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AMOURPHOUS CARBON COATING IN SPS

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Abstract

Within the LHC Injectors Upgrade (LIU) project, the Super Proton Synchrotron (SPS) underwent an upgrade programme to inject higher intensity and brighter 25-ns bunch spaced beams into the LHC. To mitigate Electron Multipacting (E.M.), a well-known limiting factor for high intensity positively charged beams, CERN developed carbon coatings with a low Secondary Electron Yield (SEY). During the 2016 & 2017 year-end technical stops (EYETS 2016-2017), such coatings were deposited on the inner wall of the vacuum chambers of some SPS quadrupole and dipole magnets by a dedicated *in-situ* setup. A much larger scale deployment was implemented during the Long Shutdown (LS) 2 (2019-2020) to coat all beam pipes of focussing quadrupoles (QF) and their adjacent short straight sections (SSS QF). In this contribution, we remind the motivation of the project, and present the results and the Q.C. (Quality Control) of the carbon coating campaign during the latter phase of implementation.

INTRODUCTION

One of the main intensity limitations of positively charged beams is electron-cloud. It can lead to emittance blow-up, dynamic pressure rises and heat loads to the beam pipes [1]. Simulations have indicated that SPS beam operation may be affected by electron-cloud related instabilities when accelerating and injecting High-Luminosity LHC beams of unprecedented intensity (2.2×10^{11} protons per bunch at 25 ns inter-bunch distance). The maximum SEY, δmax, to avoid electron multipacting in the SPS depends on the chamber geometry and varies from 1.1 in drift tubes to 1.25 for focussing quadrupoles (QF). Such low SEY are ensured by coating the inner surface of the vacuum chambers with a thin film of amorphous carbon (a-C) that provides a δmax around 1 [2]. In a preliminary measurement campaign of a-C, SPS's vacuum chambers were coated in surface laboratory and tested in the accelerator by electron cloud monitors and microwave transmission measurements [3, 4]. The experimental outcomes clearly showed that a-C films supress the multipacting; no deterioration was observed over several years of machine operation, including long exposures to air [5].

FORMER WORK

During LS1 (Long Shut down 1 in 2013-2014), 120 m of vacuum chambers were coated in the coating lab and installed in the SPS. New vacuum chambers were coated by cylindrical magnetron sputtering, while vacuum chambers already embedded in magnet yokes were coated by hollow cathode sputtering. [5].

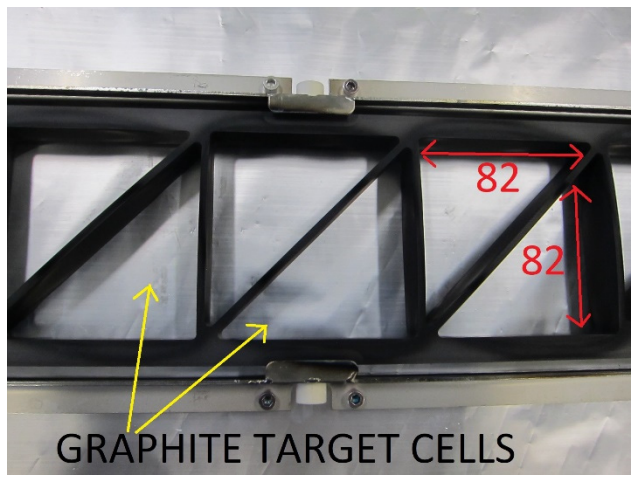

Figure 1: Hollow graphite cathode.

Figure 2: View of a SPS' arc with quadrupole (red), dipole (blue) magnets, and the interposed short straight sections. The latter must be removed to have access for the coating of the magnet's vacuum chambers.

The successful operation of SPS after LS1, with significant electron cloud reduction, validated the concept of a-C coating. To optimise the logistics for successive coating campaigns, a modular *in-situ* coating equipment was developed for the vacuum chambers of the Main Bending dipoles of type B (MBB) and the QF. To have access *in situ* for the coating of both types of chambers, it is necessary to remove the interposed SSS elements (Short Straight Section, Fig. 2). The SSS elements are transported to a dedicated coating lab, in a surface building, where they are a-C coated. In parallel, QF and MBB vacuum chambers are coated *in situ* in the SPS tunnel. After coating of all vacuum chambers, the SSS elements are re-installed in SPS, aligned, and connected to the adjacent vacuum chambers.

