SPS: SCRUBBING OR COATING?

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Abstract

The operation of the SPS with high intensity bunched beams is limited by the electron cloud building-up in both the arcs and long straight sections. Two consolidation options have been considered: suppression of the electron cloud build-up using coatings or relying, as before, on the scrubbing mitigation. A status report on both options will be given with a particular emphasis on measurements plans for 2012 and pending issues. The testing needs, corresponding beam parameters and MD time in 2012 will be addressed. The criteria for the decision making and the corresponding schedule will be discussed.

INTRODUCTION

In the frame of the LHC Injector Upgrade (LIU) Project, the SPS accelerator has to be prepared to digest high bunch intensity - up to 2.5 10^{11} ppb @ 25 ns and 3.5 10^{11} ppb @ 50 ns - and small emittances as defined by the High Luminosity LHC (HL-LHC) Project. With the existing design, this cannot be guaranteed since electron cloud (EC) limitations have been identified: beam instabilities like transverse emittance blow-up and single bunch vertical instability, pressure rise inducing beam gas scattering, dose rates to tunnel and to the components.

Therefore, three options were considered to mitigate or suppress the EC induced effects:

- Suppression of the build-up: Clearing electrodes and coatings providing very-low secondary electron yield (SEY) i.e. lower than 1.1;
- Mitigation of the build-up: Scrubbing Runs;
- Cure of the induced effects (single bunch vertical instability): High bandwidth feedback systems.

This paper reports on the status and future plans for all these options.

CRITERIA FOR DECISION

As the SPS is an operating accelerator, all following aspects have been defined as important for the decision making:

- Safety: the solution shall be safe for the operation of all SPS beams and its implementation shall not induce major personnel safety issues e.g. radiation, handling.
- Performance: the solution shall allow a routine operation with the bunch populations required by the HL-LHC Project.
- Reliability: the solution shall not degrade with time and behaviour shall be predictable and reproducible.
- Operation margin: the solution shall provide contingency in case real situation is worse than expectations.
- Other relevant criteria: the “Best value for money” approach is assumed. This means in particular that the infrastructures required must be compatible with CERN existing options.

In addition, the implementation duration shall be compatible with a long shutdown in order to avoid perturbing the LHC Physic’s program.

STATUS REPORT

Electron Cloud Suppression solutions

Clearing electrodes

The results obtained so far correspond to expectations. The measurements have confirmed that clearing electrodes are an efficient technical choice to suppress the EC. Their efficiency in presence of a dipole magnetic field has been demonstrated up to the SPS injection energy (26 GeV); the required bias is very low, about 100 V.

However, no simple engineering solution was found to retrofit clearing electrodes inside the existing SPS dipole magnet beampipes. Therefore, it was decided to conclude these studies with the validation of the variant provided by KEK Institute.

Amorphous Carbon Coatings

The selection of the amorphous carbon as baseline for the SPS resulted from previous studies [1]. Indeed, the a-C coatings provides very low SEY, below 1.1, a value compatible with ultimate bunch populations for all beampipe shapes in the SPS. If a purification of the gas is used during the deposition process, a very-low SEY (δ<1) can be obtained with a high reproducibility, as showed by Fig. 1, without the need of any bake-out. The lifetime of these coatings is being studied since three years in the laboratory but also in the SPS ring. The only drift-up of the SEY with time was observed on a-C coated samples installed in the SPS beampipe but not in direct view of beams. Samples viewing beams do not show any drift. The effect of multiple venting to atmosphere has been evaluated, in the worst case, the SEY increased up to 1.1 which remains below the EC threshold in the SPS even with HL-LHC beam parameters.

To reduce the cost and the shutdown duration, the in-situ coating of the magnet beampipes is the preferred solution. Since this coating configuration is challenging, it was decided to study also the ex-situ coating as an alternative.

The in-situ coating prevents from opening the magnets to install new beampipes. The Hollow-Cathode technique (Fig.2 and 3) is being used and so far, the MBB dipole profile has been validated as the MBA dipole profile has only gone through a 2m validation test, pending from the tooling for a real 7m MBA dipole beampipe. This validation is expected by end of April 2012. The reversibility of the coating process is not an issue since a bad coating can be removed using an oxygen glow discharge.

