ELECTRON CLOUD AND SCRUBBING IN 2012 IN THE LHC

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Abstract

During 2011, the scrubbing dose accumulated in the LHC during the tests with 25 ns beams could decrease the SEY of the chambers well below the multipacting threshold for 50 ns beams. During the Winter shut-down, the conditioning was preserved to such an extent as to guarantee smooth electron cloud free operation with 50 ns beams since the beginning of the 2012 run. However, the 25 ns injection tests that took place in July 2012 revealed that the chambers had slightly deconditioned since the last 25 ns test of 2011. Although this was not sufficient to cause electron cloud formation with 50 ns beams, this effect could noticeably impact on the quality of the 25 ns beams. A more extensive run with 25 ns beams (with stores for studies at both 450 GeV and 4 TeV and including a brief physics run) took place during December 2012 to gain experience in this mode of operation and gather more experimental information on the scrubbing process in the LHC. The outcome of this run is used to provide the guidelines to define a scrubbing strategy for operation after Long Shutdown 1 (LS1) with both 50 ns and 25 ns beams. A more general goal of the 25 ns run was also the identification of possible bottlenecks, which could prevent the safe injection and storage of the number of bunches needed to perform an efficient scrubbing process first and physics later.

INTRODUCTORY REMARKS

When an accelerator is operated with closely spaced bunches, electrons can quickly accumulate inside the vacuum chamber and fill it with a dynamic distribution dependent on both the beam structure and the properties of the chamber (i.e. geometry and maximum secondary electron yield (SEY), also referred to as $\delta_{\max}$, of the inner surface) [1]. The flux of electrons hitting the wall of the vacuum chamber is the source of both pressure rise through desorption and power deposition on the chamber wall. The presence of this electron cloud around the beam can also make the beam unstable or drive a slow process of emittance growth. The observation of the electron cloud in the LHC is for now essentially based on the direct measurement of these macroscopic effects [2]. While some of these observables are local and are mainly related to the formation of the electron cloud around specific regions of the machine (e.g. heat load in the arcs, vacuum rise at some gauges), other ones are global and give an indication of the integrated amount of electron cloud over the whole circumference of the LHC (e.g. stable phase shift, instability rise time, emittance growth, bunch-by-bunch tune shift). Both local and global indicators however include also other effects (e.g. synchrotron radiation, impedance), which need to be carefully disentangled when their contributions are comparable to that coming from the electron cloud.

Brief recapitulation of the 2011 observations

In 2011, the LHC 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. The electron cloud build up with 50 ns beams could be efficiently suppressed in most of the machine by means of an initial scrubbing run with 50 ns beams, which took place at the beginning of April 2011 [3]. Fitting the heat load data in the arcs (inferred from temperature and flow of helium on the beam screens) with electron cloud build up simulations, it was found that the maximum SEY in the beam screen of the dipole chambers was lowered from an estimated initial value of about 2.3 to slightly below 2.2. This was sufficient to guarantee an electron cloud free operation for 50 ns beams at both 450 GeV and 3.5 TeV. A further decrease of the maximum SEY in the arc dipoles was later achieved by injecting trains of 25 ns beams into the LHC. The first injection tests with trains of 24 bunches from the SPS were conducted on 29 June, 2011, and both heat load in the arcs and emittance growth of the bunches located at the tails of the trains were observed [4]. On a following MD session (26 August, 2011), there was an attempt to inject trains of 48 bunches, but the beam quickly became unstable after injection and was dumped after few hundreds of turns due to fast beam losses or large orbit excursions [5]. It was possible to efficiently cure a horizontal coupled-bunch oscillation with the transverse damper, while the strong single bunch instability observed in the vertical plane still affected the beam, even with the transverse feedback on. The beam instability observed on this occasion could be identified as triggered by the electron cloud. Its pattern over the bunch train could be successfully reproduced by means of combined PyECLOUD-HEADTAIL simulations, having assumed a maximum SEY of about 2.0, as it could be extrapolated from the SEY history based on reconstruction from the heat load data [6]. The next brief MD session with 25 ns beams (7 October, 2011) consisted of injection tests of up to 288 bunches (using high chromaticity settings, as opposed to the previous MD session, in which chromaticity was low at injection) and a store of few hours of 60 bunches per beam (in two trains of 24 and one of twelve bunches) at 3.5 TeV for the first data collection from experiments with 25 ns beams. It was only during the two last MD sessions, which took place on the 14 and 24-25 October 2011, that the LHC could be filled with 2100 bunches for Beam 1 and 1020 for Beam 2. A considerable amount of additional scrubbing could be achieved on these days, leading to an estimated final value of $\delta_{\max}$ of 1.52. By the end of the MD session on the 24-25 October 2011, trains of 72 bunches with 25 ns spacing exhibited much reduced degradation with respect to the past, although both the lifetime and the emittance evolution still indicated the presence of a significant electron cloud in the LHC [7].

25 ns BEAMS IN THE LHC IN 2012

After three weeks commissioning with beam, the 2012 physics run of the LHC started in early March colliding beams with 50 ns bunch spacing. Owing to beam scrubbing from the 2011 MD sessions with 25 ns beams, which provided a safe enough margin to guarantee electron cloud free operation with 50 ns beams, the LHC quickly became productive for physics with 50 ns beams without suffering any major limitations from outgassing, heat load, or beam instabilities. The physics run successfully continued up till the 6 December, 2012, with an intensity per bunch boosted to 1.6×10^{11} ppb within transverse emittances as low as $1.6\,\mu$m at injection. This could be achieved thanks to the careful optimization and tuning in the injectors and the implementation of the low gamma transition optics (Q20) in the SPS for the production of LHC beams [8]. The MDs and physics operation with the 25 ns beams in 2012 are described in the following subsections.

