



# Nine years of carbon coating development for the SPS upgrade: achievements and heritage.

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## Abstract

CERN has succeeded in producing carbon coatings that eradicate electron cloud in accelerators without any beam conditioning or *in situ* heating. Investing about 1 MCHF and dedicating 31 FTE (28 man-years, staff and associate members) in 9 years in the framework of LIU-SPS, CERN has increased: technological competences in thin-film coatings, worldwide visibility in surface characterisation, and capability in electron cloud measurement. Future projects are still benefiting from such an investment.

## Summary

This document describes the development performed at CERN in the period 2007-2015 aiming at producing carbon coatings with low Secondary Electron Yield (SEY) in the framework of the LIU-SPS project. Initiated by a request of the *Proton Accelerators for the Future* committee in autumn 2007, the development was started as a future mean to mitigate electron cloud in the SPS.

Very low SEY, close to 1, were achieved within few months on laboratory samples. Particle generation and outgassing rate were found compatible with the SPS vacuum system. Performance deterioration was deeply studied for several years. Several measurements indicated that the coatings was robust against air exposure, so that storage of one year in aluminium foil showed only a negligible increase of SEY. The influence of the coating parameters on the SEY performance was one of the main points of interest all along the study. The most important outcome is a clear correlation between the amount of hydrogen in the process gas and the resulting SEY value. A dedicated multipacting test-bench showed that the available power could not induce multipacting in the carbon coated chambers, in contrast to the case of uncoated stainless steel chambers.

The main innovation in coating technology, i.e. the application of hollow cathode technique for the first time at CERN and to our best knowledge also for the first time worldwide with carbon, allowed reproducible production of real SPS dipole beam pipes. Two cells (120 m) of the SPS - including MBA, MBB, quadrupole, and pumping-port shields were coated during the first long shutdown (LS1) in 2013-14.

To reduce time and costs, the *in situ* coating was studied together with *in situ* cleaning and stripping based on oxygen plasma. Suitable anodes for the cleaning were developed and successfully used to remove the carbon coating from a single MBB vacuum chamber.





The performance of carbon coatings in the accelerator environment was tested in the SPS and PS on electron cloud monitors (ECM), microwave transmission experiments and carbon coated machine cells. All results were extremely positive. No signal was detected with the ECM even after years in the accelerators enduring years of beam and months in air. Microwave transmission did not show any trace of electron cloud above the noise level. Pressure rise with LHC type beams of 25 ns bunch spacing never revealed differences of more than a factor of 2 between the coated and uncoated regions. Two experiments showed that the reason of the rises was not due a failure of the carbon coated regions, but to the electron cloud in the short parts which remained uncoated. Total suppression of pressure rise was obtained by solenoids installed on the uncoated beampipes. Doublet beams, which are unable to generate electron cloud in the drift space (uncoated), confirmed without any doubt the absence of pressure rise in the coated beampipe section.

This development has allowed CERN to master thin film coatings with low SEY in high aspect ratio beampipes embedded in magnets. The coating team has deepened its knowledge in coating processes and has become skilled at implementing hollow cathode techniques. Plasma cleaning of long chambers was developed; applications in other accelerators, including the LHC, are now possible. The development has needed a constant support of surface and material analysis, which in turn reinforced our measurement ability and updated our available set-ups. Presently, measurement of SEY at any temperature is a standard activity at CERN.

### 1. The need for low SEY without *in situ* heating:

In 2006, the PAF (Proton Accelerators for the Future) committee asked for a cost estimate for the coating of the SPS beampipes in view of suppressing electron cloud for beams beyond the nominal intensity (see Appendix 1). The suppression is possible only if the secondary electron yield (SEY) of the deposited material is below 1.3 (calculated for the MBB dipoles). Such performance had been already achieved for bakeable systems using NEG coating, as already applied in the long straight sections of LHC. However, the SPS is not bakeable and, at that time, no coating with such a low SEY was available without *in situ* bakeout.

In autumn 2007, a development to produce low SEY thin film was started (see Appendix 2). Carbon appeared as the most promising material because high-purity graphite has a low SEY (1.25) and graphitic carbon thin layers had been observed on beam scrubbed surfaces. The timeline of the project is summarized in figure 1. The SPS-U project, then LIU-SPS, and TS-MME/TE-VSC groups have provided the required budget.

