

AMORPHOUS-CARBON THIN FILMS FOR THE MITIGATION OF ELECTRON CLOUDS IN PARTICLE ACCELERATORS

S. Calatroni, P. Chiggiato[#], P. Costa Pinto, D. Hynds, M. Taborelli, C. Yin Vallgren

CERN, Geneva, Switzerland.

Abstract

To mitigate e-cloud effects in accelerator vacuum chambers which cannot be heated, sputtered amorphous-carbon coatings have been proposed. The encouraging results obtained in the laboratory and in the SPS have revealed the potential of these films, mainly through their low maximum secondary electron yield (δ_{\max}). As for other materials, the δ_{\max} of amorphous carbon films increases when their surface is exposed to air, but to a much lesser extent.

As the spreading of the eventual values of δ_{\max} is not fully understood, the increase of the secondary electron emission for long lasting exposure to air has been investigated by optimizing the sputtering parameters.

For the specific case of the SPS, the study of a coating facility for the treatment of about 700 vacuum chambers is ongoing. Should the a-C coating solution be retained, 90 beam pipes per month should be coated during 3 winter shut-downs.

INTRODUCTION

Electron cloud (e-cloud) effects are a severe limitation to the performance of modern high-energy high-intensity particle accelerators [1]. The electron multipacting phenomenon, which is the breeding mechanism for e-cloud build-up, can be erased if the maximum secondary electron yield (δ_{\max}) of the beam pipe surfaces is reduced below a threshold that depends on beam parameters and vacuum chamber geometry. For the nominal LHC beam, the threshold is about 1.3 [2].

After cleaning, traditional materials for the construction of beam pipes have δ_{\max} higher than 2. The reduction of the secondary electron yield below 1.3 can be obtained both by high temperature in-situ bakeout and by accumulating a dose of impinged electrons higher than about 10^{-3} C mm⁻² [3].

In general, a radical change in the surface properties can be achieved by thin film coating. For the specific case of secondary electron emission, many thin films have been studied in the past; for example Cr₂O₃ [4] and TiN [5]. However, their reported δ_{\max} have a wide spread after exposure to air. TiZrV coatings obtained by magnetron sputtering [6, 7] attain a δ_{\max} of about 1.1 as soon as their native oxide layer is dissolved into the bulk [8]. This process is called activation; it is carried out by heating in-situ at a temperature higher than 180°C for at least 24 h.

This ternary alloy was developed at CERN for the long straight sections of the LHC, where about 1200 TiZrV coated vacuum chambers are now installed. In addition to the low δ_{\max} , they provide high distributed pumping speed [9] and low photon and electron stimulated desorption yields [10]. Measurements carried out in the SPS [11] have shown that TiZrV films are an effective means to eradicate e-cloud provoked by an LHC beam.

The heating of the beam pipe is a mandatory step for the activation of TiZrV. As a consequence, the application of this material cannot be extended to some future accelerators where e-cloud phenomena are expected. In the present view of the SPS upgrade, the vacuum chambers cannot be heated because they are embedded in magnets. For the CLIC positron damping rings, the heating temperature may perhaps be limited to 150°C because of the presence of superconducting wigglers. In the PS2, though the maximum bakeout temperature is not yet defined, it would be convenient to maintain it as low as possible, particularly in the magnets.

This heating temperature limitation has driven to new developments in the field of thin films at CERN. They aim at finding materials with low secondary electron yield, attainable without any heating, even after exposure to air for a long time. Carbon has kept our attention.

SPUTTERED AMORPHOUS CARBON FILMS

A material with very low δ_{\max} , even after months of exposure to air, is a wish for anyone concerned about electron multipacting. For the specific application in particle accelerators, this material would have to fulfil other important requirements. It should be easily deposited onto vacuum pipes; not inclined to produce dust; UHV compatible; and not have an important impact on the global electrical impedance of the machine.