25 ns beam injection tests

The first injection tests of 25 ns beams in 2012 were made on the 10 July. Trains of 72, 144, 216 and finally 288 bunches were successfully injected for Beam 1 with chromaticity Q' set to 15 in both planes. For Beam 2, only trains of 72 and 144 bunches were injected with the same high chromaticity settings. Next, it was attempted to lower chromaticity ($Q' = 5$), only for Beam 2, and repeat the injections with increasing numbers of trains. After successfully injecting a train of 72 bunches (in spite of a horizontal instability, which could be controlled by the transverse damper), the injection of 144 bunches triggered the beam dump within 700 turns due to fast beam losses. The reason was that the beam suffered an electron cloud instability right at injection because of the low chromaticity settings.

During these injection tests, the beam lifetime was found to be initially quite poor and a strong emittance growth was measured at the tails of the trains, especially in the vertical plane. Figures 1 show snapshots from the BSRT measurements when all the bunches injected with high chromaticity settings were inside the machine. Pressure rise was observed in some of the straight sections, but mainly in common areas and never above the interlock value of 4×10^{-7} mbar. The comparison between the time evolution of the relative beam losses measured during these injection tests and those mesured during the last 25 ns MD in 2012 (25 October), displayed in Fig. 2, clearly reveals a degradation of the beam quality in 2012 for the same beam parameters and machine settings. From the heat load measured during the 2012 25 ns injection tests, it could be indeed inferred that the $\delta_{\max}$ in the arc dipoles had an initial value of about 1.65 and then quickly returned to 1.55 by the end of the MD. The deterioration with respect to the last value determined from heat load data in 2011 suggests that, although the arcs were not opened to air during the Winter shut-down 2011-2012, a deconditioning of the inner surface of the beam screen occurred. However, it is encouraging that a value of $\delta_{\max}$ of about 1.55 could be quickly recovered within less than one hour store of 712 bunches for Beam 1 and 344 bunches for Beam 2, as opposed to the almost 20 hours needed in 2011 to obtain a

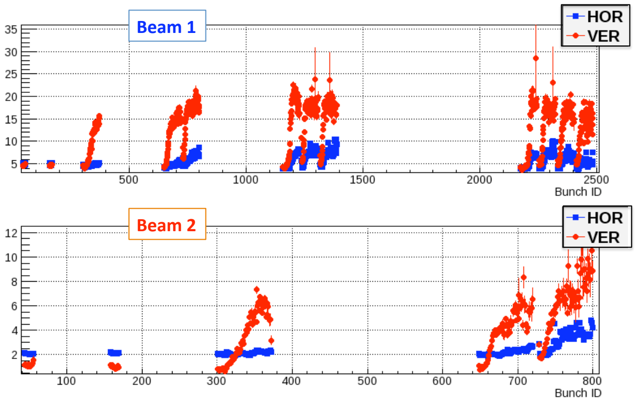

Figure 1: Snapshot of the horizontal and vertical normalized emittances for Beam 1 (top) and Beam 2 (bottom) just before the injection of the last train for Beam 2. The vertical axis is μm. Courtesy of F. Roncarolo.

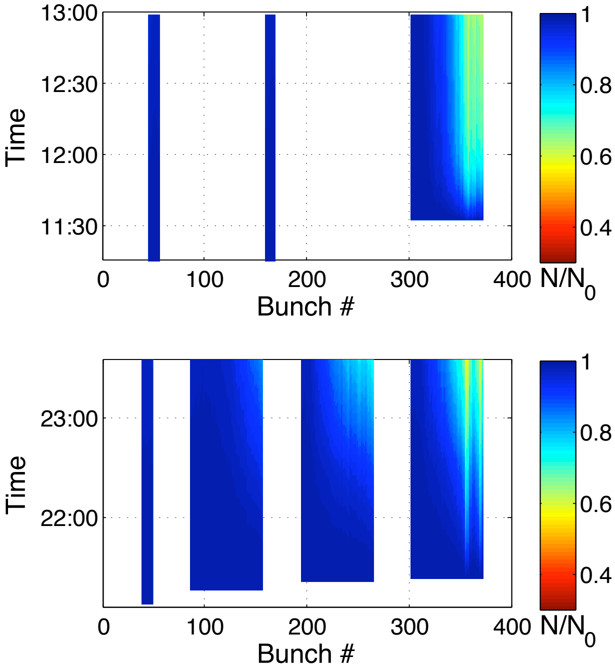

Figure 2: Comparison between the time evolution of the relative beam losses for Beam 2 during the injection test on 10 July, 2012, (top) and a store on 24 October, 2011 (bottom).