The ex-situ coating is the simplest solution since the new beampipes can follow all surface treatments required to optimise the quality of the coatings. The major drawback is that, for all dipole magnets, the beampipes will have to be installed in the magnets which implies opening 744 magnets of the SPS. With new beampipes, the well-mastered magnetron sputtering technique, used for the LHC Non-Evaporable Getter (NEG) coatings, can be used. The results obtained on all magnet beampipe profiles (MBA and MBB) are excellent. The drift straight section beampipes will be coated as well using a magnetron sputtering approach at the laboratory.

As for all coatings, the static outgassing is higher than for bare stainless steel, but no difference can be seen after second pump down (see Fig.4). The dynamic vacuum is expected to be lower than for the uncoated substrate because of the marked reduction of the electron cloud current.

The need to coat or not the entire inner surface of the beampipes has been studied in details (see Fig.5) and lead to clear conclusions: in dipole magnets, only the top and bottom parts of the beampipe needs to be coated as the entire inner surface of the beampipe needs to be coated for the field free regions and quadrupoles.

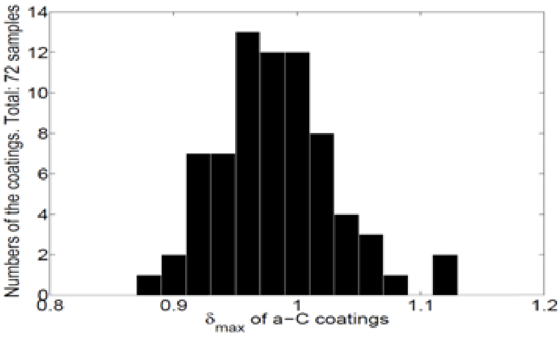

Figure 1: Distribution of the measured SEY on the coated samples.

Figure 2: Picture of the hollow-cathode being inserted in the MBA dipole magnet beampipe profile.

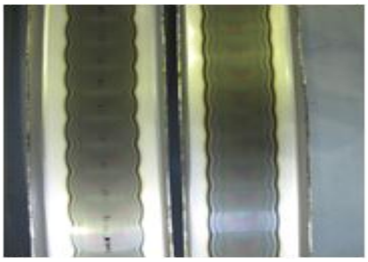

Figure 3: Picture of the a-C coating obtained using a hollow-cathode. A faster displacement of the cathode during the coating process allows reducing the ripples.

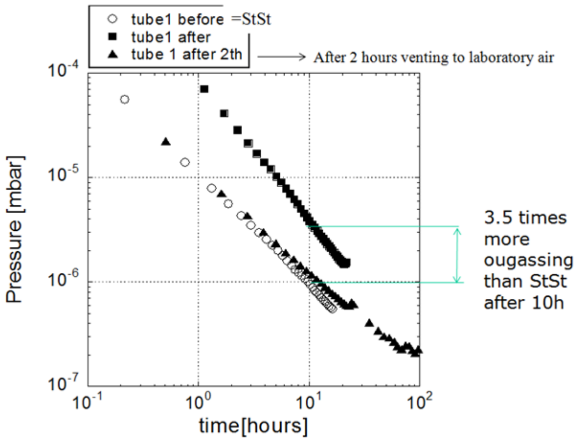

Figure 4: Evolution of the outgassing rate of an a-C coating and effect of a second pump-down.

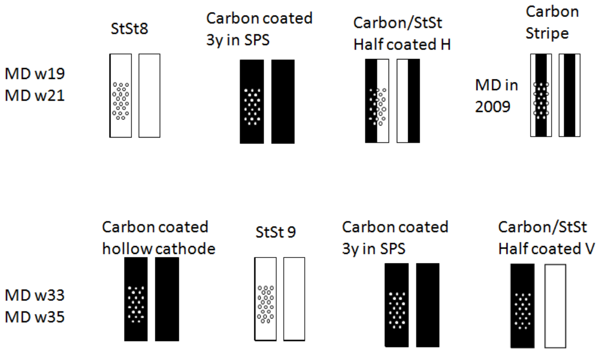

Figure 5: Configuration tested to evaluate the need to coat or not the entire inner surface of the beampipe.

Electron Cloud Mitigation solutions

Beam Scrubbing

Beam scrubbing is being successfully used since 1999 in the SPS to reduce the EC activity. However, full suppression was never achieved except in field free regions. Therefore, beam scrubbing falls in the category of the mitigation solutions and is not a suppressing method.

The EC build-up in the SPS (Fig.6) is not homogeneous along the ring. Indeed, the EC build-up is non-monotonic and depends on first order parameters such as beampipe's shape and size, bunch spacing, presence of an externally applied magnetic field and as a second order effect, bunch length and geometrical emittance (see Table 1).

