While the surface of the low heat load beam screens exhibits the native Cu_2O copper oxide, the ones from the high heat load dipole display further oxidation to CuO and show a low carbon coverage. It is demonstrated that these unexpected features affect the SEY of the surfaces and slow down their conditioning. This work shows a direct correlation between the abnormal LHC heat load and the surface properties of the beam screens, opening the door to the development of curative solutions to overcome this critical limitation.

INTRODUCTION

The electron cloud related effects have long been identified as possible performance limitations for the Large Hadron Collider (LHC) at CERN [1]. Several mitigation approaches have thus been implemented. In particular, in the cryogenic arcs, the reduction of the electron cloud effects relies on the conditioning of the beam screen copper surface by electron bombardment [1]. Throughout the LHC Run 1 (2010-2013), a clear decrease of the electron cloud effects has been observed, proving the efficiency of the implemented strategy [2, 3]. However, the arc venting for accelerator maintenance during the Long Shutdown 1 reactivated the electron cloud at the beginning of Run 2 in 2015 [2, 3]. Since then, the beam induced heat loads on the cryogenic sections of the LHC present some strong inhomogeneities along the ring, which persisted until the end of the run in 2019, when the LHC was stopped for the Long Shutdown 2 (LS2). Unfortunately, in some LHC arcs, the beam induced heat loads almost reached the available cooling capacity of the cryogenic system [4]. These abnormal loads could therefore induce significant constraints to the operation of the High Luminosity LHC as of 2027 [5–7]. The observed heat load scattering corresponds well to the one obtained from electron cloud build-up simulations, assuming different Secondary Electron Yield (SEY) of the beam screens in the different parts of the ring [8]. To assess this hypothesis, the beam screens hosted in a high and in a low heat load dipole were extracted from the ring during the LS2. The surface state of their inner copper surface was analysed in the laboratory and their conditioning behaviour at room temperature was assessed and compared to a reference beam screen. The results of these analyses are detailed in the following sections

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EXPERIMENTS

After warm-up to room temperature and venting to atmospheric pressure of the arcs with a nitrogen-oxygen (80%-20%) mixture, the selected high and low heat load dipoles were brought to a surface facility, where their beam screens were collected. A special care and an optimized extraction schedule were implemented, to limit at most their deconditioning [9, 10].

Since the electron cloud density distribution depends on the magnetic field configuration [11], beam screen samples were cut from regions within the dipole field and from field-free regions (close to the interconnections) and surface analyses were carried out in different azimuthal positions.

The chemical composition of the inner copper surface was determined by X-Ray Photoelectron Spectroscopy (XPS), and its SEY was measured using the sample bias method [9]. Conditioning experiments were carried out by irradiating the samples with 250 eV electrons.

SURFACE CHARACTERIZATION OF LHC BEAM SCREENS

Surface Composition

The Cu 2p lines for different azimuthal positions of beam screen samples in the field and field-free regions of the two dipoles are shown in Fig. 1, together with the calculated electron cloud density distributions. For the samples from the low heat load dipole, the position of the Cu $2p_{3/2}$ main peak at 932.5 eV, the shoulder at about 934.5 eV and the shape and intensity of the satellite between 939 and 947 eV indicate the dominance of the native Cu_2O oxide, with a slight coverage by copper hydroxide [12]. These observations are compatible with studies on copper conditioning and deconditioning mechanisms [9, 13]. The chemical composition is observed to be homogeneous in azimuth (flat and round beam screen sides) as well as along the beam screen (in field and field-free regions).