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This sequence was successfully tested during the extended technical top in 2016-2017 [6], with 13 coating runs performed *in situ* and 20 *ex situ*. The average maximal SEY for the whole campaign was 0.98, measured on stainless steel witness samples.

LS2 COATING ACTIVITIES

The encouraging results obtained during LHC run 2 with the SPS' a-C coated chambers favoured the decision to go for a large-scale deployment of a-C coatings. Considering the available time and manpower, a two-stage approach was implemented. The first phase took place during LS2. We coated all beam pipes of QF quadrupoles (88), adjacent SSS-QF elements and drift parts of sectors that needed to be opened for layout modification or for consolidation. A second phase is planned for the CERN Long Shutdown 3 (2025 to 2027), aiming to coat the beam pipes of the MBB magnets and respective SSS.

To cope with the large number of SSS-QF elements to be dismounted, coated, re-installed and aligned during LS2, it was decided to sequence the logistics per half-arc (8 QF per half-arc). As one half-arc had been already coated during the previous campaigns, the remaining 11 half-arcs were coated during LS2. The total time required to treat a complete half-arc is 6 weeks. In the first week, the SSS-QF elements are dismounted from the beamline and transported to the surface coating lab. The SSS-QF elements consist of drift vacuum chambers, up to 15 kg, and multipole magnets with beam pipes, weighting up to 3.5 tons. Special transport equipment, including heavy weight lifts, are used for handling and to transport these elements, from the 7 km long SPS tunnel towards the surface coating lab.

Then, four weeks are necessary to accomplish the coating. In the SPS tunnel, two mobile coating units allow to coat the chambers in the QF magnets at an average rate of two chambers / week.

Figure 3: Mobile coating unit in operation in SPS tunnel. The vacuum chambers in the QF magnets are a-C coated in situ in the tunnel.

In parallel, the radioactive SSQ-QF elements are loaded on lorries and connected to two coating units in a surface lab. Some elements are coated individually; however, in several cases, they are combined with other elements from the same half-arc. The operational rate of this surface lab is also of two coating runs / week.

In parallel with the coating planning, impedance reduction activities are deployed on SSS-QF elements and on QF magnets prior to coating [7].

One more week is then necessary to re-install the RF fingers, transport all the coated SSS-QF elements back to SPS tunnel, and for installation in their dedicated positions. Alignment of all elements is performed by the survey team, prior to vacuum connection of all vacuum chambers. Once a full sector is completely connected, the pump-down of the sector is launched. The increase of pump-down time, due to outgassing of coated vacuum chambers, was negligible.

Figure 4: Fixed coating unit in operation on SSS QF magnet in surface coating lab.

COATING PROCESS AND QUALITY CONTROL

The QF coating device consisted of mono-block graphite sputtering targets (cathode) supported on a frame (anode) equipped with wheels having UHV compatible bearings for friction free movement in vacuum chambers. The length of each target was 1.6 m, and several targets could be assembled in series to coat longer beam pipes (two targets were used to coat the 3.2 m long beam pipes in the QF magnets). The glow discharge was confined inside triangular cells (Fig. 1) by the hollow cathode principle, and the sputtered carbon atoms were deposited along a 9.5 cm wide strip on top and bottom of the chambers. The same type of targets was used to coat the QF and the SSS-QF elements. Before insertion of the coating device, all QF beam pipes were inspected by endoscopy while the shorter SSS-QF elements (up to 1.6 m) had a simple visual inspection. In some cases, dust was observed, usually near the extremities, and removed with dedicated clean-room tissues and ethanol.

Extension tubes connected to the extremities of the vacuum chambers allowed the use of sputtering targets longer than the beam pipes to avoid border effects. The witness samples, made of 100 mm x 10 mm stainless-steel strips, were inserted in these extensions and used to measure the SEY and the thickness of the coatings.

