ELECTRON CLOUD OBSERVATION IN LHC

G. Rumolo*, G. Arduini, V. Baglin, H. Bartosik, N. Biancacci, P. Baudrenghien, G. Bregliozzi, P. Chiggiato, S. Claudet, R. De Maria, J. Esteban-Müller, M. Favier, C. Hansen, W. Höfle, J. M. Jimenez, V. Kain, G. Lanza, K. Li, H. Maury Cuna, E. Métral, G. Papotti, T. Pieloni, F. Roncarolo, B. Salvant, E. Shaposhnikova, R. Steinhagen, L. Tavian, D. Valuch, W. Venturini Delsolaro, F. Zimmermann (CERN, Geneva), U. Iriso (CELLS, Barcelona), O. Domínguez, E. Koukovini-Platia, N. Mounet, C. Zannini (EPFL, Lausanne), C. Bhat (Fermilab, Batavia)

Abstract

Operation of LHC with bunch trains at different spacings has revealed the formation of an electron cloud inside the machine. The main observations of electron cloud build up are the pressure rise measured at the vacuum gauges in the warm regions, as well as the increase of the beam screen temperature in the cold regions due to an additional heat load. The effects of the electron cloud were also visible as instability and emittance growth affecting the last bunches of longer trains, which could be improved running with higher chromaticity or larger transverse emittances.
A summary of the 2010 and 2011 observations and measurements and a comparison with models will be presented. The efficiency of scrubbing to improve the machine running performance will be briefly discussed.

HISTORICAL

Since mid 2010 the Large Hadron Collider (LHC) has been operating with trains made of closely spaced proton bunches. In the first phase, beams with 150 ns bunch spacing were injected, accelerated and brought to collision. During this period of operation, the only possible signature of electron cloud build up was a pressure rise observed in the common vacuum chamber, close to the Interaction Regions. Subsequently, at the end of October 2010, an attempt was made to switch to 50 ns spacing operation. After an initial physics fill with 108 nominal bunches (filling scheme with 1 pilot bunch and 9×12 bunches), some important dynamic pressure rises were observed at injection when filling with trains of 24 bunches. In fact, the first attempt of injection in batches of 24 even led to the closure of the vacuum valves in point 7 after the injection of 108 nominal bunches per beam, as the interlock level of 4×10^{-7} mbar was reached on two vacuum gauges. After that, since it became clear that further improvements in the LHC performance were hampered by the electron cloud, emphasis was put on machine studies to characterize the electron cloud build-up in the LHC, its effects and possible cures. It was also decided that a comparative study with the behaviour of 75 ns beams was necessary to define a path for the 2011 run. Toward the end of the 2010 proton run, a Machine Development (MD) session was devoted to the set up of the LHC with 50 ns bunch trains. During this MD, three effective days of beam time were used for the setting-up proper as well as for studies and machine scrubbing. The study of the 75 ns beam took place in another dedicated MD period, while the LHC had already switched to ion operation. About 2.5 days were devoted to the setting-up of the injection and capture of the 75 ns beam and, later on, to comparative studies with the 50 ns beam. This MD gave a clear indication that, probably also benefiting from the previous MD's scrubbing with 50 ns beams, the electron cloud effects with 75 ns appeared significantly less pronounced than with 50 ns beams, such that this bunch spacing could be regarded as a relatively safe option [1].

The LHC operation was therefore resumed in 2011 directly with 75 ns beams. After the scrubbing run in 2010 it was expected that up to 200-300 bunches could be injected and accelerated without major problems. This was confirmed during the start-up with beam. After about one month of operation, the LHC could successfully collide trains of 200 bunches distributed in batches of 24 bunches each. At the beginning of April, 10 days were devoted to scrubbing of the LHC with 50 ns beams. The goal was to prepare the machine to switch to 50 ns beams and thus extend the luminosity reach for the 2011 run. During the scrubbing run, up to 1020 bunches per beam were injected into the LHC in batches of 36 and stored at injection energy. The strategy 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 and efficiently reduce the Secondary Electron Yield (SEY) of the walls to a value below the threshold for build up. The success of the scrubbing run was proved by the subsequent smooth LHC physics operation with 50 ns spaced beams. Between mid April and end June the number of bunches collided in the LHC was 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 scrubbing has naturally continued with the electron cloud activity decreasing both in terms of pressure rise and beam instability. The switch to 50 ns beams with lower transverse emittances (1.5 μm) caused a little recrudescence of the electron cloud effects, but a further scrubbing step took place very quickly. Thanks to these tinier beams, the LHC peak luminosity could easily score an additional 50% step up. The next step to push up luminosity is the increase of the inten-