Table 1: SEY thresholds simulated for different shapes and bunch populations

Beampipe profiles	SEY thresholds @ 1.1 10^{11} ppb	SEY thresholds @ 2.5 10^{11} ppb
ID 156 (LSS)	1.4	1.1
ID 130 (LSS)	1.45	1.05
MBA (Dipole)	1.4	1.45
MBB (Dipole)	1.15	1.25

The very-low EC thresholds shown by Table 1 are an indication of the high demands in terms of reduction of the SEY of the beampipe surfaces, in particular for the HL-LHC beam parameters. Similar simulations for the LHC with HL-LHC beams are not yet done. This puts more constraints on the beam scrubbing efficiency and points out its intrinsic limitations.

Reaching smaller SEY needs a much larger electron bombardment doses since the dose effect follows a logarithmic behaviour as shown by Fig.7. Going from an SEY of 1.6 down to 1.4 requires an order of magnitude more electron dose than from 1.8 to 1.6 and another order of magnitude is necessary to go down to 1.3! Meanwhile, for a constant bunch population, the bombardment dose decreases when approaching the EC threshold (see Fig.8). The simulations made for the SPS showed 3 orders of magnitude reduction of the electron bombardment flux! Thus, going from a SEY of 1.4 down to the 1.3 required for the operation of the SPS (at nominal LHC bunch population) implies 100 times more beam scrubbing duration! 10 times more electron dose meanwhile, the electron flux is decreasing by a factor of 10.

At this stage, it is important to remind that the efficiency of the dose effect depends on the nature of the material. In the case of the SPS which uses stainless steel beampipes, a saturation of the dose effect at $\delta_{saturation}$=1.3 was observed in the laboratory (SEY saturates at 2.2 for Aluminium!). This value is well above the simulated thresholds for the HL-LHC beam parameters (Table 1).

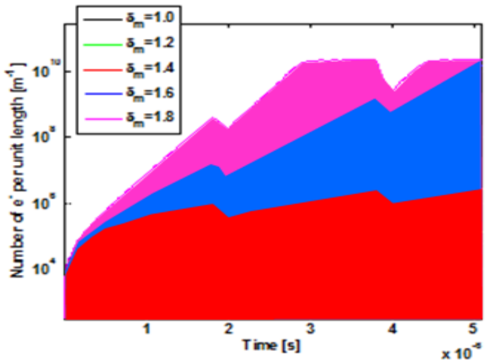

Figure 6: Simulations of the EC build-up with time as a function of the beampipe SEY.

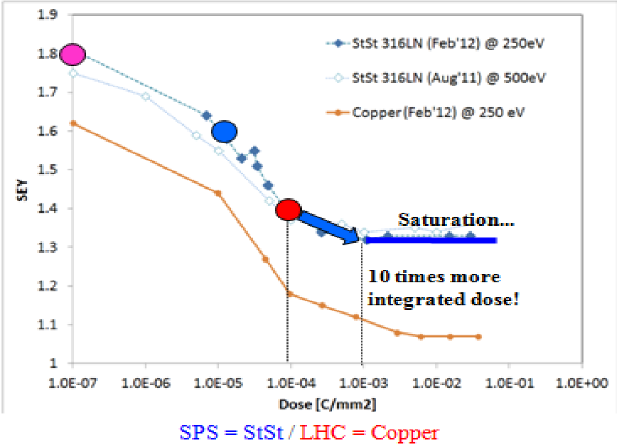

Figure 7: Effect of an electron bombardment on the SEY of copper and Stainless Steel materials.

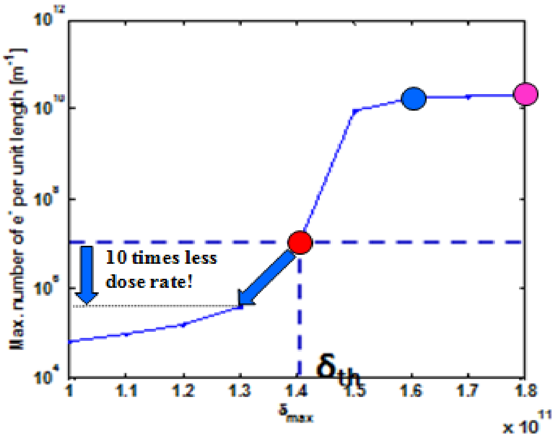

Figure 8: Reduction of the electron density in the electron cloud while approaching the multipacting threshold.

