ELECTRON CLOUD AND SCRUBBING: PERSPECTIVE AND REQUIREMENTS FOR 25 ns OPERATION IN 2015

G. Iadarola* and G. Rumolo (CERN, Geneva)

Abstract

In order to routinely operate the LHC with 25 ns bunch spacing during Run 2, electron cloud effects will have to be mitigated through beam induced scrubbing. Therefore, the Run 1 experience with 25 ns beams will be reviewed and used for defining the most effective scrubbing strategy. In particular, the potential of using a dedicated scrubbing scheme based on the "doublet" beam, following the promising SPS tests in 2012, will be described and analysed. The impact of this scheme on the LHC equipments and machine protection will be discussed. The different stages of the scrubbing process, including the high energy tests, will be outlined in terms of beam requirements and expected duration. To conclude, possible alternatives of post-scrubbing scenarios will be also considered, which will depend on the degree of success of the scrubbing run.

BRIEF SUMMARY OF ELECTRON CLOUD OBSERVATIONS IN LHC RUN 1

The electron cloud observations in the LHC during Run 1 are of high importance to define the roadmap after the LHC start up in 2015. Before 2011, while LHC was producing physics with 150 ns spaced beams, electron cloud effects could be mainly seen in the interaction regions when both beams were circulating in the machine. Only when 50 and 75 ns spaced beams were first injected into the LHC, electron cloud effects became visible with single beam. In 2011, the LHC evidently suffered from electron cloud both at the beginning of the 50 ns run and then later, during all the machine study sessions with 25 ns beams. An initial scrubbing run with 50 ns beams, which took place at the beginning of April 2011 [1], could scrub the beam chambers just enough as to allow the LHC to move into physics with 50 ns beam and guarantee safe operation at both 450 GeV and 3.5 TeV. Further scrubbing was later achieved by using trains of 25 ns beams. The first injection attempts of this type of beams were hindered by severe electron cloud effects in terms of heat load in the arc screen, emittance growth of the bunches located at the tails of 24-bunch trains [2] and coherent instabilities at the tails of 48-bunch trains leading to dumps due to fast beam losses or large orbit excursions [3]. As LHC got gradually further scrubbed, 72-bunch trains of 25 ns beams could be injected with high chromaticity settings, reaching 2100 bunches for Beam 1 and 1020 for Beam 2. Though initially these beams suffered heavy degradation from electron cloud, a considerable amount of additional scrubbing could be achieved. The maximum Secondary Electron Yield (SEY or $\delta_{\rm max}$), on the screen of the arc dipoles, as estimated from PyECLOUD simulations, decreased from a value of about 2.1 at the end of the 50 ns scrubbing run to 1.5. By the end of 2011, trains of 72 bunches with 25 ns spacing exhibited much reduced degradation with respect to the first injections, although both their lifetime and emittance evolution still indicated the presence of a significant amount of electron cloud in the LHC [4]. The top plot of Fig. 1 shows the calculated electron cloud induced heat load in the arc dipole screen as a function of $\delta_{\rm max}$ for both 25 and 50 ns beams. From the two curves it is clear that, while a $\delta_{\rm max}$ value of 2.1 can be sufficient to ensure low electron cloud operation with 50 ns beams, the achieved value of 1.5 is still not enough as to completely suppress the electron cloud in the arc dipoles with 25 ns beams.

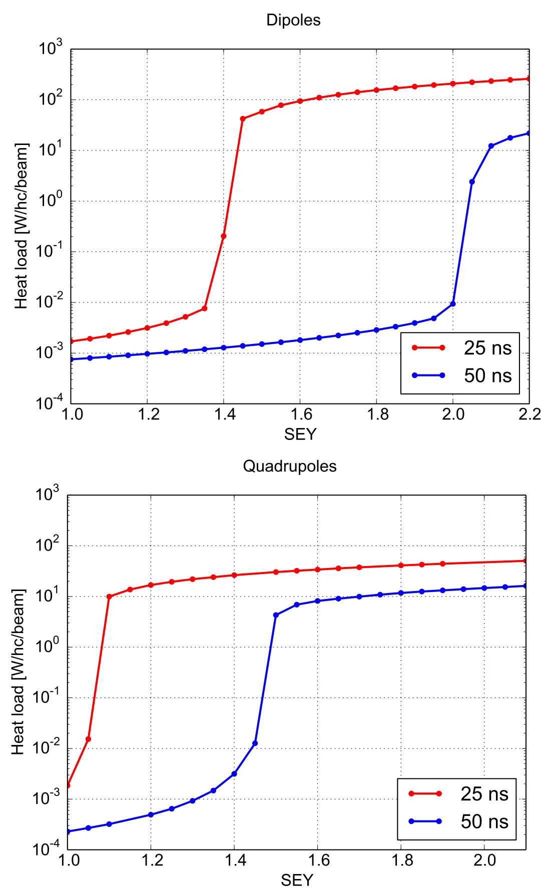

Figure 1: Calculated electron cloud induced heat load on the arc screen (top: dipole, bottom: quadrupole) as a function of $\delta_{\rm max}$ for both 25 (red)and 50 ns (blue) beams.

The bottom plot of Fig. 1 depicts the calculated electron cloud induced heat load on the arc quadrupole screen as a function of $\delta_{\rm max}$ for both 25 and 50 ns beams. Due to the length ratio between arc dipoles and quadrupoles (≈15), as