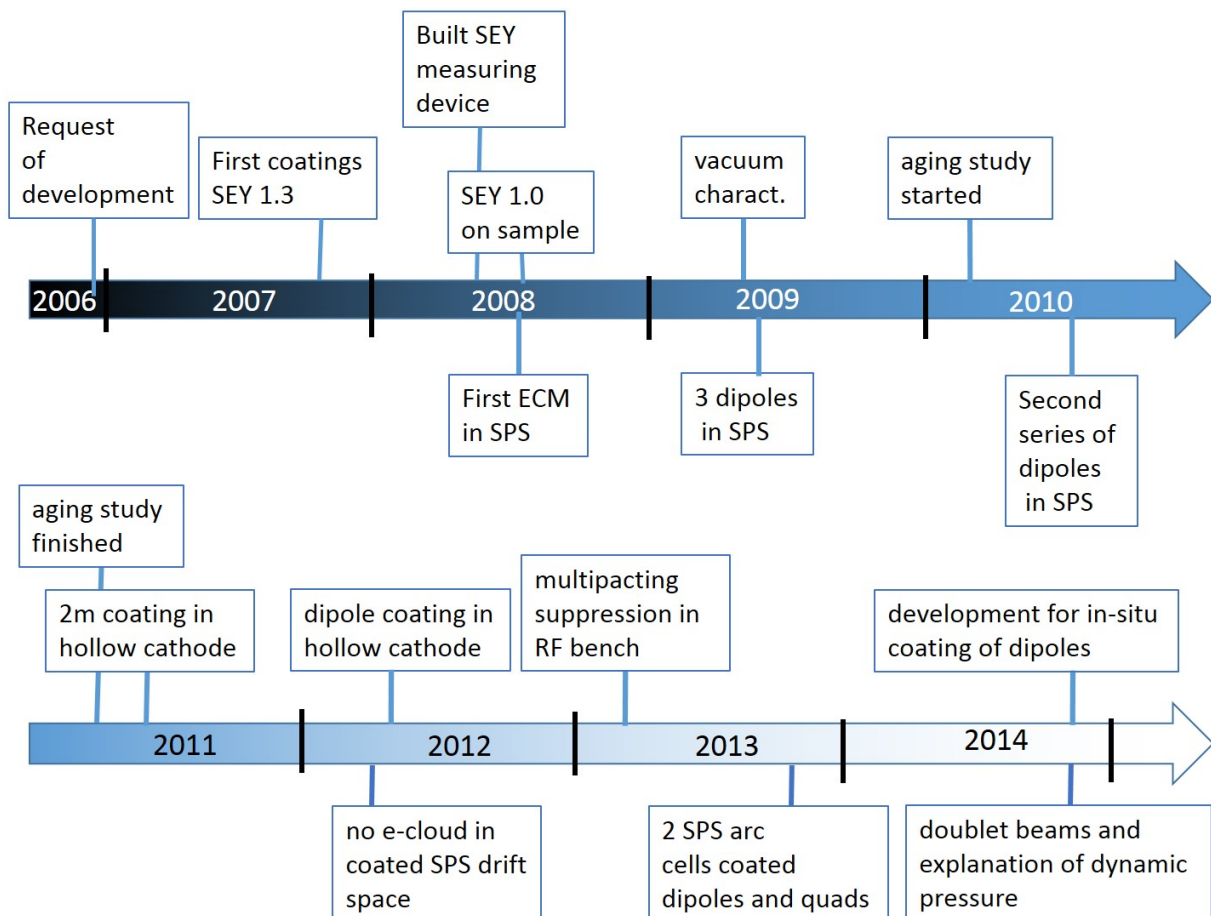


Figure 1: Summary of the timeline of the project (ECM: Electron Cloud Monitor)



The first dedicated coatings were produced before end 2007 on cm-size flat samples by DC cylindrical magnetron sputtering using a graphite rod as target and Kr as process gas. In parallel, coatings in DC planar magnetron configuration were also produced, using a graphite disc as target and Kr, Ne and Ar as process gas.

Encouraged by promising measurements done in an external lab (CSIC Madrid), a new device for the measurement of SEY, coupled to the existing X-ray photoemission spectrometer (XPS), was designed and built at CERN in spring 2008. The design was based on in-house experience, and it enabled the measurement of the sample and collector current as a function of primary energy of the electrons.

Run by run, the maximum SEY of the coatings quickly improved from 1.5 to values close to 1 [1], well below the maximum SEY of Highly Oriented Pyrolytic Graphite (HOPG). The above mentioned SEY values refer to samples previously exposed to air, hence representative of technical surfaces applied in large accelerator facilities. It was not immediately understood that the key ingredient of the improvement was the decrease of outgassing from the vacuum system and the cathode (see below) during film growth. The XPS analysis showed that the coatings contained a dominant  $sp^2$  fraction of C orbital hybridisation [2]. Early 2009, thanks to a collaboration with the University of Cambridge, Raman spectroscopy showed that the fraction of nanocrystalline  $sp^2$  domains varied from one coating to the other without a clear trend in the explored range of process parameters, except for the substrate temperature: a higher substrate temperature, tested up to 350°C, increases the nanocrystalline graphitic character. In general, the coatings can be classified as amorphous carbon a-C [3] with some of them extending to the region of a-C:H (more than 3% at of H according to [3]).

Several issues with the coatings were still open at that point:

- production of dust;
- compatibility of outgassing rate with the SPS vacuum system;
- evolution of the maximum SEY for prolonged air exposure;
- behaviour in an accelerator (deterioration, peel off....);
- performance reproducibility.

The production of dust was quickly discarded by comparing the result of a particle counter (size 3-5  $\mu\text{m}$  and above 20  $\mu\text{m}$ ) on a coated (DC cylindrical magnetron sputtering) and uncoated stainless steel tube; no difference could be detected between the samples even after gently hammering on the coated chamber [4]. The outgassing rates after 10 h of pumping was found to be about 4 times higher than for stainless steel and dominated by water vapour [5]. Electron stimulated desorption (ESD) measurements were performed [6]. The desorption yields without bake-out are comparable to those measured for stainless steel: for CO it is about twice and for  $\text{H}_2$  about half of the respective value for stainless steel. It should be remarked that, where e-cloud occurs, the electron induced desorption is several orders of magnitude larger than the thermal outgassing rate; therefore, suppressing the e-cloud with the coating will largely improve vacuum.



