MONITORING THE PROGRESS OF LHC ELECTRON-CLOUD SCRUBBING BY BENCHMARKING SIMULATIONS AND PRESSURE RISE OBSERVATIONS *

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Abstract

Electron bombardment of a surface has been proven to reduce drastically the secondary electron yield of a material. This technique, known as scrubbing, provides a mean to suppress electron cloud build-up and its undesired effects (e.g. vacuum pressure rise, heat load, beam instabilities) in particle accelerators operating with intense beams. Its effectiveness has been already observed at the LHC. In this paper we present the latest observations on the vacuum chamber conditioning and a proposal to optimize the scrubbing process by means of the map formalism.

INTRODUCTION

Electric fields present in many vacuum systems may accelerate electrons (produced by photoemission, residual gas ionization, field emission, etc.) towards the vacuum chamber wall. If these primary electrons acquire enough energy, they produce secondary electrons, which may also be accelerated. In accelerators beams with tight bunch spacing and high bunch populations and brightness multipacting can occur for Secondary Electron Yields (SEY) above a given value. This can lead to the formation of an electron cloud (EC). EC effects in accelerators are described in [1, 2].

The LHC mitigation strategy against electron cloud includes several measures (sawtooth pattern on the beam screen inside the cold arcs, NEG coatings, solenoids, etc.). However beam scrubbing, i.e. the bombardment of a surface with electrons produced thanks to the beam itself, is the ultimate solution to reduce the Secondary Electron Yield, suppress multipacting and mitigate the detrimental electron cloud effects for the LHC (mainly large pressure rises, excessive cryogenic heat load and coherent plus incoherent instabilities). In order to achieve the nominal LHC performance [3], it is necessary to drastically reduce the secondary electron yield of the vacuum chamber surface (e.g. [4]).

Since at the LHC no in-situ secondary-yield measurements are yet available, it has been necessary to develop a method to infer different key beam-pipe surface parameters (namely δ_{max}, ε_{max} and R [5]) by benchmarking simulations and pressure-rise observations [6]. This method has allowed monitoring the scrubbing process both at 50 and 25 ns bunch spacing, thanks to dedicated Machine Development (MD) studies, and helping to decide on the most appropriate strategies for machine operation.

In particular during 25 ns experiments, strong EC effects have been observed,which led to fast beam degradation (losses, emittance growth, etc.) [7, 8]. This degradation significantly reduces the scrubbing efficiency. In order to optimize the scrubbing process the map formalism [9] has been applied to the LHC for both warm-warm uncoated straight sections and for the bending magnets. This has allowed us to identify filling schemes which could yield a better scrubbing performance by producing less degradation in the beam while maintaining a high flux of electron on the chamber wall.

LHC CONDITIONING STATUS

After the scrubbing run which took place in April 2011, LHC has been working smoothly for physics at 50 ns bunch spacing. Nevertheless, some pressure rises were still observed in certain pressure gauges during the injection of trains containing 4 SPS batches (i.e. 4 batches of 36 bunches each separated by 225 ns). However, these pressures rises were small enough not to affect significantly the performance of the accelerator even despite the fact that the bunch population had been ramped up from June 2011 onwards (up to $N_b \approx 1.45 \cdot 10^{11}$ p). The first beam with 25 ns bunch spacing was injected during an MD session on 29 June 2011 with batches of 24 bunches. Two more injection tests at 25 ns were carried out on 26 August and 7 October 2011. The last two MD sessions with 25 ns took place on 14 and 25 October 2011. In these sessions, batches of 72 bunches were stored for longer times (approximately 4h on average). At the end of the last MD a shorter fill was used to obtain stable pressure measurements for benchmarking observations and simulations. Thanks to the method described in [6] an evolution of δ_{max} during 2011 could be sketched. From Fig. 1 we can observe that the estimation of δ_{max} at the end of 2011's LHC proton run (30 October 2011) is around 1.35 for $R \approx 0.3$. No variation of these values is expected to take place during LHC lead-ion runs (which do not suffer from EC).