* Giovanni.Iadarola@cern.ch

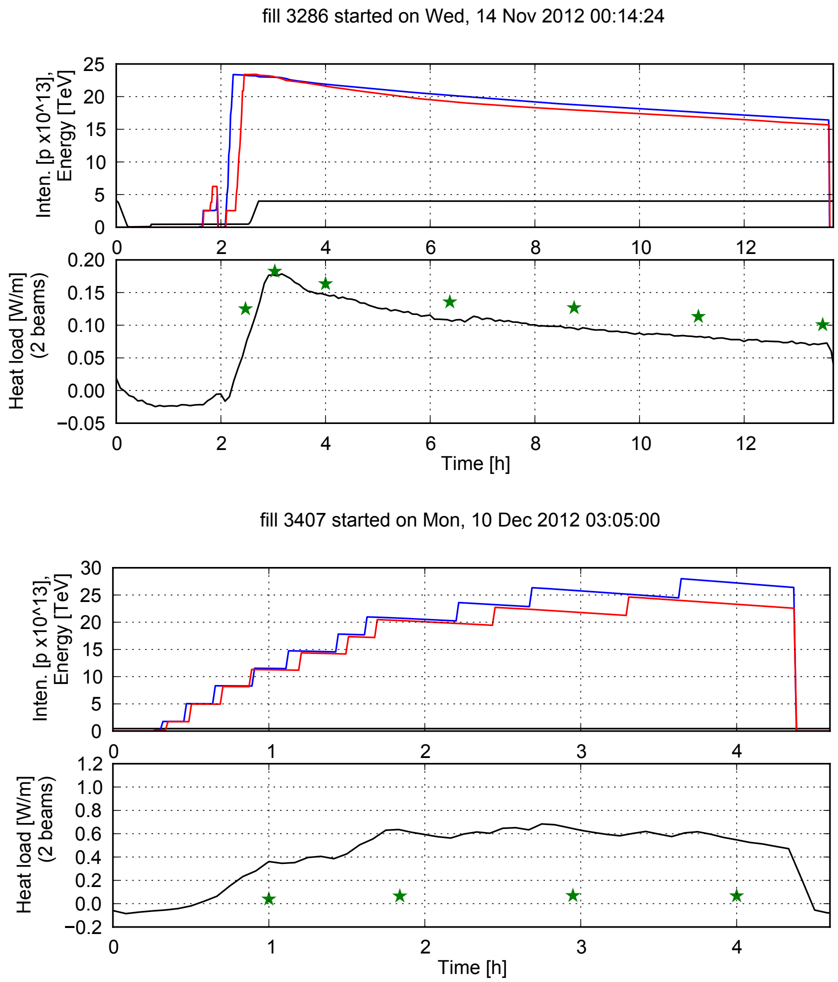

Figure 2: Top plot: Typical 50 ns fill with measured heat load in the arc beam screen and calculated values from the beam screen impedance model (green stars). Bottom plot: Scrubbing fill with 25 ns beam with measured heat load in the arc beam screen and calculated values from the beam screen impedance model (green stars).

long as the electron cloud in the dipoles is strong enough, the dominant contribution seen in the measured heat load comes from the dipoles and no conclusion can be made on the $\delta_{\max}$ of the quad screens. The quadrupole heat load becomes significant in the balance only when the $\delta_{\max}$ of the dipole screen has reached down the knee of the heat load curve (i.e. for values below 1.5 with 25 ns beams).

Thanks to the margin gained with the 25 ns beams in 2011, operation with 50 ns in 2012 was smooth and electron cloud free. It was only during the scrubbing run in December 2012, when the LHC was filled with 25 ns beams (up to 2748 bunches per beam) and reached the record intensity of 2.7×10^{14} p stored per beam, that heat load, emittance growth at the tails of the trains and poor beam lifetime indicated again the presence of a strong electron cloud with this mode of operation. However, a clear improvement in the electron cloud indicators over the first 70 hours was observed, followed by a sharp slow-down of the scrubbing process. The emittances of the bunches at the tails of the trains were blown up during the injection process, especially for sufficiently long bunch trains. The electron cloud continued to be present also during a few test ramps to 4 TeV and the two days of pilot 25 ns physics run and exhibited an important dependence on energy. A detailed summary of the observations and our present degree of understanding is presented in [5] summarized the next sections.

LESSONS LEARNT IN RUN 1

Both the MDs with 25 ns beams in 2011 and a relatively little deconditioning over the 2011-2012 end-of-year technical stop (EYTS) were the basic reasons why the LHC could be operated with 50 ns beams throughout the 2012 proton-proton run without electron cloud in the arcs [6]. This can be concluded from Fig. 2, top plot, which displays the evolution of the heat load in the arc screen measured during a typical 50 ns physics fill (solid black line) together with the calculated values of power loss obtained summing the contribution from impedance and that from synchrotron radiation (green stars). The agreement within less than 10% between calculated and estimated values shows that in this case no additional contribution to the heat load of the arc beam screen is expected from electron cloud. However, when the 25 ns beam was injected into the LHC in 2012 (notably during the scrubbing run, 6 – 8 December, 2012), the electron cloud returned, which manifested in a heat load in the arcs becoming one order of magnitude larger than the values expected from the theoretical calculation based on impedance and synchrotron radiation. This is depicted in the bottom plot of Fig. 2, in which both the measured and calculated heat loads are plotted for a typical 25 ns scrubbing fill.

Distribution of electron cloud in the LHC arcs

As was mentioned in the introduction, a decreasing trend in the measured heat load as well as an improvement of the beam quality and lifetime were observed in the first part of the 2012 scrubbing run, while any improvement tended to become marginal in the later scrubbing phases [6]. This observation suggested that the process of beam scrubbing was saturating in the arcs, in the sense that any further little improvement would require increasingly longer running times with 25 ns beams.

Based on the simulated heat load curves in dipoles and quadrupoles shown in Fig. 1, an attempt was made to interpret the observed saturation of the scrubbing process and thus envisage possible solutions for Run 2. In particular, assuming the different SEY thresholds in dipoles and quadrupoles discussed above, the behaviour of the electron cloud evolution during the scrubbing run could be compatible with the following scenario:

1. The SEY in the dipole beam screen might be coming asymptotically closer to the threshold value for electron cloud build up leading to indeed much lower electron cloud in the dipole chambers, but not yet full suppression;

2. The SEY in the quadrupole beam screen, though probably scrubbed to a similarly low value as the dipole one, is still high enough to cause strong electron cloud in the quadrupole chambers.

Since in the arc cells it is not possible to disentangle the contribution to the heat load given by the dipole chamber (total length 14.2 m$\times$3 per half cell) from that given by the quadrupole chamber (total length 3 m per half cell), the only way to have an indication on the plausibility of the above scenario is to look into the heat load in the so-called Stand Alone Modules (SAM). These include several matching quadrupoles and separation dipoles situated the Insertion Regions (IRs). Several matching quadrupoles have their own cooling circuits and their heat loads can be independently evaluated. The separation dipoles D3 at left and right of point 4 (D3L4 and D3R4) are the only dipoles to be equipped with independent cooling circuits. Other matching quadrupoles are paired with the close-by separation dipoles in one single cooling circuit. These are called semi-SAMs and their heat load would still come from the combination of a dipole and a quadrupole (though with different length ratio than in the arcs). A full inventory of SAMs and semi-SAMs in the LHC can be found in [7].

Figure 3 shows the evolution of the heat load per unit length at the beam screen of the matching quads Q5's (taking the average of the values measured in Q5 left and right of points 1 and 5) and that at the beam screen of the separation dipoles D3's (taking the average of the values measured in D3 left and right of point 4) over a 25 ns fill towards the end of the scrubbing run.