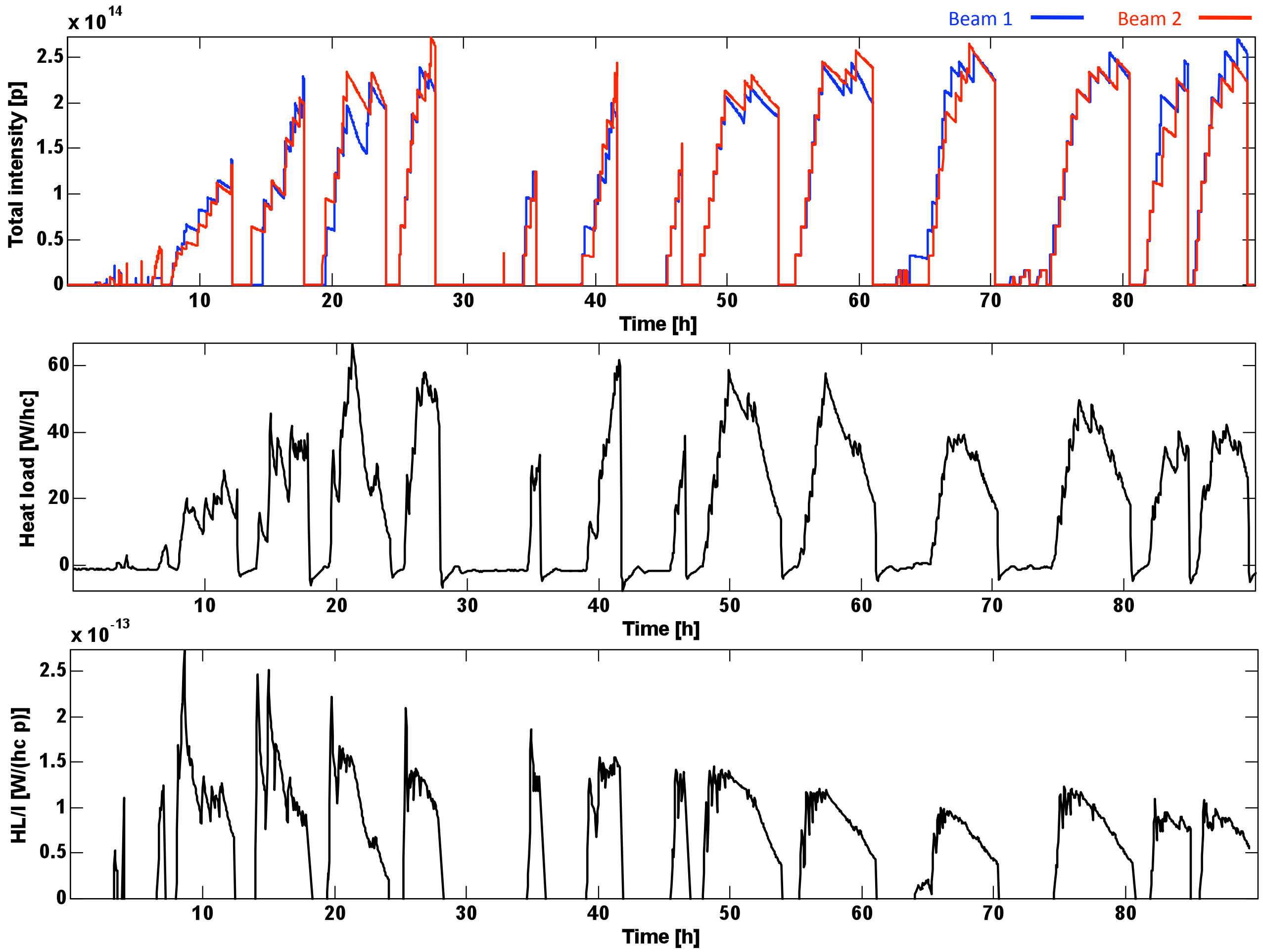

Figure 3: Beam current evolution (top), heat load in the Sector 5 – 6 (middle) and nomalized heat load in the Sector 5 – 6 (bottom) during the 2012 scrubbing run. The 0 time corresponds to the 6 December, 2012, at noon. Heat load data are courtesy of L. Tavian.

similar decrease in $\delta_{\max}$ with a larger beam filling fraction machine.

2012 scrubbing run

The 2012 scrubbing run of the LHC with 25 ns beams had the following goals:

(a) Further reduce the SEY over the whole machine by storage of 25 ns beams at 450 GeV, while monitoring electron cloud observables and beam quality evolution;

(b) Collect additional information on the evolution of the SEY as a function of the accumulated electron dose (especially in the low SEY region) and compare machine data with existing models. This is an essential step to validate and improve models, and establish strategies for the post-LS1 era;

(c) Enable LHC to be eventually ramped to 4 TeV with a few hundreds of bunches of 25 ns beams for electron cloud studies and for other studies with 25 ns beams (e.g. beam-beam, UFO) without significant electron cloud perturbations;

(d) Learn about other possible differences in 25 ns vs. 50 ns operation (e.g., equipment heating, beam longitudinal and transverse stability, UFO rates);

(e) Enable a 25 ns pilot physics run and possibly provide additional scrubbing.

Beams with 25 ns spacing were injected into the LHC and kept at 450 GeV for scrubbing purposes between the 6 and 10 December (08:00 am), 2012. Figure 3 depicts the evolution in terms of beam intensity for both Beam 1 and Beam 2 during these days (top plot). The inferred heat load in the beam screen of the arc of Sector 5 – 6 and the heat load normalized to the beam current are displayed in the middle and bottom plots.

The operation during the scrubbing run was rather smooth and no fundamental showstoppers were found. Thanks to the excellent machine availability, a significant scrubbing dose could be maintained all along the scrubbing period. During the initial stages, the overall efficiency was determined by the vacuum pressure in the MKI region. Prior to the run, the interlock levels for the MKI magnets had been increased to 4×10^{-9} mbar from 2×10^{-9} mbar, while

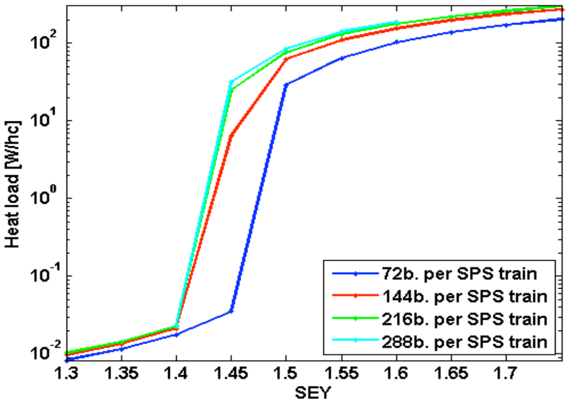

Figure 4: Heat load in the arcs (in W per half cell) as a function of the maximum SEY for different filling patterns.

