# AMORPHOUS CARBON THIN FILMS FOR ELECTRON CLOUD MITIGATION IN THE LHC ARCS: DEVELOPMENTS TOWARDS IN-SITU IMPLEMENTATION*

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*Abstract*

The electron-cloud-induced heat loads on the cryogenic system of the LHC at CERN, which exhibited unexpectedly high values over LHC Run 2 and 3, are recognized as a critical limitation to the achievable High-Luminosity LHC beam intensity. Amorphous carbon thin films, sputtered on the inner surface of the beam pipe and exhibiting a low Secondary Electron Yield, have proven to efficiently limit electron cloud build-up. This contribution presents the development, prototyping and validation phases towards the in-situ deployment of amorphous carbon coatings over more than 10 kilometres of beam screen in the LHC arcs during the Long Shutdown 3 (2026-2030). The films are deposited using an assembly of 4 mobile graphite targets, displaced through 47 mm-diameter beam lines over a length of 53.5 m. The design of the coating system, the characterization of the coatings, particularly under electron irradiation at 15 K, and the validation of the process in a full-scale mock-up are presented, highlighting the constraints for upscaling the technology to kilometres of vacuum pipes within the geometrical restrictions of the LHC superconducting magnets.

## INTRODUCTION

Since 2015, abnormally high beam-induced heat loads have been observed on the beam screens of some superconducting magnets of the Large Hadron Collider (LHC) at CERN [1]. In particular, heat load degradation has consistently occurred after each of the two Long Shutdowns (LS) to date [2], where the beam lines were warmed up and vented to air for maintenance. Analysis of beam screens extracted from the LHC showed the unexpected build-up of CuO on the copper surface of some beam screens, increasing their Secondary Electron Yield (SEY), and explaining the intense electron cloud intensity observed [3]. As of 2030, following around four years of upgrades during LS3, the LHC will enter its High-Luminosity phase (HL-LHC) where the heat loads generated by higher beam intensities would overcome the capacity of the cryogenic cooling system if no mitigation strategy is deployed [2]. The Beam Screen Treatment project aims to reduce these beam-induced heat loads. For this, a thin, amorphous carbon film will be *in-situ* sputtered on the beam screen surface to ensure that low SEY can again be achieved through beam conditioning and guarantee the robustness of the surfaces against future ventings. The coatings will be performed in the LHC arcs, in a selection of 53 m-long half-cells, consisting of three dipole magnets and one quadrupole magnet. A total length of about 12 km of beam line will be coated in this way.

## COATING PROCESS

### *Coating system*

The coating system used for this project is an adaption of the one developed at CERN for the carbon coating of tubes up to 20 m long [4], [5]. It consists of a mobile coating train, shown in Figure 1, carrying the graphite targets on which a plasma discharge is ignited to sputter carbon atoms. The train will need to safely pass through the RF-shielded bellows (Plug-In Module, PIM) and Beam Position Monitors (BPM) of the half-cells and is therefore equipped with guiding and supporting wheels ensuring smooth motion even in changing cross sections.

Figure 1: Carbon coating train

The train, which is about 60 cm long, will need to be inserted in the beam line to be coated at the level of a magnet interconnection, through an opening of only 15 cm, corresponding to the space left by the extraction of the PIM connecting the beam lines of adjacent magnets together. The train is therefore designed for stepwise assembly within this restricted space while being gradually inserted into the beam screen to be treated. Figure 2 shows the assembly and insertion of a coating train within a magnet interconnection.

Figure 2: On-going assembly of the coating train (central part) in the beam screen, within a magnet interconnection.

The train is attached at its front and back to a stainless-steel mechanical cable. An Ultra-High Vacuum (UHV) coating chamber is connected at each extremity of the beam line to be coated, hosting the pumping stations, gas injection system, vacuum gauges as well as a spool system onto which the free extremity of the mechanical cables is wound. Synchronized external motors actuate the in-vacuum spools so that the cable at the front of pulls the train (spool winding), while rear cable is released (spool unwinding), allowing for the longitudinal displacement of the train along the beam screen. Due to the slight curvature of the beam line in the LHC arcs, the half-cell beam line does not offer a line of sight between its two extremities located 53 m apart. Therefore, any cable pulled between its two ends would end up touching the beam screen surface on the inside of the curvature with potential damage to the cable and the beam screen surface. However, by using an assembly of 4 trains spaced by the length of a magnet (i.e. 15.5 m for the dipoles and 6.4 m for the quadrupole – BPM assembly) instead of a single train, the cable can be periodically recentred in the beam screen by the trains themselves. In addition, multiplying the number of trains in the beam line allows for the coating of several sections simultaneously, decreasing the overall coating time required.