During 2008 and 2009, comparison with different materials (BN, TiN, MgB<sub>2</sub>, BC<sub>x</sub>) and with carbon-metal coatings (a-C:Me, Me= Ti, Cu) showed that none of them could attain as low SEY after short (minutes) air exposure as the carbon coatings. Rough thin films were also tested but discarded: Cu black due its high SEY of 1.4; despite its SEY below 1, Au black due to its mechanical fragility and dust production.

The effect of long storage in different atmospheres was explored along 2010-2011 [2, 7] and showed that the coating is robust against one-year air exposure: storage in air in aluminium foil preserved the SEY value below 1.04 (0.96 initial) and storage in a desiccator gave no measurable increase of SEY. The worst case was found for storage in a polymer box (1.3), but this is anyway known to be the worst condition also for preserving UHV parts. The behaviour in accelerator environment is treated in section 3.

The SEY of the samples produced by different methods and set-ups (see the coating technology in section 2) exhibited some scatter, but in XPS the only quantity which is correlated with the SEY is the intensity on the high binding energy side of the carbon line [2]. However, there is no explanation for the origin of this correlation, yet.

Along 2011-2012 a clear correlation between the amount of hydrogen in the process gas and the resulting SEY value was confirmed: thin films produced in presence of hydrogen have systematically high SEY values, compared to the coatings produced with the purest environment [2, 8, 9]. The correlation between the hydrogen partial pressure in the processing gas and the relative amount of hydrogen in the film was demonstrated by glow discharge mass spectroscopy in a dedicated system at CERN: more hydrogen in the plasma leads to more hydrogen in the coating and to higher SEY. Monitoring the purity of the discharge gas during the coating process through residual gas analysis is of paramount importance to ensure a low SEY.

Therefore, the scattering in the quality of the coatings produced from the beginning of the study was ascribed to the hydrogen outgassing rate from the walls and from the cathode. Since then, all measures to reduce the outgassing of the setup have been considered. In the DC planar magnetron system, where the cathode is cooled, we could further demonstrate the importance of outgassing and pre-sputtering the cathode; the latter reducing also other detrimental impurities measurable by XPS [10]. A direct measurement of the hydrogen concentration in the coating was attempted by thermal desorption spectroscopy at CERN, but the results were partly contradictory. No sign of CH<sub>x</sub> bonds could be revealed by FT-IR in Attenuated Total Reflection mode or in transmission on silicon substrates. The precise amount of hydrogen in the thin films is still not known precisely: Elastic Recoil Detection Analysis (ERDA) on few samples revealed concentrations up to 20 at% [2].

In addition to the characterization mentioned above and to the tests in the accelerators described below, a multipacting test-bench was set-up with the help of the BE-RF group and operated between 2010 and 2015 [11]. The device enables to test the performance of the coatings in a situation very close to the real accelerator with an RF powered wire mimicking the electric field of the proton beam. It consist of a thin tungsten wire powered by RF and stretched along the main axis of the vacuum chamber to be characterized. The SEY of the inner wall of the chamber defines the power threshold at which electron multiplication occurs and the phenomenon induces RF power reflection, pressure rise and multipacting current.

The measurements were performed on MBB and MBA dipoles and on MBB type liners equipped with SPS-like e-cloud monitors (ECM). The results always showed that the available power could not induce multipacting in the carbon coated chambers [12]. In contrast, the multipacting was clearly observed for the uncoated stainless steel chambers, including the evolution through beam conditioning.

## 2. Coating technology for the SPS-dipole vacuum chambers

The development of the coating technology has been driven by the geometry and boundary conditions of the objects to be coated (the beampipes are embedded in the magnet coils) and by the possible implementation strategies in the machine. The first samples in 2007 and beginning 2008 were produced by DC magnetron sputtering in planar geometry (disc cathode) and in cylindrical geometry (rod cathode) over lengths below 1 m. The need to insert a liner in an ECM of the SPS in spring 2008 imposed the first modification to a cathode constituted of several rods (figure 2), in order to match the hippodrome cross section.

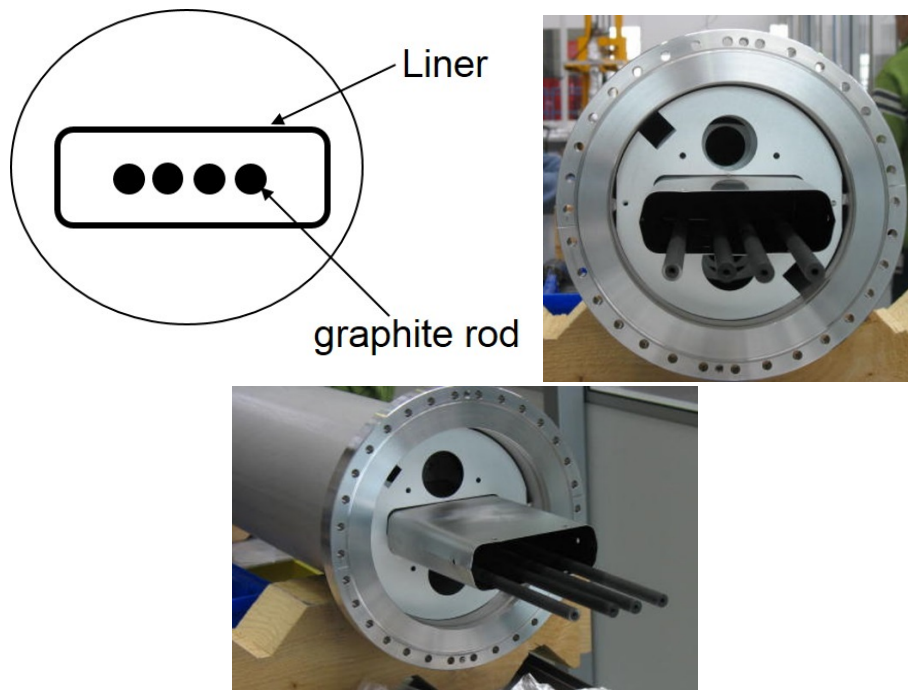


Figure 2: Geometry of the cathodes applied to coat the ECM liners

In parallel, the development of a coating technology which could be applied to the 6.5 m long SPS dipole chambers took into account several constraints:

- a) the weight of the object strongly limits the possible manipulations;
- b) the temperature of the beampipe should not exceed  $150^{\circ}\text{C}$  to preserve the integrity of the electromagnet coil;
- c) the vacuum chamber of the magnet is trapped and cannot be extracted from the dipole without cutting and re-welding the heavy iron yoke;
- d) the need to only coat a 60 mm wide band on the upper and lower surfaces of the quasi-rectangular vacuum chamber (picture) .

The SPS dipole could not be inserted in the existing 8 m long vertical solenoids at building 181, used for the DC magnetron NEG coating of the LHC-LSS chambers. Apart from the space hindrance and weight of the vacuum chamber/dipole magnet assembly, it would have been difficult to obtain an axial magnetic field with an external coil in a chamber trapped in a huge iron yoke, designed to make a transversal field. The method of opening the yoke and inserting a chamber coated by DC magnetron sputtering in the vertical solenoids of building 181 (called hereafter method I, figure 3a) could be applied for few preliminary trials, but was not adapted to a large series. For the coating of the chamber inside the dipole, three additional options were investigated along 2009 and 2011 [8]:

- II. DC magnetron sputtering using the dipole's magnetic field using additional anodes in the centre (Fig. 3b);
- III. DC magnetron sputtering by inserting a permanent magnet assembly fully integrated in the cathode (Fig. 3c);
- IV. DC hollow cathode sputtering (Fig. 3d).

The option II enabled the installation of three coated MBB dipoles in the SPS already in March 2009 [11]. The cathodes were graphite rectangular bars separated by two anodes in the middle. Dissection of the chamber after one year, in 2010, revealed that the profile of the coating was not uniform [13]. The "open path" electron trapping, resulting from the applied electric and magnetic field configuration, lead to a non-uniform plasma along the axis of the beampipe that is at the origin of the uneven thickness distribution [9].

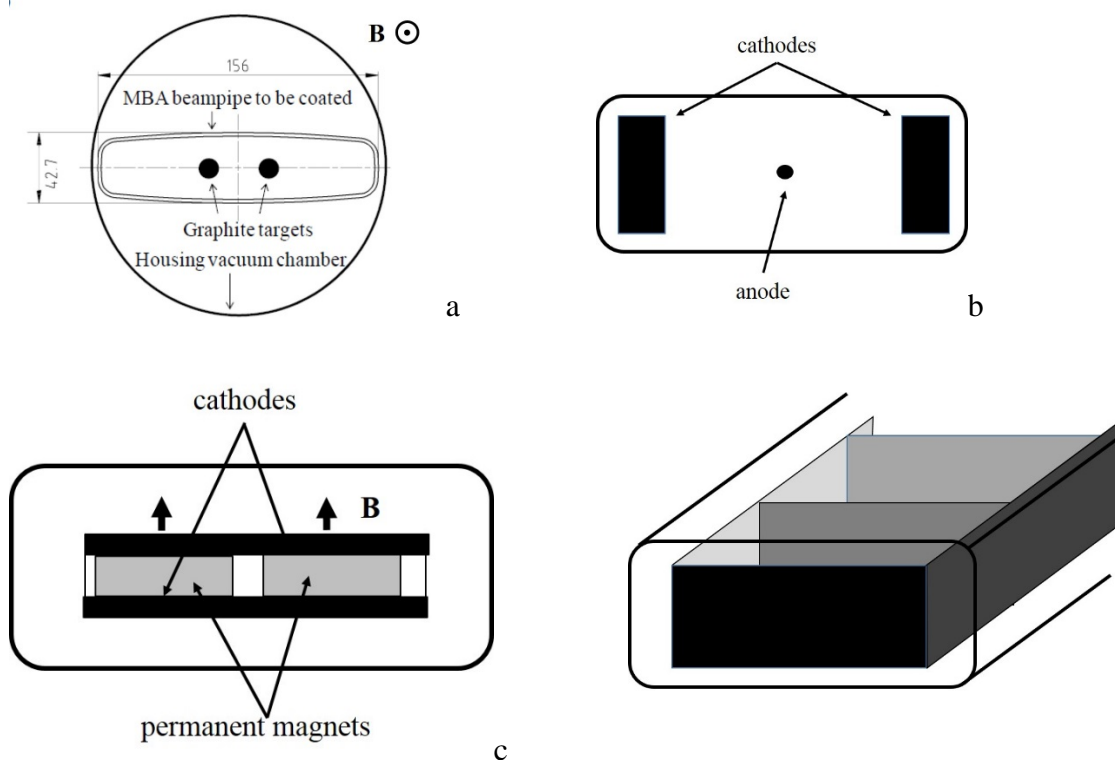


Figure 3: a) Cathode configuration for method I; b) method II; c) method III; d) method IV



In parallel to the developments on the coating process and in order to insert a homogeneously coated dipole chamber, the most primitive method I was adopted for 4 dipoles. Vacuum chambers coated in a separate system could be inserted in the dipole by cutting the yoke in two parts, an operation that is generally done for heavy maintenance of the magnets in case of leaking vacuum chambers or coil repair, and welding the end-flanges with some precautions to avoid contamination. These dipoles were installed in the SPS in 2010.

