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Performance of Carbon Coatings for Mitigation of Electron Cloud in the SPS

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Amorphous carbon (a-C) coatings have been tested in electron cloud monitors (ECM) in the Super Proton Synchrotron (SPS) and have shown for LHC type beams a reduction of the electron cloud current by a factor 10^4 compared to stainless steel (StSt). This performance has been maintained for more than 3 years under SPS operation conditions. Secondary electron yield (SEY) laboratory data confirm that after more than 1 year of SPS operation, the coating maintains a SEY below 1.0. The compatibility of coexisting StSt and a-C surfaces has been studied in an ECM having coated and uncoated areas. The results show no degradation of the properties of the a-C areas. The performance of diamond like carbon (DLC) coating has also been studied. DLC shows a less effective reduction of the EC current than a-C, but conditioning is faster than for StSt. Three a-C coated dipoles were inserted in the SPS. However, even with no EC detected, the dynamic pressure rise is similar to the one observed in the StSt reference dipoles. Measurement in a new ECM equipped with clearing electrodes to verify the relation between pressure signals and intensity of the EC, as well as an improvement of the diagnostics in the dipoles are in progress.

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Amorphous carbon (a-C) coatings have been tested in electron cloud monitors (ECM) in the Super Proton Synchrotron (SPS) and have shown for LHC type beams a reduction of the electron cloud current by a factor 10^4 compared to stainless steel (StSt). This performance has been maintained for more than 3 years under SPS operation conditions. Secondary electron yield (SEY) laboratory data confirm that after more than 1 year of SPS operation, the coating maintains a SEY below 1.0. The compatibility of coexisting StSt and a-C surfaces has been studied in an ECM having coated and uncoated areas. The results show no degradation of the properties of the a-C areas. The performance of diamond like carbon (DLC) coating has also been studied. DLC shows a less effective reduction of the EC current than a-C, but conditioning is faster than for StSt. Three a-C coated dipoles were inserted in the SPS. However, even with no EC detected, the dynamic pressure rise is similar to the one observed in the StSt reference dipoles. Measurement in a new ECM equipped with clearing electrodes to verify the relation between pressure signals and intensity of the EC, as well as an improvement of the diagnostics in the dipoles are in progress.

INTRODUCTION

An electron cloud build-up in high-energy particle accelerators is driven by the SEY of the beam pipe inner surface. After 3 years of successful tests with the a-C thin film coating produced by DC magnetron sputtering both in lab and in the ECM of the SPS using LHC type beams, a-C thin films are considered as one of the most promising solutions for electron cloud mitigation in the high-energy accelerators with unbaked vacuum system [1, 2, 3, 4]. A detailed summary of the production and characterization of the thin film as well as the performance during operation with beams in the SPS can also be found in [5]. In this paper, we mainly focus on the recent results obtained on a-C coatings compared to other materials in the SPS.

EXPERIMENTAL

All investigated carbon coated liners for ECMs as well as machine bending magnets were prepared by DC magnetron sputtering in different geometries, with several types of cathodes all made of graphite [5].

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To study and confirm the long-term reliability of the a-C coatings, an inspection was done in 2010 of four a-C coated liners extracted from the SPS ECM, as shown in Fig. 1. These a-C coated liners have all been tested during MD 2 - MD 12 runs in 2008 and 2009, with 3-4 batches of nominal LHC beam accelerated to 450 GeV/c. In Fig. 1, the perfectly homogeneous dark coating shows no peel-off and no damage caused by the circulating beam on all four extracted liners after more than one year of operation in the SPS. The SEY measurements of samples cut from these liners after extraction have also been performed in the lab. The increase of the SEY is negligible as shown in Fig. 2 and all the inspected coatings maintain a SEY below 1.0.

