RECENT EXPERIMENTAL RESULTS ON AMORPHOUS CARBON COATINGS FOR ELECTRON CLOUD MITIGATION

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Abstract

Amorphous carbon (a-C) thin films, produced in different coating configurations by using DC magnetron sputtering, have been investigated in laboratory for low secondary electron yield (SEY) applications. After the coatings had shown a reliable low initial SEY, the a-C thin films have been applied in the CERN Super Proton Synchrotron (SPS) and tested with Large Hadron Collider (LHC) type beams. Currently, we have used a-C thin film coated in so-called liner configuration for the electron cloud monitors. In addition the vacuum chambers of three dipole magnets have been coated and inserted into the machine.

After describing the different configurations used for the coatings, results of the tests in the machine and a summary of the analyses after extraction will be presented. Based on comparison between different coating configurations, a new series of coatings has been applied on three further dipole magnet vacuum chambers. They have been installed and will be tested in coming machine development runs.

MOTIVATION

In a proton or positron particle accelerator, an electron cloud can be generated by residual gas ionization, by photoemission when synchrotron-radiation photons hit the surface of the vacuum chamber and by subsequent secondary emission via a beam induced multipactoring process [1]. This process reduces the machine luminosity and beam quality. It leads to dynamic pressure rise, transverse emittance blow up, thermal load and beam losses. The goal of this work is to find a method to eliminate the e-cloud in the CERN Super Proton Synchrotron (SPS) in order to make the SPS able to deliver the ultimate beam to Large Hadron Collider (LHC) and reach maximum luminosity for the machine. Four important requirements are: the solution must be implementable in the existing SPS dipoles, does not require any bake out since the SPS has heating limitation, is robust against venting and also has a long life time. Simulations [2], [3] show that the threshold value for the SEY in order to avoid e-cloud in the SPS with nominal LHC beam is = 1.3.

In this work, carbon is chosen as coating material due to its few valence electrons and its non-reactivity. Carbon thin film coatings produced by DC magnetron sputtering in different coating set-ups have been tested for different applications.

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THIN FILM COATINGS

Four different coating configurations have so far been used due to the different geometries of the chambers to be coated, as listed in Table 1. Different discharge gases (Ne, Kr, Ar) and different coating parameters, such as temperature of substrate, discharge gas pressure, power applied during coatings have been tested. To maximize sputtering efficiency and reduce the risk of implantation of heavy discharge gas ions, such as Argon and Krypton, on the coating surfaces, we chose to use Neon as discharge gas after many tests.

In a perfectly cylindrical vacuum chamber, one graphite rod is used as cathode for the DC magnetron sputtering and this method was used for making most of the lab samples for SEY investigation as well as vacuum characterizations in the lab. In Fig. 1(a), the 7 meters long solenoid used to provide magnetic field parallel to the cathode in the cylindrical tube configuration is shown.

Since the shape of the vacuum chambers in the SPS is not perfectly round, we need to find other solutions to make a homogeneous coating. A configuration of a liner with rectangular cross section in a round tube with 4 graphite rods has been tested, as shown in Fig. 1(b). This configuration has been applied for both lab samples and liners for electron cloud monitors (ECM) used for electron cloud measurements in-situ the SPS, as shown in Fig. 1(c). The surface temperature can go up to 250 C during the coating.

To detect electron cloud we used the same type of monitors as in previous tests [1], [4], [5]. The schematic drawing of the device is shown in Fig. 1(c). The Electron Cloud Monitor (ECM) equipped with stainless steel (SS) liners with or without coating is then installed in a special dipole C magnet which provides a magnetic field perpendicular to the beam direction. Unless otherwise specified, during all the experiments the field was kept at 1.2 kG (the SPS injection value). On one side of the liner, small holes with a transparency of 7% are drilled to pass the electrons generated by e-cloud through the liner. Under those holes there is a multi strip detector to collect the escaped electrons, if any.

After the lab results showed a SEY lower than 1.3, the threshold value calculated by simulations [2] [3], three of the SPS dipole magnets were coated and tested with the LHC type of beams. In Fig. 1(d), an SPS MBB dipole and the vacuum equipment used for coating can be seen. Inside the dipole, the magnetic field during coating was provided by the dipole itself and was perpendicular to the cathodes. The power used during coating was also kept limited not to damage the coil. Three MBB dipoles have been coated in this way and tested in the machine with beam. A visible disadvantage, as shown in Fig. 1(e), with this type of coating is the non-uniformity. To improve the homogeneity of the coating in the SPS dipole magnet, another three dipole magnet vacuum chambers coated in the same way as ECM have been tested. Indeed this configuration results in more uniform coating, but requires to coat the chamber separated from the dipole coil. For the coating the chamber must be extracted from the dipole and inserted in the coil (Fig. 1(a)) so that the magnetic field this time is parallel to the cathode. With the present SPS magnets such a process is very time and resource consuming.