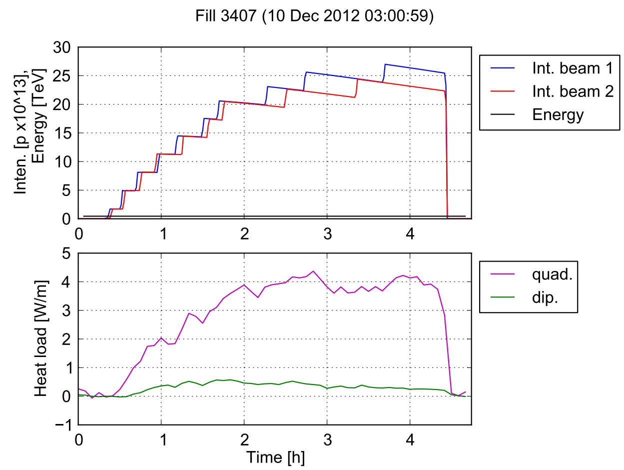

Figure 3: Heat load per unit length (W/m) measured in the matching quadrupoles Q5 on both sides of the IRs 1 and 5 (purple, average among the four magnets) and in the separation dipoles D3 of the IR 4 (green, average between the two magnets) over one of the last fills of the 2012 scrubbing run. Beam currents for both beams are shown in the upper plot.

This plot strongly supports the scenario presented above. First of all, the specific heat load in the quadrupole beam screen exceeds by over one order of magnitude that in the dipole beam screen. Considering the factor about 15 difference in length, this would translate in basically equivalent contributions to the heat load from the dipoles and the quadrupole in an arc half cell. Secondly, the heat load in the dipoles exhibits a decay with the beam degradation even despite new injections, while that in the quadrupoles hardly decreases with deteriorating beam conditions. This suggests that, while the SEY of the dipole beam screens could be close to the electron cloud build up threshold value, that of the quadrupole beam screens is still far from it. The scenario of an electron cloud close to suppression in the dipoles at 450 GeV means that an electron cloud enhancing technique could be applied to achieve full scrubbing in the dipoles (see following section on the doublet beam), although a significant amount of electron cloud could still survive in the quadrupoles.

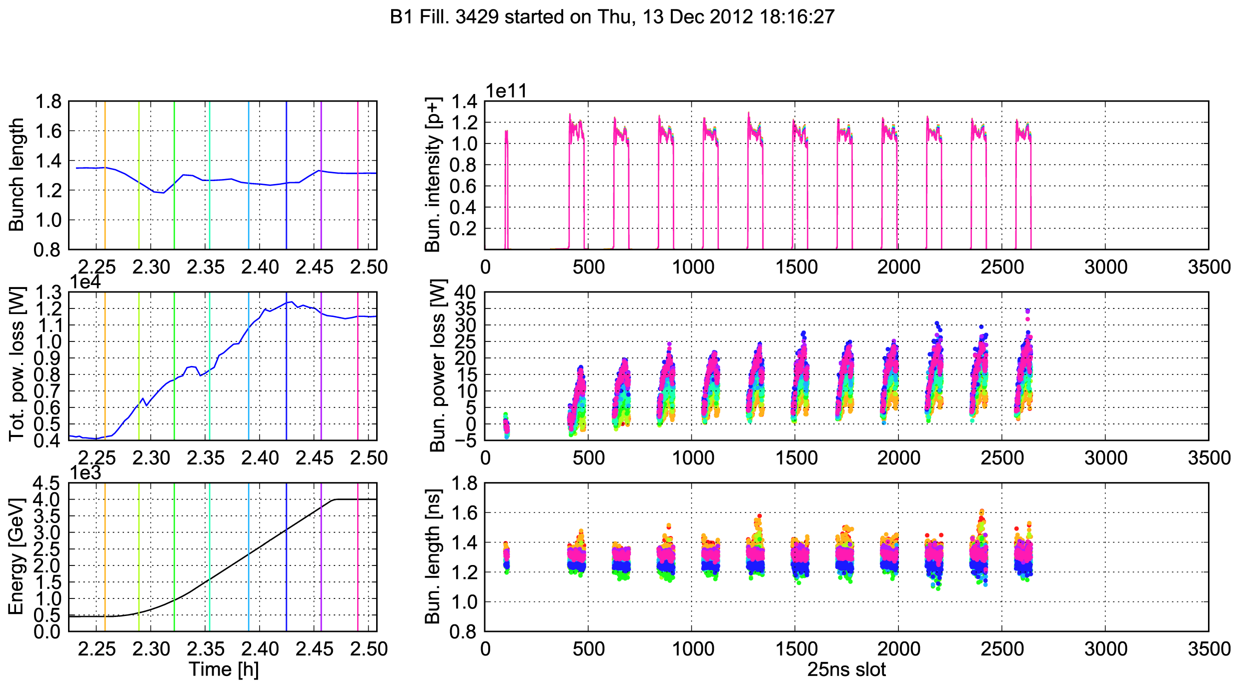

Figure 4: Beam energy and bunch-by-bunch energy loss measurements for beam 1 during the energy ramp of a fill with about 800 bunches with 25 ns spacing. The different traces in the right plot correspond to different times indicated by vertical bars in the left plot.

Energy dependence of the electron cloud in the arcs and effect on the beam

After the 2012 scrubbing run, increasing numbers of bunches of 25 ns beam were ramped to 4 TeV over several subsequent fills. Both heat load in the arcs and beam energy loss measurements from the bunch-by-bunch synchronous phase shift [8] showed a sharp increase over the ramp, which would be consistent with a growing electron cloud with the beam energy. An example of beam energy loss behaviour for an energy ramp with 800 bunches distributed in equally spaced trains of 72 bunches is fully displayed in Fig. 4. The plots on the left side share the same time axis and represent, from bottom to top, the energy ramp, the sum of the bunch-by-bunch energy loss as estimated from the synchronous phase shift and the average bunch length. At the eight time cuts highlighted with coloured vertical bars, on the right hand side the snapshots of the bunch-by-bunch intensity, energy loss and bunch length are depicted from top to bottom using the same colour convention. A steady increase of beam energy loss, which reveals an increasing electron cloud activity, is clearly visible along the energy ramp. One possible explanation of this behaviour is that the electron cloud enhancement is first triggered by the bunch shortening occurring at the beginning of the ramp and is later sustained by the photoelectrons, whose rate of production becomes significantly higher than that due to gas ionisation only at around 2 TeV. The fact that the electron cloud is most likely responsible for this increase is also confirmed by the snapshots of the bunch-by-bunch energy loss along the ramp. The bunches suffering the highest enhancement of energy loss are those located towards the end of each bunch train, while those at the beginning of the trains even at 4 TeV keep losing the same amount of energy as at 450 GeV. The pattern of the energy loss is also reminiscent of an electron cloud build up with the rise over one train to a defined saturation value and basically little memory between trains (only visible in the slower rise of the first train, probably due to the electron cleaning effect of the 12-bunch train). Hardly any sign of beam loss or anomalous lengthening or shortening for selected bunches can be spotted along the ramp, which leads to the encouraging conclusion that the enhanced electron cloud, probably thanks to the increasing beam energy, is not detrimental to the beam (although it is responsible for a fourfold increase of the heat load in the arcs).

