LHC EXPERIENCE WITH DIFFERENT BUNCH SPACINGS IN 2011 (25, 50 and 75ns)

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Abstract

LHC operation in 2011 had a smooth start in March with 75ns beams and only one month later moved to 50ns beam, after a successful dedicated scrubbing run. Several observables, such as pressure rise, heat load in the arcs, beam instability, emittance growth and synchronous phase shift, clearly pointed to the presence of an electron cloud inside the machine during the first days of operation with 50ns beams. The gradual reduction of all these effects, and their eventual disappearance, over the days of the scrubbing run, indicated electron cloud mitigation and allowed physics production to shift to 50ns beams. Up to the end of the run the quality of the 50ns beams was increased by regular stages (first lower transverse emittances, then higher intensities), so that these beams could provide steadily improving peak luminosities. Furthermore, five MD sessions with 25ns beams took place in the period June-October, but the quality of these beams was always deteriorated by severe electron cloud effects. However, a clear improvement was noticed also with the 25ns runs. An estimation of the present state of conditioning of the machine and the required scrubbing time can be inferred from electron cloud simulations compared with measured data.

BUNCH SPACINGS IN LHC IN 2011

When an electron cloud builds up in an accelerator running with closely spaced bunches, the beam chamber becomes filled with an electron gas whose distribution and flux to the walls depend on the beam structure and the properties of the beam chamber (i.e. geometry and secondary electron yield, $\delta_{\max}$, of the inner surface) [1]. The flux of electrons hitting the wall of the vacuum chamber is the origin of both pressure rise through desorption and power deposition on the chamber wall. The presence of electrons around the beam can make the beam unstable or feed a process of slow emittance growth. All these macroscopic effects of the electron cloud are our main observables in LHC [2].

Operation with 75ns beams

After three weeks commissioning with beam, the 2011 physics run of the LHC started in March colliding beams with 75ns bunch spacing. Owing to beam scrubbing from the late 2010 MD sessions with 75 and 50ns beams, the LHC quickly became productive for physics with 75ns beams without suffering any major outgassing limitations or beam instabilities. In only a couple of weeks, the LHC was already able to successfully accelerate and collide two 75ns beams each made of 200 bunches distributed in batches of 24. During the intensity ramp up with 75ns beams, no electron cloud indicator appeared in LHC.

Operation with 50ns beams: scrubbing run and physics

The full week 5–12 April, 2011, was devoted to the scrubbing run with 50ns beams, although three days were lost due to issues independent of the scrubbing program and the last day was devoted to tests of accelerating/colliding beams with 50ns spacing (up to 228 bunches). The goal was to prepare the machine to switch to 50ns beams and thus extend the luminosity reach for the 2011 run. Over the scrubbing run, the number of bunches injected into the LHC was gradually ramped up to a maximum of 1020 per beam (in batches of 36). Several stores at injection energy with different numbers of bunches took place. During the first days of scrubbing, pressure rise, heat load in the arcs, coherent beam instabilities as well as emittance growth were observed [3]. Nevertheless, the beams could be kept in the LHC at injection energy thanks to the fact that:

- The heat load could be handled by the cooling capacity of the cryogenic system;
- The pressure rise was tolerable or, where needed, the interlock level on the pressure value was temporarily raised so as not to cause beam dump;
- High chromaticity settings, acceptable at injection energy, were used for damping the coherent instability;
- The incoherent emittance growth and the associated intensity loss, mainly affecting the last bunches of each batch, were sufficiently slow as not to trigger the Beam Loss Monitors (BLMs).

In these conditions, the electron cloud produced by the circulating beams served the purpose of scrubbing the inner wall's surface of the LHC beam chambers. The strategy adopted to optimize the scrubbing process consisted of constantly topping the total beam intensity in the LHC with the injection of more trains, such that the vacuum activity, and therefore the electron cloud, could be kept at a constant level. This was expected to efficiently reduce the SEY of the walls to a value eventually at the limit for a significant electron cloud build up (and below the threshold for beam instability at nominal intensity). After approximately 17 effective hours of beam scrubbing time — corresponding to about 72h of beam time — the pressure improved by an

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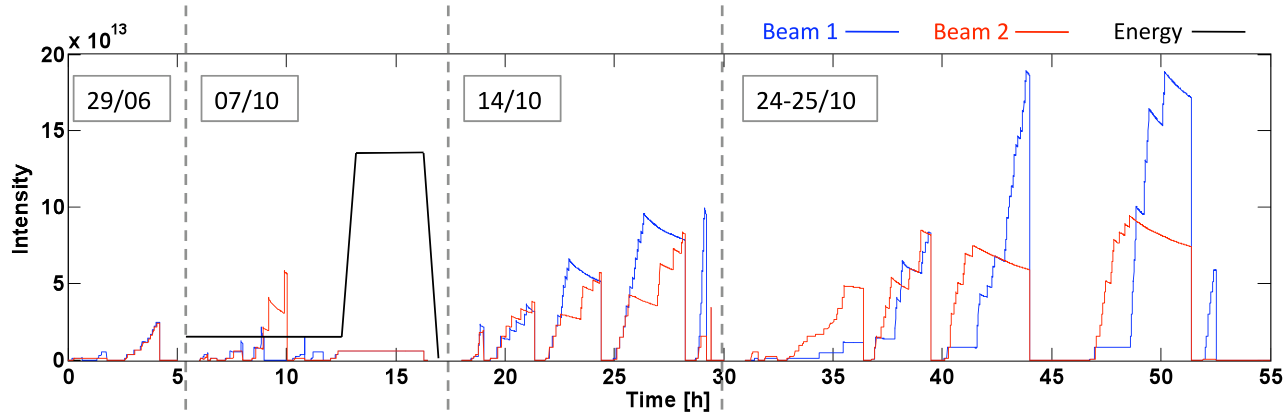

Figure 1: MD sessions labeled (a), (c), (d) and (e): injected beams.

order of magnitude throughout the machine [3]. At the end of the scrubbing run, a residual pressure rise was still observed in some cold-warm transitions and straight sections, while in the arcs both the heating of the beam screen and the pressure increase disappeared. Also, no electron cloud instability or emittance growth was seen to affect the beams towards the end of the scrubbing run.

The success of the scrubbing run was proved by the subsequent smooth LHC physics operation with 50ns spaced beams. Between mid-April and end-June the number of bunches collided in the LHC was steadily increased up to its maximum value of 1380 per beam, while the intensity per bunch and the transverse emittances remained constant at their nominal values (i.e., 1.15×10^{11} ppb and 2.5 μm). During this whole period, the surface scrubbing naturally continued, as witnessed by an additional one-order-of-magnitude decrease of the dynamic pressure level around the machine [4]. By the end of June, beams in a full machine and colliding for 20h hardly exhibited any emittance growth during their time in stable beam mode. The switch to 50ns beams with lower transverse emittances (1.5 μm) allowed the LHC peak luminosity to easily score an additional 50% increase, while not leading to any critical recrudescence of the electron cloud. This can be explained by the weak dependence of electron cloud formation on the beam transverse emittances. Finally, to push the peak luminosity further up, the intensity per bunch was adiabatically increased to approximately 1.5×10^{11} ppb over the final few months of the run. Again, no significant return of the electron cloud was observed during this phase [5].