Finally, the use of high bunch populations during extensive scrubbing periods to increase the beam scrubbing efficiency is known to induce collateral effects like the heating of kickers, internal dump by trapping higher order modes (HOM) which can lead to equipment damages. These effects are enhanced if the bunch length is shortened.

Simulations

As a matter of fact, beam scrubbing can only become a valuable alternative to coatings if solutions are found to enhance the EC close to the threshold. An amazing work was done on the side of simulations in particular for the dipoles in which measurements are difficult to carry on.

The following configurations have been looked at:

- 5ns bunch spacing
- Slip stacking of bunches
- 5-10% uncaptured beam (alternative to filling SPS with 8 x 72 b @ 25 ns and 26 GeV)
- PS bunch splitting deregulation (Bunch intensity modulation).

A deeper analysis has discarded the first two options since not compatible with the existing RF systems in the

PS or SPS. The 5-10% uncaptured beam option looks promising close to the EC threshold in particular if only 3 batches can be circulated in the SPS. This could be useful if confronted to equipment overheating due to HOM effects. The last option does not provide any EC enhancement.

The simulations to assess the EC induced instability threshold in dipoles assume a homogeneous distribution of the electrons in the beampipe. But this is not the real situation in presence of a dipole field; electrons are confined along the field lines in three (3) strips (see Fig.9): one central and two laterals. While increasing the bunch population, the lateral strips moves away from the beam [3]. After some scrubbing, the central strip tends to disappear faster (see Fig.10) resulting from the presence of high energetic electrons in the central strip. Indeed, the electrons are getting the strongest kick by the beams.

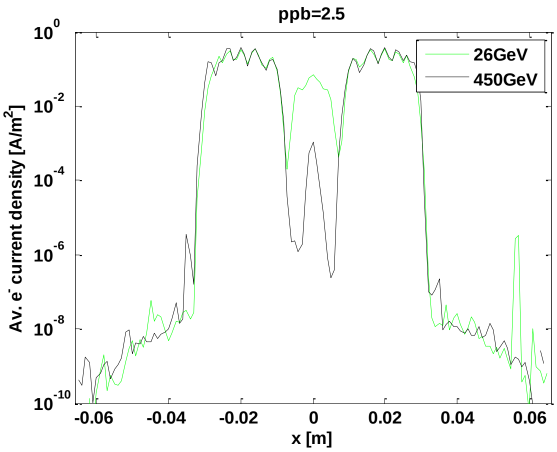

Figure 9: Transverse distribution of the electrons in an SPS dipole beampipe (simulations)

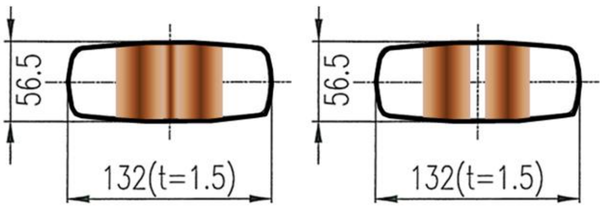

Figure 10: Cross-section of the MBB dipole magnet beampipe showing the EC spatial distribution. After few hours of beam scrubbing, the central strip disappears leaving only the two-lateral stripes.

Electron Cloud curing solutions

High bandwidth transverse feedback system

The status was reviewed in November 2011 by the LIU project and details can be found at [2]. The aim of the ongoing studies is demonstrating the efficiency of the transverse damping of intra bunch headtail motion caused by impedance and e-cloud, with a GHz bandwidth. The full system implementation could be ready for 2018 if proof of principle (see Fig.11) is demonstrated before LS1, i.e. 2012. The test set-up is operational in SPS (see Fig.12).

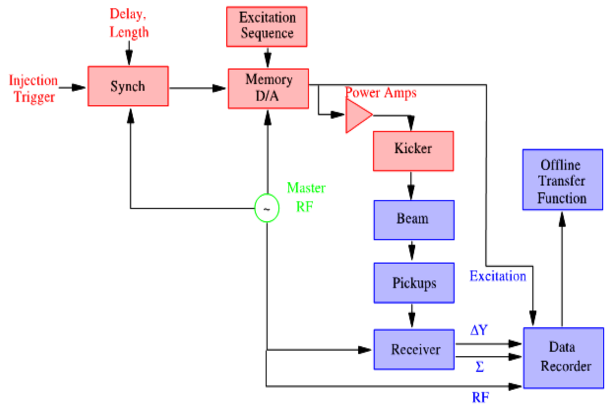

Figure 11: Functional schematic of the high bandwidth transverse feedback system

Figure 12: Picture of the pick-up installed in the SPS ring.