* Giovanni.Rumolo@cern.ch

sity per bunch up to about 1.5×10^{11} ppb, planned to be applied over the next few months until the end of the 2011 run. The SPS experience, and first LHC observations, suggest that this could also favor a return of the electron cloud activity and may therefore require some additional scrubbing, which is gradually achieved without dedicated effort through the adiabaticity of the ramp up.
Beams with 25ns spacing were injected into the LHC only during an MD session in June. The filling scheme consisted of 9 batches of 24 bunches separated by increasing gaps (2.28, 5.13 and 29.93 μs) to check whether memory effects of the electron cloud would be visible. More MDs are planned in the future to study electron cloud effects with longer batches [2].

PRESSURE RISE AND HEAT LOAD

When an electron cloud builds up inside a machine, the flux of electrons hitting the wall of the vacuum chamber and its energy distribution, $\dot{\Gamma}_e(E)$, are the origin of both pressure rise ΔP and additional heat load ΔW:

$$\Delta P = kT\frac{\int \eta_e(E)\dot{\Gamma}_e(E)dE}{S_{\text{eff}}} \qquad \Delta W = \int \dot{\Gamma}_e(E)EdE \tag{1}$$

Here k is the Boltzmann constant, T the temperature, S_{eff} the pumping speed, η_e the desorption yield.

2010 Observations

In 2010, the electron cloud first made its appearance in the LHC during the operation with 150 ns bunch spacing. A pressure rise was seen in the common beam pipes around the experimental areas, with both beams circulating in the machine. This was ascribed to the fact that, because of the two beams coming from both directions, the effective bunch spacing in these regions can be as low as 75 ns and electron cloud becomes likely to form. Solenoids were installed around the vacuum gauges and their field could suppress the pressure increase. This proved that the origin of the outgassing was electron stimulated desorption from the presence of an electron cloud [3].
The studies with 75 ns beams were conducted by injecting into the LHC several trains of 48 bunches, each obtained from one single SPS injection of two batches of 24 spaced by 225 ns. First, it was determined that the threshold for electron cloud build up with only one beam inside the machine was between 0.9 and 1.1 $\times 10^{11}$ ppb. A pressure rise of up to 10^{-6} mbar was measured in the straight sections with 680 bunches in the machine. The vacuum activity in the common beam pipes became more severe with both beams inside the machine.
Several studies were carried out using beams with 50 ns spacing. The threshold bunch population for multipacting was determined by measuring the pressure rise for one injection of 36 bunches when varying the bunch intensity, and found to be 0.8×10^{11} ppb. Other tests aimed at estimating the survival time of the electron cloud after a bunch train passage. Two trains of 24 $\times$ 50 ns spaced bunches were injected into the LHC with distances between them from 1 to 40 μs. The pressure on different gauges, recorded for the different batch spacings, showed that the survival time of the electron cloud after the batch passage is as long as 10 μs. Finally, the pressure rise as a function of the total current in the machine was measured and found to be consistently about twice the values with 75 ns beams for the same total intensity (see Fig. 1).