However, even during the physics run at 50ns, there have been some indications that the electron cloud has not yet systematically disappeared in all regions of the LHC and for all beam parameters. For instance, a pressure rise in the common beam chamber in proximity of ALICE has been observed at the locations with a wide beam chamber installed ($r = 400$mm) [6, 7]. Electron cloud simulations have confirmed that this is a multi-turn effect that takes place almost all along the wide chamber due to the hybrid bunch spacing from the two 50ns beams and the short clearing gaps. Also, a higher heat load has been observed in some arc cells during the ramp, which has been suspected to be related to electron cloud formation from bunch shortening [8].

Machine Development with 25ns beams

Beams with 25ns spacing were injected into the LHC only during five MD sessions of the 2011 run — see Fig. 1 — which are described here:

(a) **29 June, 2011**: first injections of 25ns beams into the LHC. The filling scheme consisted of nine batches of 24 bunches separated by increasing gaps (2.28, 5.13 and 29.93 μs). Pressure rise around the machine as well as heat loads in the arcs were observed. All the last bunches of each batch suffered losses and emittance growth [9];

(b) **26 August, 2011**: first injections of a 48-bunch train into the LHC with 25ns spacing. Two attempts were made to inject a 48-bunch train from the SPS, which led to beam dump triggered by large beam excursion and beam loss interlocks, respectively. During the first injection test, the transverse damper was on and it is believed that the beam suffered a coherent electron cloud instability in both planes (more critical in vertical) soon after injection. During the second test, the transverse damper was switched off and the beam was affected by a coupled bunch instability [10]. This MD session had then to be interrupted because of a cryo failure caused by a thunderstorm;

(c) **7 October, 2011**: injection tests and first ramp. In the first part of the MD, trains with 48-72-144-216-288 bunches from the SPS were injected into the LHC. Given the experience during the previous MD, the chromaticity Q' was set to around 15-20 units in both the horizontal and vertical planes in order to keep the beams stable against the electron cloud effect. In the second part, only 60 bunches per beam were injected in trains of $12 + 2 \times 24$, were accelerated to 3.5 TeV and collided during approximately 5h;

(d) **14 October, 2011**: first long stores of 25ns beams at injection energy in the LHC. During this session up to 1020 bunches per beam were injected in batches of 72. The chromaticity was kept high in both planes ($Q'_{x,y} \approx 15$) in order to preserve the beam stability. First, a dedicated fill for pressure measurements was made, with batches injected at gradually reduced distances from 4 to 2 μs (in steps of 1μs). Subsequently, the batch spacing was kept constant for each of the next three fills and it was set to 6.3, 3.6 and 1 μs (rounded values). Strong emittance growth and slow losses affecting the last bunches of each train were observed throughout this MD session;

(e) **24–25 October, 2011**: record number of bunches in the LHC. Four long fills took place (average store time was approximately 4h), with 25ns beams injected into both rings in batches of 72 separated by 1μs. In the third and fourth fills, 2100 bunches were injected for beam 1, while the number of bunches could not exceed 1020 for beam 2, due to a vacuum interlock on one of the injection kickers (MKI). Although the situation seemed to improve over the MD, slow losses and emittance growth kept affecting both beams. Before starting the fourth fill, the horizontal chromaticity Q'_x was lowered from 15 to 3 units and the horizontal damper gain was slightly increased. Probably due to that, some horizontal instabilities could be observed from the signal of the damper pick up during the fourth fill, but the overall performance did not appear degraded from the previous fill. The MD ended with a 30' fill with only beam 1, during which batches of 72 bunches were injected into the LHC at different spacings in order to provide the stable pressure measurements needed for the modeling of the electron cloud build up in the straight sections (see next Section).

For sake of compactness, we have chosen to concatenate the MD sessions (a), (c), (d) and (e) and represent them on a continuous time axis, which will be systematically used throughout this paper when referring to the studies with the 25ns beams.

COMPARISON BETWEEN MACHINE DATA AND SIMULATIONS

The estimation of the $\delta_{\max}$ of the chamber wall has been made separately for the straight sections and for the arcs. The former is based on the pressure data from the vacuum gauges, while the latter relies on the measured heat load on the beam screens. In reality, the SEY is not the only adjustable parameter used in our model of the secondary electron emission. Also the reflectivity of the electrons at zero energy, R_0, and the energy at which the maximum of the SEY occurs, $\epsilon_{\max}$, are additional model parameters that we could either fix based on previous experience or try to infer from our measurements. Laboratory measurements carried out in the past mostly assign to R_0 values ranging between 0.5 and 1 [11, 12], while a reasonable value for $\epsilon_{\max}$ for Cu surfaces seems to be around 330 eV [13].

Uncoated straight sections

The pressure measurements from the two vacuum gauges VGI.141.6L4.B and VGPB.2.5L3.B have been used for determining the pair $(R_0, \delta_{\max})$ of the local chamber wall at a certain time. These gauges are located in warm-warm transitions with NEG coating on both sides.
The procedure to infer the surface parameters from the pressure data has been described in detail in Refs. [2, 14]. It was applied four times: before and after the scrubbing run, on 19 May (with 50ns beams) and on 25 October with 25ns beams (last visible fill, only with beam 1, in Fig. 1). An attempt was also made on 14 October but, due to the rapidly changing beam and vacuum conditions, the data could not be easily used. The fitted electron reflectivity at zero energy R_0 is in the range 0.2 – 0.3, while $\delta_{\max}$ has exhibited a decrease from the initial 1.9 to 1.35. The history of $\delta_{\max}$ is summarized in Fig. 2. In the same plot, we have also drawn the horizontal lines of the electron cloud build up thresholds at both 50ns and 25ns (at 450 GeV and 3.5 TeV), as well as the vertical line representing the first injection of 25ns beams into the LHC.