EXPERIMENTS

The measurements of SEY in the lab are carried out with an electron gun, which sends primary electrons (PE) of 50-2000 eV to the surface of the sample, and a collector for the emitted electrons. The collector is biased to +45 V in order to capture all secondary electrons, whereas the sample is biased to -18 V. All reported SEY measurements were carried out at normal PE angle of incidence. The electron dose was calculated to be below 1 10 C/mm over irradiated areas of about 2 mm for a full SEY measurement. Each sample was measured as received after extraction from the deposition chamber and transfer to the SEY measurement apparatus through air. The time in air during the transfer is approximately 2 hours. The precision of the measured SEY values is estimated to 0.03. After the SEY measurement, an X-ray Photoemission Spectroscopy (XPS) spectrum to determine coating compositions is usually taken after a transfer under UHV from the SEY system to the XPS system. More details about the SEY measurements are given in [6].

Four ECMs can be used at the same time to measure the electron cloud current during one SPS machine development (MD) run. During each MD run, an ECM with an SS liner has been used as reference. The SS liner has been exchanged before certain MD runs in order to have a non-conditioned surface as reference. Various amorphous carbon (a-C) coatings have been tested in several MD runs, as well as a NEG (TiZrV) to compare the various effect on electron cloud elimination.

After successful tests with a-C coated liners in 2008 (see [4]), three dipole magnets of B-type (MBB) have been coated with a thin film of the same material and installed in the SPS in March 2009. Positions of the MBB dipoles installed in the SPS are shown in Fig. 1(f). The total air exposure time of the coating before installation (on the ground and in the tunnel) was around one week. Pressure measurements (1 Hz sampling rate) were performed with Penning gauges installed on the pumping port between two uncoated dipoles used as reference and between a-C coated dipoles. In addition a gauge was placed between a coated and an uncoated dipole. The inter-magnet pumping ports with RF shields are made of bare SS. In some MD runs, the RF shield between the two carbon coated magnets was also coated to maximize the elimination effect on e-cloud.

RESULTS AND DISCUSSIONS

The SEY of a witness sample coated simultaneously with each liner was measured in the laboratory.

For a clear view of how the a-C coating works for e-cloud suppression compared to SS, the SEY curves measured in the lab for the SS and two typical a-C coated liners is shown in Fig. 2(a) and the ECM signals measured in the SPS on SS and on two typical a-C coated liners is shown in Fig. 2(b) on logarithmic scale. The SEY of both a-C liners is well below the SEY of SS, as well as the threshold value (= 1.3) of the SPS with nominal LHC beam [2] [3], e-cloud signal presented on SS liner was clearly shown about 10 times higher compared to that on the a-C coated liners.

Figure 2(c) shows the normalized e-cloud signal on linear scale versus time measured in three different MD runs for one a-C coated liner. This liner was inserted in the SPS with an initial SEY of 1.14 and a visible decrease of measured electron current occurred after 5 hours of operation during MD 1 (3-4 batches of nominal LHC beam accelerated to 450 GeV/c). The measured dose of the electron bombardment on the liner after 5 hours of MD was about 1.2 10 C/mm . After two months in the SPS vacuum (10 mbar, unbaked) and with normal SPS operation (without LHC type beams but with the usual beam delivery to CNGS and other fixed target experiments) a new run with LHC type beam did not reveal any ageing from the e-cloud signal. In addition, this liner was kept in the SPS during the 2008/2009 winter shutdown and was vented to air during two months. After re-pumping and operating the machine during 6 months, the test with the LHC type beam exhibited an even stronger reduction of the electron current signal on the liner. The visible improvement of electron current on the liner cannot be explained by scrubbing effect, since the e-cloud was too low. The pressure from MD1, 2, 3 has been compared and the result confirms a significant improvement in pressure, by a factor of 10. The possible reason of the improvement of electron signal is the improvement of pressure in the SPS which decreased the current measured due to ionization of the residual gas by the beam. In conclusion this liner remained more than one year in the machine, sustained a prolonged venting during shutdown and did not show any sign of deterioration. Testing for longer term is still in progress.

After the successful tests with the liners in 2008, a-C coatings were applied to the three SPS magnet vacuum chambers in March 2009. Microwave transmission measurements detected e-cloud related signals in one of the uncoated magnets and no signal was measurable in one of the coated magnets [7].