To provide power to the plasma, a Kapton-insulated cable is connected to each train, ensuring an independent powering of each discharge and offering a full control of the coating process. Another set of spools ensures that the electrical cables follow the motion of the trains during the coating process.

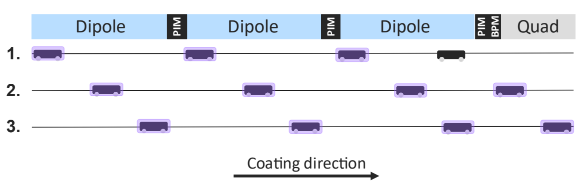

Figure 3: Coating sequence (not to scale): 1. powering of the trains in the dipoles (purple) and start of the displacement, 2. powering of the last train when entering the quadrupole, 3. completed motion, end of the coating.

The schematic of Figure 3 shows the coating sequence. While the discharges on the 3 trains in the dipoles are ignited from the beginning to the end of the motion, the last train is powered only when entering the quadrupole, to avoid coating the previous dipole twice and to prevent any possible damage to the BPM.

### *Coating parameters*

After pump-down of the beam line for 15-20 hours, a base pressure in the high $10^{-4}$ mbar range is reached. Argon is then injected dynamically up to $1.0\times10^{-1}$ mbar in the beam line (injection and pump-down at the quadrupole extremity, the other end of the beam line being closed). Each train is powered in High Power Impulse Magnetron Sputtering (HiPIMS) mode, at a frequency of 500 Hz, pulse length of 50 µs and a time-averaged power of 20 W, limited by uncooled permanent magnets inside the graphite targets. The displacement speed of the train assembly defines the coating thickness which has been set to 10 nm in this study.

## COATING CHARACTERISATION

### *As-coated characterisation*

A beam line mock-up reproducing the same geometry as the LHC arc beam line (including all elements – beam screen, PIMs and BPM, length and curvature) has been coated as described in the previous section. Witness samples, both degreased copper and copper pre-oxidized to CuO, were installed all along the beam screen and were collected after the coating run. After short air exposure, both SEY measurements and X-ray photoelectron spectroscopy (XPS) were performed on each sample.

In addition to carbon, XPS analyses revealed the presence of oxygen up to 17 at.% in the dipoles with a gradual drop to 10 at.% in the quadrupole (pumping extremity), clearly linking oxygen presence to the low conductance of the beam line. Traces of copper and nitrogen below 0.5 at.% were also detected.

The maximum SEY profile is shown in Figure 4. The SEY after coating varies from 1.6 (closed beam line extremity) to 1.2 (extremity with pumping), which is already lower than the SEY of air exposed copper (1.8-2.0 [2]). However, the SEY of the as-coated surface remains above the multipacting threshold of 1.1 [6]. The high SEY can at least partially be related to the high content of oxygen in the layer, but further analyses (e.g. thickness measurements) and tests are on-going to assess the role of other factors.

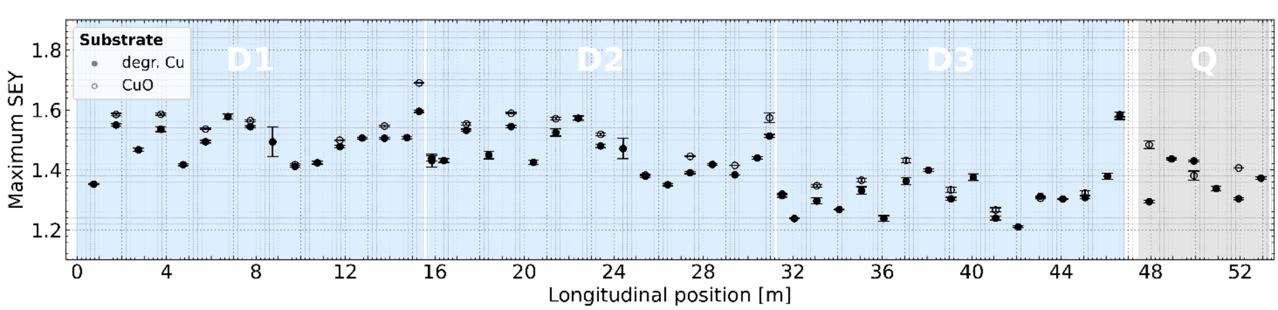

Figure 4: Maximum SEY as a function of the longitudinal position following coating of a half-cell beam line mock-up.