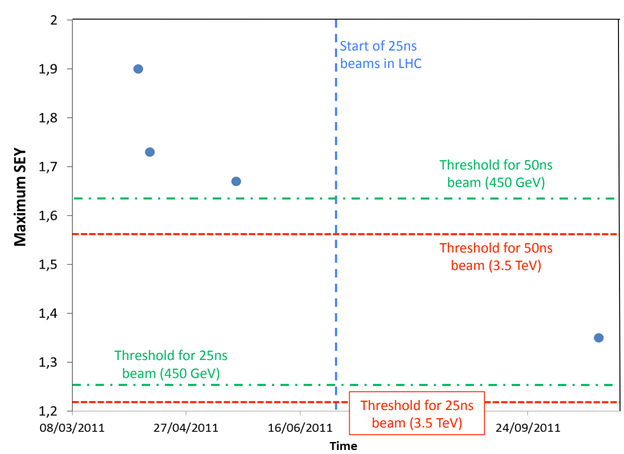

Figure 2: Evolution of $\delta_{\max}$ in proximity of two selected vacuum gauges from the beginning of the scrubbing run to the last 25ns run on 25 October, 2011.

It is clear that before the injection of the first 25ns beam, the SEY had only become about as low as the threshold value for 50ns beams, as is also proven by the disappearance of all the electron cloud indicators with this type of beams. Only subsequently more scrubbing has taken place thanks to the 25ns beams. The value of $\delta_{\max}$ has further decreased to 1.35 and is still above the build up threshold with 25ns beams. An additional scrubbing step would be required to suppress the electron cloud in the uncoated locations of the straight sections.

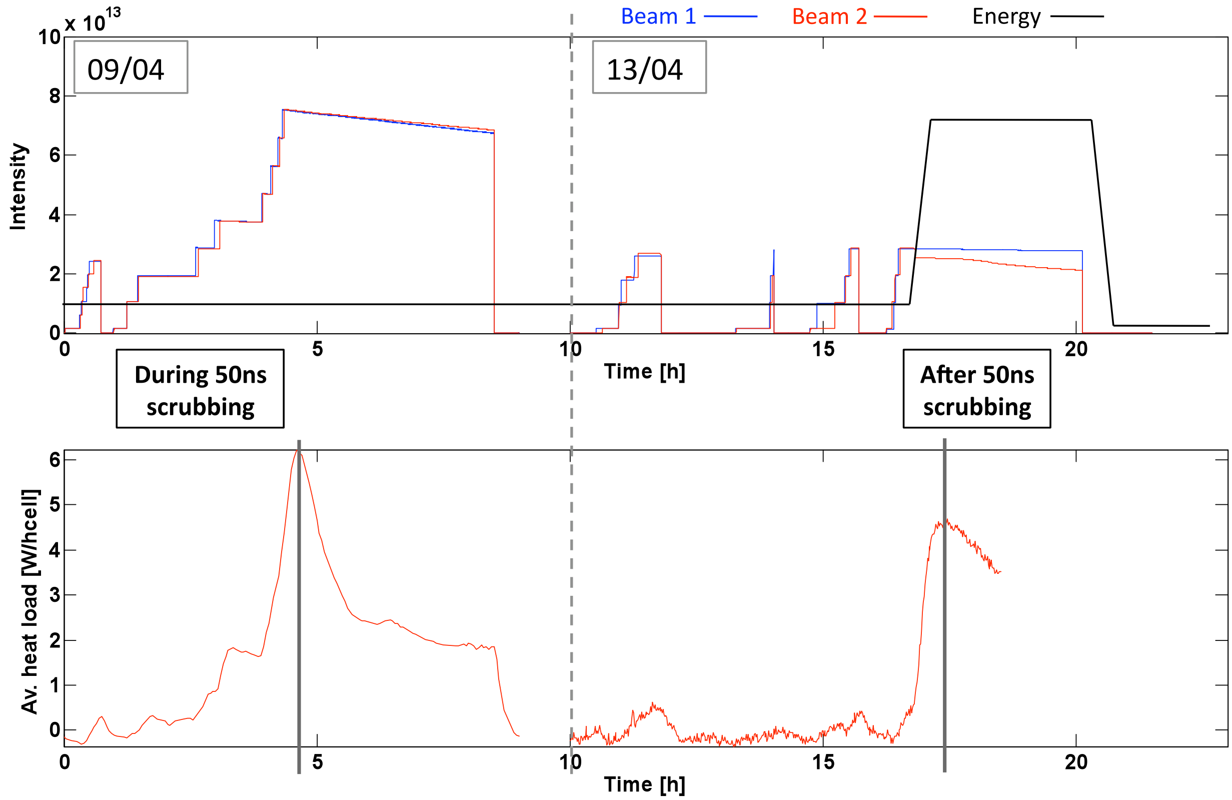

Figure 3: Beams injected into the LHC at the beginning of the scrubbing run (09/04/2011) and during the first physics fill after the scrubbing run (13/04/2011) — top picture — and the heat loads correspondingly measured (bottom picture). The vertical bars represent the measurement points used to compare heat load with electron cloud simulations.

Arcs

In the arcs, the estimation is based on the heat load data from the cryogenic system, which give the total power dissipated (in W/half-cell) on the beam screens of both beams 1 and 2. The exact procedure is explained in Ref. [2] and is based on the comparison of the heat load data with PyECLOUD simulations [15], run with realistic bunch-by-bunch intensities and lengths (data from the fast BCT and the BQM). To estimate the evolution of $\delta_{\rm max}$ during the scrubbing run at 50ns spacing, we used the heat load data from the first LHC fill with 1020 bunches per beam (09/04/2011) and those from the physics fill 1704 of 13 April, 2011 (recorded during the ramp with 228 nominal bunches per beam). Injected beams, beam energy and measured heat loads are plotted in Fig. 3. Using the bunch-by-bunch intensity and length data at the times marked with vertical bars in the bottom plot of Fig. 3, PyECLOUD simulations were run scanning $\delta_{\rm max}$, so that the curves of the simulated heat loads as a function of $\delta_{\rm max}$ could be produced for both measurement points. The electron reflectivity at zero energy was fixed to the value of 0.7. The $\delta_{\rm max}$ corresponding to each heat load measurement was then found matching the simulation to the measured value. In particular, $\delta_{\rm max}$ was estimated to be 2.28 at the last injection of the first analyzed fill and it had already decreased to 2.18 during the ramp of the fill 1704. This is compatible with the known build up thresholds of 2.2 at 450 GeV and 2.1 at 3.5 TeV for 50ns beams [2].

