ISBN: 978-3-95450-168-7 doi:10.18429/JACoW-IPAC2015-THPF091

DETAILED STUDIES OF BEAM INDUCED SCRUBBING IN THE CERN-SPS

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Abstract

In the framework of the LHC Injectors Upgrade (LIU) project, it is foreseen to take all the necessary measures to avoid electron cloud effects in the CERN-SPS. This can be achieved by either relying on beam induced scrubbing or by coating the vacuum chambers with intrinsically low Secondary Electron Yield (SEY) material over a large fraction of the ring. To clearly establish the potential of beam induced scrubbing, and to eventually decide between the two above options, an extensive scrubbing campaign is taking place at the SPS. Ten days in 2014 and two full weeks in 2015 are devoted to machine scrubbing and scrubbing qualification studies. This paper summarizes the main findings in terms of scrubbing efficiency and reach so far, addressing also the option of using a special doublet beam and its implication for LHC.

INTRODUCTION

The electron cloud effect has been identified as a possible performance limitation for the SPS since LHC type beams with 25 ns spacing were injected into the machine for the first time in the early years of 2000. At that time a severe pressure rise was observed all around the machine together with transverse beam instabilities, significant losses and emittance blow-up on the trailing bunches of the train [1]. Since 2002, scrubbing runs with 25 ns beams were carried out almost every year of operation in order to condition the inner surfaces of the vacuum chambers and therefore mitigate the electron cloud. Extensive machine studies showed that by 2012 the conditioning state of the SPS was such to avoid any possible beam degradation due to electron cloud on the cycle timescale for 4 batches of 72 bunches with $N \approx 1.35 \times 10^{11}$ p/b and normalized transverse emittances of about 3 μm [2]. For higher intensities ($N \approx 1.45 \times 10^{11}$ p/b injected) a seemingly electron cloud driven transverse instability was observed after the injection of the third and the fourth batch, leading to emittance blow up and particle losses on the trailing bunches of the injected trains. Since the SPS was never scrubbed with such high beam intensities, an additional scrubbing step might be required for suppressing these effects. If scrubbing is not sufficient for suppressing the electron cloud effect with the high beam intensity and small transverse emittance produced with LIU, or in case the reconditioning process is very slow after large parts of the machine are vented (like during a long shutdown), the inner surface of the SPS vacuum chambers might have to be coated with a low Secondary Electron Yield (SEY) material. The solution developed at CERN is to produce a thin film of amorphous Carbon (a-C) using DC Hollow Cathode sputtering on the inner walls of the vacuum chamber [3]. The suppression of electron cloud in coated liners equipped with electron cloud strip monitors was already proved with beam in the SPS. An additional four SPS half cells (including quadrupoles) have been coated with a-C during Long Shutdown 1 (LS1), seeking for further experimental evidence of the coating efficiency with beam operation in Run 2.

The total or partial coating of the SPS machine with a-C is a major task, which requires careful preparation and planning of resources. The decision whether or how much of the SPS needs to be coated has therefore to be taken no later than mid 2015. After LS1, a first scrubbing run took place during the whole Week 45 in 2014 with the main goal of recovering the operational performance, as it was expected that the good conditioning state of the SPS will be degraded due to the long period without beam operation, partial venting, and the related interventions on the machine. Two and a half additional days of scrubbing in Week 50 were also used to start exploring the SPS behaviour with 25 ns beams with higher intensity as well as accelerated doublets and other LHC beam variants [4]. Two more weeks for scrubbing will be performed in the first half of 2015 in order to assess the potential to fully scrub the machine for high intensity 25 ns beams or the limitations of this approach. Only after collecting all the additional experience and the important information from the extensive experimental scrubbing from post-LS1 operation, the final choice between coating and scrubbing will be made in mid-2015.

WEEK 45: RECOVERY OF THE PRE-LS1 PERFORMANCE

The goals of the SPS scrubbing run in Week 45 were:

- Recover the 2012 performance with LHC 25 ns beams;
- Qualify the machine behaviour with LHC beams after long shutdown and extensive machine venting;
- Test doublet beams for SPS scrubbing and as preparation for LHC scrubbing in 2015.

In oder to make scrubbing efficient, the pressure interlocks on the injection kicker MKP-S and the beam dump (TIDVG), exchanged during LS1, had to be raised. The summary plot showing the maximum current per cycle (in

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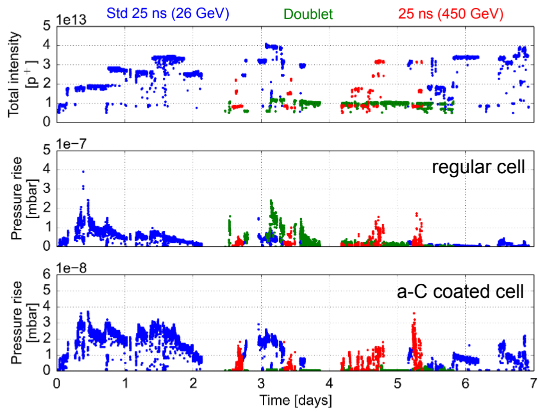