One question concerning the electron cloud enhancement over the energy ramp is again whether it is localised in some specific elements of the LHC. In principle, a way to determine its distribution would be applying a similar approach to that shown in the previous section to disentangle the contributions to heat load from dipoles and quadrupoles in the arcs. Figure 5 shows the evolution of the heat load per unit length at the beam screen of the matching Q5's (average of the values measured left and right of points 1 and 5) and that at the beam screen of the separation dipole D3's (average of the values measured left and right of point 4) over the injection and ramp phases of the 25 ns fill already discussed for Fig. 4. It is clear that, while at 450 GeV the heat load in the quads is more than one order of magnitude larger than the one in the dipoles, the ramp causes an enhancement of the heat load only in the dipoles. This is not surprising, because the SEY in the dipoles is close to

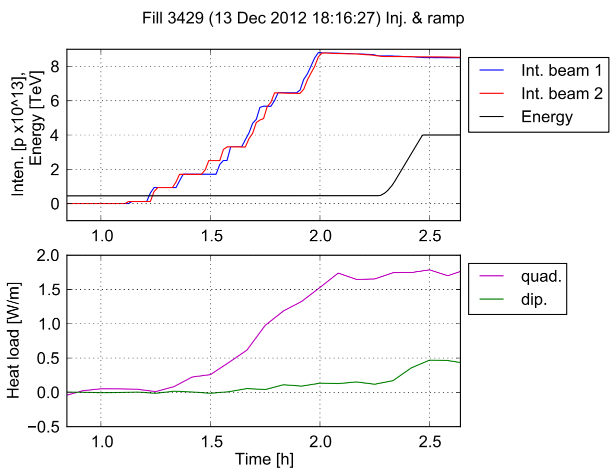

Figure 5: Heat load measured in the matching quadrupoles Q5 on both sides of the IRs 1 and 5 (purple, average among the four magnets) and in the separation dipoles D3 of the IR 4 (green, average between the two magnets).

the build up threshold and the electron cloud there is most sensitive to the bunch shortening and/or enriched seeding from photoelectrons, while these effects would play only a marginal role if the SEY had been far above this threshold (e.g. in the quadrupoles). At 4 TeV, the specific heat load measured in D3 becomes only about one third of that measured in the quadrupoles. By merely applying these values to the arc dipoles and quadruples, and scaling by their lengths, one finds that, while at 450 GeV arc dipoles and quadrupoles would contribute about equally to the measured heat load, at 4 TeV the integrated contribution of the dipoles becomes again dominant and at least fivefold that of the quadrupoles. The fact however that this heat load remains then nearly constant over the whole fill duration (8 hours of 4 TeV store) [5, 6] also indicates that the SEY of the dipole screen has entered a region in which the increase of scrubbing flux associated to the electron cloud enhancement is not sufficient to impart a significant acceleration to the scrubbing process.

The beam behaviour at 4 TeV has been analysed through the evolution of the bunch-by-bunch transverse emittance over the stores of 25 ns beams. The store discussed above in this subsection was not a physics fill and the beams were not squeezed nor brought into collision. Therefore, the only emittance measurements available at 4 TeV for this store were those from the Beam Synchrotron Radiation Telescope (BSRT), which unfortunately worked only for Beam 1 at the time of the 2012 scrubbing run. A look at the snapshots taken over the eight hours during which the beam was stored in the LHC reveals that only a small emittance growth can be measured, affecting uniformly all bunches of the train and therefore not ascribable to electron cloud effects [6]. Later on in the 2012 run, three physics fills with 25 ns beams took place. For these fills, the bunch-by-bunch emittance evolution could be reconstructed from the luminosity in ATLAS and CMS, providing a very reliable measurement all over the whole length of the physics store. A very interesting case was the last physics fill of the 25 ns pilot physics run, with 396 bunches per beam distributed in trains of 2 × 48 bunches collided for over six hours. Figure 6 shows seven snapshots of the bunch-by-bunch emittances from the moment of declaration of stable beams (time 0h) to six hours later (6h). The emittance pattern over the trains clearly exhibits the imprint of the electron cloud, with typically growing emittances towards the tails of the trains. The zoom on the second train displayed in the picture, however, allows us to spot even more interesting features of the emittance distribution and its evolution. Firstly, the electron cloud patten is present already from the first snapshot (i.e. at time 0h), meaning that the shape was created at injection energy (this could be also confirmed by means of BSRT measurements on Beam 1). Secondly, the emittance growth over the fill duration is such that the electron cloud pattern tends to even out, which suggests a blow up rate that is larger for the first bunches of the trains (with lower initial emittances) and lower for those at the tails (with higher initial emittances). This observation is consistent with an emittance growth mechanism at 4 TeV certainly different from electron cloud and emittance dependent. To summarise, the available 2012 beam observations seem to point to the electron cloud as a fast degrading effect for the beam at 450 GeV but not the main determinant of the beam quality at 4 TeV.

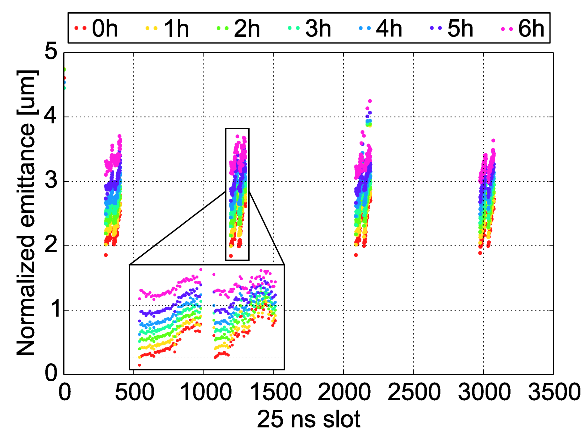

Figure 6: Bunch-by-bunch transverse emittances estimated from luminosity at the ATLAS experiment during a fill with 396 bunches with 25 ns spacing. Different traces correspond to different moments during the store.

