AMORPHOUS CARBON THIN FILM COATING OF THE SPS BEAMLINE: EVALUATION OF THE FIRST COATING IMPLEMENTATION

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Abstract

As part of the LHC Injector Upgrade (LIU) project, the Super Proton Synchrotron (SPS) must be upgraded in order to inject 25 ns bunch spaced beams of higher intensity in the LHC. At the moment, one of the limiting factors of the SPS is the Electron Cloud (EC) induced by multipacting. To mitigate the Electron Multipacting (EM) phenomenon in the SPS, CERN developed thin film carbon coatings with a low Secondary Electron Yield (SEY). The development went from coating small samples, up to coating 6 m long vacuum chambers directly installed in the magnets. To deposit the low SEY amorphous carbon (a-C) film on the vacuum chamber inner wall of SPS ring components, a modular hollow cathode train was designed. The minimization of the logistical impact requires a strategy combining in-situ and ex-situ coating, depending on the type of components. To validate the implementation strategy of the a-C thin films and the in-situ coating process along the 7 km long SPS beamline, 2 cells of B-type bending dipoles and 9 focussing quadrupoles were foreseen to be treated with the a-C coating during the Extended Year-End Technical stop (EYETS) 2016-2017. We will discuss the coating technique and evaluate both the implementation process and the resulting coating performance.

INTRODUCTION

The electron-cloud phenomenon is one of the main limitations in beam intensity that occurs when accelerating beams of protons with high intensity and short bunch spacing. It can lead to emittance blow-up, dynamic pressure rises and heat loads to the beam pipes [1]. The High Luminosity - LHC era will require the SPS to deliver beams to the LHC with intensities higher than previously achieved (2.2x10^{11} protons per bunch) and the operation may be limited by instabilities due to electron cloud. A possible solution to suppress this effect is to coat the inner surface of the vacuum chambers with a thin film of low SEY material [2]. For this purpose, CERN developed a-C (Amorphous Carbon) coatings with an SEY value around 1. After laboratory evaluation of the SEY performance, the a-C coating was tested at small scale in the SPS using electron cloud monitors and by microwave transmission measurements [3, 4]. The coating does not need any conditioning of the surface or bake-out to achieve this low SEY. Also, the a-C coating outgassing rate is compatible with the SPS vacuum system, it does not increase the amount of dust particulates in the vacuum chamber and it has proven to maintain an unchanged performance over several years of machine operation, including long periods of air exposure during major technical stops [5].

IMPLEMENTATION STRATEGY

In Fig. 1, a standard arc cell of SPS is shown. It consists of MBA and MBB type bending dipoles, defocussing and focussing quadrupoles (QDs and QFs), short straight sections (SSS) and long straight sections (LSS). Two cells (120m) of a-C coated magnets have already been installed in SPS during LS1 (Long Shutdown 1 in 2013-2014). The chambers of these magnets were coated in the lab and afterwards installed in the SPS ring. In order to optimise logistics for a full scale deployment of the a-C coating, an in-situ coating approach was preferred. In addition, a careful selection of the different elements in the SPS ring had to be made in order to maximise the impact of EC mitigation and minimise the number of elements to treat. This selection was based on PyECLOUD simulations of the multipacting threshold for the different chamber apertures [6]. Simulations benchmarked by machine development runs indicate that the MBA type dipoles do not need an a-C coating since the inner surface of the chamber can condition to a sufficiently low SEY in an acceptable operation time. For QD and LSS type vacuum chambers the EM threshold from simulation is 1.05, while for MBB and QF type chambers the SEY of the surface should not exceed 1.25 and 1.2, respectively. For both QD and LSS type chambers, the complete inner surface has to be covered with amorphous carbon. For MBB and QF magnets, a stripe of 7.5 and 9.5 cm, respectively on the top and bottom inner surface would be sufficient to mitigate the electron multipacting phenomenon.

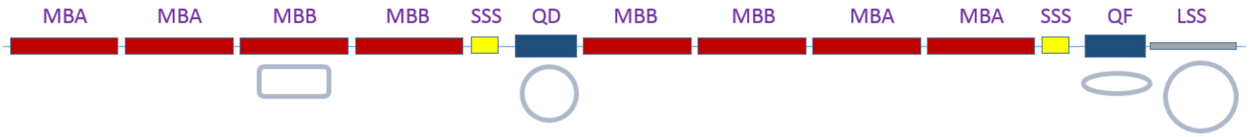

Figure 1: 64 m long SPS arc cell with drift section (LSS). The standard chamber aperture of the elements that should be treated is shown. The aperture of the SSS sections that require an a-C coating is of the QF or QD type.