Figure 1: Week 45: Cycle-by-cycle maximum injected intensity in the SPS in protons (top), dynamic pressure rise in a regular cell (middle), dynamic pressure rise in an a-C coated cell (bottom).

number of protons) injected into the SPS is displayed in Fig. 1, upper plot. Three main cycles were used over the week. A long cycle at constant energy (26 GeV) allowing for several injections of 72 bunches of 25 ns beam (labeled as 'Std 25 ns (26 GeV)') was used especially in the first part of the scrubbing run. The number of injections as well as the storage time in the SPS was gradually increased over the first 2.5 days of scrubbing, as the sensitive elements MKP-S and TIDVG became more conditioned, thus increasing the margin for the dynamic pressure rise. Nevertheless, after about three days the heating of the MKP-S caused enough outgassing to push the static pressure to its interlock value (independently of the dynamic rise). The cool-down of the MKP-S could be achieved using doublet beams on a short 4 s cycle at 26 GeV (labeled 'Doublet'), which have the advantage to keep conditioning the arcs without enhancing the outgassing in the sensitive elements. This behaviour was explained by the fact that doublet beams (with about 1.6×10^{11} p/doublet) can enhance the electron cloud in presence of dipole magnetic fields, but they have higher thresholds of electron cloud build up in field free regions and induce less heating due to the different beam spectrum. Therefore, the doublet beam was taken from the third day onwards. Finally, the nominal LHC filling cycle (up to four injections of standard 25 ns beam and accelerated to 450 GeV, labeled '25 ns (450 GeV)') was also used in the middle of the scrubbing week to both use the enhanced scrubbing induced by the shorter bunches on the energy ramp and qualify the efficiency of scrubbing by the quality of the accelerated beam.

The evolution of the dynamic pressure rise in a regular SPS cell and in one of the two a-C coated cells is depicted in the middle and bottom plots of Fig. 1. While the dynamic pressure rise was already one order of magnitude lower in the a-C cell at the beginning of the scrubbing process, conditioning is visible in both cells over the week. It is noteworthy that, while the doublet awakens the electron cloud in the regular cell and brings back the pressure rise to the same values reached at the beginning of the week, no pressure rise is visible with this type of beam in the a-C cell. This is due to the fact that the observed pressure rise in the a-C cell comes from the electron cloud in short uncoated field-free regions between the magnets. This is another important proof of the electron cloud suppression achieved with a-C coating of the inner chamber walls.

The recovery of the pre-LS1 performance of the SPS for 25 ns beams is illustrated in Fig. 2. Four batches of 72 bunches with nominal intensity (1.2×10^{11} p/b) were injected and accelerated to 450 GeV with less than 10% losses along the cycle (top plot) and emittances of 2.6 μm, as measured at the end of the injection plateau. No electron cloud pattern could be observed in the evolution of the bunch-by-bunch intensity along the cycle (bottom plot).

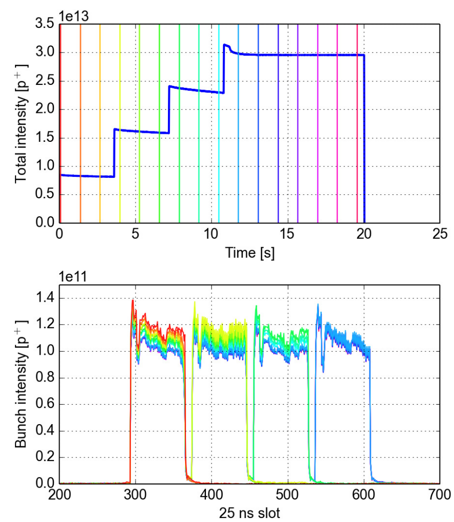

Figure 2: Four batches of 25 ns beam injected and accelerated to 450 GeV with 'acceptable' beam losses. The lower plot shows the snapshots of the bunch-by-bunch intensity taken at the cuts shown in the above plot.

WEEK 50: HIGH INTENSITY 25 ns BEAMS AND LHC BEAM VARIANTS

The goals of the SPS scrubbing in Week 50 were:

- Start testing high intensity 25 ns beams at 26 GeV to gain information in view of LIU decision coating vs. scrubbing in 2015;
- Explore SPS performance reach when accelerating one or two batches of 72 doublets;
- Test LHC-type beam variants, including the already used BCMS beams and the new 8b+4e beams.