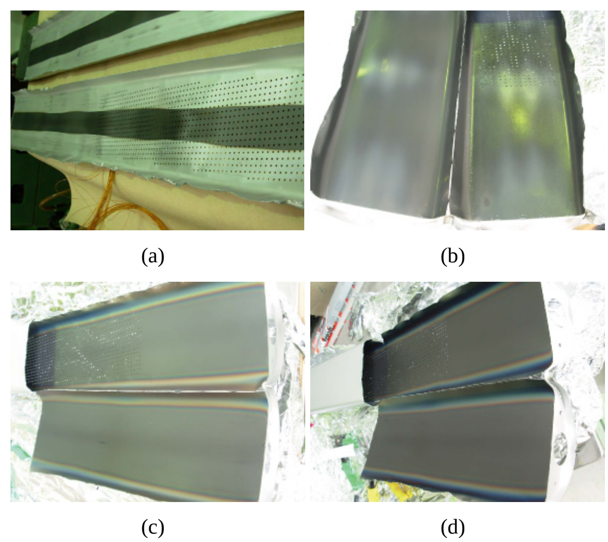

Figure 1: Inspection of four a-C liners extracted from the SPS. (a): C-stripe, a-C coating used for confirming the minimum of coating width. (b): C/Zr, a-C on rough Zr coating. (c): C-Ne3. (d): C-Ne4.

During the last few MD runs the marked reduction of e-cloud signal in an a-C coated liner, which has been kept in the SPS for 3 years in operation, compared to StSt has been confirmed (Fig. 3(a), 3(d)). In addition two other new coated liners have been tested. A liner has been coated with a-C only on the right part with respect to the beam trajectory. The left part consists of bare StSt. The goal was to exclude degradation of the properties of the a-C areas even if e-cloud can occur close to the coating. As seen in Fig. 3(b), a sharp edge separates an area with strong electron cloud signal and the other with no electron signal at all. This liner has been tested during 2 MD runs without

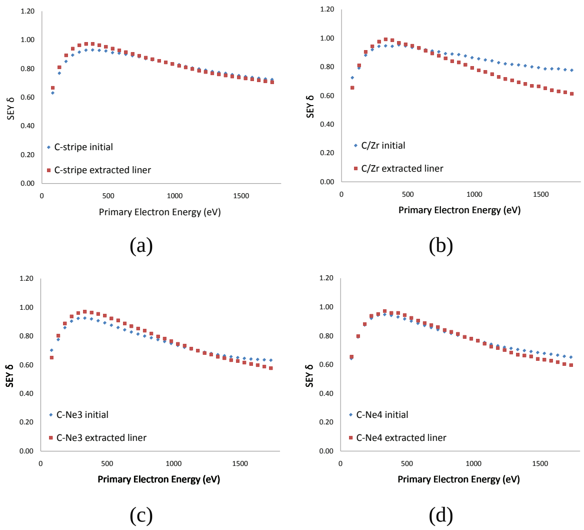

Figure 2: SEY measurements on four a-C coated liners before and after operation in the SPS. (a): C-stripe, a-C coating used for confirming the minimum of coating width. (b): C/Zr, a-C on rough Zr coating. (c): C-Ne3. (d): C-Ne4.

degradation of the SEY of the a-C area. A diamond-like carbon (DLC) coating has been produced at KEK with RF Plasma-CVD using acetylene gas that does not require any magnetic field [6]. The DLC chamber has been installed to KEKB LER straight section and arc sections for e-cloud measurements [7]. In order to test another allotropic form of carbon mainly constituted of sp^3 bond, compared to dominant sp^2 for the a-C coating, a liner with such a coating of DLC has been sent to CERN. Before the insertion in the ECM in the SPS, a SEY measurement on a witness sample simultaneously coated with the liner has been done in the lab. The maximum SEY of the witness sample was 1.85 as seen in Fig. 4. A comparison of the electron signal measured during the same MD run on ECMs with the LHC type beam of 3 batches at 25 ns bunch spacing on StSt, CNe70 half coated liner, DLC liner and a-C coated liner is shown in Fig. 3. Fig. 5 illustrates the e-cloud signal normalized to the average beam intensity versus supercycle number in two MD runs with LHC beam at 50 ns and 25 ns bunch spacing, respectively. With 50 ns LHC beam, a suppression of e-cloud by a factor 10 on the DLC liner compared to the StSt liner is observed. With 25 ns LHC beam, the suppression of e-cloud on the DLC liner reduced to a factor 2 compared to the StSt liner. After an estimated dose of about 2×10^{-3} C/mm^2 received on the DLC, the e-cloud reduction for DLC gained a further factor 2 compared to StSt at the end of the MD run. The reduction upon conditioning is much more pronounced than that for StSt, which in addition has received a larger dose due to the stronger e-cloud intensity.

