BEAM DYNAMICS OBSERVATIONS OF THE 2015 HIGH INTENSITY SCRUBBING RUNS AT THE CERN SPS

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Abstract

Beam quality degradation caused by electron cloud effects has been identified as one of the main performance limitations for high intensity LHC beams with 25 ns bunch spacing in the SPS. In view of the beam parameters targeted with the LHC injectors upgrade (LIU) project, about two weeks of SPS machine time in 2015 were devoted to dedicated scrubbing runs with high intensity LHC 25 ns and dedicated 'doublet' beams in order to study the achievable reduction of e-cloud effects and quantify the consequent beam performance improvements. This paper describes the main observations concerning the coherent instabilities and beam dynamics limitations encountered as well as a detailed characterisation of the performance reach with the highest beam intensity presently available from the pre-injectors.

INTRODUCTION

The electron cloud effect has proven to be an important performance limitation for the SPS when running with LHC type beams. Back in 2000, a large pressure rise all around the machine, as well as transverse beam instabilities, significant beam losses and transverse emittance blow-up on the trailing bunches of long trains were the clear indicators of the presence of electron cloud in the machine when it first operated with 25 ns spaced bunch trains [1]. Since 2002, scrubbing runs of variable length have been carried out almost at every machine start up after the winter technical stops in order to clean the inner surfaces of the vacuum chambers, and therefore lower their Secondary Electron Yield (SEY), by means of intensive running with 25 ns beams in high electron cloud regime. This strategy led to a very advanced conditioning state of the SPS already in 2012, visible both in the low dynamic pressure rise and the achieved LHC beam quality. Extensive machine studies showed that in 2012 four trains of 72 bunches of the 25 ns beam could be successfully accelerated with $N \approx 1.3 \times 10^{11}$ p/b at 450 GeV and without sign of electron cloud induced degradation. First attempts to further increase the bunch intensity ($N \approx 1.6 \times 10^{11}$ p/b injected) resulted in the onset of transverse instabilities after the injection of the third and the fourth batch, causing emittance blow up and particle losses on the trailing bunches of the injected trains [2]. About 10 days of scrubbing in 2014, just after the SPS had been fully vented during Long Shutdown 1 (LS1), turned out to be sufficient for both the conditioning of newly installed elements and the recovery of the previous conditioning state in the arcs. After only five days of scrubbing, the nominal LHC beam (4 batches with 72 bunches per batch) was recovered with $N \approx 1.15 \times 10^{11}$ p/b and transverse emittances below 3 μm at 450 GeV. However, the high intensity LHC beam at 26 GeV/c was again found to suffer from strong electron cloud effects, causing both poor lifetime and coherent instabilities at the tails of the batches. The successful deployment of the doublet beam [3] helped scrubbing by enhancing the electron cloud in high field regions while lowering it in field-free regions (some of which are sensitive because of heating and outgassing, such as the injection kickers). This feature of the doublet beams also confirmed the experimental evidence of electron cloud suppression in the four SPS half cells (including quadrupoles) coated with amorphous Carbon (a-C) [4] during LS1: the observed suppression of pressure rise in these cells with doublet beams could be ascribed to the absence of electron cloud in both the coated magnets and the uncoated field-free regions between coated magnets [3].

The two weeks of scrubbing in 2015 were conducted mainly with high intensity 25 ns beams ($N \approx 2 \times 10^{11}$ p/b) at 26 GeV/c in order to assess the potential to successfully scrub the SPS also for higher intensity 25 ns beams in reasonable time. The evolution of the maximum beam current and the corresponding dynamic pressure rise in a representative vacuum gauge of the arc over the whole scrubbing time in 2015 is displayed in Figure 1. The goal of the exercise was to provide input to the LHC Injectors Upgrade (LIU) project [5] to decide whether scrubbing would be sufficient for suppressing the electron cloud effect in future operation, or the SPS vacuum chambers would have to be coated with a thin film of a-C during Long Shutdown 2 (LS2). The experience in these two weeks showed mainly that the SPS can run stably with 25 ns beams up to the tested values of intensity, although beam losses are observed to increase and beam stabilisation relies on machine non-linearities as well as a fully functional transverse damper. After the results of the 2015 scrubbing run, an extended review took place at CERN and the strategy for the SPS future operation against electron cloud was outlined and approved [6].

SPS SCRUBBING 2015: EXPERIENCE WITH HIGH INTENSITY 25 ns BEAMS

In 2015, two full weeks were devoted to SPS scrubbing, with the principal goals of running 25 ns beams at 26 GeV/c with high intensity ($N \approx 2 \times 10^{11}$ p/b) and thus assessing both limitations and machine 'scrubbability' in these running conditions. Scrubbing is intrinsically a difficult and challenging procedure, as scrubbing beams create by construction a strong electron cloud and inevitably suffer from it. Ideally, the machine should be made to operate with constant settings always close to the margin of stability, therefore maximising the amount of electron cloud and the scrubbing efficiency while preserving the beam stability over the used