More heat load observations in the arcs have been made with 25ns beams. Measurements in some reference cells from the first LHC MD with 25ns beams (MD session (a), 29 June, 2011) can be found in Ref. [9]. Figure 4 shows the heat load data, sector by sector, collected during the MD sessions (c), (d) and (e). We can notice that the additional heat load peaked to values of nearly 50 W/half-cell (i.e. approximately an average of 0.5 W/m/beam) during the last fill with 2100 bunches for beam 1 and 1020 bunches for beam 2. A decay of the measured heat load between injections, and in any case after the last injection, is also clearly visible in the examined cases and it is due to the weakening of the electron cloud activity from scrubbing and also from intensity loss (compare, for example, with the BCT signal in Fig. 1, acquired at the same time).
The same procedure as for the 50ns beams was applied to estimate $\delta_{\rm max}$ at the measurement points highlighted in Fig. 4, and in addition at the end of the fill of MD session (a) of 29 June. We note that three points are marked with red vertical bars, because they correspond to situations in which the total heat load could be only (or mainly) attributed to beam 2. This gives the opportunity of making a separated estimation of $\delta_{\rm max}$ only for the beam screen of beam 2. We have then collected together the $\delta_{\rm max}$ values matching the heat loads for all the analyzed measurement

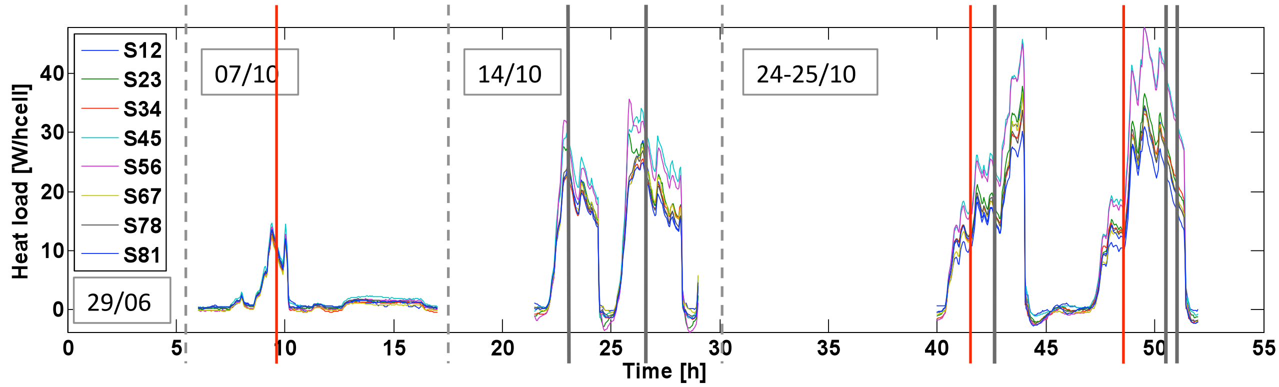

Figure 4: Heat load measured during the MD sessions (c), (d) and (e), in the same time coordinate as in Fig.1. The vertical bars represent the measurement points used to compare heat load with electron cloud simulations. The red vertical bars correspond to the measurement points in which only beam 2 was in the machine.

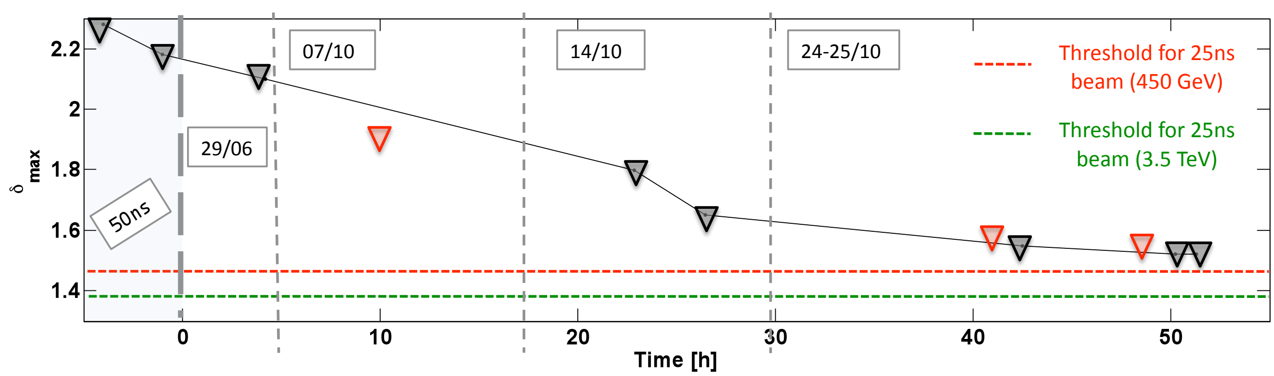

Figure 5: Estimated evolution of $\delta_{\max}$ on the inner surface of the beam screen in the dipole chambers. The first two points correspond to the measurements done with the 50ns beams during and after the scrubbing run, while the other points corresponding to the vertical bars of Fig. 4.

points, i.e. including the two points with 50ns beams (represented at negative times in our convention) as well as the measurement point during the MD session (a) plus all the remaining points shown in Fig. 4. The evolution of $\delta_{\max}$ on the inner surface of the beam screen is drawn in Fig. 5. From this curve we can see that $\delta_{\max}$ was about 2.28 at the beginning of the scrubbing run and then it had already decrased to 2.1 by the time the first 25ns beams were first injected into the LHC. According to the evaluation from the last two measurement points chosen during the same store, the $\delta_{\max}$ has presently decreased to 1.52. Looking at the last three black points in the plot of Fig. 5, it is clear that, while a little scrubbing effect is still observed between the second to last and the last 25ns store, no significant decrease of $\delta_{\max}$ can be detected over the last two points belonging to the same store. This suggests that, although the electron cloud has not yet disappeared from the arcs, the $\delta_{\max}$ has already entered a region in which the electron doses required to continue the scrubbing can be only accumulated over much longer times. The decay of the heat load after the last injection cannot be attributed to scrubbing, but only to beam loss.

The three measurement points with the contribution of beam 2 alone (red in Fig. 5) show that, while it seems plausible that at the beginning of the 25ns MDs the beam screen of beam 2 was more quickly scrubbed than that of beam 1, the conditioning status of the two screens has become later equalized. The last two points for beam 2 can be hardly distinguished from the values obtained from the total heat load.

In Fig. 5 we have displayed the scrubbing curve of the arc chamber along with the threshold values of $\delta_{\max}$ for electron cloud build up with 25ns beams at injection energy (450 GeV) and at the present top energy (3.5 TeV). Suppressing the electron cloud for the 25ns beams will still require a further scrubbing step to decrease $\delta_{\max}$ by approximately 0.18 (to ensure no multipacting at top energy). Another important output of our PyECLOUD simulations is the bunch-by-bunch energy loss per turn, obtained from a simple energy balance for the electron cloud [2]. This quantity can be directly compared with the one estimated from the bunch-by-bunch stable phase shift measurements [16], which in principle show the bunch-by-bunch evolution of the electron cloud along the beam. The best fit for