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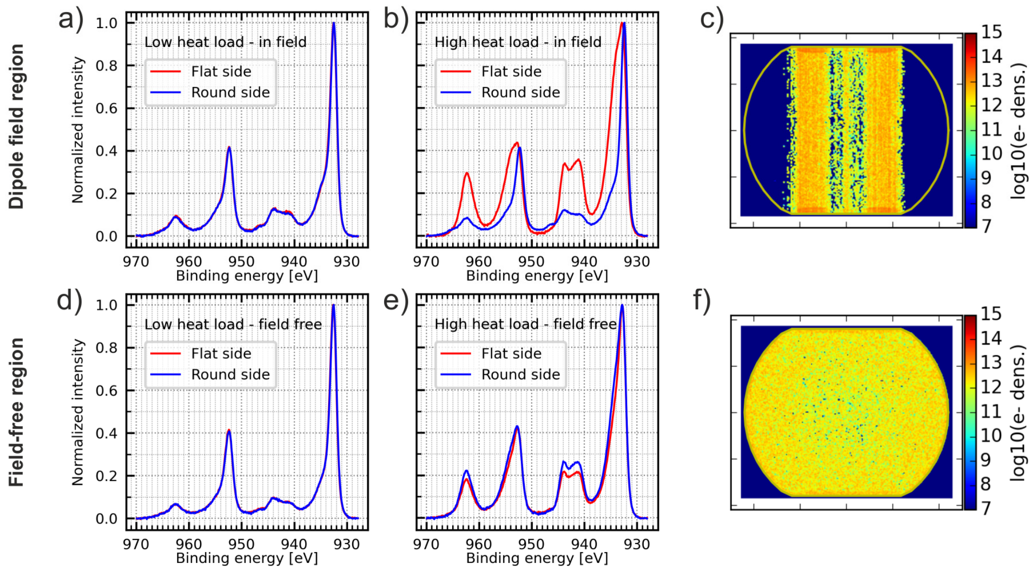

Figure 1: Cu 2p XPS spectra acquired on the low (a, d) and high (b, e) heat load beam screens, in different field configurations. The corresponding electron cloud density distributions from electron cloud build-up simulations [11] are shown for comparison (c, f).

For the high heat load beam screen, a different shape of the Cu 2p line is observed in the most irradiated parts of the beam screen, i.e. on the flat sides in the dipole field and at all azimuths in the field-free region. Indeed, in these areas, the Cu 2p lines lie at 933.5 eV and a high intensity satellite with a characteristic shape is observed between 939 and 947 eV. These observations indicate the dominance of CuO oxide [12]. In the least irradiated zones (round sides in field region), the copper chemical state is similar to the one of the low heat load beam screen.

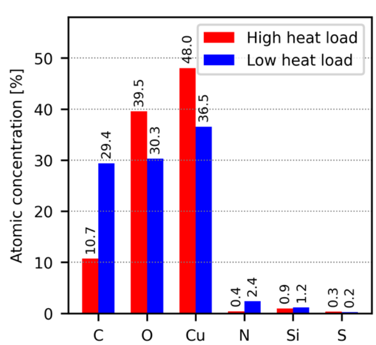

Figure 2: Elemental surface concentrations determined by XPS of the different beam screens surfaces (flat sides, in field region).

The atomic concentrations of the different elements found on the surface of the low and high heat load beam screens are shown in Fig. 2. While the surface composition of the low heat load beam screen is compatible with expectations [9, 13], the high heat load beam screen shows a very low amount of carbon, typically lower than achievable by the detergent cleaning applied to the beam screens before their insertion in the accelerator.

All these differences of surface composition have been consistently observed for the two beam screens of each dipole and at different longitudinal positions of each of them.

The matching observed in the high heat load beam screen among the azimuthal patterns of CuO, electron cloud density and energy distributions, as well as carbon depletion indicate that the beam operation has a major influence on these surface modifications.

Consequences on Conditioning

The electron-induced conditioning behaviour of the low and high heat load beam screens were assessed at room temperature. The corresponding evolution of maximum SEY as a function of the irradiation dose is shown in Fig. 3. The conditioning curve of a reference beam screen (spare from the stock) is also shown.