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To minimise disassembly or transport of SPS elements to the surface, an in-situ coating option was developed to treat 2 MBB's (~ 13 m) in a single coating run. To access the MBB pairs it is necessary to remove the adjacent SSS and QD adjacent quadrupoles are also serving as alignment reference for other elements of the machine, the neighbouring QF could not be removed at the same time as the QD. This motivated the development of an in-situ solution for the QFs as well. To decouple the QF and MBB in-situ coating campaign, 9 QFs in arc 4+ were selected for an in-situ a-C treatment during EYETS 2016-2017, while the selected MBBs were situated in arc 5-, adjacent to the coated magnets installed during LS1. This choice also allows a synergy between the a-C coating campaign and the impedance reduction campaign of SPS. The SSSs and QDs which were removed to facilitate the access for in-situ coatings, were coated in 2 different coating labs on the surface. For the LSS in vacuum sector 440 (±27 m), 9 new vacuum chambers were manufactured and coated before installation with a DC magnetron sputtering setup described in [7].

THE COATING SETUP AND PROCESS

For the MBB in-situ coating system, the validated hollow cathode sputtering technique which was developed at CERN in 2011 [5] needed to be adapted to a modular system. A new hollow cathode geometry was developed to coat the QF quadrupoles, since during LS1 the elliptical aperture chambers of the QFs were treated by the standard DC magnetron sputtering, a method that could not be applied in-situ.

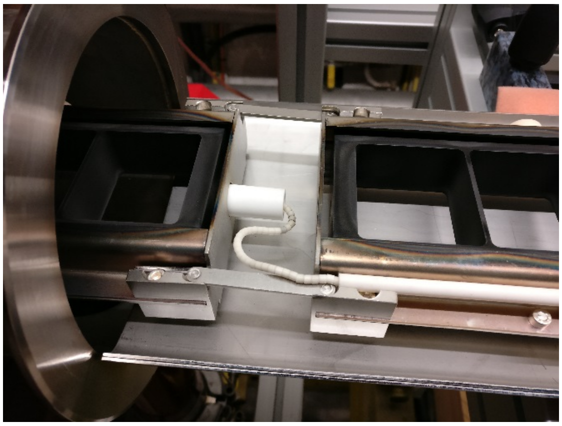

Figure 2: The electrical connection to the second part of the MBB coating train loops around the first 3 wagons. This allows to feed the 13.2 meter long cathode with two independent power supplies, facilitating operation of the plasma. The hollow cathode cells of the graphite monoblock are also visible.

To facilitate insertion of the train in the vacuum tube, each train segment has a maximum length of 2 m. In total the coating train consists of 7 wagons, each with a monoblock graphite sputtering target, an anode and wheels with vacuum compatible bearings so that the train can freely be pushed into the vacuum chamber. A looped electrical connection had to be implemented to power the last four wagons with a second power supply to cope with plasma instability problems encountered when feeding the full 13.2 m long train with a single power supply. The use of 2 independent power units allows a better control the plasma over the complete length of the vacuum chamber. Both the looped electrical connection and the graphite sputtering target are shown in Fig. 2.

The graphite sputter target for vacuum chambers with an elliptical aperture (as shown in Fig. 1 for the QF quadrupole) has a width of 102 mm compared to the 75 mm of the MBB. This dimension accommodates for the wider surface coverage necessary for the full EC suppression in QF magnets [6]. The geometry of the graphite monoblock for this particular cathode also follows the inner profile of the vacuum chamber to ensure a homogeneous a-C layer thickness. Since the cell size of such a cathode would be too large to efficiently sustain a glow discharge in hollow cathode regime, triangular cells were chosen instead of the standard square cell of the MBB cathode. A QF cathode wagon has a length of 1.6 m, one train consists of 2 wagons. Because of the shorter length of a QF magnet (~3.2 m), a single power supply is sufficient to distribute the plasma evenly along the length of the vacuum chamber. An identical cathode, shown in Fig. 3, is used to coat the SSS sextupoles and octupoles in the lab.

Figure 3: QF type cathode inserted in a SSS magnet with elliptical vacuum chamber.

A fully mounted coating station is shown in Fig. 4. Coating systems for MBB and QF are identical. During deposition, the trains are continuously moving back and forward, with an amplitude of 12 cm to improve the film coverage over the full chamber length. The base pressure before launching the process is below 5×10^{-6} mbar and the Argon pressure during the coating is regulated between 0.11-0.12 mbar. The sputtering power is kept constant at 120 W/m and the total effective coating time is 22 hours to yield a 400 nm thick a-C layer. Since it was previously established that the residual hydrogen has a large effect on the SEY of a-C coatings [8], the hydrogen present in the plasma during the deposition is monitored by a Residual Gas Analyser (RGA) and by an Optical Emission Spectrometer (OES). For the in-situ coatings, a preand post-endoscopy was carried out to evaluate the surface condition before coating and the coverage of the a-C layer.