An open question after the LHC 2011 run was whether the conditioning reached thanks to the scrubbing could be maintained after the yearly winter shutdown. Due to the tight schedule for physics at the LHC during 2012 no experiments with 25 ns have been allocated so far this year. Nevertheless no pressure rise has been observed up to now in the single beam uncoated warm-warm regions at injec-
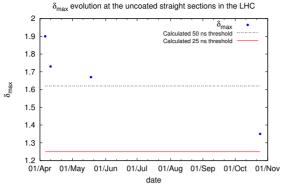

Figure 1: Estimated evolution in time (from April to October 2011) of $\delta_{\max}$ in the uncoated straight sections of the LHC. The lowest value reachable with scrubbing corresponds to the 25 ns thresholds. The first injection with a 25 ns bunch spacing beam took place on 29 June 2011. The thresholds for 25 and 50 ns have been calculated for $R = 0.3$ and $N_b = 1.1 \cdot 10^{11}$ ppb

tion energy except for some parts of the machine which were opened during the shutdown (see Fig. 2). This allows us to observe the evolution of conditioning in the regions which were opened and to set an upper-bound value for $\delta_{\max}$ for the gauges located in the rest of the machine.
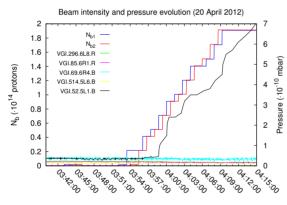

Figure 2: Pressure evolution during injection of physics fill on 20 April 2012. The five gauges shown are placed in different sectors, three corresponding to beam 1 and two to beam 2. The sector 5L1 was opened during the shutdown and exhibits pressure rise in the single-beam-pipe gauge VGI.52.5L1.B.

The pressure gauges located in the regions opened during the shutdown [A4L2, A4R8, D5L4 (only inner beam), A5L1 (only inner beam), I5R8, G5R8, E5L4 (only outer beam)] measured significant pressure rises during the first injections of 36 bunches (3 April 2012). Figure 2 shows that, for example in the case of gauge VGI.52.5L1.B, 504 bunches were necessary to trigger the EC in the last physics fill so far (20 April 2012). That illustrates the fast reconditioning that these surfaces are experiencing. Further analysis is foreseen to quantify this reconditioning effect more precisely.

Concerning the large rest of the machine (the parts not

opened during the shutdown) where no pressure rises are observed, $\delta_{\max}$ is below the threshold value for 50 ns bunch spacing. The average bunch population during the physics fills at the beginning of 2012 LHC run has been $N_b = 1.3 \cdot 10^{11}$ ppb although in the last fills so far this value has been increased up to $N_b = 1.4 \cdot 10^{11}$ ppb. The calculated threshold values at these intensities and considering $R = 0.3$ are $\delta_{\max, \text{ thr.}} \approx 1.57$ for $N_b = 1.3 \cdot 10^{11}$ ppb and $\delta_{\max, \text{ thr.}} \approx 1.55$ for $N_b = 1.4 \cdot 10^{11}$ ppb. Unfortunately the lack of measurements at 25 ns bunch spacing prevents a better estimation. This information is not sufficient to discern whether some conditioning has been partially lost during the technical shutdown in these regions. For this purpose 25-ns beams would be needed.

SCRUBBING OPTIMIZATION THROUGH MAP FORMALISM

The map formalism, which describes the evolution of the electron density during the beam passage through simple polynomials, was first introduced in [9] for the RHIC machine. The main advantage of using maps for the description of an EC is the large reduction in the computing time (about 7 orders of magnitude), allowing a filling scheme optimization in order to reduce the EC effect. This formalism has been later applied to the LHC dipoles at 7 TeV with success [10]. In addition, it has been shown that this formalism is also valid for the estimation of the electron flux impinging in the vacuum chamber walls [11]. In this section we briefly show that this procedure can be used also for LHC field free regions and dipoles at injection energy (450 GeV) aiming at finding filling schemes which could optimize the scrubbing process.