The summary plot showing the maximum current per cycle (in number of protons) injected into the SPS is displayed in Fig. 3, upper plot. Up to four batches of high intensity 25 ns beams (2.0×10^{11} p/b) were injected on the long flat bottom cycle (labeled 'High intensity 25 ns

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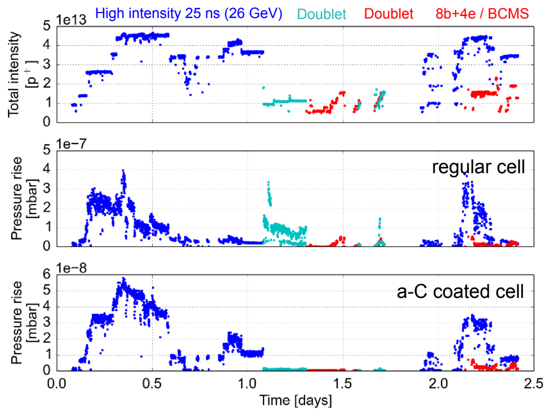

Figure 3: Week 50: Cycle-by-cycle maximum injected intensity in the SPS in protons (top), dynamic pressure rise in a regular cell (middle), dynamic pressure rise in an a-C coated cell (bottom).

(26 GeV)') during the first day. The lifetime of this beam was quite poor, as a horizontal instability appeared after injection of the second batch, as well as beam losses and emittance growth at the end of the batches (see Fig. 4). At these intensities, the SPS is back to be affected by strong and visible electron cloud effects, probably because of two concurrent effects. First, the electron cloud build up gets stronger not only in drift regions and quadrupoles due to the higher intensity, but also in the dipoles due to moving of the stripes of highest electron cloud density to unscrubbed regions. Second, the beam becomes more sensitive to coherent instabilities due to its higher intensity. On the second scrubbing day, first tests of acceleration of doublet beams (up to 2.0×10^{11} p/doublet) took place on both the LHC nominal ramp and a three times slower ramp to ease constraints on the needed RF power (labeled 'Doublet'). This beam was strongly affected by horizontal instabilities and losses so that the maximum intensity reached at flat top was about 1.4×10^{11} p/doublet, however with a large emittance growth at the tails of the doublet trains. Dedicated set up time will be needed for this beam in 2015 to make it operational for the LHC. On the third day, other LHC beam variants were tested, like BCMS and 8b+4e [4] (labeled 'BCMS / 8b+4e'). They both induced less pressure rise compared to the standard 25 ns beam and did not suffer beam degradation up to 450 GeV. In particular, the 8b+4e beam experimentally qualified as back up solution for the LHC in case of persisting electron cloud problems.

The further conditioning of the arcs in Week 50 is visible from the dynamic pressure rise evolution in the middle (regular cell) and bottom (a-C coated cell) plots of Fig. 3.

CONCLUSIONS

SPS scrubbing in 2014, weeks 45 and 50, benefited from high beam availability and led to important conditioning of both newly installed elements (MKP-S and TIDVG) and pressure in the arcs. The successful deployment of the doublet beam helped by enhancing the electron cloud in high-field non a-C coated regions as well as lowering both electron cloud and heating in the sensitive regions. It also confirmed the experimental evidence of electron cloud suppression with a-C coating. The nominal LHC beam (4 batches of 72 bunches each) at 450 GeV was recovered after LS1 with low losses and transverse emittances below 3 μm already after five days of scrubbing. However, the high intensity LHC beam at 26 GeV was found to still suffer from strong electron cloud effects, causing both poor lifetime and coherent instabilities at the tails of the batches. Additional work is still needed to set up the doublet beam with acceleration to 450 GeV, which is crucial for the scrubbing of LHC in view of its operation with 25 ns beams.

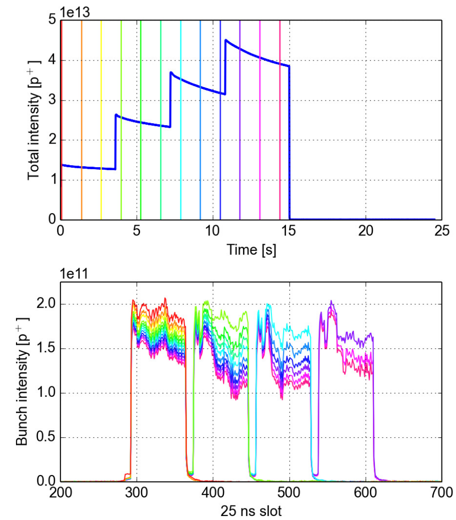

Figure 4: Four batches of high intensity 25 ns beam with large beam losses. The lower plot shows the snapshots of the bunch-by-bunch intensity taken at the cuts shown in the above plot.

ACKNOWLEDGEMENTS

The authors would like to thank G. Arduini, T. Argyropoulos, E. Carlier, K. Cornelis, H. Damerau, J. Esteban Muller, A. Findlay, S. Gilardoni, A. Guerrero, S. Hancock, W. Höfle, V. Kain, A. Lasheen, M. Meddahi, E. Métral, B. Mikulec, G. Papotti, E. Piselli, A. Romano, R. Salemme, B. Salvant, and the PS complex for the preparation of the challenging beams.

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