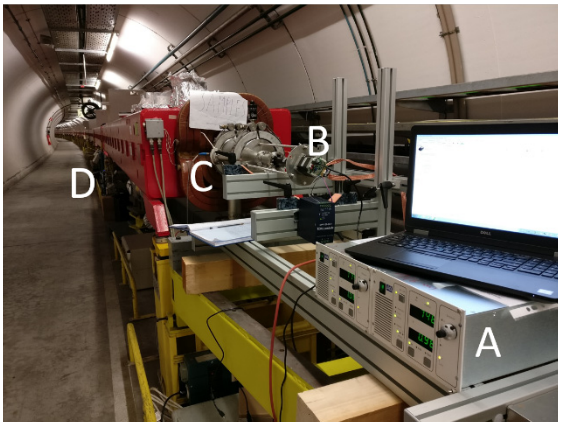

Figure 4: An assembled setup ready to start the coating for 2 MBB type magnets in the SPS tunnel. A: Power supplies; B: Stepper motor; C: Optical fibre for OES; D: Pumping station.

RESULTS

For every coating run, stainless steel witness samples were placed in an extension of the SPS vacuum chambers. These samples allowed the measurement of the SEY of the coatings (more details on the measurement setup can be found in [9]). For all the 33 coating runs performed during EYETS 2016-2017, the maximal SEY of the witness samples remained below the EM threshold.

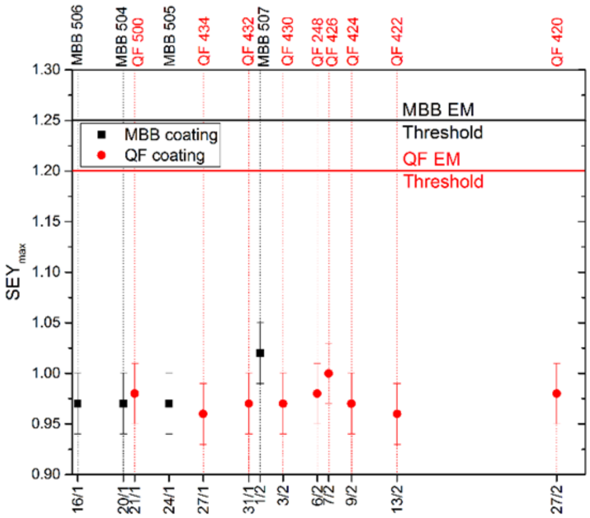

Figure 5: Position of the MBB and QF magnets together with coating start date and the maximal SEY on the witness samples.

The average of the maximal SEY of the samples coated in-situ is 0.98, with a standard deviation of 0.02. For the samples coated with DC magnetron sputtering, the average maximum SEY is 0.97, with a standard deviation of 0.03. The ex-situ hollow cathode coatings (SSS magnets and drift chambers), resulted in samples with an average maximal SEY of 0.99 and a standard deviation of 0.03. The fact that the standard deviation remains below or equal to the accuracy attributed to the SEY measurement (±0.03) [9], confirms the consistency of the in-situ coating process.

The post endoscopy inspection revealed no problems with the mechanical stability of the layer (delamination) or soot formation. For the MBB runs, the layer was evenly distributed along the chambers while for the QF type, the width of the coating stripe in the zones facing the electrical connections was ~ 5 cm instead of 9.5 cm. Nevertheless, this represents less than 1% of the total area relevant for EC, remaining within the project specifications.

CONCLUSIONS

In total, 13 in-situ and 20 ex-situ coating runs were successfully performed during EYETS 2016-2017. No cases of delamination or soot formation were observed on the 33 runs realized, representing more than 130 meters of coated beam pipes. For all coatings, the SEY measurements on witness samples were within the parameters to successfully suppress the EC build-up in SPS and demonstrates the consistency of the in-situ coating process. The communication between the different partners involved in the project, (transport & handling, the magnets and beam instrumentation groups, radiation protection, alignment, mechanical workshop, beam vacuum operation and the coating unit), played a key role on the accomplishment of the project and will be of paramount importance for larger scale execution. To conclude, the EYETS 2016-2017 a-C coating campaign proves the successful scalability of the in-situ a-C coating process to an industrial level and is now mature for a full scale implementation during the next long shutdowns.

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