Figure 3 shows a comparison between the electron flux calculated through full simulations and maps for a warm-warm uncoated straight section of the LHC considering a realistic filling pattern. Disagreement between simulations and maps never exceeds 15% for the cases studied (both for gauges and dipoles at 450 GeV). This fact instills confidence for its use as a tool to study long term behaviour in a very short amount of time (typically, with maps, the simulation of a whole turn of the LHC takes milliseconds), and can inform future operation strategies.

Since no further scrubbing is possible with 50 ns in most of the machine (where we are below the threshold for EC build up with 50 ns), this study has been focused on 25 ns beams. In this case, the SPS can inject single batches of 72 bunches into the LHC. The minimum distance between batches is 925 ns (rise time of the LHC injection kicker). It is also possible to inject longer trains up to four batches, spaced by 225 ns, with a minimum distance of 925 ns between them. Each batch of 72 bunches is formed out of 6 PSB bunches, which reach the SPS already split in 12 bunches each. This allows operators to easily create a 12-bunches hole within an LHC batch by removing one injection from the PSB to the PS. These are our degrees of freedom to work out filling schemes which could yield a better performance in terms of beam stability (mainly reducing
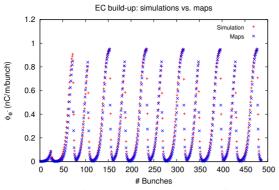
Figure 3: Comparison between the electron flux per bunch obtained with full simulations and applying map formalism considering a realistic pattern.

Figure 5: Comparison between a standard and an alternative filling scheme. The region shown is a fraction of an LHC turn of the length of the alternative pattern.

beam losses and emittance growth) and electron dose deposited in the vacuum chamber walls (to be as large as possible).

During the last 25 ns experiment (25 October 2011) the filling scheme consisted of 72-bunch batches spaced by 925 ns. Figure 4 shows a sketch of different possible filling schemes studied to improve the scrubbing effect in future experiments. The strategy consists in finding schemes which would yield lower flux peak values whilst maintaining or increasing the electron dose. The best trade off between both conditions could be obtained with the scheme b) in Fig. 4. Figure 5 compares the peak values between schemes a) and b) in Fig. 4 in a dipole for a typical set of parameters ($\delta_{max} = 1.7$, $R = 0.7$ and $\varepsilon_{max} = 330\ eV$ [7, 8]). We observe that the peak value is similar, but it is achieved 32 times in the case of the standard scheme and 13 times with the alternative, leading very likely to lower beam degradation. This prediction has to be confirmed by experiments. The integrated dose per turn is equivalent in both cases (around 4% higher for the alternative scheme). Similar options with trains of 2 and 4 batches have also been examined with worse results (either too high a peak value or too low an integrated dose).
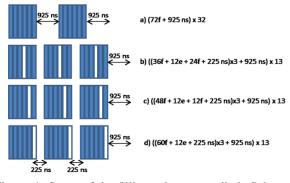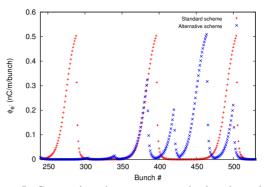
CONCLUSIONS

At the end of the 2011 LHC proton run the estimated values for δ_{max} and R were 1.35 and 0.3 respectively in the uncoated warm-warm regions. There is no sufficient information about the possible lost of conditioning but we could infer an upper-bound value of $\delta_{max} = 1.55$, which corresponds to the calculated threshold for 50 ns bunch spacing, since no pressure rises in individual vacuum chambers have been observed in regions not opened during the winter shutdown. The map formalism has been introduced to optimize future scrubbing runs and a possible alternative filling scheme for this goal has been proposed.

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Figure 4: Some of the filling schemes studied. Scheme a) has been already used in past experiments.