The option with the permanent magnets (III) was promising, but was discarded because of the high sensitivity of the sputtering process to dimensional changes, which were induced by thermal gradients on the cathode. This type of approach could not be successfully scaled to a 7 m long cathode [9].

In 2011, the study of the coating of the MBA dipole chamber in DC magnetron with the method I revealed the influence of hydrogen outgassing, which is strongly enhanced by the narrow cross section and low gas conductance of this type of chamber. The hydrogen problem was solved by adding lateral NEG cathodes which were powered at the same time as the graphite cathode during the coating and provided additional pumping speed [9]. This was the first demonstration that the hydrogen concentration during coating could be reduced by simultaneous NEG deposition.

Plasma Enhanced Chemical vapour deposition (PECVD) was also explored [2, 9], since it is based on the formation of a plasma without the need of an external magnetic field and cathode. All the tests, using acetylene as working gas, produced thin films, probably containing high amounts of hydrogen, some of them being insulating, transparent and displaying an XPS spectrum similar to the hydrogen rich samples. In any case the PECVD coatings had SEY above 1.4, a fact which is fully consistent with the influence of hydrogen observed for the carbon coatings.

After some trials in magnetron configuration using the magnetic field of the dipole, it was realized that it was not possible to cope with the orientation of the field with respect to the cathode and that the only solution was a process without applied magnetic field. In 2011, the development of the DC hollow cathode system started (method IV) and proved to be successful first on 50 cm prototypes and finally on 7 m length chambers with films of SEY equal or close to 1 [9]. It was the first coating by DC hollow cathode technique at CERN and to our best knowledge also the first with carbon worldwide. The first dipoles coated by hollow cathode without dismounting the vacuum chamber and respecting all the given boundary conditions were produced successfully in 2012. This technology was considered ready for the baseline strategy in order to coat the MBB and MBA dipoles of the machine by removing all of them from the SPS and perform the coating in a surface workshop or in the SPS cavern at point 5. The DC hollow cathode process was used in order to produce two coated cells (120 m) of the SPS during the first long shutdown (LS1).

After a break for production during LS1 a further improvement was investigated starting from middle 2014 with the aim of coating strings of components *in situ*, without removing them from their position in the tunnel. The basic concept is a cathode train constituted of short modules which are assembled on site during insertion in two adjacent dipoles of the same type (MBB or MBA) and built as a 13 m long cathode unit. Each run of coating would include two adjacent dipoles. Since the dipoles



would not be removed a cleaning *in situ* based on oxygen plasma has been developed [5]. The oxygen plasma, operating with an anode providing distributed gas injection, was also successfully applied to remove the carbon coating from a single MBB vacuum chamber.

### 3. Tests in the SPS in electron cloud monitors (ECM) and magnets

The performance of carbon coatings in the accelerator environment was tested in the SPS and PS on electron cloud monitors, microwave transmission experiments and carbon coated machine cells. We summarize here only the SPS experiments, the experiments on PS being fully consistent.

The first coated liner with MBB cross section was installed in the ECM of SPS in spring 2008 [13, 14]; this first sample was replaced soon after with two other liners having a uniform coating. The ECM work in a magnetic field, which is equivalent to the injection field of the dipoles. These two liners, as well as all the further carbon coated liners installed in the ECM (6 in total) never exhibited e-cloud signal even for the highest beam intensity injected in the machine ( $2.0 \text{ e}^{11} \text{ p/b}$ ). The only current detected so far was a faint stripe in the central axis of the detector, which is compatible with beam ionization of the residual gas. In comparison, the stainless steel liners, installed for comparison, never showed complete suppression of the e-cloud for 25 ns bunch spacing even after prolonged conditioning during scrubbing runs. One of the coated liners installed in 2008 is still in place (2015) and survived without loss of performance after several cycle of venting to air including a prolonged venting (several months) during LS1. A liner with the coating on a central stripe of 40 mm width only [13] was inserted in 2010 to define the upper and lower area on the dipole vacuum chamber to be covered with carbon, and design the cathode setup accordingly. In another ECM in 2010 the coating was only applied to half of the liner on one side of the beam axis (Fig. 4) so that the effect of the beam at the same place and time could be compared on both surfaces. A sharp separation was observed between the left part, where no e-cloud occurred and the right part, where the current had the value expected for stainless steel [15].

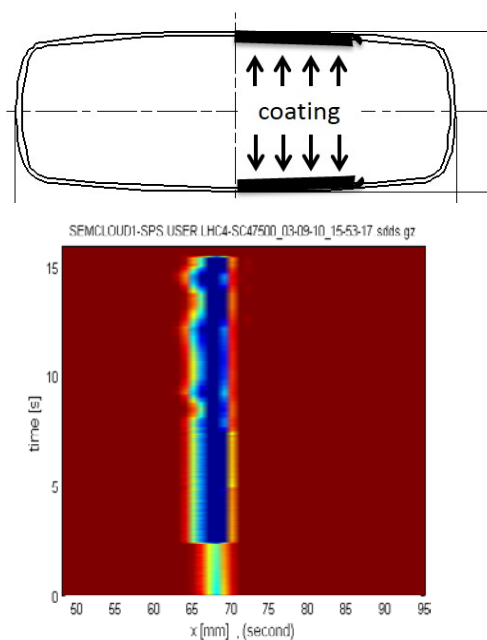


Figure 4: Half coated liner and the resulting ECM signal.