those in the interconnects between the kicker modules had been raised from 5×10^{-9} mbar to 1×10^{-8} mbar. The vacuum interlocks in the interconnects between MKI2 Magnet D and Q5, between MKI8 magnet D and Q5 and between the MKI8 magnets A and B had to be further increased to 4.5×10^8 mbar, 4.5×10^8 mbar and 3×10^8 mbar, respectively, during the run. Later on, when higher intensities were injected into the LHC, cryogenics slowed down the injection process requiring 10 – 15' between successive injections of 288 bunches from the SPS. This was mainly due to the limited cooling power for some of the standalone modules, while no limitation in the arcs appeared at this time. For high scrubbing efficiency, and also to avoid strong fluctuations on a 120 A current lead temperature in the matching section R8, the beams were dumped after the heat load had significantly dropped. The vacuum pressures along the ring were continuously monitored over the scrubbing period. Apart from the aforementioned MKIs and shortly ATLAS during the first night, pressure rises did not cause significant slow down. However, in order to keep temperature and pressure values below the interlock levels, heating and outgassing of the TDIs had to be avoided by retracting them after each injection. Probably because of the frequent movements, one jaw of the TDI in point 8 got blocked twice in open position and the motor had to be remotely reset. Besides, one of the LVDTs of TDI.4L2 LU had to be exchanged at the end of the scrubbing run, because its reading was found to trigger a warning/error on the lower limit due to drift while cooling down. Probably thanks to the longer bunches and smaller bunch intensities, no anomalous heating was observed during the scrubbing run on other sensitive elements (e.g. collimators, BSRT, MKIs).

The first half day of scrubbing was mainly devoted to the set up of injection (up to 288 bunches per train for both beams) and of the transverse damper. After that, there was only one fill with trains of 72 bunches, during which the quality of the beams could be seen to improve significantly from injection to injection and the chromaticity value Q' could be lowered from the initial 15 to about 7 units without triggering electron cloud instabilities. As illustrated in Fig. 4, electron cloud build up simulations for the arc dipoles suggest that, for values of $\delta_{\max}$ in the 1.40-1.55 range, it is important to use filling patterns made of longer trains than 72 bunches in order to efficiently continue the scrubbing process to lower SEY values. These simulations rely on the assumptions that: 1) the main contribution to the electron cloud remains in the arc dipoles, and 2) primary electrons are generated via residual gas ionization and 3) the SEY curve is parametrized according to [9] with 70% probability of low energy electrons to be elastically backscattered from the surface. Additionally, injection of longer trains from the SPS would allow for up to 30% more bunches in the LHC, which translates into more scrubbing power. Based on these considerations, from the second fill onwards, it was decided to switch to trains of 288 bunches per injection and maximize the scrubbing efficiency. Within the first 24 hours, the number of injected bunches reached the maximum in both rings (2748) and a record intensity of 2.7×10^{14} p was stored for Beam 2. Several stores with full machine took then place over the scrubbing period, as visible in Fig. 3, top plot. The normalized heat load in Sector 5 – 6 during the scrubbing run, as depicted in the bottom plot of Fig. 3, indicates that the scrubbing process successfully carried on over the first 60 – 70 hours. However, the fact that the normalized heat load flattened out over the last few fills of the run also suggests that no further improvement due to scrubbing took place in the last part of the scrubbing run. Beam observations also seem to confirm this trend. While a clear improvement in the overall beam quality (lifetimes, emittances) can be observed when comparing a fill at the beginning of the run and one at the end (see, for instance, the plots of the bunch-by-bunch loss for Beam 1 displayed in Fig. 5), no

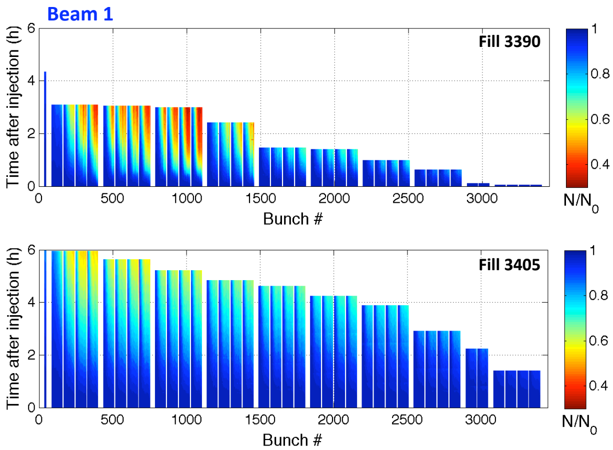

Figure 5: Bunch-by-bunch intensities for Beam 1 over the fills 3390 (top, beginning of the scrubbing run) and 3405 (bottom, end of the scrubbing run), normalized to the initial intensities. While the losses observed during fill 3390 are very strong (more than 60% in three hours), the situation looks much improved during Fill 3405 (losses below 40% in six hours).

evident progress can be observed over the last fills. This is confirmed by the evolution of the beam lifetimes during the 3.5 days of the scrubbing run (Fig. 6). The beam lifetimes shown in this figure were evaluated by averaging on the lifetimes after 1 hour store of only the last five bunches of each 72 bunch train. To be noted that, towards the end of the scrubbing run, it was necessary to increase the octupole current to 23 A (from the nominal setting of 6.5 A at injection) because it was found that this could suppress an instability affecting the first injected train of 72 bunches from the SPS and causing a "hunch" in the transverse emittance values between the middle and the tail of this train. It was suspected that the origin of this instability could be electron cloud, because it does not affect 50 ns beams and is compatible with a maximum of the electron central density seen in simulations, which is reached only along the first build up of the electron cloud in dipoles (i.e. for the first train) and becomes later suppressed by the build up of the stripes and space charge effects during the passage of the following trains.