Should it not be dusty, graphitic carbon would be a good candidate. It has a δ_{\max} of about 1 [12]; it is a good electrical conductor and not prone to adsorb atmospheric gases; its vacuum behaviour is acceptable, though not comparable to that of metals. On the other hand, diamond, the other allotropic form of carbon, is not suitable for such an application in the slightest, as it is an insulator and a strong secondary electron emitter.

[#] paolo.chiggiato@cern.ch

When graphite is sputtered onto a substrate, the carbon atoms lose their original hexagonal structure. In general, the resulting carbon film is neither pure graphite nor pure diamond. The film grows with lack of long-range order, namely in an amorphous state (a-C films). Locally, the hybridization of the s and p orbitals of the carbon atoms can be either sp^3 (leading to tetrahedral bonding, as in diamond) or sp^2 (threefold coordinated planar bonding, as in graphite) [13].

Carbon films, mostly in the diamond-like structure, are produced on a regular basis by Industry in the manufacture of consumer goods [14].

From the comparison of the yields of graphite and diamond, it seems reasonable to think that amorphous carbon films with the lowest δ_{max} should have the highest possible sp^2 character [15]; however a clear experimental verification is not yet available. What is well known in the literature is that C films produced by DC magnetron sputtering have dominant sp^2 hybridization [16], i.e. they are graphite-like.

By means of the set-ups already used for the TiZrV coatings, we have been producing a-C films since November 2007. With respect to δ_{max} , the obtained results are encouraging. As-received samples, measured a few hours after exposure to air, without any heating show δ_{max} of about 1 ± 0.1 . This value does not depend on coating thickness in the range between 50 and 1300 nm. Scanning electron microscopy reveals that the a-C films are compact and, in general, smooth. Measurements performed by an optical particle counter do not indicate an increased number of loose particles in pipes coated with a-C, as compared with bare stainless steel. The adherence of the a-C film is remarkable; film stripping is possible only by strong acid attack.

The outgassing rate of water vapour is of paramount importance for any material installed in an unbaked vacuum system, like that of the SPS. For the specific case of the a-C thin films, it has been shown that this characteristic depends on the sputtering parameters, in particular the process gas pressure and geometry of the vacuum chamber. Outgassing rates of the same order as that of stainless steel have been obtained by reducing the process gas pressure. This phenomenon is attributed to the resulting reduced nanoporosity [17]. At low pressure, sputtered atoms are less likely to lose energy by collisions with gas process atoms. The higher energy deposition onto the growing film results in a more compact film.

Measurements of electron- and photon-induced desorption for a-C films are in progress. Although preliminary, the results are of the same order as for stainless steel.

DETERIORATION OF AMORPHOUS CARBON FILMS

As for any other material, a-C films are expected to adsorb atmospheric gas when exposed to air. The resulting change in the surface nature is known to increase the δ_{max} . Fully conditioned traditional materials, like copper and stainless steel, suffer a steep increase of δ_{max} up to about 1.5 following a few hours of exposure. An additional and progressive rise is recorded during the following months of exposure, eventually leading to a δ_{max} higher than 2. This drift of the secondary emission has been attributed to the adsorption of airborne hydrocarbons [18].

The δ_{max} rise has been also recorded for the a-C films, but to a lower extent. Most of the increase is observed in the first 10 days, while a stable value seems to be obtained after about 20 days. The latter depends on the sample tested and varies between 1.05 and 1.4. The reason for this long-term divergence is not yet fully understood; because of its relevance, most of the present effort is addressed to its explanation. First insights indicate that the distance between substrate and cathodes, and the temperature attained by the substrate during the coating are key-parameters. The roughness of the substrate, and of the film itself, seems also to be important. At present, we are investigating the film structure, hydrogen and process gas content, together with the role of the sputtering parameters (deposition rate, pressure, power, substrate temperature, etc).