Microwave transmission experiments were performed by the BE-RF team on the first series of coated MBB magnets in 2010 and on the second series in 2011 [16, 17]. In all cases the transmission of RF did not show any traces of electron cloud above the noise level; the electron cloud signature in the non-coated dipoles, used as reference, was ten times larger than the noise level.

The influence of the coating on the ultimate pressure of the SPS was verified first on the short sections (up to 3 dipoles) installed in 2010 and finally on the section of two arc cells, which were installed during LS1. The coating was applied on the dipoles, quadrupoles and pumping port shields, but not on the short straight sections. After two months of pumping (without beam), the pressure in the coated cells was only 30% higher than the average reading of the Penning gauges in the rest of the ring ( $1.1 \times 10^{-8}$  mbar instead of  $8 \times 10^{-9}$  mbar).

For the dynamic pressure most of the measurements performed during MD runs with LHC type beams of 25 ns bunch spacing from 2010 to 2014 never revealed differences of more than a factor of 2 between the coated and uncoated regions [13]. This fact induced some doubts on the effectiveness of the suppression of the e-cloud and related dynamic outgassing. We remark here that, in contrast to the laboratory multipacting test-bench, it was not possible in the SPS to have a setup, which enables to measure at the same location the pressure rise and the e-cloud current. The main dipoles do not permit to install a gauge at the centre of the magnet and the ECM are too short to allow a reliable measurement of the local pressure excluding the influence of the neighbouring vacuum parts. Two experiments showed that the reason of the dynamic pressure rise is not due to the carbon-coated regions, but to the short parts that remain uncoated.

The first experiment was performed in 2012. A solenoid was placed around a carbon coated drift space of 12 m length [9]. Shorter solenoids were placed also at both ends of the drift space, where short (less than 1 m) uncoated stainless steel chambers with the same cross section were present. During MD runs with LHC type beams, powering the small solenoids in the uncoated regions could markedly reduce the pressure rise at the centre of the coated drift space and no effect was observed when powering the main long solenoid on it. This demonstrated that the pressure rise in the coated drift space was dominated by the effect of the uncoated ends and that e-cloud was suppressed in the coated region, since the main solenoid had no effect on pressure rise.

The second experiment was performed in 2014 when the “doublet beam” was used during the scrubbing run in the same cycle as the LHC type beam. The doublet beam, which consists of a sequence of bunches spaced by 25 ns having the intensity distributed in two adjacent RF buckets, strongly enhances the electron cloud in the machine [18]. However, this enhancement is not equal for all components and, in particular, the doublet does not provoke electron cloud in drift space regions [19]. No pressure rise was measured in the coated two-cell section with the doublet beam circulating, but it was clearly present with the LHC type beam: this unambiguously demonstrates that the pressure rise in the two-cell zone is given by the drift space in the short straight sections, which remained uncoated.



#### 4 Resources invested in the development

The resources in terms of personnel invested in this project (2007-2015) are estimated as follows:

Category	FTE
Staff at engineer level (CP E)	6
PhD student	3
Fell	5.5
Tech. Stud	4
Other trainees (internship, Pakistan collaborators, VIA...)	4
Technicians	8.5
TOTAL	31

The material costs are estimated at 900 kCHF. The initial proposal (see Appendix 2) included about 600KCHF and 16.5 FTE for the first 3 years.

#### 5 What we have learned

In conclusion, the series of experiments and developments on carbon coatings have demonstrated that such a material is compatible with a UHV vacuum system in an accelerator, from the point of view of static and dynamic vacuum. The coating never showed peel-off after dismantling and particle counter measurements never showed significant differences compared to stainless steel chambers. The low SEY close to 1 can be obtained without bake-out (in contrast to the NEG case) and enables a reduction of the electron cloud effects below the detection limit of the ECMs of the SPS for all beams applied so far. The low SEY is preserved when cooling at cryogenics temperature. Prolonged venting did not degrade its performance.

The team gained a solid understanding of the main coating parameters which are crucial for the low SEY of the carbon coatings. Other properties of the carbon coating were explored and in particular the high emissivity of the layer might be exploited for radiation heat dissipation in the accelerators.

The other indirect benefits gained through this development are:

- On film deposition technology:
  - Competence gained on magnetron sputtering for complex geometries, including by hollow cathode.
  - Competence gained on plasma characterisation (ion and electron energy distribution measurements).
  - An improved knowledge on the detection and reduction of hydrogen partial pressures in plasma discharges.



- The competence to produce carbon coatings by plasma enhanced chemical vapour deposition.
- On material science:
  - The understanding of the role of hydrogen in the production of low SEY carbon coatings.
  - The competence to evaluate the hydrogen content in thin films by glow discharge mass spectroscopy.
  - The competence gained in oxygen plasma cleaning of vacuum chambers.
- On material characterization at CERN:
  - The development and availability of instruments to measure SEY at room (and cryogenic) temperature.
  - The development and availability of the multipacting test-bench.
  - The knowledge of Raman spectroscopy.
- On accelerator operation:
  - An improved knowledge on the physics of beam scrubbing.
  - The development and availability of a retarding field analyser (RFA) to measure the electrons energy distribution function during multipacting.