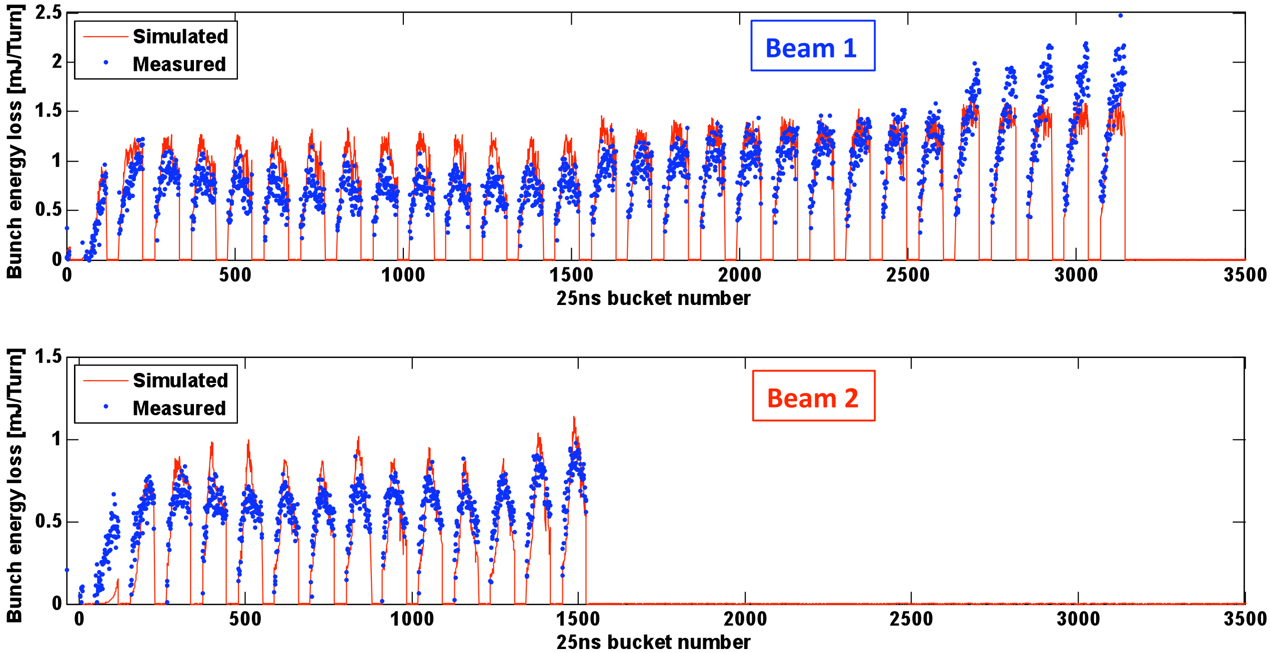

Figure 6: Bunch-by-bunch stable phase shift for beams 1 (top) and 2 (bottom): measurements and simulations.

the measured data has been found with the PyECLOUD simulation for $\delta_{\max} = 1.5$ and a 10% uncaptured beam present in the gaps between trains and also in the abort gap. The resulting plot is shown in Fig. 6 for both beams. The absolute values, as well as both the intra-batch and batch-to-batch trend, seem to be very well caught by the simulation. Furthermore, when zooming on single batches (Fig. 7), we can see that the simulations can successfully reproduce the measurements down to a surprisingly high level of detail.

Beam quality

While the 50ns beam proved to be stabilized in the LHC by the electron cloud mitigation achieved with the scrubbing run, the 25ns beam has exhibited clear signs of transverse instability and emittance growth throughout all the dedicated MD sessions. Despite a clearly improving trend from one fill to the next one, these signs have not completely disappeared. During the first tests on 29 June, when only batches of 24 bunches were injected from the SPS, the beam could be kept inside the machine because the level of electron cloud reached along each batch was enough to cause significant emittance growth, but no coherent instability and fast beam loss [9]. When, on the following MD session, batches of 48 bunches were for the first time transferred from the SPS to the LHC, the beam was twice dumped after few hundreds of turns, due to the excitation of a transverse instability leading to unacceptable beam losses [10]. During the successive MD sessions, this problem was circumvented by injecting the beam into the LHC with high chromaticity settings. Values of $Q'_{x,y}$ around 15 were chosen, as they had been found to be sufficiently stabilizing in HEADTAIL simulations [17]. Using these settings, the beam could be kept in the LHC, although with significant losses and degraded transverse emittances. The observed emittance blow up and bunch-by-bunch lifetimes steadily improved over the 25ns MD sessions, i.e. the effects of the electron cloud on the beam moved later along the train and became less severe from fill to fill [2]. This can be seen, for example, in the color plot showing the bunch-by-bunch losses measured on the 24-25 October MD session, Fig. 8. Figure 9 shows that, despite the improvement, the transverse emittances were still significantly blown up during the last fill of 25 October, 2011. The effect is hardly visible on the first and second 72-bunch batches and becomes dominant only from the fourth batch on. This trend is qualitatively in agreement with the simulated electron cloud build up during this fill, displayed in the bottom plot of Fig. 9.

ESTIMATION OF THE SCRUBBING TIME FOR 25ns OPERATION

Several sets of laboratory data are presently available, which show how the maximum SEY of a surface decreases under the effect of electron bombardment (scrubbing in controlled conditions). For example, Refs. [13, 18] display curves showing the scrubbing of Cu and StSt surfaces after receiving known doses of electrons at different energies (500 eV, 200 eV, 20 eV, 10 eV). These curves are characterized by two distinct regions: an efficient one, in which the SEY lies in a high range of values (depending on the material, e.g. above 1.3 for Cu, above 1.6 for StSt) and the electron doses required to lower it are relatively small; an inefficient one, in which the electron doses

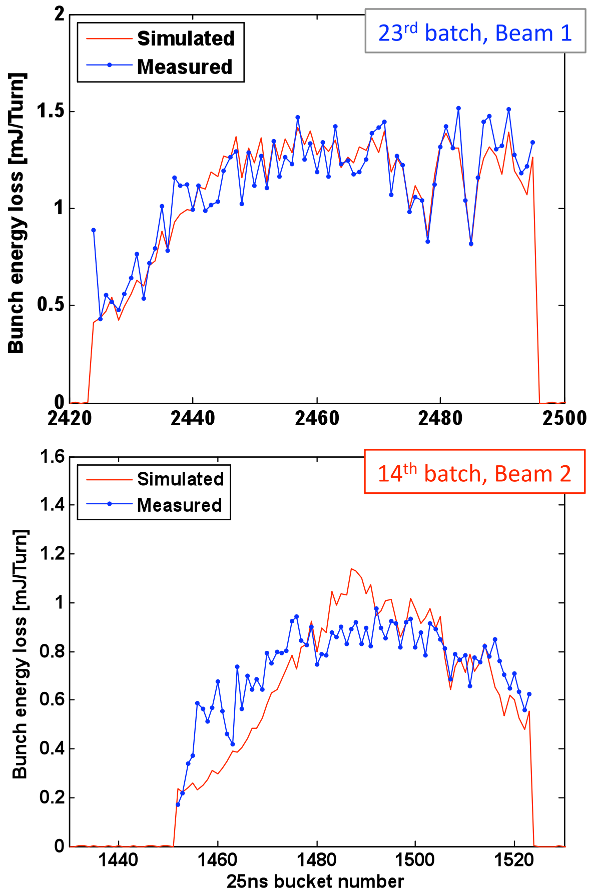

Figure 7: Close up on two selected batches of the bunch-by-bunch stable phase shifts of Fig. 6. Both measurements (blue lines) and simulations (red lines) are displayed in these plots.