The dynamic pressure rise is shown in Fig. 3(a) for an LHC type beam. The resolution of the measurement is only 1 s, but the cycle time (21.6 s) and the effect of the acceleration ramp is well visible. The scattering in the pressure

Table 1: Four different coating configurations were used with DC magnetron sputtering. Different discharge gases (Ne, Kr, Ar) and different coating parameters (temperature of substrate, discharge gas pressure, power) can be used.

Coating configuration	**Magnetic field**	**Samples**
Cylindrical tube with one graphite rod cathode	Parallel to the cathodes	Lab samples for SEY investigations and vacuum characterizations
Liner in tube with 4 graphite rods	Parallel to the cathodes	Lab samples for SEY investigations and liner for e-cloud monitors
MBB magnet chamber in-situ chamber in the dipole with Multi-electrode	Perpendicular to the cathodes and chamber axis	Version I: MBB coating in-situ in SPS dipoles
MBB magnet chamber stand-alone with liner configuration	Parallel to the cathodes	Version II: MBB coating outside SPS dipoles

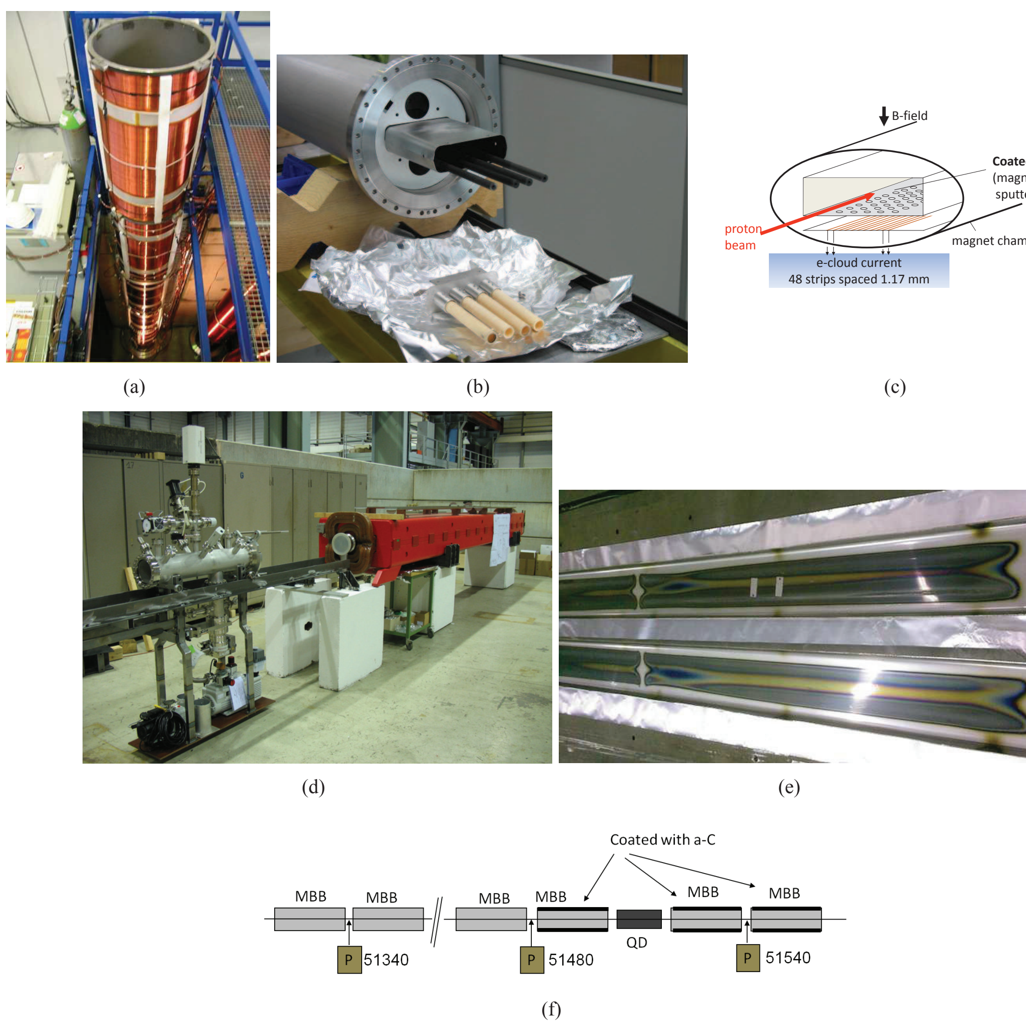


Figure 1: (a): 7 m long solenoid used to provide a magnetic field parallel to the cathodes used during the coatings. (b): Liner configuration with four carbon cathodes to provide a homogeneous coating. (c): Electron Cloud Monitor used to observe electron cloud activity in-situ the SPS. (d): MBB dipole magnet equipped with vacuum system. Inside the dipole, three graphite cathodes and the same magnetic field provided by the dipole self was used, which was perpendicular to the cathodes. The power used during coating was kept limited not to damage the coil. (e): Inspection of the extracted a-C coated MBB after operation in the SPS. (f): The design of the coated and the uncoated magnets in the SPS. MBB: Magnetic Bender B-type. QD: defocussing quadrupole. P: penning gauge.