The introduction of the hollow cathode process at CERN as a new capability can be extended to further applications for coatings in complex geometries. At present this method is the baseline to demonstrate the feasibility of coating of the LHC triplets beam screens *in situ* at Pt 2 and Pt8. It can furthermore be applied in other cases, where it is not possible to apply an external magnetic field. The hollow cathode option applied to the NEG is also under investigation as a method to solve cases of coating large diameter vessels (like the ALICE-ZDC chambers in LSS2) and when the magnetron principle cannot be applied (for example the ELENA's longitudinal Schottky pick-up).

A method to reduce the hydrogen contamination during coating was applied for the first time by powering a NEG cathode at the same time as the carbon cathode; this principle is also exploited now for the feasibility study of the LHC triplet coatings, since the conductance problem is even more severe than in the MBA case.

The complex geometry and long beampipes to be coated for this project required a deeper understanding and characterization of the plasma discharge. This, together with the HIE-ISOLDE project, stimulated the improvement of the control of the plasma by Optical Emission Spectroscopy and put in evidence the need of advanced simulation tools in this domain. For the first time at CERN, the transport of sputtered atoms through a buffer gas was simulated by Monte-Carlo codes.

The characterization of the samples produced implied the construction of an SEY measuring bench, which is now available and working, serving not only the CERN community but also external institutes.



The construction of the multipacting test-bench provides a system where materials and treatments can be tested before insertion in the SPS ECM, which is independent of the schedule of the accelerators. Studies about the conditioning dynamics of stainless steel beampipes were also carried out in this system, including the effect of hydrocarbons in the residual gas, the reconditioning after air exposure, and the characterization of the carbon layer growth under the bombardment of the electrons from the cloud. The electron energy distribution function was measured with a dedicated RFA that can eventually be used in the ECM of the SPS.

Last but not least, through literature search and external collaboration we gained a better knowledge of the interpretation and measurements of Raman spectra, which is the main characterization tool for the structure and morphology of carbon.



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## APPENDIX 1




Tue 04/04/2006 15:02

Elena Chapochnikova <elenas@mail.cern.ch>

SPS chamber

To  Paolo Chiggiato

 You replied to this message on 04/04/2006 17:22.  
We removed extra line breaks from this message.

Dear Paolo,  
On behalf of PAF (see for explanations <http://paf.web.cern.ch/paf/>) I would like to ask you to give us your advice on the possibility of coating of the SPS chamber as a cure for one of the intensity and beam quality limitations in the SPS - e-cloud. If this is possible, we need (already this week, sorry) very rough (+/- 30%) estimation of money and manpower required for this project.

Thank you very much in advance,  
Elena Chapochnikova AB/RF

--




Fri 07/04/2006 14:37

Elena Chapochnikova <elenas@mail.cern.ch>

RE: SPS chamber

To  Sergio Calatroni

Cc  Paolo Chiggiato

 We removed extra line breaks from this message.

Dear Sergio,  
Sorry to bother you again but it looks like we need some very rough estimation already today.  
Could you please estimate the cost for coating of existing 750 SPS stainless steel vacuum chambers, 6 m long each with 2 main types of cross sections: 39.3mm x 156mm and 52.3mm x 132mm.

The cost of magnet dismantling can be estimated separately.

Thank you very much, Elena

On Tue, 4 Apr 2006, Paolo Chiggiato wrote:

> Dear Elena,  
> it is not possible to give you cost details  
if I do not have number and length of the chambers.  
Do the chambers already exist?  
Roughly I would say for 100 chambers  
600 CHF per chamber for internal diameters lower than 100 mm, but this has to be checked.  
I will be back to CERN on the next Monday.  
It will be useful to meet you with my  
colleagues Sergio Calatroni and Pedro Costa Pinto.  
> Best Regards,  
>  
> Paolo Chiggiato  
>





## APPENDIX 2

**Preliminary version**

Project proposal

**Studies of Secondary Electrons Emission for the LHC injectors upgrade**

S. Calatroni, P. Chiggiato, P. Costa Pinto, M. Taborelli

TS-MME  
Coatings, Chemistry and Surfaces

## 1. Introduction

Electron cloud related phenomena are considered to be limiting factors for the development of the LHC injectors. Although beam dynamic corrections are partially effective in reducing the resulting beam instabilities, the decrease of the secondary electron yield (SEY) of the vacuum chamber inner surfaces below a given threshold could eradicate the problem. In addition, surface materials with low SEY would allow a faster beam conditioning and a resulting gain of machine-time for the experiments.

These simple considerations indicate clearly the importance of pursuing studies in this field with the precise aim of finding both materials with low SEY and viable production techniques for application to long vacuum chambers for accelerators.

The present situation at CERN in this domain does not fit with the ambitious projects announced for the next 5 to 10 years for the LHC injectors. The home-made system installed in the 90<sup>ies</sup> for the measurement of SEY is completely obsolete and, though an important campaign was done in the past for the characterisation of copper and NEG films, the analyses of unusual materials were sporadic. The CERN delay in this area of development is even more astonishing when comparing our effort with that done by other laboratories, like SLAC or KEK. To fill part of the gap, a new project is proposed for 3 years. It consists in testing several families of materials and deposition techniques with particular emphasis to unbaked vacuum systems, like that of the SPS. The main tools for this investigation are dedicated deposition systems and a new SEY measurement apparatus to be coupled with an existing X-ray photoelectron spectroscopy device.