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After insertion of the sputtering device, the vacuum chambers were pumped-down for one night, without bake-out cycle, reaching a base pressure below 5 x 10^{-6} mbar. During the coating process, argon was injected at a pressure of 0.11-0.12 mbar. The sputtering targets were continuously displaced back and forth with an amplitude of at least 80 mm to improve the film's homogeneity. The sputtering power density was 120 W/m and a conditioning phase of 1 hour at the nominal power, followed by 1.5 hours of pump down at full pumping speed, allowed a significant reduction of the base pressure below 1 x 10^{-6} mbar (mainly water, one of the main species contributing to the incorporation of hydrogen in the films). Thereafter a 400 nm thick a-C film was coated in a 20-hour run. Since it was previously observed that the residual hydrogen has a large negative effect on the SEY of the a-C coatings [8], the presence of this gas was monitored in the plasma by a Residual Gas Analyser and by an Optical Emission Spectrometer. Significant reduction of hydrogen content was observed, particularly during the conditioning phase. After cooling down for one night, the system was vented to dry air and then dismounted. The coated chamber was inspected with an endoscope. The stainless-steel witness samples were extracted for SEY measurement.

The vacuum chambers of the 88 QF magnets, corresponding to a total length of 294 meter, were coated in the SPS tunnel according to the described procedure (Fig. 3), while the 110 SSS-QF elements, with a total length of 104 m, were coated in 96 runs in the surface coating lab (Fig. 4).

Finally, the drift chambers (159-mm internal diameter) were coated by DC cylindrical magnetron sputtering from 10-mm diameter graphite rods in the system described in reference [5].

Figure 5: Drift chambers (159-mm diameter) on the horizontal assembling bench, before insertion in the vertical solenoid for DC cylindrical magnetron sputtering.

To optimize the coating capacity, the drift chambers were assembled up to a total length of 6.8 meters (Fig. 5). Witness samples were placed in extension chambers. The system was then pumped down for one night and a bake-out cycle of at least 12 hours at 150 ºC was applied. The base pressure before launching the process is in the 10^{-9} mbar range. During the coating process the argon pressure is regulated at 2.5-3.5 x 10^{-2} mbar and the power density applied to the sputtering targets is 160 W/m. A 400 nm thick a-C coating was performed in a 30-hours run. After an overnight cool-down, the system was vented with dry air, dismounted, and the witness samples extracted for SEY and thickness measurements.

Fourteen coating runs were necessary to coat the 29 drift vacuum chambers with a cumulative length of 80 m.

The measurement of the SEY from the 198 coating runs was performed according to the standardized procedure described in [9] and the results are presented in the form of a histogram in Fig. 6.

For all coating runs the maximum SEY remained below the lowest threshold for electron multipacting (1.1). The average of the maximum SEY for the chambers coated by the hollow cathode sputtering technique, *in situ* (QF magnets) and *ex situ* (SSS-QF elements), was 0.99, with a standard deviation of 0.03. For the samples coated with DC cylindrical magnetron sputtering (159-mm diameter chambers) the average maximum SEY was also 0.99 (+/- 0.04).

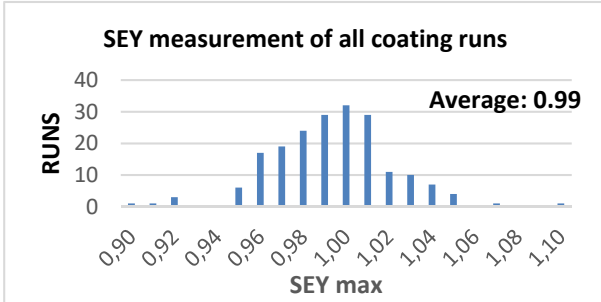

Figure 6: Histogram of maximum SEY for all coating runs.

CONCLUSIONS

After successful validation of the coating technology during the extended technical stop in 2016-2017, the first stage of the full-scale implementation of a-C films in the SPS was deployed during LS2. In total 198 coating runs were successfully performed involving 3 different facilities. For the first time a large number of thin film coatings were performed *in situ* in the CERN underground areas without technical problems during the whole coating campaign. No delamination or soot formation were observed on the coated chambers. For all coatings, the SEY measurements on the witness samples remained within the specifications to successfully suppress the electron multipacting in the SPS. The synchronization and close collaboration of the different partners involved, from transport and handling, to magnets, beam-instrumentation, radiation protection, alignment, beam vacuum operation and coatings, were key factors for the successful accomplishment of the project. The duration of the campaign was 15 months and finished under strict Covid-19 imposed regulations.

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