### *Electron irradiation at 15 K and ageing cycles*

A similar coating has been produced in a 5 m-long beam line equipped with a conductance so that its pumping speed is equivalent to the one at the closed end of a 53 m-long beam line. A witness sample, carbon-coated on a CuO substrate, was conditioned by 250 eV electron irradiation at 15 K, i.e. the average operational temperature of the beam screen in the LHC. After having reached saturation of the SEY decrease the sample was warmed up to room temperature, vented and stored in 100 % relative humidity for at least 3 months. This ageing cycle, aiming to reproduce the change between physics runs (with electron irradiation from the electron cloud) and periods of maintenance with (humid) air exposure, was performed 3 times. The change in the atomic concentration of carbon after the three conditionings of the carbon-coated sample is shown in Figure 5 (top), while the SEY evolution as a function of the electron dose is shown in Figure 5 (bottom), together with the results for a spare beam screen and a copper sample oxidized to CuO.

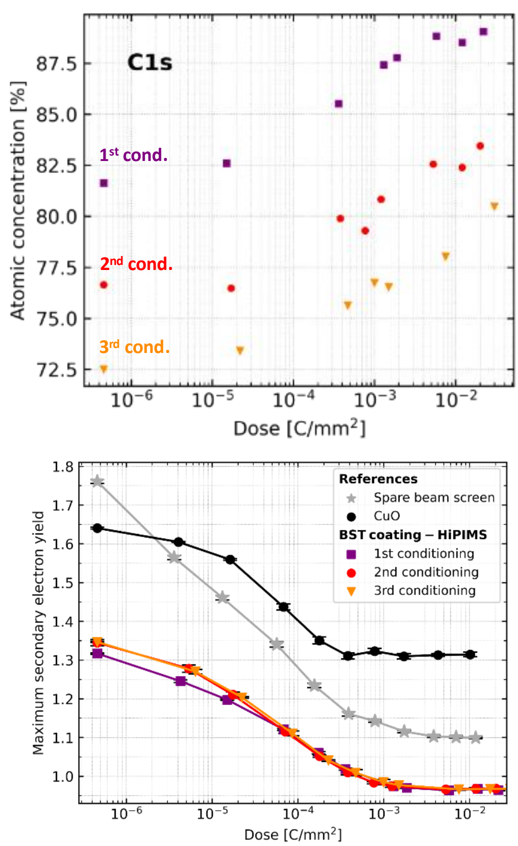


Figure 5: Top: Atomic concentration of carbon versus electron dose for the carbon coated surface; bottom: SEY versus electron dose (250 eV, 15 K).

At the beginning of each conditioning cycle, a reduction in the carbon concentration is observed, mostly due to the adsorption of oxygen-rich contaminants. Irradiation causes electron-stimulated desorption of these contaminants, and therefore the carbon concentration to increase. However, CO compounds are also typically formed during air exposure and can later be desorbed, leading to a global decrease in the carbon content cycle after cycle.

Electron irradiation of the carbon coating on CuO reduces its SEY well below the one of the CuO sample, and even below the multipacting threshold of 1.1. The SEY at the beginning of the second and third conditioning (i.e. after one or two ageing cycles) remains below the SEY of the spare beam screen, showing that there is a strong memory effect for the conditioning, which is very beneficial for the accelerator restart after venting. It has been previously shown that the presence of carbon, being graphitized during electron irradiation, is essential for SEY reduction during conditioning [7]. However, it is demonstrated here that, despite a gradual loss of carbon observed over ageing cycles, the SEY reached at the end of second and third conditioning is identical to the one reached at the end of the first conditioning, proving the robustness of the coated surface against multiple air exposures.

## CONCLUSION

High beam-induced heat loads, ascribed to a degradation of the beam screen surface state in the LHC arcs, require mitigation in view of the High-Luminosity upgrade of the LHC. A coating system has been designed to coat the beam screens of half-cells of the LHC arcs with a thin amorphous carbon layer. It consists of a modular carrier of the graphite targets (coating train), that is stepwise assembled and inserted in the beam line through a 15 cm aperture. During the coating, a system of spools and cables allows the displacement of the coating train along the beam line. An assembly of 4 coating trains powered independently is deployed to cope with the curvature of the beam line over 53 m. 10 nm coatings deployed with this system result in an SEY below the one of air exposed copper. After performing three cycles of electron irradiation at 15 K followed by humid air exposure it was still possible to reach an SEY below the multipacting threshold of 1.1. This proves the robustness of the coated surface against venting during future maintenance.

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