After the tests at 4 TeV, described in the next subsection, three more fills at 450 GeV took place, two of which were made with trains of 288 bunches and one with trains of 72 bunches. The peak heat load measured during the fills with trains of 288 bunches did not exhibit any significant decrease from the values measured before the 4 TeV tests. The fill with trains of 72 bunches caused a heat load about a factor two lower than that produced by the same total intensity in trains of 288 bunches. This confirms the effect of the train structure on the amount of electron cloud in the arcs. Nonetheless, the fact that the heat load remains visibly above the resolution level also when filling the LHC with shorter trains indicates that the electron cloud in the arcs is still significant also in this configuration and, therefore, the memory between trains could be stronger than assumed in simulations.

The reasons why the scrubbing process in the arcs has sharply slowed down, or even reached saturation, after the first part of the scrubbing run still remains unclear and is presently the object of studies trying to explore different options. Possible explanations under investigation include, for instance, the existence of other regions of the arcs with much lower SEY thresholds, or model inaccuracies in the low energy part of the SEY curve. Both would be compatible with lower values of the threshold SEYs, either in the arc dipoles or in other components of the arcs, for which the rate of reduction of the SEY as a function of the electron dose logarithmically decreases (as found in laboratory measurements of SEY reduction with the electron dose).

Tests at 4 TeV

Despite a clear improvement with respect to the first day of scrubbing, 25 ns beams made of trains of 288 bunches in the LHC remained affected by quite degraded lifetime and significant emittance growth at the tails of the trains even after the full scrubbing run. Consequently, it was decided to stick to the plan to ramp up in energy only trains of 72 bunches sufficiently spaced. This would have the advantage of limiting the beam quality degradation due to electron cloud thanks to both less electron cloud build up and shorter injection time, possible because of the reduced heat load engendered by this filling scheme. After about 60 hours since the end of the scrubbing run, mainly devoted to access, TDI alignment verification and collimator set up for $\beta^* = 1$ m, trains of 72 bunches with 25 ns spacing were finally injected into the LHC and ramped to 4 TeV during two days, 13 – 14 December, 2012. The overview in terms of beam intensity for both Beam 1 and Beam 2 during these days, together with the beam energy, is plotted in the top graph of Fig. 7, while the inferred heat load on the beam screen of the arc in Sector 5 – 6 can be seen in the bottom one (units of the heat load are Watt per half cell).

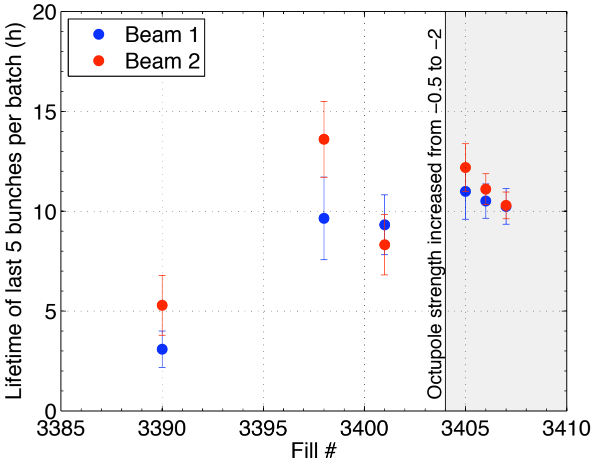

Figure 6: Beam lifetimes (after 1 hour store, averaged over the last five bunches per 72-bunch train) as a function of the fill number during the scrubbing run. The shaded region is after the change of the octupole settings.

The number of bunches injected into LHC and ramped to 4 TeV was gradually increased.

1. The first fill had 84 bunches, injected in a train of 12 followed by a train of 72 bunches for both beams. This fill was used for a long-range beam-beam MD, during which the crossing angle was changed in steps;

2. Two short stores with 156 and 372 bunches took place to continue the intensity ramp up process;

3. One long store with 804 bunches (one train of 12 and 11 trains of 72 bunches) was kept for about 8 hours for scrubbing purposes and to study the evolution of the beam paramters at top energy;

4. One short store with 804 bunches with the same scheme as the previous fill and lower intensity per bunch (around 9×10^{10} ppb), aiming to investigate the heat load dependence on the bunch intensity, concluded the 4 TeV tests.