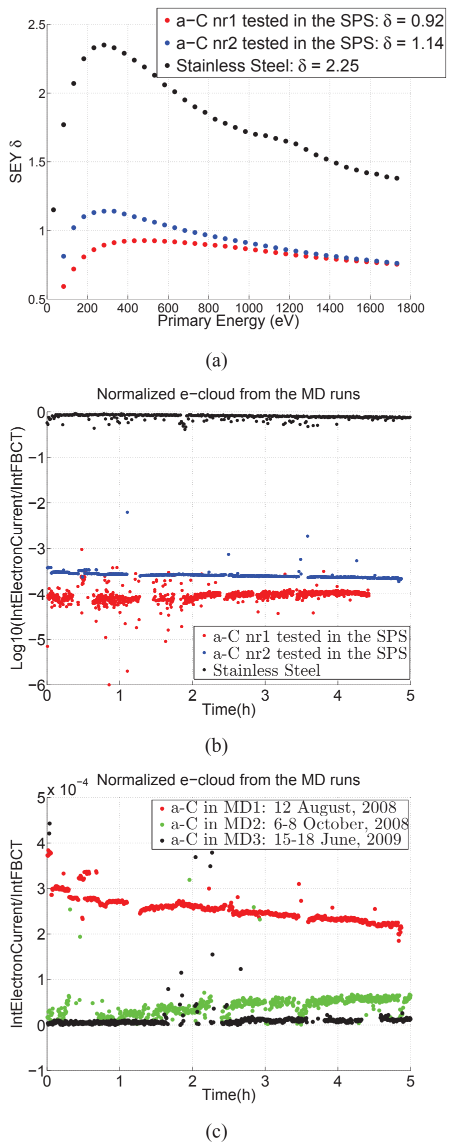


Figure 2: (a): Comparison of the SEY of SS and a-C coatings measured in the lab. (b): ECM signals from SS and a-C coatings in the base-10 logarithm of integrated electron current signal for each supercycle divided by integrated intensity (FBCT) for each supercycle as a function of supercycle number [nC/10 protons per bunch]. (c): ECM signals from different a-C coatings. EC has a magnitude of 10 . Integrated electron current signal for each supercycle divided by integrated intensity (FBCT) for each supercycle as a function of supercycle number [nC/10 protons per bunch].

rise is large and the pressure also changes with the various parameters (e.g. RF voltage). However it is obvious that the decrease in pressure rise due to the coating, if any, is not as marked as for the e-cloud signal in the ECM.

The result of a recent inspection of one of a-C coated MBB chambers is shown in Fig. 1(e). The coating of the extracted MBB dipole does not look as uniform as expected, and some part of the chamber is even without coating. In the middle part of the chamber, the coating layer is thin and appears very transparent. This laterally non-uniform coating color indicates differences in thickness and possibly composition. The SEY measurement of this magnet has also been performed in the lab, see Fig. 3(b). The highest SEY occurred in the middle part of the shorter side of the chamber with a value of 1.33 as shown in Fig. 3(b).

The same inspection has been done on four a-C coated liners extracted from the SPS. These a-C coated liners have all been tested during MD 2 - MD 9 runs in 2009, with 3-4 batches of nominal LHC beam accelerated to 450 GeV/c. The longest has been inserted in the SPS for more than 1.5 years. In Fig. 4, a perfectly homogeneous, dark coating shows no peeling off and no damage of the beam on all four extracted liners after more than one year operation in the SPS. The SEY measurements of these liners after extraction have also been performed in the lab. The increase of the SEY is negligible as shown in Fig. 5.