If all changes of the sputtering parameters proved ineffective in attenuating the δ_{max} rise, another solution would exist. It consists of roughening the inner wall of the vacuum chamber prior to the a-C coating. This additional roughness can be produced by mechanical and chemical techniques, or also by coating. The latter method is the easiest to implement in vacuum chambers that are already assembled and inserted in magnets, as is the case for the SPS. For this purpose, rough Zr films (about 1 μm) have been produced and coated by a thin layer of a-C (about 100 nm, see fig. 1). The measurement of the secondary electron yield has shown a remarkable decrease in δ_{max} and a less pronounced deterioration over a period of at least 4 months (see fig. 2).

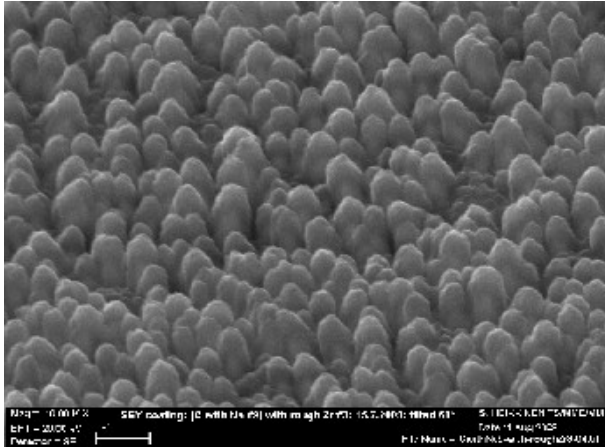


Fig 1: Electron microscopy view of a rough Zr thin film produced by magnetron sputtering. The height of the tips is about 1 μm . Courtesy of S. T. Heikkinen and S. Sgobba, CERN EN-MME.

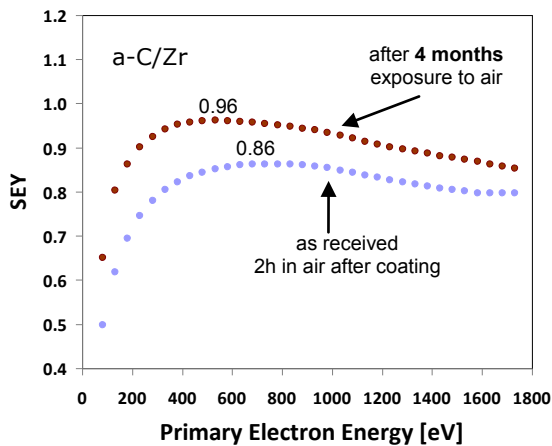


Fig. 2: Secondary electron yields as a function of the primary electron energy for rough Zr thin film coated with a-C, 1 μm and 100 nm thick respectively. The SEY values are measured after 2 h and 4 months in air following the coating process.

Although it is beyond argument that the rough underlayer brings benefits, two important drawbacks have to be tackled. First of all, the resulting rougher surface would increase the outgassing rate of the coated beam pipe. The second issue concerns the lengthier coating procedure, which has a direct impact on the production pace and costs. An optimization of the sputtering set-up could quicken the coating production; for example by depositing the rough layer and the a-C film during the same coating run.

STUDY OF E-CLOUD MITIGATION BY AMORPHOUS CARBON FILMS

The e-cloud mitigation efficiency of the a-C coatings has been tested by an experimental bench installed in the SPS (LSS5) [19]. Slotted stainless steel liners have been

coated and then inserted into a dedicated vacuum chamber, which is set into a dipole magnet (1.2 kG intensity). The electron activity has been measured through the slots by strip detectors [20]. The SPS beam structure produced on purpose for this test is similar to that for the LHC: 72 proton bunches in 2 or 3 batches, 25 ns bunch spacing, at the typical SPS energy of 450 GeV. The results were obtained during the SPS MD run in week 28 [21]. The electron current is normalized to the integral over one cycle of the fast beam current transformers (FBCT) reading. The data is compared to that recorded for bare ($\delta_{\text{max}} \approx 2.5$) and TiZrV coated (activated, $\delta_{\text{max}} \approx 1.1$) stainless steel liners. The normalized electron current for the a-C thin film is 10^4 times lower than that for the bare stainless steel and of the same order of that obtained for the activated TiZrV coating. Similar results for the a-C film have been obtained after 15-day exposure in air (MD run week 33), and two months in the SPS vacuum system without LHC beam (MD run week 41). These results are in agreement with beam dynamics simulation.