Extrapolation to 2015 beam parameters

Before describing the roadmap of the 2015 scrubbing run, which should enable operation of LHC at 6.5 TeV with 25 ns beams, it could be useful to extrapolate the expected heat load in the arcs in 2015 if we run in the same conditions as we had after the 25 ns scrubbing run of December 2012. This exercise is fully summarised in Table 1.

The reference fill for this extrapolation is the one of eight hours with 800 bunches in trains of 72, which was dis-

	Measured in 2012 with 800 b. at 4 TeV	Rescaled to 2800 b.	Effect of tighter filling scheme	Effect of higher energy (6.5 TeV)
Dipoles	40 W/hcell	(×3.4) 136 W/hcell	(×2) 272 W/hcell	(×1.6) 435 W/hcell
Quadrupoles	5 W/hcell	(×3.4) 17 W/hcell	(×1) 17 W/hcell	(×1) 17 W/hcell
Total	45 W/hcell	153 W/hcell	289 W/hcell	450 W/hcell

Table 1: Expected distribution of the heat load in the arc dipoles and quadrupoles for the 25 ns 8 hours store with 800 bunches (reconstructed from 2012 measurements in the first column, rescaled to full machine in the second column, rescaled for the packed filling scheme in the third column and rescaled to 6.5 TeV in the fourth column)

cussed in the previous subsection. Assuming that the measured heat load in the arcs of 10 W/(half cell) after the end of the injection of both Beam 1 and Beam 2 is attributable in equal parts to dipoles and quadrupoles and that the increase to 45 W/(half call) with the ramp only comes from the dipoles, one can conclude that, after the scrubbing of December 2012, the heat load of 800 bunches at 4 TeV would be distributed 11% on the quadrupole beam screen (5 W/(half cell)) and the remaining 89% on the dipole beam screen (40 W/(half cell)). To extrapolate to 2015, we need to first rescale both these numbers by 2800/800 to account for the increased number of bunches (full machine). Then, we can further apply a factor 2 to the value in the dipoles as an effect of the more packed filling pattern and a factor 1.6 as an effect of ramping to 6.5 TeV instead of 4. For the quadrupoles, given the experience of 2012, we would expect neither the filling scheme nor the beam energy to significantly affect the electron cloud build up (heat load scaling factor 1). Table 1 shows that, after applying these scalings and regrouping together the heat load from dipoles and quadrupoles with full machine at 6.5 TeV, we find a value of 450 W/(half cell), which exceeds by almost a factor three the available cooling power of 160 W/(half cell) available in the LHC at 6.5 TeV.

In conclusion, even assuming that we can live with the beam degradation induced by electron cloud at injection, it would be impossible to fill LHC with a standard 25 ns beam, because the cryogenic system would not have enough power to cope with the induced heat load in the arcs. A strategy to achieve more scrubbing of the dipole beam screens (ideally, full suppression of the electron cloud in the dipoles) is therefore necessary to guarantee 25 ns operation for the LHC during Run 2.

SCRUBBING IN 2015

The experience of LHC Run 1 has shown that the electron cloud can potentially limit the achievable performance with 25 ns beams mainly through both beam quality degradation (transverse emittance blow-up, poor lifetime) at low energy and intolerable heat load on the arc beam screens at high energy. To avoid this scenario, a scrubbing program aiming at a significant mitigation (ideally, suppression) of the electron cloud in the dipole beam screens must be envisaged. This would benefit both the heat load at top energy, which would be brought back within the limits of the cooling capacity, and the preservation of the beam quality throughout the 450 GeV injection plateau.

Several improvements implemented during LS1 are expected to have a beneficial impact on our knowledge on the electron cloud in LHC and/or the efficiency of the scrubbing run:

- *Cryogenics* [9]. The cooling capacity of the SAMs, which limited the speed of the injection process in 2012 by delaying the time between successive injections, and leading thereby to beam deterioration, has been increased by about a factor 2. The cooling capacity for Sector 34, which was half in 2012, has been restored to nominal. In terms of diagnostics, three half cells in Sector 45 have been equipped with extra thermometers. This will allow for magnet-by-magnet heat load measurements and disentangling the heat load in the arc dipoles from that in the quadrupole.

- *Vacuum* [10]. In general, pressure rises did not limit the efficiency of the 2012 scrubbing run, but it was not possible to monitor the pressure in the arcs due to the sensitivity of the vacuum gauges. High sensitivity vacuum gauges have been installed in the same Sector 45 half cells equipped with thermometers. Vacuum Pilot Sectors (Q5L8-Q4L8) are being equipped with gauges and e-cloud detectors to study behaviour of NEG coated vs. unbaked Cu beam pipe.

- *Injection kickers* [11]. At the very first stages of the scrubbing run, another limitation for the speed of the injection process was also the outgassing at the injection kickers (MKI). A new design of the beam screen with capacitively coupled ends allows for 24 screen conductors and, consequently, reduced beam induced heating. The by-pass tubes have been NEG coated and a NEG cartridge has been also added at the interconnects, which should result in a much improved vacuum.

- *TDIs* [12]. During the 2012 scrubbing run, heating and outgassing of these injection protection devices could be kept under control by retracting them between subsequent injections. Besides, a few problems with detected misalignment or stuck jaws were