PENDING ISSUES

The validation of the beam scrubbing or coating solutions need measurements with beams or alternatively in the laboratory.

Measurements in the Laboratories

The SEY behaviour, electron dose and venting to atmosphere effects are studied in the laboratory. The validation of a coating inside a dipole beampipe was only possible by cutting a piece of the beampipe to get it installed in the SEY measurement stand. The dynamic behaviour of the coatings such as electron stimulated desorption, static outgassing and the ageing, and peel-off are also studied in the laboratory.

As the measurements cannot be done in presence of a magnetic field, it was decided to study new means to validate the coatings directly in the dipole magnets. The newly developed system, called Multipactor test bench, is now fully validated and allows measuring a coated beampipe installed in a real SPS dipole magnet. Fig.13 shows the schematic of the system with its associated pressure instrumentation providing also an indication of multipacting conditions in the beampipe. The later allows benchmarking the RF measurements. Fig. 14 and Fig. 15 show the typical results obtained with this set-up.

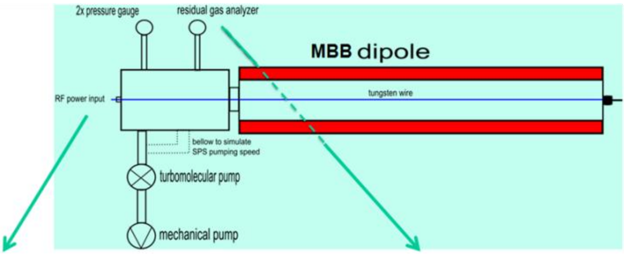

Figure 13: Schematic of the Multipactor test bench.

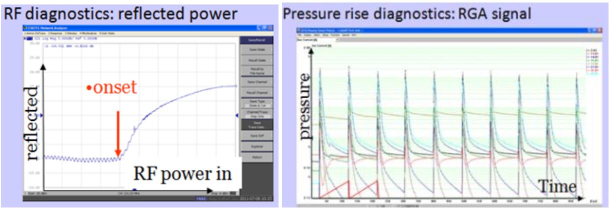

Figure 14: Typical signal observed in presence of multipacting: reflected power associated to pressure rise induced by the electrons bombarding the beampipe.

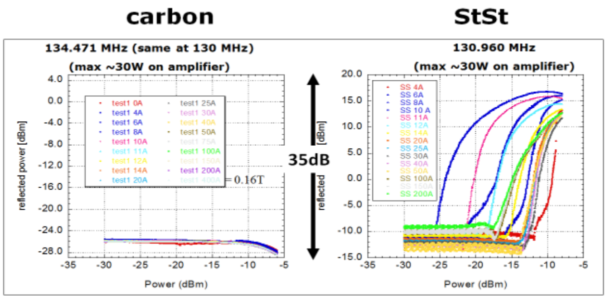

Figure 15: Comparison of signals obtained on an a-C coated and bare stainless steel beampipes. The first does not show any multipacting.

Measurements with beams

The EC study zone in SPS-LSS5 has been equipped with strip detectors, pick-ups, sample extractor and extended vacuum instrumentation but nothing has yet been done inside a real 7m long SPS magnet with an MBB or MBA aperture. Installing an electron probe at the centre of a dipole magnet was studied and finally abandoned. Indeed, the simulations done for 0.12 T in the dipole field indicate that the combined effect of the dipole field at higher values (1T) with the transmission of the collector in the strip detectors will hinder a correct detection of the EC multipacting.

It was therefore decided to coat a longer part of the SPS ring to decrease the border effects and use pressure gauges as multipacting indicators. The objective was to install two half-cells (HC) with a-C coated magnets, one HC with magnetron and one HC using the hollow-cathode. This objective has been delayed due to the unexpected workload during the 2011-12 Winter Technical Stop (WTS). Instead, coated circular beampipes without magnetic field but with more diagnostics will be installed in the half-cell HC514 (Fig.16). Taking profit from the Technical Stop in June 2012, the last coated MBA dipole will be installed in the HC513 (Fig.17). The measurements during the following 5 months with beams will allow validating the behaviour of entirely coated hall-cells.