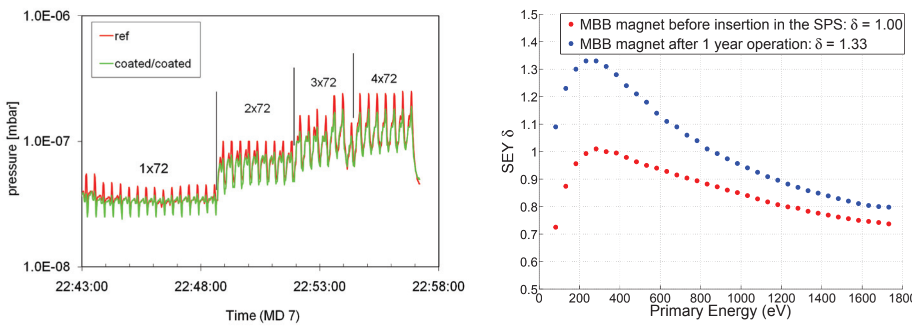
These inspections of the coated liners and dipoles confirmed that the coating in the magnets was significantly inferior to the coatings in the liner, which gave a complete suppression of e-cloud. Therefore, to improve the homogeneity and the quality of the coating in the SPS dipole magnet, another three dipole magnet vacuum chambers coated in the same way as ECM have been tested. They have been installed in the SPS and will be tested with beam in coming MD runs.

CONCLUSION AND OUTLOOK

In conclusion the experiments have shown that a complete suppression of e-cloud can be achieved by coating of liners with a thin layer of amorphous carbon, which has an SEY close to 1.0 as measured in the laboratory. The coating does not show ageing after more than one year of exposure in the SPS vacuum with the machine in operation with beams. The inspection of the coated magnet from the first series, which was coated by using the magnetic field of the dipole itself confirmed that the coating was significantly inferior to the coatings in the liner, which gave a complete suppression of e-cloud.

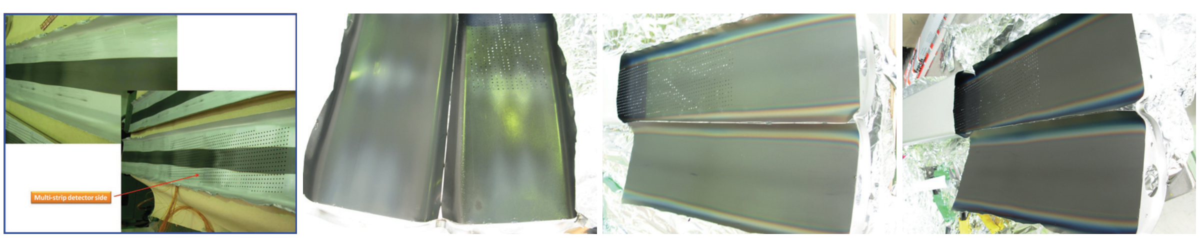
Future activity will now be focused on the development of a configuration to coat beam pipes without dismounting the chamber from the dipole on a large scale with the same quality of coating as in the ECMs. We will also follow the ageing development of the new version of MBB coating and try to understand the relationship between dynamic pressure rise and e-cloud effect.

The first implementation on a large scale with this type



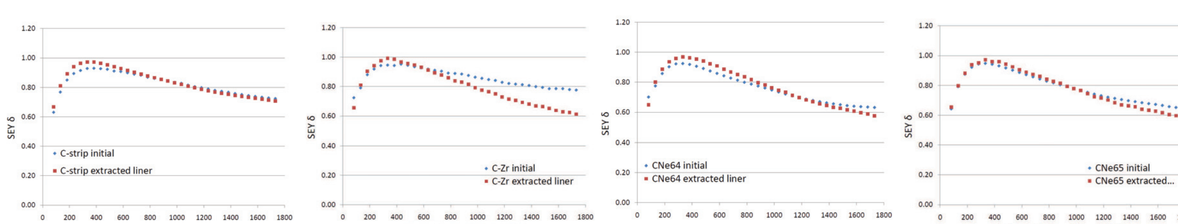
(a) (b)

Figure 3: (a): The comparison of the pressure measurements of the uncoated and coated dipoles. The nominal LHC beam which consisted of 1, 2, 3 and 4 batches with 72 bunches at 25 ns spacing and intensity of 10 protons/bunch. (b): SEY measurement on the coated MBB magnet before and after operation in the SPS.



(a) (b) (c) (d)

Figure 4: Inspection of four a-C liners extracted from the SPS. (a): a-C Strip, a-C coating used for confirming necessity of coating width. (b): C-Zr, a-C on rough Zr coating (c): CNe64, a-C number 64. (d): CNe65, a-C number 65.



(a) (b) (c) (d)

Figure 5: SEY measurements on four a-C coated liners before and after operation in the SPS. (a): a-C Strip, a-C coating used for confirming necessity of coating width. (b): C-Zr, a-C on rough Zr coating (c): CNe64, a-C number 64. (d): CNe65, a-C number 65.

of a-C coating is now planned to be performed in the SPS magnets of total 200 meters during the shutdown 2012/2013.

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