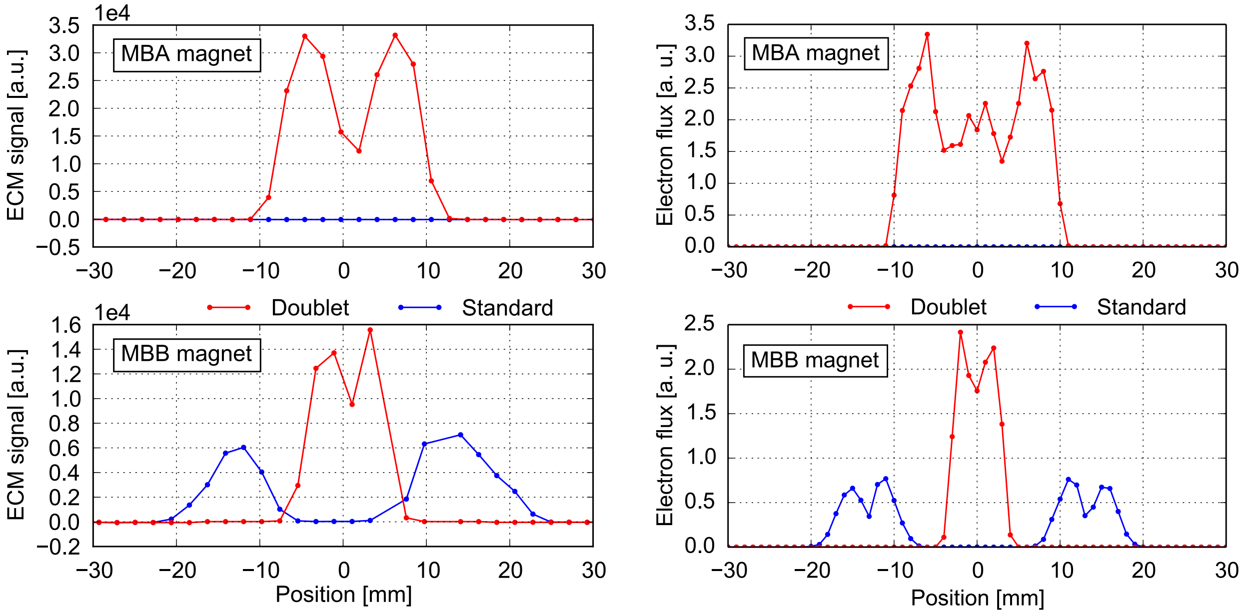

Figure 7: Electron flux to the wall of an MBA-type chamber with SEY=1.5 (top) and an MBB-type chamber with SEY=1.3 (bottom) as a function of the horizontal position for the standard 25 ns beam (1.7×10^{11} p/b, blue trace) and a doublet beam (1.7×10^{11} p/doublet, red trace). In the left column are the measured signals while in the right column are the simulated distributions.

encountered especially toward the end of the scrubbing run. The improvements introduced during LS1 include a reinforced beam screen made of Stainless Steel, a Ti flash to reduce SEY on the Al blocks, the installation of temperature probes that will allow monitoring heating, mechanics disassembled and serviced, which should minimise the risk of alignment problems.

- *On-line electron cloud monitoring*. New software tools for on-line monitoring of the scrubbing process and its steering are being prepared. Virtual variables for the heat load in the beam screen of the arc half cells for all sectors as well as SAMs and triplets have been implemented in the LHC logging database [13]. Furthermore, a specific application for the on line reconstruction of the bunch-by-bunch energy loss data from the RF stable phase is also under development.

Beside the above list, during Run 1 a special beam to enhance electron cloud production with respect to a standard 25 ns beam was developed and successfully produced at the SPS at 26 GeV. If accelerated to 450 GeV and then extracted to the LHC, this beam, called the doublet beam and described in detail in the next subsection, will be shown to have the potential to perform the further scrubbing step needed to run the LHC with 25 ns beams.

The "doublet" scrubbing beam

The idea of facilitating the scrubbing process by enhancing the EC while keeping the beam stable with high chromaticity was already proposed in order to speed up the scrubbing process in the SPS [14]. Exploratory studies in 2011 indicated that a promising technique for EC enhancement consists of creating beams with the hybrid bunch spacings compatible with the 200 MHz main SPS RF system and tighter than the nominal 25 ns. The schemes initially envisioned to produce these beams, i.e. slip stacking in the SPS or RF manipulations in the PS, turned out to be inapplicable due to technical limitations of the RF systems in the two accelerators. However, a novel production scheme was proposed to create a beam with (20+5) ns spacing. The scheme is based on the injection of long bunches in 25 ns spaced trains from the PS on the unstable phase of the 200 MHz SPS RF system, resulting in the capture in two neighbouring buckets and the generation of 5 ns spaced "doublets" out of each incoming PS bunch. Successful tests were conducted in the SPS and further details can be found in [15]. As a highlight, we display in Fig. 7, right column, the signals from the electron cloud detectors (in both the SPS dipole chamber types, i.e. MBA and MBB) during a machine development session with a standard 25 ns beam with 1.7×10^{11} p/b and a doublet beam with the same intensity per doublet. This measurement provided a direct evidence of the stronger electron cloud production and showed that the signals measured in the machine matched the distributions anticipated in simulations to a high degree of accuracy (Fig. 7, left column). So far the doublet beam has been only produced in the SPS and stored at 26 GeV for few seconds. To be used in the LHC, it will be necessary to accelerate it with the desired intensity and preserving the beam quality before extraction to LHC.

The proof-of-principle of the production and efficiency of the doublet beam in the SPS, as well as the validation of our simulation tools for predictions, was an essential milestone to consider this beam as a future option for scrubbing the SPS after LS1. The capability of the doublet beam of further scrubbing the LHC dipole beam screens in order to lower the electron cloud level with 25 ns beams can be fully explained looking at Fig. 8. Here the simulated heat load is plotted as a function of the SEY for the 50 ns beam (1400 bunches), the 25 ns beam (2800 bunches) and the doublet beam (900 doublets in trains of 144 doublets per injection from the SPS, limited by the cryogenic capacity). Simulations were done for an LHC arc dipole at injection energy. As a reference, the line of the cryogenic limit, given by the cooling capacity, is also drawn as a yellow line. Scrubbing first with 50 and 25 ns beam can lead in a reasonable amount of time (4–5 days from previous experience) to the blue point close to the knee of the 25 ns blue curve. At this point, we can inject the doublet beam (red curve) and rely on high chromaticity settings to enhance the electron cloud without triggering instabilities, thus increasing the scrubbing flux on the dipole beam screens up to the available cooling capacity. One of the main challenges for this phase will be to keep an acceptable quality of the doublet beam while scrubbing at 450 GeV. If we succeed in maintaining a large scrubbing flux with the doublet beam (we can also top up with more injections if needed), further scrubbing down the red curve can be accumulated, leading eventually to an SEY point, for which the electron cloud in the dipoles has been completely suppressed with standard 25 ns beams.

Table 2, upper line, shows the values of expected heat load in the arcs for a full machine with 25 ns beam (2800 bunches) and the relative distribution of specific heat loads in dipoles and quadrupoles at the end of the 25 ns scrubbing (blue point at the knee of the heat load curve in Fig. 8). At this stage, the arc heat load with this type of beam is about evenly distributed in the dipoles and quadrupole. Furthermore, as an example, also the power loss in a sensitive element like the TDI is displayed. The lower line of the table shows the same quantities calculated for the fill with 900 doublets, which has been envisaged as the natural step following the saturation of the scrubbing process with 25 ns beams (higher red point in Fig. 8). The total heat load in the arcs increases to the value of the cooling capacity and becomes mainly located in the dipoles. The heating of the TDI is four times less severe than with the full 25 ns beam.

After a general review on the use of doublet beams in LHC [16], the following points have been assessed.