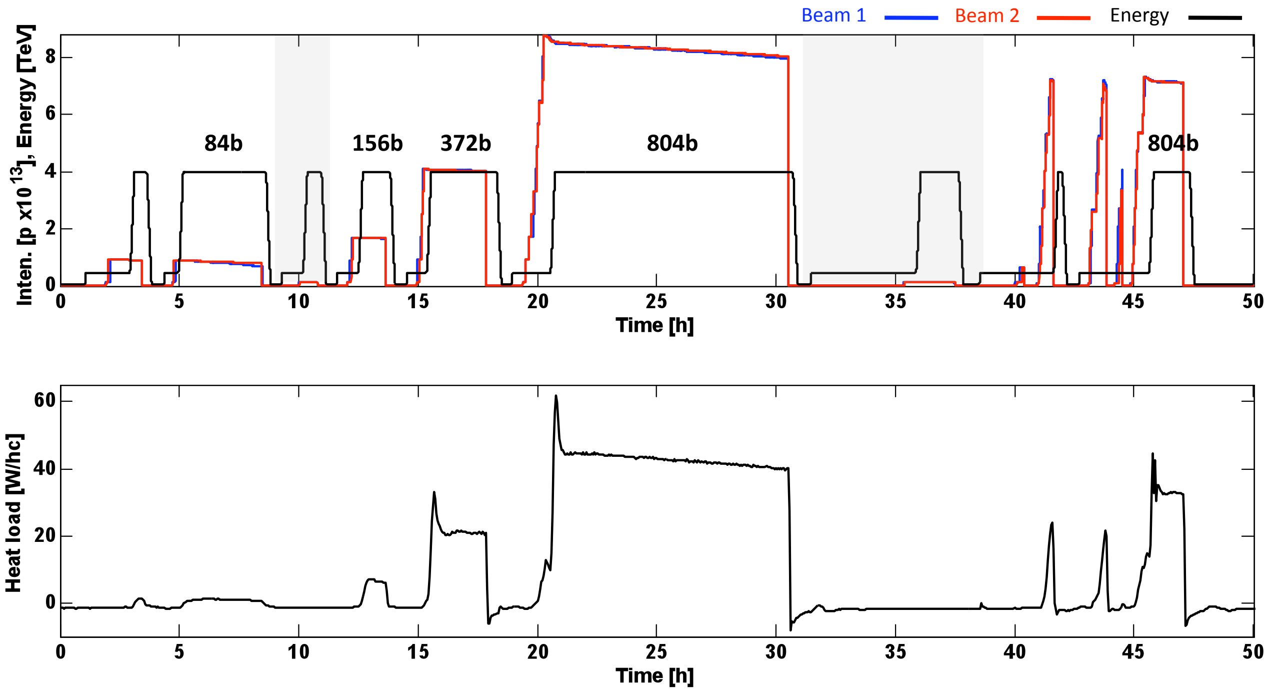

Figure 7: Beam current evolution (top) and heat load in the Sector 5 – 6 (bottom) during the test ramps with 25 ns beams (12 – 14 December, 2012). The 0 time corresponds to the 13 December, 2012, at midnight. Heat load data are courtesy of L. Tavian.

It can be noted that, during the studies, a few hours (specifically those around $t = 10$ h and then again in the time between 30 and 40 h, following the time reference as in Fig. 7) were used for further collimator verification and loss maps. A few aborted filling attempts (wrong octupole settings, software interlock due to missing BPM data) caused an additional loss of about five hours just before the last exercise of filling LHC with 804 bunches with lower intensity. The bottom plot of Fig. 7 shows the evolution of the heat load in the arcs during the two days of the tests ramps. Probably due to photoelectrons, the measured heat load was significantly enhanced at 4 TeV. For example, 804 bunches at 4 TeV were found to produce about the same heat load as 2748 bunches at 450 GeV, i.e. slightly above 40 W/half cell. The rapid increase of the heat load during the ramp required to increase the flow of helium on the beam screens before the start of the ramp. This fact caused the artificial peak observed in the heat load evolution plots, which is explained by initial overcompensation, and also limited in practice the number of bunches that could be injected into LHC. In fact, just looking at the steady values of the heat load, the cryogenic system would have allowed for at least twice the number of bunches (limited in this case by the Sector 3 – 4, which was running with approximately half the nominal cooling capacity) [10]. The increase of the heat load proportional to the number of bunches injected, as well as the flat heat load curve observed every time that the beams were kept for a long time at top energy, suggest that no further significant reduction of the SEY was achieved during these stores. Notwithstanding this, thanks to the increased beam rigidity at 4 TeV, the beam quality during the high energy stores did not exhibit any signs of degradation that could be attributed to electron cloud. Bunch by bunch losses were uniform and very small. Similarly, bunch by bunch emittances uniformly grew over the 8 hour store by less than 10% over the whole store length, as depicted in Fig. 8. Bunch by bunch stable phase measurements confirm the increase of the energy loss along the ramp also seen through the heat load measurements in the arcs, as well as the stabilization of the energy loss while the beams stayed at top energy [11].

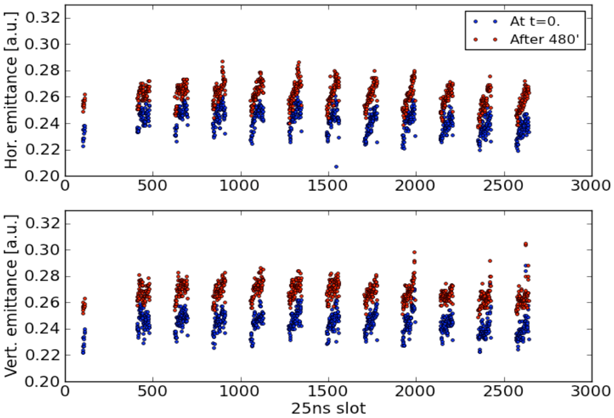

Figure 8: Snapshots of the bunch by bunch emittances from the BSRT taken at the beginning of the 4 TeV store and after 8 hours (fill with 804 bunches and nominal intensity per bunch).