PRELIMINARY STUDY OF AMORPHOUS-CARBON COATING FOR THE SPS UPGRADE

If a-C thin films are retained for the improvement of the SPS, the coating of 700 magnet vacuum chambers will mean the use of infrastructures and manpower resources equivalent to those employed for the LHC LSS [22], with some additional complications. In fact, because the vacuum chambers are embedded in the magnets (about 16 tons each), their handling is riskier. Moreover, most of the magnets are lightly radioactive. A reasonable scenario would be the installation of the coating facility in the ECX5 underground cavern of the SPS. This choice would shorten the magnets movement.

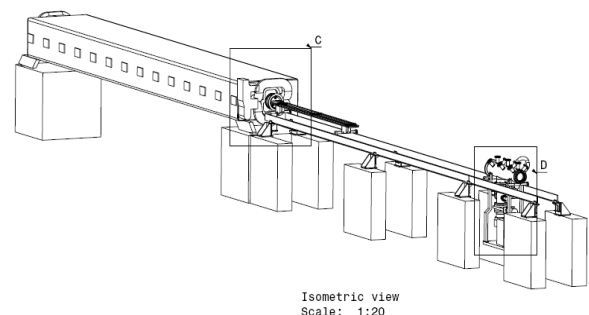


Fig. 3-a

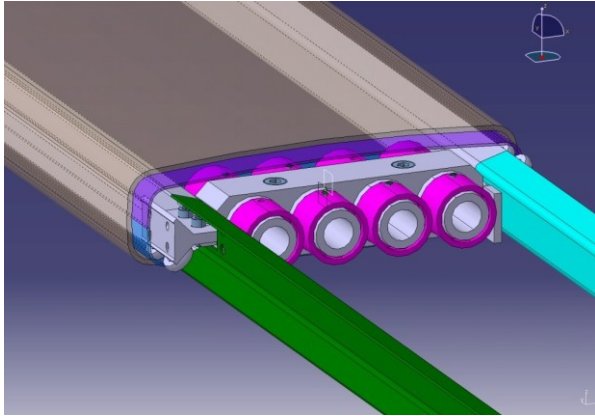


Fig. 3-b

Fig.3: Schematic view of the facility proposed for the coating of the SPS dipole magnet vacuum chambers (a); technical drawing of the graphite cathode holding and insertion system (the vacuum chamber is depicted in gray) (b). Courtesy of G. Foffano, CERN EN-MME.

The length and weight of the magnets impose another constraint. Because the magnets are not easily placed in the vertical position, the graphite cathodes should be installed horizontally. This configuration defines the coating system lay-out, namely geometry of the cathode, holding system and insertion bench (see fig. 3 a and 3 b for a preliminary version of the coating set-up). The expected coating pace is about 90 vacuum chambers per month during 3 consecutive winter shut-downs of the SPS.

As soon as possible, 3 MBB dipole chambers will be coated and installed in the SPS to ascertain the feasibility of the coating facility and quality of the films produced therein.

CONCLUSIONS

E-cloud effects can be moderated by TiZrV thin film coatings if the beam pipes are bakeable at temperatures higher than 180°C. In the case of heating temperature limitations, as for the SPS, magnetron sputtered amorphous-carbon films are a potential solution. At present, the optimization of a-C films is in progress to reduce their δ_{\max} , outgassing rate and deterioration provoked by long lasting exposure to air. E-cloud tests of a-C coatings have been carried out in the SPS with LHC beam. The results are encouraging since they show similar behaviour as for activated TiZrV.

The design and manufacture of a prototype facility for the coating of the about 700 beam pipes of the SPS arcs is ongoing. Three vacuum chambers are to be coated and installed as soon as possible.

This study has been pursued for the upgrade of the SPS. Nevertheless, it could also be useful for other accelerators, for example PS2 and CLIC damping rings.

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