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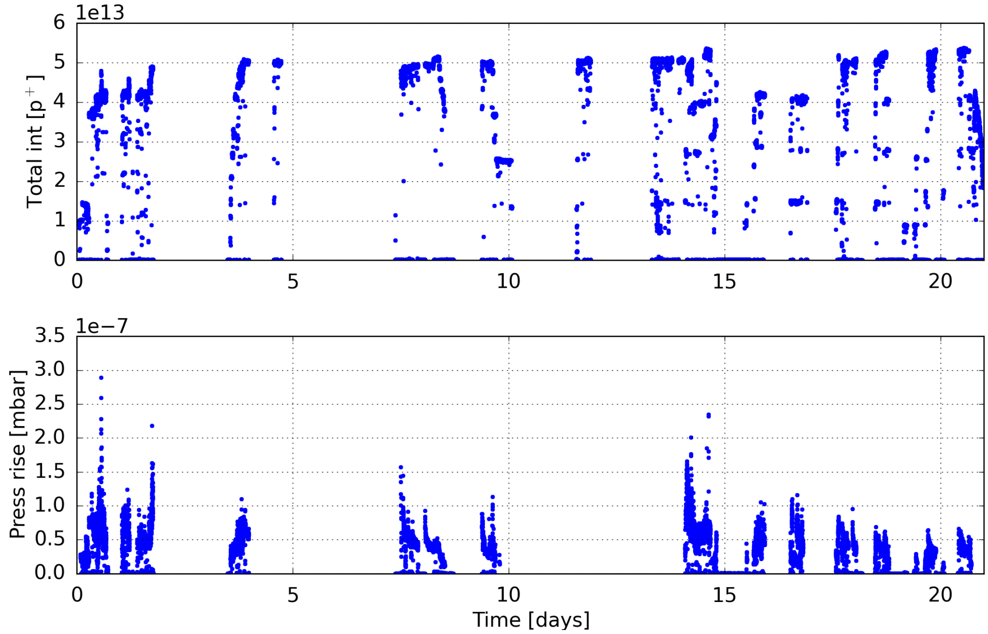

Figure 1: 2015 scrubbing: Cycle-by-cycle maximum injected intensity in the SPS in protons (top), and dynamic pressure rise in a regular arc cell (bottom).

cycle. In this way, one could observe the improvement of beam quality and at the same time monitor the evolution of the electron cloud observables. In reality, apart from short spans of time in which the machine settings are not changed, in general there is a continuous effort from the operation crews to adaptively optimise the different settings (e.g., RF, tunes, chromaticities, octupoles, transverse damper), which makes it difficult to disentangle a posteriori how much improvement comes from scrubbing and how much from machine tuning. Besides, even in the ideal condition in which settings are not changed, the improvement of beam quality due to scrubbing would still affect the measurement of the direct electron cloud observables. Because of all the above considerations, it is clear that qualifying in absolute terms the scrubbing process is not straightforward.

First experiences with injecting batches of 72 bunches with $N \approx 2 \times 10^{11}$ p/b showed that the beam suffers from transverse instabilities in both planes, depending on the SPS settings. In particular, a vertical instability appeared when the vertical chromaticity setting was very close to zero. This manifested itself as a single-bunch-type instability mainly affecting the tails of the batches. Since this effect could be efficiently cured by means of slightly increasing the vertical chromaticity with marginal deterioration of the beam lifetime, it was concluded that this would only pose a minor issue and would not be a real intensity limitation. At high enough vertical chromaticity and without octupoles, however, a horizontal high-order coupled-bunch instability was found to limit the SPS performance. This instability appeared only after the injection of the second or third batch and manifested itself with a strong horizontal emittance blow-up accompanied by significant particle losses for the trailing bunches, as displayed in Figure 2. The observed pattern is typically due to electron cloud and, at least for lower bunch intensities, this effect could be efficiently suppressed by high horizontal chromaticity settings and/or the horizontal feedback system. However, for the high bunch intensities used during the 2015 scrubbing run, neither the damper nor higher chromaticity values turned out to be sufficient to cure the observed unstable coupled bunch mode at 20 MHz (Figure 3). Fortunately, early enough during the run, it was found that the focusing octupole magnets in combination with a high chromaticity setting and the transverse feedback system at maximum gain manage to stabilise the beam, although significant incoherent losses remain, certainly also due to the increased machine non-linearities. Single bunch tests showed that, by avoiding the use of the octupole magnets and high chromaticity, the amount of incoherent losses may indeed be reduced, which suggests that the full exploitation of the transverse feedback system is certainly one of the keys to the future operation with high intensity 25 ns beams.