- *Production*. Splitting at SPS injection is the most favourable scheme (compared to splitting at high energy in SPS, or at LHC injection) both for beam quality and electron cloud enhancement

- *RF*. No major issue has been found. The phase measurement will average over each doublet, for which the Low Pass Filter bandwidth needs to be optimised. If the bunch length from SPS stays below 1.8 ns, the capture losses will be comparable to those for standard 25 ns beam

- *Transverse Damper*. The common mode oscillations of the doublets are damped correctly, but the system will not react to pi-mode oscillations, i.e. when the two bunchlets oscillate in counter phase. This kind of instabilities (if observed) will have to be controlled with chromaticity and/or octupoles

- *Beam Instrumentation*. No problem is anticipated for Beam Loss Monitors (BLMs), DC Current Transformers (DCCTs), Abort Gap Monitors, Longitudinal Density Monitors (LDMs), DOROS and collimator Beam Position Monitors (BPMs). BBQ (gated tune), Fast Beam Current Transformers (FBCTs), Wire Scanners, Beam Synchrotron Radiation Telescopes (BSRTs) will integrate over the two bunchlets. The Beam Quality Monitor (BQM) or LDM will be adapted to monitor the relative bunch intensity information. The BPMs might suffer errors up to 2-4 mm, especially for unbalanced doublets in intensity or position. Orbit measurements could still rely on the synchronous mode and gating on a standard bunch. However, the interlocked BPMs in IR6 will suffer the same issues as the other BPMs, but need to be fully operational on all bunches to protect the aperture of the dump channel. A possible strategy to circumvent this issue could be a reduction of the interlock setting (presently 3.5 mm) according to the results on error studies conducted in the SPS first (2014) and then in LHC with single doublet.

Scrubbing stages and operational scenarios

The different phases of the LHC start up, including all the stages relevant for scrubbing and 25 ns operation with mitigated electron cloud, are detailed in Fig. 9.

After LS1, the situation of the beam screen in the arcs will be likely reset. Upon resuming of the LHC operation in 2015, since most of the machine parts will be either new or exposed to air, it is reasonable to assume that the SEY in the arcs will have returned to values above 2.3, as was before the 2011-2012 machine scrubbing. For this reason, it will be necessary to envisage and schedule a period devoted to machine conditioning in order to get into physics production with 50 ns first, and later on with 25 ns beams. After an initial re-commissioning with low intensity, based on the experience of 2011, five to seven days with increasingly longer trains of 50 ns beams will be needed for vacuum conditioning and first scrubbing of all the machine parts exposed to air during LS1 or never exposed to beam

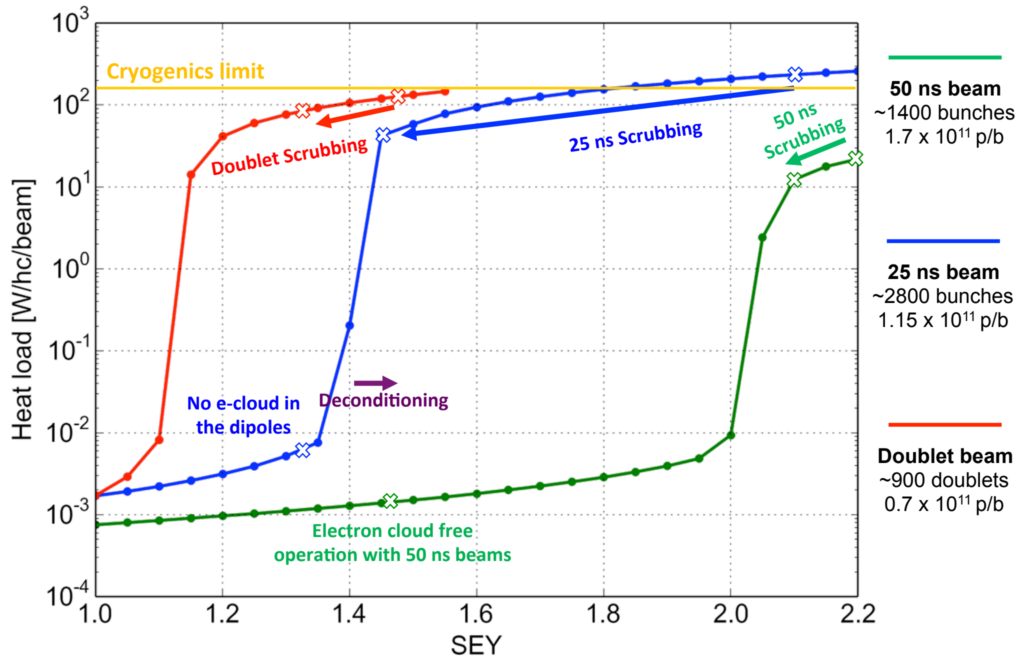

Figure 8: Heat load in the LHC dipole beam screen as a function of the SEY for 50 ns (1400 bunches, green line)), 25 ns (2800 bunches, blue line) and doublet beams (900 doublets, red line).

	$N_{bunches}$	Bunch intensity	Total intensity	Heat load	P_{dip}	P_{quad}	P_{TDI}
Std. 25 ns beam	∼2800 bunches	1.15×10^{11} p/bunch	3.2×10^{14} p/beam	71 W/hcell/beam	1 W/m	9.2 W/m	415 W
Doublet beam	∼900 doublets	1.4×10^{11} p/doublet	1.2×10^{14} p/beam	125 W/hcell/beam	2.6 W/m	3.2 W/m	107 W

Table 2: LHC beam parameters and heat loads (arc dipoles, arc quadrupoles and TDI) for full machine with a standard 25 ns beam (upper line) and for a fill with 900 doublets (lower line)

before. This will lead to a general reduction of the desorption yield all over the machine and will also lower the SEY in the arcs to a value close to the threshold for electron cloud build up for 50 ns beams. At this point, to allow LHC to gain enough margin to ensure electron cloud free operation with 50 ns beams, this phase could be ideally ended by one or two days with injections of trains of 25 ns beams aiming at lowering the SEY in the arcs below 2.0. After a short physics production period with 50 ns beams at 6.5 TeV, during which the 6.5 TeV operation will be established with the well mastered 50 ns beams and further surface conditioning will be achieved thanks to the enhanced synchrotron radiation, the switch to 25 ns operation will rely on performing a second scrubbing step with the 25 ns beam and doublet beams. By simply adding up the 50 hours of 25 ns MDs in 2011 and the 60 to 70 hours of efficient scrubbing in 2012, we obtain that a maximum of 5 days of run with increasingly longer trains of 25 ns beams at injection energy should be sufficient to get back to the same situation we had in December 2012 after the 25 ns scrubbing run. After that, the machine will be ready to receive doublet beams to enhance the electron cloud in the arc dipoles and continue the scrubbing down to values lower than the build up threshold in the dipoles for 25 ns beams. The next step is to ramp the 25 ns beams up to 6.5 TeV, while the number of bunches can be gradually increased.