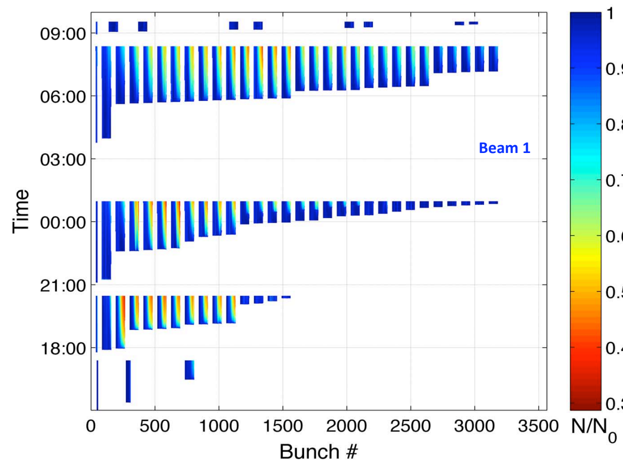

Figure 8: Normalized bunch-by-bunch beam losses measured during the MD session (e).

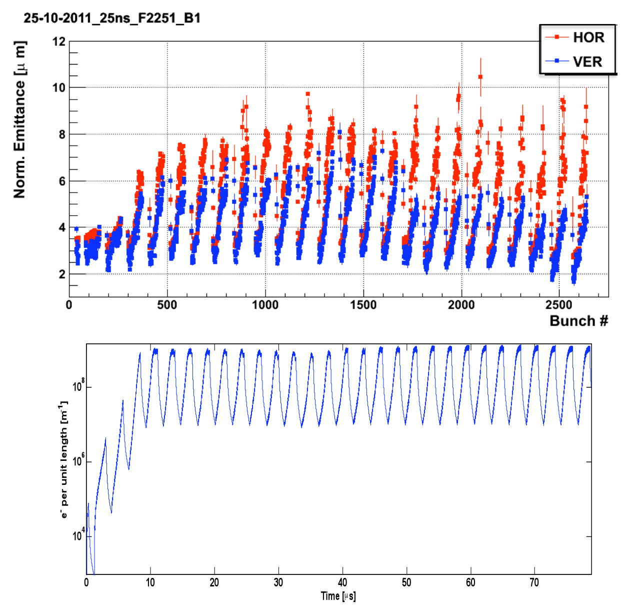

Figure 9: Snapshot of the horizontal and vertical emittance measurements for beam 1 during the last fill of 25 October MD (top plot) and simulated electron cloud build up along the train for the same fill (bottom plot)

required to further lower the SEY exponentially increase. These measured curves, together with PyECLOUD simulations — providing the expected electron flux to the wall and its energy spectrum for a given beam in a given chamber — have been used as the base ingredients to set up a tool to estimate the time needed to scrub the inner surface of a beam chamber.

The starting point of the procedure is the definition of the scrubbing scenario (beam, chamber) and the construction of a curve that shows the electron current density to the wall produced by the chosen beam as a function of the $\delta_{\max}$ of the chamber wall. Usually only electrons above 10 eV are counted in, because lower energy electrons are considered inefficient for scrubbing. For example, to make a prediction of the scrubbing time for the LHC arcs using 25ns beams, we could reasonably assume that the scrubbing beam will have the same structure as the 25ns beam stored during the last 25ns fill. Snaposhots of the bunch-by-bunch intensities and lengths of this beam, captured soon after the last injection, are depicted in Fig. 10. A $\delta_{\max}$ scan of build up simulations using this beam and the LHC arc chamber geometry will then provide the electron current density to the wall for different values of $\delta_{\max}$. Two such curves have been produced for beam 1 and beam 2, and are displayed in Fig. 11. One can see here that the electron current to the wall obviuosly steeply decays when $\delta_{\max}$ approaches its threshold value for the electron cloud build up. This happens at a slightly higher value for beam 2, due to the lower number of bunches.

At this point, we need to first define the initial conditions of the surface in terms of received electron dose and SEY, and then we will have to go iteratively through the following steps:

1. Time $n\Delta t$: The surface has so far received an electron dose $d(n\Delta t)$ and its SEY has reached the value $\delta_{\max}(n\Delta t)$. It therefore produces an electron current density to the wall $J(n\Delta t)$, given by the curve de-

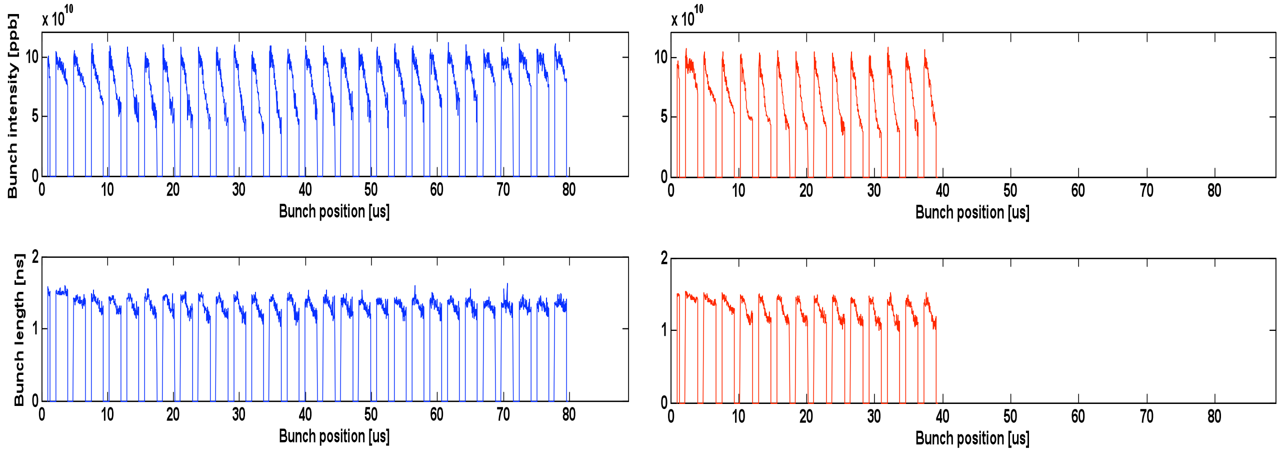

Figure 10: Bunch-by-bunch intensity and full bunch length at the time of the fifth measurement bar in Fig. 4 (following the usual convention, blue plots on the left side refer to beam 1, while red plots on the right side are for beam 2).

picted in Fig. 11.