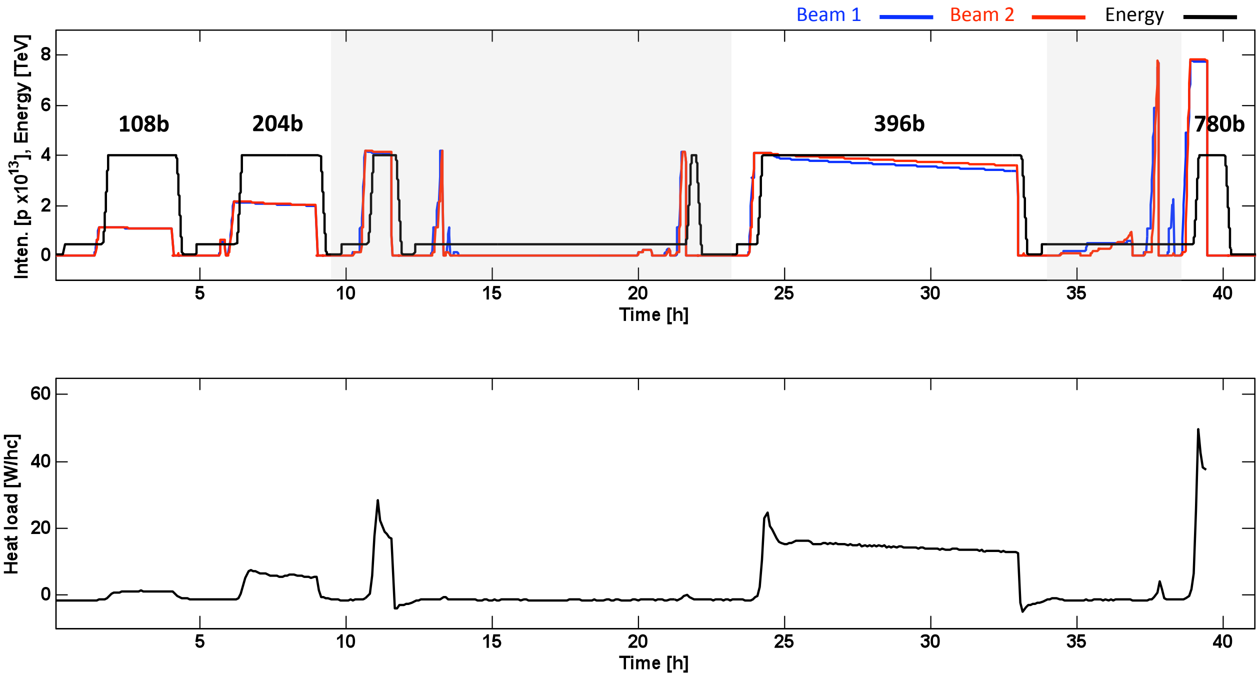

Figure 9: Beam current evolution (top) and heat load in the Sector 5 – 6 (bottom) during the pilot physics run with 25 ns beams (15 – 17 December, 2012). The 0 time corresponds to the 15 December, 2012, at noon. Heat load data are courtesy of L. Tavian.

Pilot physics run with 25 ns beams

The improvement achieved with the scrubbing run together with the experience acquired with the test ramps to 4 TeV finally enabled a short physics run with 25 ns beams just before the 2012 Christmas stop. The pilot physics run with 25 ns beams took place for about 48 hours from the 15 to the 17 December (08:00 am), 2012. During this run, in order to provide the experiments with the highest possible luminosity with 25 ns beams, it was decided to use low emittance beams from the injectors (BCMS production scheme, [12, 13] and references therein). With this scheme, the beams coming from the SPS are grouped in trains of 48 bunches (up to three trains within the same injection) and have transverse emittances of $1.4\,\mu$m at injection into the LHC. The total intensity was ramped up through three successive fills with 108, 204 and 396 bunches. The time of the third store was longer to ensure a good amount of data collection for the experiments. The last fill with 780 bunches also went successfully through acceleration and squeeze, but the beams were accidentally dumped by ALICE, due to too high luminosity. Single 48-bunch trains were used during the first two physics fills, while the third one and the final fill with 780 bunches were based on filling patterns made of double 48-bunch trains. The overview in terms of beam intensity for both Beam 1 and Beam 2 during these days, together with the beam energy, is shown in the top plot of Fig. 9. Unfortunately, due to miscellaneous RF synchronization problems and investigation, almost 15 hours were lost when first trying to fill the LHC with trains of 2×48 bunches from the SPS. In addition, on the last night before the end of the proton run, about five hours were also lost for physics, as multiband instability monitor and longitudinal damper tests with 50 ns beams had to take place and then the first attempt to ramp 780 bunches per beam was dumped by a software interlock on the orbit feedback. The evolution of the inferred heat load in the beam screen of the arc of Sector 5 – 6 can be seen in the bottom plot of Fig. 9. Comparing the measured heat load of these three fills with those in previous stores with comparable total beam currents, we can observe a decrease by about 20%. This has not yet been investigated in detail. In principle, it could be attributed to an effect of slow scrubbing, but also to the different train structures or the lower transverse emittances of the physics fills with respect to the test ramps. The beam emittances at top energy during the collisions (averaged over the two transverse planes and Beam 1 and Beam 2) could be reconstructed from the luminosity data. Figure 10 shows the emittances for the three physics fills with 108 (top), 204 (middle) and 396 bunches (bottom). The fills with 108 and 204 bunches show bunch by bunch emittances about 30% larger than their values at injection (measured with the wire scanners on the first train), but with only a faint signature of the electron cloud effect over the 48 bunch trains. The bunch by bunch emittances from the fill with 396 bunches clearly exhibit the typical electron cloud pattern along the $2{\times}48$-bunch trains. Even more interestingly, the fact that the three last trains injected are strongly affected by the electron cloud emittance growth even within their first 48 bunches shows the presence of a non-negligible memory effect between trains (over 25 μs, that is about the distance between the trains). This could be related to the fact that, unlike in the previous fill with