After the MD runs, we extracted and cut-opened the DLC test liner for inspection. The SEY measurements of a sample from the opened liner after extraction were performed in the lab (Fig. 4). The central part of the liner along the beam axis, where the e-cloud intensity is concentrated, showed a stronger decrease of SEY compared to the more peripheral regions. The conditioned DLC showed a SEY of about 1.46, which is consistent with the low e-cloud observed in the ECM. Although a fast conditioning occurs by electron beam-induced bombardment in the SPS on the DLC coating, the final SEY is still higher than the threshold value (1.3) for the machine at 25 ns bunch spacing.

Figure 6 shows a summary of the normalized ECM signals as a function of SEY collected on all the measured liners for the beam at 25 ns and 50 ns respectively. It confirms that in the case of a 25 ns beam for a surface with a SEY at about 1.0, e.g. the case of a-C, the signal of EC is 10^3-10^4 times lower compared to a surface with a SEY at above the threshold value (1.3), e.g. conditioned/un-conditioned DLC and StSt. Whereas, in the case of beam at 50 ns bunch spacing, a surface with a SEY lower than 1.6, e.g. a-C and conditioned DLC shows a reduction of EC of a fact 10^4 compared to a surface with a SEY above 1.7, e.g. StSt and un-conditioned DLC. These results are well consistent with the threshold values shown in simulations [8].

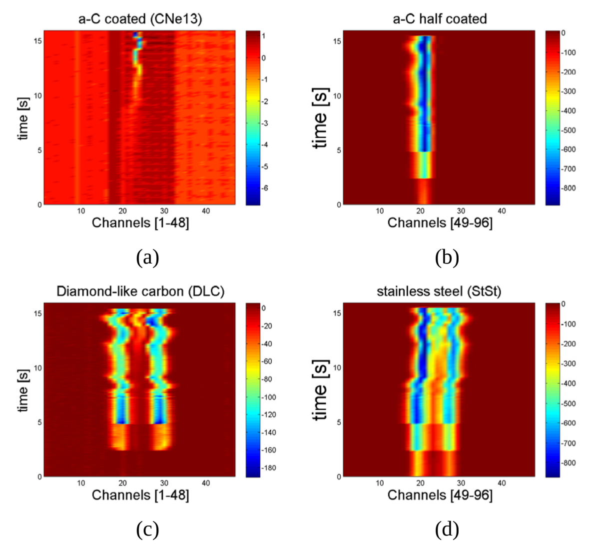

Figure 3: Comparison of the electron signal measured with ECM at a magnetic field of 0.12 T with LHC type beam of 3 batches at 25 ns bunch spacing in the SPS on (a): a-C coated liner (CNe13) kept in the SPS since August, 2008 (CNe13). (b): Half coated with a-C on bare stainless steel (CNe70 half coated). (c): Diamond-like carbon coating (DLC, KEK). (d): Stainless Steel (StSt).

Three dipole magnets of B-type (MBB) coated with the same sputtering technique as used for ECM have been installed in the SPS in March 2009. More details about the layout of the set-up for pressure measurements and earlier results can be found in [1, 3]. Pressure measurements were performed with Penning gauges installed on the pumping port between two uncoated dipoles used as reference and between a-C coated dipoles. Even when no EC was detected in the coated dipoles by using microwave measurements [4], the dynamic pressure rise was still similar to the

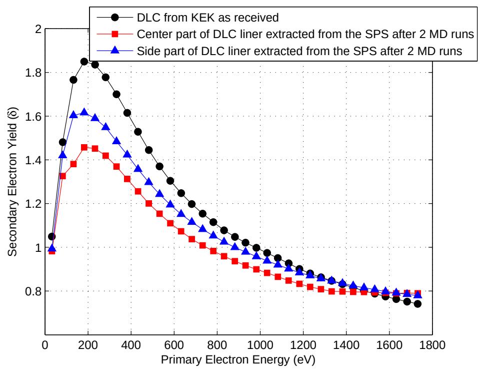

Figure 4: The SEY as a function of primary electron energy for the DLC liner produced at KEK before and after 2 MD runs in the SPS.