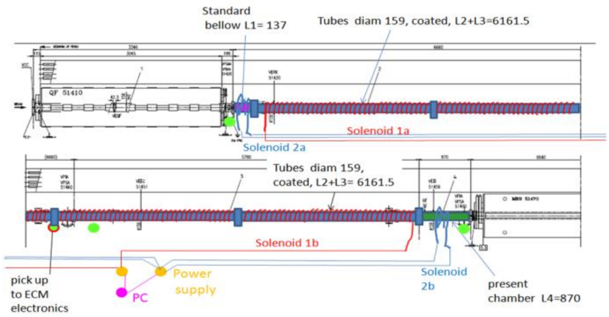

Figure 16: SPS HC514: a-C coated beampipes instead of magnets

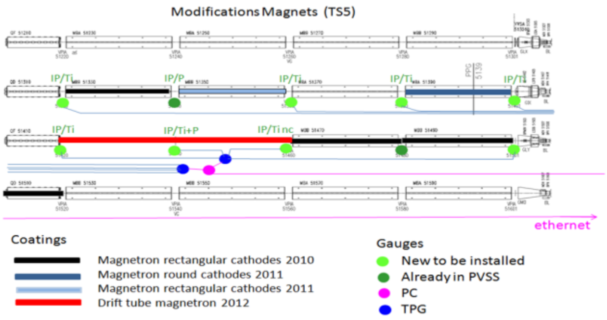

Figure 17: SPS HC513: a-C coating magnets as from June'12

REVIEW OF OBJECTIVES

Several objectives were fixed following the review made to prepare the Chamonix 2011 Workshop and all of them are progressing according to the defined schedule.

Since last Chamonix Workshop, four objectives were achieved:

- Feasibility studies on the clearing electrodes.
- Industrialisation of the a-C coating techniques for in-situ and ex-situ options.
- Development of additional EC diagnostics, which could help the final decision.
- Definition of the strategy for LS1 shutdown: 2 coated half-cells to be installed.

Four (4) others are being completed:

- Studying means to enhance the EC build-up.
- Preparation of SPS MD measurements to validate the efficiency of the proposed solutions.
- Preparation of one half-cell coated with a-C to get it installed during the WTS 2011-12.
- Proceed with the complete evaluation of the proposed solutions.

And three (3) medium term actions have been reviewed:

- Two additional new-coated half-cells will be installed in the SPS if the results obtained during the 2012 Run are not conclusive.
- Validation with beams of the 2 (or 4) half-cells coated installed in the SPS ring as from 2014 to LS2 shutdown.
- Full implementation in LS2.

CONCLUSIONS

Amorphous Carbon Coatings

At the present stage of the technology development, the amorphous carbon (a-C) provides the guaranty of suppression of the electron cloud. Despite the long list of potential further validations with beams, it is important to underline that the a-C coating technology is at the same level of validation than the NEG coatings when approved for their extensive use (more than 1400 beampipes) in the LHC. The remaining concerns are: costs, resources, infrastructures, duration and radiation dose to personnel.

The a-C coating is the project baseline and CERM teams are presently working towards assumption that this will be needed. The large scale quality assurance is not a showstopper since already done for LHC NEG coated beampipes.

Beam Scrubbing

The beam scrubbing to decrease the SEY of the inner surface of the beampipes to mitigate the electron cloud is a serious alternative with two major advantages: low cost and short duration (few days/year). The completion of the ongoing simulations and the results from the scrubbing MDs are prerequisite to a decision since important pending issues need to be addressed. First, solutions exists on paper (new beams) to enhance the multipacting close to EC threshold and thus speed up the dose effect on SEY but the feasibility in the accelerators needs to be confirmed. The saturation of the SEY dose effect measured on the stainless steel ($\delta_{saturation}$=1.3) represents a limitation for the MBB dipoles (1/3 of SPS). An increase of the instability threshold resulting from the non-homogeneous distribution of the EC in the dipoles - still to be validated by the simulations - could compensate partly the effects of the SEY saturation. Simulations are ongoing to determine the required scrubbing time profiting from excellent LHC data and simulations.

It is obvious that the beam scrubbing scenario assumes that beam equipments like RF cavities, Septa and Kickers will be consolidated to become compatible with the new beams used during the long (several days) scrubbing runs.

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[2] https://indico.cern.ch/conferenceDisplay.py?confId=162989.

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