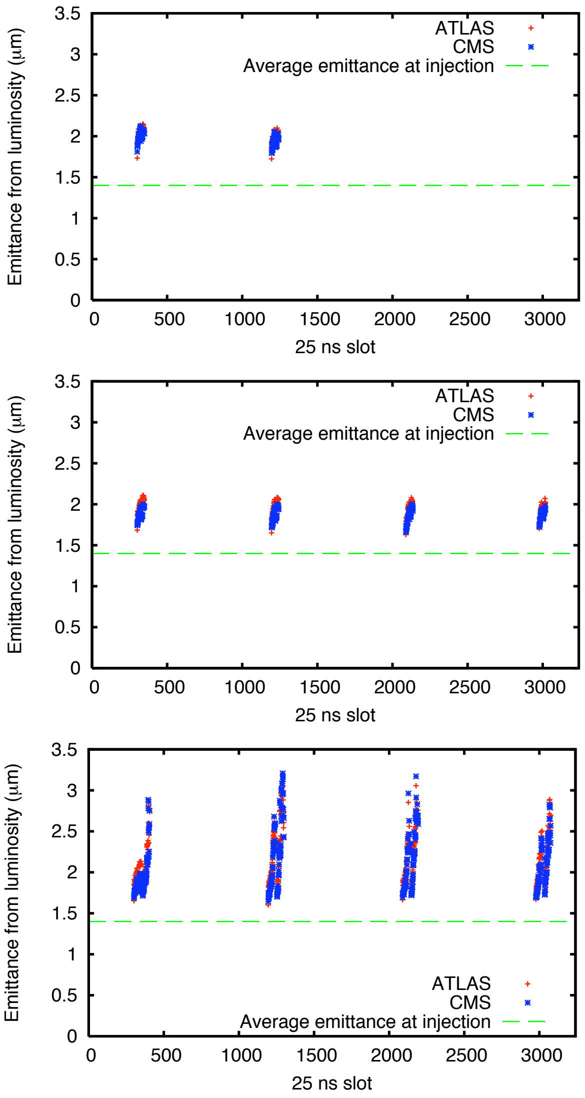

Figure 10: Snapshots of the bunch by bunch emittances from luminosity for the fill with 108 (top), 204 (middle) and 396 bunches (bottom). The line of the measured emittances at injection is also drawn. Courtesy of M. Hostettler and G. Papotti.

trains of 48 bunches, in this case the build up of the first injected train can generate a high enough electron density in the chamber that is not completely reset before the arrival of the next train. Finally, the fact that the first 48 bunches of the first train do not appear to be suffering from the same effect could be explained by the cleaning effect from the train of twelve bunches between the last and the first train. This explanation appears to be also supported both by simulations and by the stable phase shift data [11]. In fact, a first look into the bunch by bunch stable phase shift data at top energy for this physics fill reveals an electron cloud structure building up along the first train from a lower level than that of the following trains.

FUTURE SCRUBBING SCENARIO

After LS1, the situation of the beam screen in the arcs will be likely reset and, upon resuming of the LHC operation in 2015, it is reasonable to assume that the $\delta_{\max}$ in the arcs will have returned to values higher than 2.3, as it was before the 2011-2012 machine scrubbing. In these conditions, it will be necessary to envisage and schedule a period devoted to machine conditioning, or scrubbing, in order to get into physics production with 50 ns or 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 for lowering the SEY in tha arcs to a value close to the threshold for electron cloud build up for 50 ns beams. At this point, in the case of 50 ns operation, this scrubbing run could be ended by one-two days with injections of trains of 25 ns beams aiming to lower $\delta_{\max}$ in the arcs below 2.0 and gain a safe enough margin to ensure electron cloud free operation with 50 ns beams. After a possible physics production period with 50 ns beams at 6.5 TeV, the 25 ns operation will require to perform a second scrubbing step with the 25 ns beam. By simply adding up the 50 hours of 25 ns MDs in 2011 and the 60-70 hours of efficient scrubbing in 2012, we obtain that 5 days of run with increasingly longer trains of 25 ns beams at injection energy should be sufficient to reach a condition in which the first ramps of 25 ns beams (shorter trains) to 6.5 TeV can be made. At this point, the LHC would be able to move into physics at 6.5 TeV with 25 ns beams. According to the 2012 experience, the scrubbing process described above will however not be sufficient to suppress the electron cloud in the LHC and further scrubbing will have to be achieved then during the physics run. It is worth noticing that the 25 ns operation of the LHC will entail the following:

- The electron cloud and its detrimental effects will be present, at least for some time (this remains to be estimated), mainly producing emittance blow-up at injection. Heat load, emittance blow up and low lifetime will slow down the process of intensity ramp up and affect the experiments because of the luminosity loss;
- As was observed in 2012, deconditioning will occur when the 25 ns beam does not circulate in the LHC for some time. This means that 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);
- Other effects, like UFOs, will have to be closely monitored because there has been evidence of recrudescence with 25 ns beam in 2012 [14]. Beam induced heating did not seem to be an issue during the 2012 25 ns tests, but it will also have to be carefully controlled when the beam parameters will be pushed to higher brigthness [15].

CONCLUSIONS

During the 3.5 days of scrubbing run at 450 GeV, the LHC could be filled several times (up to 2748 bunches per beam) with 25 ns beams, reaching the record intensity of

2.7×10^{14} p stored per beam. An improvement of the heat load and beam lifetime 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 long enough trains of bunches. Two days were then devoted to test ramps to 4 TeV and two days for a pilot 25 ns physics run. When performing the test ramps, fills with 84, 156, 372 and 804 bunches per beam were kept at 4 TeV for several hours in the LHC to monitor the evolution of the heat load and beam parameters. It was observed that, probably due to photoelectrons, the heat load exhibits a steep increase when ramping to 4 TeV (also confirmed by the stable phase shift data). Nevertheless, even in conditions of enhanced electron cloud, no significant blow up of transverse emittances occurs at flat top and the final bunch by bunch distribution of the emittances is mainly determined by the injectors and the blow up at injection energy. During the pilot physics run, up to 396 bunches per beam were brought into collision, while up to 780 were successfully accelerated and squeezed. Clear signs of electron cloud driven emittance blow up were observed in the fill with trains of 2×48 bunches, while the two previous fills with shorter trains did not suffer from serious beam quality degradation, except a uniform 30% emittance blow up between injection and collisions nearly independent of electron cloud.

Finally, we described a scenario to resume the LHC operation in 2015 after LS1. In particular, one week of vacuum conditioning and scrubbing will be required for the 50 ns run. After that, one more scrubbing week will be needed to get into physics with 25 ns beams. If operation with 25 ns will be chosen as standard operation after LS1, coexistence with electron cloud will be probably inevitable at least in the first part of the physics run.

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