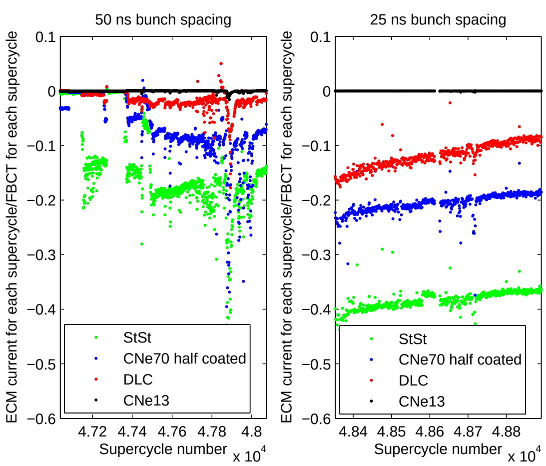

Figure 5: ECM signals from StSt, CNe70 half coated, DLC and CNe13 coated liners during the same SPS MD runs: integrated electron current signal for each supercycle divided by integrated FBCT for each supercycle as a function of supercycle number [nC/10^{10} protons per bunch]. 2 MD runs have been performed, one with 50 ns LHC beam and the other with 25 ns LHC beam. To be noticed: (1) CNe70 half coated a-C liner shows hlaf of the elctron cloud signal compared to the one from the StSt liner. (2) The difference between StSt 50 ns and StSt 25 ns is a factor 4.

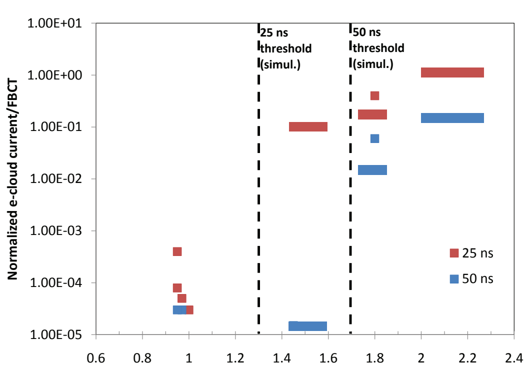

Figure 6: Normalized ECM signals as a function of SEY.

one observed in the StSt reference dipoles. Furthermore, a new ECM equipped with clearing electrodes has been installed in the SPS. The clearing electrodes in the ECM showed a complete suppression of EC, however, the effect on the pressure rise close to the ECM was almost negligible. This could be due to i) the large conductance of the beam pipe which results in the influence from the uncoated regions or ii) the cause of pressure rise is not electron stimulated desorption induced by EC.

CONCLUSION AND OUTLOOK

In conclusion, a complete suppression of e-cloud can be achieved by coating of liners with a thin layer of amorphous carbon, which has a SEY close to 1.0 as measured in the laboratory. After 3 years SPS operation, the a-C coating does not show ageing in the SPS vacuum with the machine in operation with beams. The inspection of the coated liners confirmed that the coating is significantly reliable in terms of the SEY measured in the lab.

Future activity will now be focused on adapting the coating system in order to find the best solution for coating the dipole magnets as well as the quadrupoles with the same quality of coating as in the electron cloud monitors. The decision between the potential solutions (coatings, clearing electrodes, feedback, conditioning strategies and etc.) in order to operate SPS with beams of higher intensity will be taken by the end of 2011.

At present the only direct measurement of e-cloud in the dipole has been made by microwave [4] and the possibility to directly measure the e-cloud current with an appropriate local pick-up is under study. In addition, RF induced multipacting in relation with pressure measurements as diagnostics tool to be implemented directly in a coated dipole before insertion in the accelerator is under development.

Finally a pilot sector with coated vacuum chambers will be installed in SPS in 2013, to enable more conclusive pressure measurements, which will not be affected by neighboring uncoated regions.

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