If all the previous phases have been successful, the LHC will finally be able to move into physics production with 25 ns beams at 6.5 TeV under controlled electron cloud effects. However, it is worth noticing that during the 25 ns operation of the LHC, the electron cloud, though mitigated, will still be present in the quadrupoles (and possibly other machine regions, e.g. the higher order multipoles, the inner triplets) even after scrubbing. This entails the following effects, which shall be taken into consideration:

- The integrated effect of this residual electron cloud

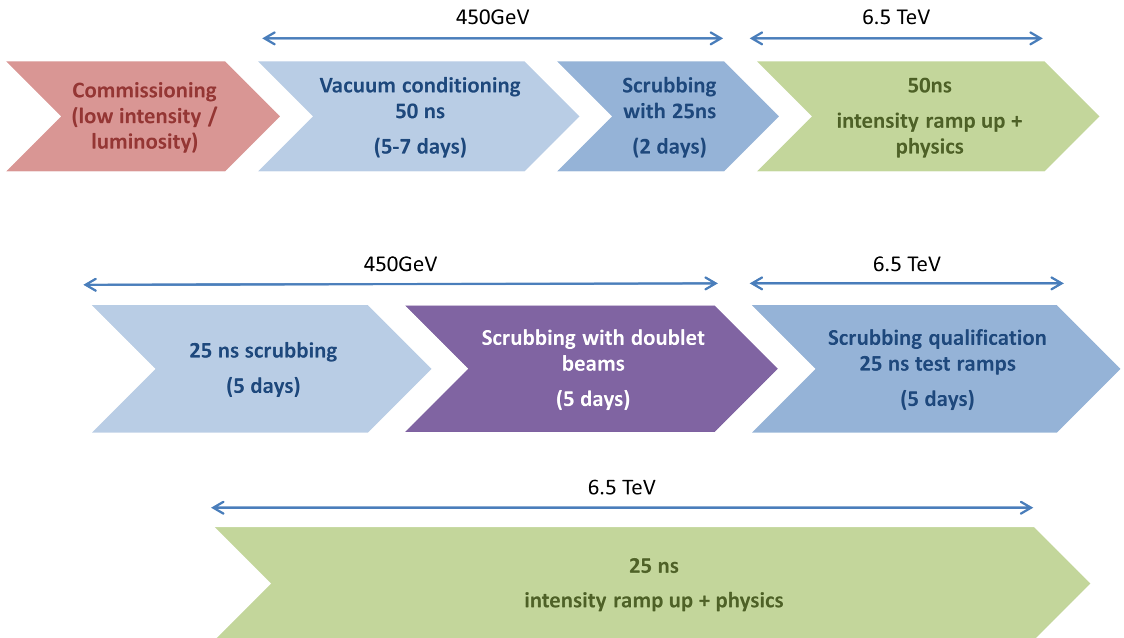

Figure 9: Timeline of the LHC scrubbing in 2015.

might result into a significant emittance blow-up at injection. To limit the luminosity loss due to this effect, the injection speed will be crucial, but also some beam parameters could be better tuned to minimise the amount of electron cloud seen by the beam at 450 GeV (e.g. bunches can be lengthened);

- If there is still a heat load limitation on the ramp or at 6.5 TeV, an optimal configuration in terms of number of bunches, bunch intensity and bunch length might have to be sought and applied;
- It was observed in 2012 that some degree of deconditioning occurs in absence of scrubbing beam for some time. If the extent of the deconditioning is such as to re-awaken the electron cloud with 25 ns beams, a few hours for scrubbing could become necessary after each longer stop (i.e. certainly after every Winter stop, but possibly also after each Technical Stop).

If the scrubbing phases detailed above will not be sufficient to eliminate the electron cloud from the machine dipoles and 25 ns operation will still be hampered by heat load on the ramp and beam quality degradation, the main fallback option foresees the use of the 8b+4b filling scheme [15]. This will allow storing up to 1900 bunches/beam in the LHC with the advantage of having both a higher multipacting threshold compared to the standard 25 ns beam (shown by PyECLOUD simulations) and the potential to accept a higher intensity per bunch (to push up luminosity within the desirable limits of the pile-up). This scheme, although already proven in simulations, still needs to be confirmed experimentally in the injector chain. The gain in terms of electron cloud build up also needs to be assessed experimentally, once this beam will be available in the SPS. A second option would be to stick to the 50 ns spacing and run the LHC again like in Run 1 (although instabilities at 6.5 TeV could be an important intensity limiting factor for this scenario). In this way we could store up to 1380 bunches in the LHC and rely on a multipacting threshold much larger than for the standard 25 ns beam or the 8b+4e.

CONCLUSIONS

To conclude, the experience from LHC Run 1 has taught that the electron cloud can seriously limit the achievable performance with 25 ns beams mainly through beam degradation (poor lifetime, emittance blow up) at low energy and high heat load at top energy. The scrubbing achieved in 2012 could strongly weaken the electron cloud in the beam screen of the dipoles, but did not fully suppress it. After LS1, to cope with the nominal number of bunches, we need to scrub LHC more efficiently than in 2012 and aim at the total suppression of the electron cloud from the dipole beam screens. To accomplish that, we will benefit from:

- Several hardware and instrumentation improvements, which will allow for better scrubbing efficiency;
- The doublet scrubbing beam based on 5 ns spaced bunchlets separated by 25 ns, which was produced and tested at the SPS, and looks very attractive for LHC scrubbing. The compatibility of this type of beam with the LHC equipment was reviewed and no major showstopper has been found. Presently, the only

pending issue is the possible offset on the interlock BPMs in IR6 and this is being followed up.

A two stage scrubbing strategy is proposed for the LHC start up in 2015. This will rely on: 1) a first scubbing/conditiong run with 50 ns beams (and possibly one or two days with 25 ns beams) to allow for safe operation with 50 ns beams at 6.5 TeV; 2) A second scrubbing run with 25 ns and doublet beams to allow for operation with 25 ns beams at 6.5 TeV. If scrubbing will turn out to be still insufficient, even with the doublet beam, the 8b+4e scheme could be used for providing a significant electron cloud reduction with 50% more bunches than the 50 ns beam and similar bunch intensities.

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