2. The electron dose can be updated to the next time step: $d[(n+1)\Delta t] = d(n\Delta t) + J(n\Delta t) \cdot \Delta t$

3. The scrubbing curves from the laboratory measurements are used to change consequently the SEY value at the step $(n+1)\Delta t$: $d[(n+1)\Delta t] \rightarrow \delta_{\max}[(n+1)\Delta t]$

4. Time $(n+1)\Delta t$: Back to step 1.

By applying the procedure above and making use of the scrubbing data with 20 eV electrons from R. Cimino [18], we can then fully describe the scrubbing process in the LHC arcs. The reason why we are choosing here to refer to the scrubbing data from 20 eV electrons is that they provide the closest scrubbing evolution to that observed in the machine. The laboratory data with electron energies of 200 or 500 eV would result in extremely fast scrubbing times (in the order of few minutes), while the data with electron energies of 10 eV would give too long scrubbing times. The dynamics of the scrubbing process calculated with the procedure outlined above is then fully described by the three plots of Fig. 12. The top plot shows the decrease of $\delta_{\max}$ with time. As long as we are far enough from the threshold value for electron cloud build up, the scrubbing seems quite efficient. This is because for these SEY values, the scrubbing curve has not yet entered its inefficient region. However, at some point the values tend to saturate to 1.45 and 1.48 for beam 1 and beam 2, respectively, because the electron cloud production steeply drops at these $\delta_{\max}$ values (see Fig. 11) and the scrubbing effectively stops. In the middle plot we can see the evolution of the heat load with time. This shows that in practice scrubbing ends when there is no measurable heat load left (having assumed the same type of beam all along the scrubbing process). The bottom plot finally displays the maximum electron cloud line density as a function of time. This number is directly related to the maximum central density of the electron cloud seen by some of the bunches and can be seen as the driving term for coherent instabilities or emittance growth. By the time we consider the scrubbing process concluded, we can see that the electron density has actually only decayed by about a factor 10 and not by several orders of magnitudes, as we could have expected for a full suppression. This fact unveils another interesting aspect of scrubbing, i.e. the process stops when the scrubbing beam is not able anymore to produce an electron cloud that saturates over at least one of the batches. This means that, even after scrubbing, the electron cloud can still exhibit an exponential rise inside the beam chamber, but its values remain significantly below its theoretical saturation value. In this situation, we can expect that the heat load has disappeared, the pressure rise has also become negligible and most probably coherent instabilities are not excited, but incoherent effects of emittance growth can still affect the last bunches of each batch.

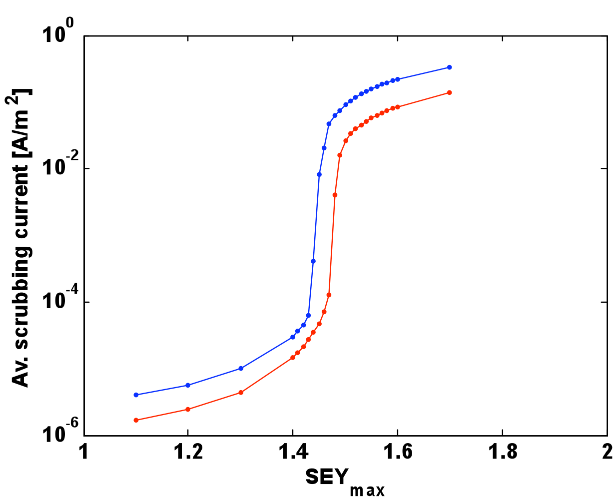

Figure 11: Calculated electron current density to the wall as a function of the $\delta_{\max}$ of the chamber wall. The two curves have been calculated for beam 1 (blue) and beam 2 (red), as previously shown in Fig. 10

Furthermore, the accelerator would be running now at the limit for electron cloud build up, so that a small change in some key parameters, like number of bunches and gaps, bunch shortening or increase of the seed electrons (e.g. ramping the beam energy to 3.5 TeV and producing photoelectrons) could revive the electron cloud build up and its related detrimental effects. This was observed for example with the 50ns beams, when the arcs became sufficiently scrubbed for the beam at 450 GeV, but then there was a sudden return of the electron cloud phenomena (instability, heat load) during the first ramp to 3.5 TeV. Figure 12 also explicitly shows the scrubbing times to lower $\delta_{\max}$ from:

- 1.7 to 1.52 $\rightarrow$ The scrubbing simulation takes about 2h for beam 1, while it can be estimated that it took 3h of equivalent beam 1 time in the LHC, based on the scrubbing history shown in Fig. 5. This suggests that the scrubbing model we are applying is probably quite close to reality, but it may be still underestimating the real scrubbing time by about 50%;
- 1.52 to 1.45 for beam 1 $\rightarrow$ This takes an additional 9h in this model;
- 1.52 to 1.48 for beam 2 $\rightarrow$ This takes an additional 8h in this model.

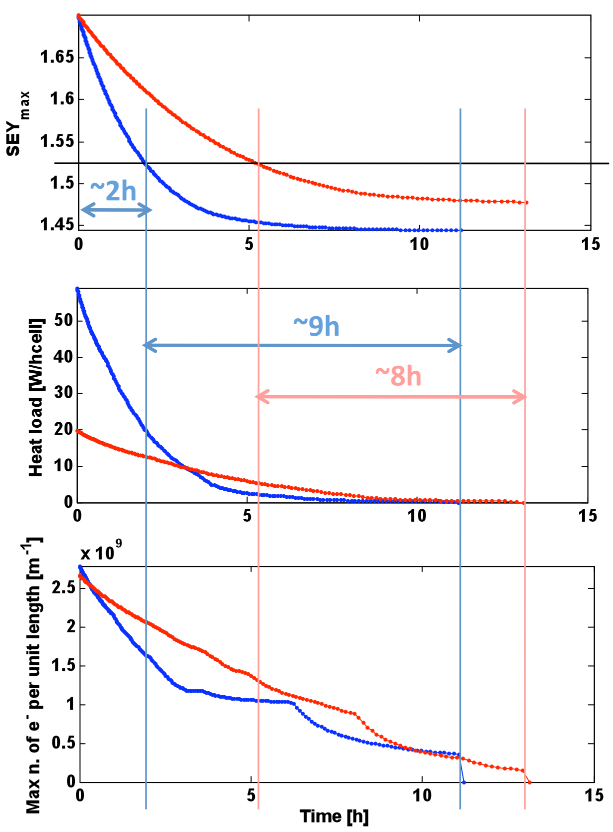

Figure 12: Scrubbing process: $\delta_{\max}$ (top), heat load (middle) and electron line density (bottom) are plotted as a function of time (in hours).