As figures of merit to qualify the SPS performance over the scrubbing periods, we have focused on the average bunch intensity in the SPS 11 s after the first injection (i.e. just before the accelerating ramp in a nominal LHC filling cycle) and the SPS transmission, defined as the ratio between the total intensity at 11 s and the total injected intensity (sum of the intensities extracted from the PS). Only cycles with four successful injections were considered in the statistics. As a result of both machine parameter optimisation and scrubbing, both the SPS transmission and average bunch intensity available at 11 s steadily increased over the first

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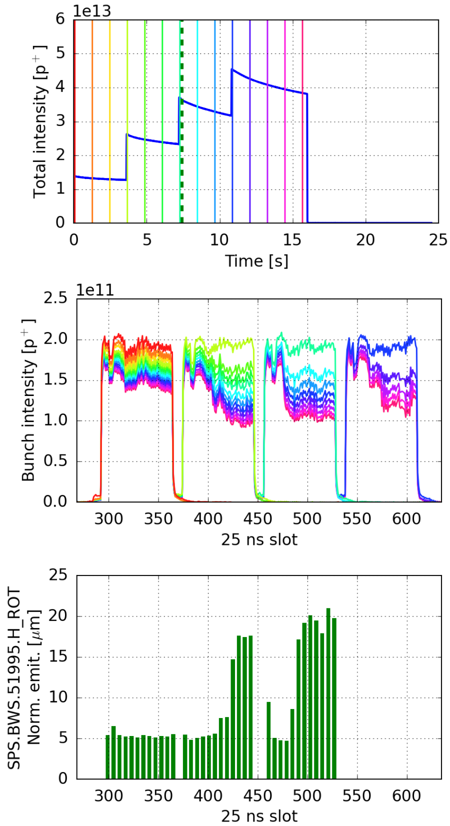

Figure 2: Four batches of high intensity 25 ns beam injected and stored at 26 GeV/c in the SPS. The upper plot shows the beam current signal as a function of the cycle time, the middle plot displays snapshots of the bunch-by-bunch intensity taken at the cuts shown in the above plot (roughly every second), the bottom plot shows a bunch-by-bunch horizontal emittance measurement at the cut indicated with a vertical green dashed line in the top plot.

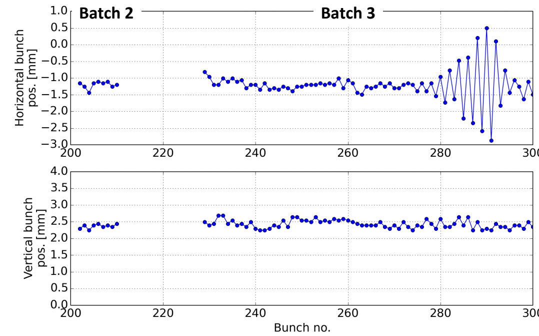

Figure 3: Snapshot of the bunch-by-bunch horizontal (top) and vertical (bottom) positions along the third batch while the horizontal instability is developing.

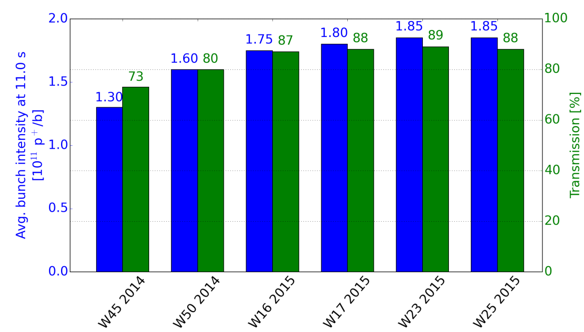

Figure 4: Evolution of the average bunch intensity in the SPS at 11 s and the SPS transmission over the scrubbing periods in 2014 and 2015.

scrubbing periods, although no further improvement was observed beyond the fourth scrubbing block (see Figure 4). On the positive side, after the top performance was reached, no emittance growth along the batches was observed and this performance could also be easily recovered from one scrubbing block to the next one. The current limits are therefore an intensity of $N \approx 1.85 \times 10^{11}$ p/b with a transmission of 89%. Losses of 11% at $N \approx 2 \times 10^{11}$ p/b injected are unfortunately still beyond the desired value. Using the 2015 trend to extrapolate the percentage loss to the future LHC beam intensity ($N \approx 2.5 \times 10^{11}$ p/b), and adding on top at least 2% expected from uncaptured beam at the beginning of the ramp and 3% from scraping at high energy, the total losses to be expected for future operation would become as high as 20%. This would be unsustainable without the design and implementation of a collimation system to avoid excessive activation around the machine.

CONCLUSIONS

The SPS scrubbing experience in 2015 has shown that high intensity 25 ns beams can be stored stably in the SPS at 26 GeV/c if the transverse instabilities are controlled by means of a combined action of transverse damper, high chromaticity and high octupole settings. However, incoherent losses remain an issue, because the extrapolated performance points towards future beam losses in the order of 20%. Even if this is made acceptable by the installation of a collimation system, it would still entail a 10% reduction of achievable beam brightness compared to the LIU baseline. As an outcome of the LIU-SPS review on scrubbing [6], it was decided that

- Scrubbing would be retained as e-cloud mitigation measure for the immediate post-LS2 operation (Run3)
- The vacuum chambers of the most critical magnets of one sextant of the machine would be a-C coated.

The partial coating will then both prove logistically the feasibility of the procedure in-situ and open the path to a staged coating campaign, to be concluded at the next long shutdown, if the high intensity LIU beams are still found to suffer from important e-cloud limitations during Run 3.

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