## 2. Low SEY materials and related subjects

Nitride and carbide of transition metals will be produced and tested at CERN. Boron carbides, graphitic carbon, C:H, and C:N coatings will be also tested. The role of accumulated electron dose will be underlined for any material. Stability of SEY in an accelerator environment and SEY deterioration after several air venting-conditioning cycles will be considered. The identification and the role of surface contaminations will be addressed thoroughly.

## 3. Production techniques

Sputtering is the technique of choice for thin film coating and, at CERN, the experience in this domain was reinforced by two demanding and successful activities: the Nb coated RF-SC cavities for the LEP2 and the NEG coated vacuum chambers for the LHC. However deposition of compounds, like nitrides and carbides, requires a detailed study of the



sputtering process. In addition, application of coating solutions to the km-long scale of CERN accelerators requires an intense design phase for the selected production facility, in particular for the SPS upgrade.

#### 4. Characterisation: SEY and surface composition measurement

The design, production, and operation of a new apparatus for the measurement of SEY is the most important and crucial part of the proposed project. The basic idea is to provide SEY values for fully characterised surfaces: top surface composition and SEY values will be obtained on samples during the same measuring run without air venting. To do that, the new SEY apparatus will be installed in an existing, though dated, XPS system. The samples will be transferred from one side to the other of the modified facility by means of manipulators. The same system will allow in-situ heating, ion bombardment and plasma cleaning.

A dedicated flange will allow the insertion of samples previously mounted and conditioned in the SPS. For this purpose, an UHV sample transfer system, whose design and production is not covered by this proposal, will consent to transport samples from the SPS to the XPS laboratory without air venting.

#### 5. UHV characterisation

Coatings for the reduction of SEY have to be UHV compatible before any application in the vacuum system of accelerators. Therefore, any interesting material will be characterised by degassing rate measurement (thermal outgassing, electron and photon induced desorption). In this context collaboration with the ESRF (Grenoble) has to be considered in order to access a powerful synchrotron light source.

#### 6. Costs assessment

The proposed investment is distributed in three years. It covers the costs of the following equipments:

- a. SEY apparatus and modification of the existing XPS system.
  - i. a new UHV chamber and viewports;
  - ii. a transfer system to the XPS;
  - iii. port for introduction of samples from SPS;
  - iv. manipulators;
  - v. pumping system (pumps, gauges, etc...);
  - vi. holding frame for chamber and transfer line;
  - vii. electron gun and flood gun for conditioning;
  - viii. electron optics for secondary electron collection.
  - ix. power supply for electron gun and flood gun;
  - x. data acquisition boards and software
  - xi. two nanoamperemeters
- b. Deposition systems (a large part of the activity will use existing set-ups, modification are needed for reactive sputtering).
  - i. quadrupoles gas analysers for monitoring of partial pressures during reactive sputtering;



- ii. pumps and pressure gauges;
  - iii. gas injection lines;
  - iv. RF generator for reactive sputtering and plasma cleaning;
  - v. material targets;
  - vi. feedthroughs and vacuum hardware components.
  - vii. gas flowmeters
- c. Systems for UHV characterisation.
- i. Pumps and pressure gauges;
  - ii. Residual gas analyser.
  - iii. Vacuum chambers for tests

In addition, the costs of the CERN technical services ('internal invoicing') have to be taken into account: design, surface cleaning, and thermal treatment, as well as running costs for consumable. Finally, the cost of the collaboration with ESRF has to be added.

The **manpower** request is limited to one CERN fellow (or scientific visitor) and a technical student for the three years of the project duration. Most of the manpower needs will be covered by staffs: this will be the most important contribution of the TS department to the project (about 4 man-years x 3).

**MATERIAL, SERVICES, DESIGN, AND RUNNING COSTS (KCHF)**

Year	Sample production		XPS+SEY measurement	Vacuum Chamber Characterisation	
	Coupons	Pipes		UHV compatibility	In the SPS ecloud set-up
2008	40	60	180	75	15
2009	25	50	70	50	15
2010	25	70	30	50	35

The total cost of the proposed project is: 370 KCHF in 2008, and 210 KCHF for the other two years.

**SECOND VERSION (April 11, 2008)**

Year	Sample production		XPS+SEY measurement	Vacuum Chamber Characterisation	
	Coupons	Pipes		UHV compatibility	In the SPS ecloud set-up
2008	40	10	<del>180</del> 80	<del>75</del> 50	15
2009	25	10	<del>70</del> 40	<del>50</del> 30	15
2010	25	10	<del>30</del> 30	<del>50</del> 45	<del>35</del> 15

195 KCHF in 2008, 120 KCHF in 2009 and 125 in 2010.  
Grooves development: 25 KCHF per year.



MANPOWER REQUEST

Year	Sample production	XPS+SEY measurement	Vacuum Chamber Characterisation
<b>2008</b>	1 tech. st. 1.5 TS staff	1 fellow 2 TS staff	0.5 TS staff
<b>2009</b>	1 tech. st. 1.5 TS staff	1 fellow 1 TS staff	1 TS staff
<b>2010</b>	1 tech. st. 1.5 TS staff	1 fellow 1 TS staff	1.5 TS staff

P.C. October 11, 2007