Therefore, including the aforementioned 50% underestimation and allowing for some margin, we can assume that 20h beam time can be regarded as sufficient to scrub the arcs of LHC with 25ns beams. This number of hours translates then into about two weeks machine time, if we also consider the time to inject the maximum number of bunches with the shortest gaps for both beam 1 and beam 2 (including the time for the set up of the injection of 72-144-216-288 bunches) and running then a few test ramps with increasing number of bunches for the completion of the scrubbing process [19].
It is worth mentioning at this point that a possible source of error in the estimation of the scrubbing time comes from the uncertainty on the absolute values of $\delta_{\max}$, due to the assumption $R_0 = 0.7$. In fact, while we are confident in the reported 1% precision in relative terms between the $\delta_{\max}$ values in Fig. 5, the absolute values might actually all shift up or downwards due to a different value of R_0. Any shift upwards for lower values of R_0 would result into even lower scrubbing times, because we would move to the most efficient part of the scrubbing curves. On the contrary, a shift downwards could have an adverse effect on the scrubbing times. For instance, if we had assumed $R_0 = 1$, the 25 ns scrubbing of the arcs would have gone from $\delta_{\max} = 1.8$ on 29 June to $\delta_{\max} = 1.45$ on 25 October, with threshold values of 1.35 at 450 GeV and below 1.3 at 3.5 TeV. The shape of the scrubbing curves of Cu found in literature suggests that this would not have a dramatic impact on the estimated scrubbing time. However, if absolute values turned out to be lower yet, due to some other memory mechanism neglected in the heat load analysis (e.g. the uncaptured beam needed to match the bunch-by-bunch energy loss measurements), we could then quickly end up in the inefficient region of the scrubbing curves, with the uncomfortable consequence that the estimated scrubbing time would become significantly longer.

CONCLUSIONS

The LHC did not exhibit signs of electron cloud build up during the 75ns physics run at the beginning of 2011. Later on, several electron cloud indicators made a short appearance with 50ns beams and came back decisively only with 25ns beams. Thanks to both pressure rise and heat load data, the evolution of $\delta_{\max}$ in 2011 (i.e. over the scrubbing run with 50ns beams and the five 25ns MD sessions) could be fully reconstructed in both the arcs and uncoated straight sections. The present status of the machine is summarized in Table 1, in which the threshold values for electron cloud formation with 25ns and 50ns beams are also reported.

The achieved values of $\delta_{\max}$ are certainly low enough as to ensure electron cloud free operation with nominal 50ns beams. PyECLOUD simulations of 50ns beams with higher charges per bunch have also been carried out and show that stable operation with respect to electron cloud should also be guaranteed in the full intensity range targeted for 2012 (i.e. up to 1.8×10^{11} ppb).

Table 1: Estimated and threshold $\delta_{\max}$ values in the uncoated straight sections and in the arcs.

	Uncoated straight section	Arc dipoles
Estimated $\delta_{\max}$	1.35	1.52
Threshold $\delta_{\max}$ (25ns, 450 GeV)	1.25	1.45
Threshold $\delta_{\max}$ (25ns, 3.5 TeV)	1.22	1.37
Threshold $\delta_{\max}$ (50ns, 450 GeV)	1.63	2.2
Threshold $\delta_{\max}$ (50ns, 3.5 TeV)	1.58	2.1

Beams with 25ns spacing still produce significant electron cloud in the LHC, as their build up threshold values of $\delta_{\max}$ are lower than those currently achieved. Therefore, they are also affected by detrimental processes like coherent instabilities and emittance growth, which lead to fast degradation of the beam quality. Additionally, the energy loss due to the electron cloud is also still present and measurable through the stable phase shift. Further scrubbing is required to suppress the electron cloud with this type of beams. Using a simplified model based on PyECLOUD simulations and laboratory data from controlled scrubbing experiments, we have estimated the scrubbing time necessary to prepare LHC for 25ns physics operation. It turns out that the total 25ns beam time required to suppress the heat load and reduce the electron cloud density by about one order of magnitude is in the order of 20h. This realistically translates into about 2 weeks machine time to ensure the efficiency of the scrubbing in the final desired running conditions (i.e. with the maximum number of bunches in both beams, injected in batches of 288 bunches from the SPS, and after ramping the energy to 3.5 TeV).

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REFERENCES

[1] Proceedings of the Mini Workshop on Electron Cloud Simulations for Proton and Positron Beams, **ECLOUD'02**, 15–18 April, 2002, CERN, Geneva, Switzerland, edited by G. Rumolo and F. Zimmermann, CERN-2002-001

[2] G. Rumolo *et al.*, in Proceedings of the LHC Beam Operation Workshop - Evian 2011 (12-14 December, 2011, Evian, France)

[3] G. Arduini *et al.*, CERN-ATS-Note-2011-046 MD (2011)

[4] V. Baglin, private communication

[5] G. Rumolo *et al.*, THOBA01 in proceedings of IPAC'11 (San Sebastian, Spain)

[6] G. Bregliozzi *et al.*, in Proceedings of the LHC Beam Operation Workshop - Evian 2011 (12-14 December, 2011, Evian, France)

[7] V. Baglin *et al.*, elsewhere in these proceedings.

[8] L. Tavian, "Beam Induced Heating Assessment on LHC Beam Screens" in LHC Beam Operation Committee (LBOC) meeting, 27/09/2011

[9] B. Goddard *et al.*, CERN-ATS-Note-2011-050 MD (2011)

[10] H. Bartosik and W. Höfle, CERN-ATS-Note-2012-027 MD (2012)

[11] R. Cimino *et al.*, Physics Rev. Lett. **93**, 014801 (2004)

[12] F. Le Pimpec *et al.*, SLAC-TN-04-046 LCC-0146 (2004)

[13] C. Yin Vallgren, Ph.D. thesis, CERN-THESIS-2011-063 (2011)

[14] O. Dominguez *et al.*, TUPZ015 in proceedings of IPAC'11 (San Sebastian, Spain)

[15] G. Iadarola, "PyECLOUD", in Electron Cloud Simulations Meeting, 28/11/2011

[16] J. Esteban-Müller, "RF Observations: Stable Phase Measurements" in LHC Beam Operation Committee (LBOC) meeting, 12/04/2011

[17] K. Li and G. Rumolo, MOPS069 in proceedings of IPAC'11 (San Sebastian, Spain)

[18] R. Cimino, "A surface study on the origin of SEY reduction on accelerator walls", in Electron Cloud Simulations Meeting, 29/07/2011

[19] G. Arduini *et al.*, elsewhere in these proceedings