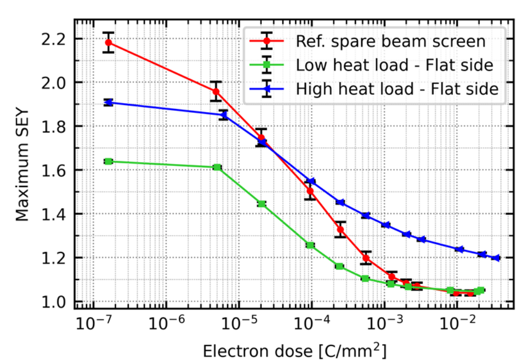

Figure 3: Conditioning curves of the high and low heat load beam screens. The conditioning curve of a reference beam screen (spare from the stock) is also shown for comparison.

The *as extracted* SEY (dose of 1.6 x 10^{-7} C/mm^2 for a single SEY measurement) is significantly lower for the low

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heat load beam screen than for the reference, proving a - at least partial - memory of its *in-situ* conditioning state. The *as extracted* SEY is however higher for the high heat load beam screen, indicating a possible amplification of the electron cloud density due to the presence of CuO. In addition, while the SEY decrease along electron irradiation allows to reach a SEY lower than 1.1 for the low heat load beam screen (similarly to the reference beam screen case), the conditioning of the high heat load beam screen is significantly slower and the SEY remains as high as 1.2 after a dose three times larger than the one usually required to reach the SEY stabilization. The presence of CuO seems therefore to have a detrimental effect on the conditioning behaviour of the affected surfaces.

This difference of conditioning kinetics between the CuO-rich and CuO-free surfaces can be explained by different conditioning mechanisms. Indeed, the usual surface modifications were observed during the conditioning of the low heat load beam screen, i.e. surface cleaning, reduction of copper hydroxide and carbon graphitization [13]. On the other hand, the conditioning of the high heat load beam screen involves the reduction of CuO to Cu_2O, as shown in Fig. 4, where the intensity of the CuO-related satellite clearly decreases during irradiation. However, in cryogenic conditions, the reduction of CuO to Cu_2O under electron bombardment could be strongly hindered [14], therefore leading possibly to an even more limited SEY decrease during conditioning.

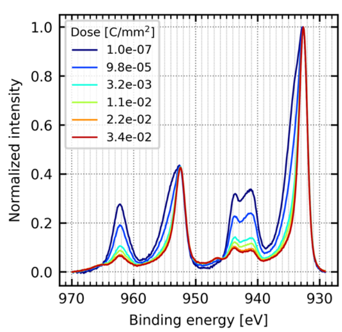

Figure 4: Cu 2p XPS spectra of the high heat load beam screen at different electron doses during conditioning.

CONCLUSION

The beam screens hosted in a high and in a low heat load LHC dipole magnet were extracted during the Long Shutdown 2. Their inner copper surface was analysed in the laboratory. While the findings on the low heat load beam screens are compatible with studies on copper conditioning and deconditioning mechanisms, the beam screens from the high heat load dipole exhibit unexpected properties. The presence of the non-native CuO copper oxide with an azimuthal distribution matching that of the electron cloud density and energy, as well as a very low carbon coverage, were not expected and they are clearly influenced by the accelerator operation. These differences in surface composition have important impact on the SEY of the respective surfaces and their conditioning behaviour.

Therefore, the presence of CuO and the low carbon coverage observed on the high heat load beam screens are currently considered as most likely responsible for the high heat load observed in some parts of the LHC ring. A cryogenic equipment is currently under commissioning to assess the conditioning behaviour of these surfaces at low temperature in the laboratory. In parallel, the mechanisms of CuO build-up and carbon depletion will be investigated. Furthermore, different paths are currently studied for an *in-situ* treatment of the affected beam screens to recover their initial performance, providing the forthcoming high intensity proton runs confirm the simulated heat load behaviour and evidence such a necessity [7].

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