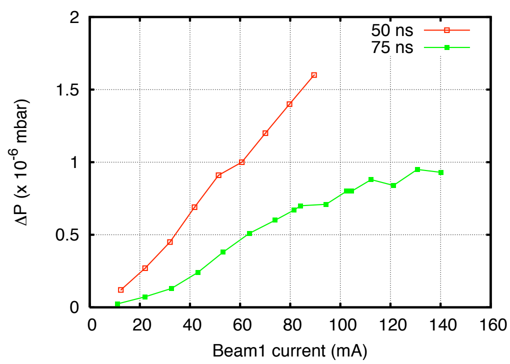

Figure 1: Pressure rise at the "worst" gauge as a function of the total beam intensity for 50 and 75 ns beams. Beams were injected in batches of 24+24 separated by 1.85 μs.

Measurements of the heat load were performed both with 50 and 75 ns beams in some reference magnet cells. While the heat load with the 75 ns beam was compatible with the estimated contributions from image currents and synchrotron radiation, the one with the 50 ns beam exceeded these estimations by $\approx$ 40 mW/m/beam (measurement resolution 5–10 mW/m/beam). The additional heat load is therefore induced by the electron cloud.
Clear effects of scrubbing could be seen after the 50 and 75 ns short runs. A reduction by a factor seven of the dynamic pressure increase induced by the injection of a train of 36 bunches was observed after approximately 16 hours of operation with 50 ns beams with configurations leading to pressure rises larger than 10^{-7} mbar. Assuming an exponential decay of the pressure rise as a function of the beam time, this would correspond to a time constant of approximately 8 hours. The pressure increase in the vacuum gauges installed in cold-warm transitions exhibited an improvement by factors 3 to 6 after 5 to 16 hours of beam. The effectiveness of the scrubbing at 450 GeV/c with a 50 ns beam was also proven by comparing the heat load in the beam screen of the reference cells before and after the scrubbing run for beams consisting of 108 bunches with the same filling pattern and bunch population. A reduction of the heat load from about 20 mW/m/beam to less than 5 mW/m/beam (i.e., the resolution of the measurement) was observed after a scrubbing period of 16 hours. Fitting the measured pressure data to ECLOUD simulations, it turns out that the wall SEY span from values well above 2.0 in the dipole arc chambers [4] to about 1.9 in the chambers of the straight sections [5].

2011 Observations

The LHC run started physics in 2011 with beams with a bunch spacing of 75 ns. Thanks to the beam scrubbing from the late 2010 MD sessions with 50 ns beams, the LHC went quickly into physics with 75 ns beams without suffering from major outgassing limitations or beam instabilities. In less than one month time, the LHC could already successfully accelerate and collide two 75 ns beams made of 200 bunches each. Strong pressure rise was again observed when the first 50 ns beams were injected into the LHC in 2011 at the beginning of the scrubbing run. One of the first fills with 50 ns beams consisted of injecting several batches of 36 bunches separated by increasing batch spacings in the LHC. The goal was to provide the pressure rise data to infer through simulations the SEY properties of the chamber walls in the vicinity of some vacuum gauges. Later on, several fills with 50 ns spaced bunches (up to 1020 per beam) were made to achieve the maximum machine conditioning during the allocated scrubbing time. The pressure improved by an order of magnitude all over the machine after 17 effective hours of beam time. At the end of the scrubbing run, residual pressure rise was still observed in cold-warm transitions and straight sections, while in the arcs both the heating of the beam screen and the pressure increase seemed to have disappeared. At this point, the LHC started routine physics operation with 50 ns beams. The number of bunches was increased to its maximum value of 1380 within 3 months. During this time, the machine got further conditioned while running for physics, as witnessed by an additional order of magnitude decrease in pressure.
An ECLOUD simulation study based on the pressure data from the gauges in the straight sections and on the measured heat load data in the reference cells of the arc dipoles, showed that the SEY has decreased from about 1.9 to roughly 1.7 during the scrubbing run. This latter value is about the electron build up threshold with 50 ns beams in most of the LHC vacuum chambers.

EFFECTS ON THE BEAM

In presence of an electron cloud, the beam also exhibits two typical signs, i.e. instability of the bunches at the end of some batches and synchronous phase shift to compensate for the energy loss from the beam-cloud interaction.
In 2010, the instability of the last bunches in some batches (seen through emittance growth and beam loss) was observed with both 50 and 75 ns beams. Like a typical electron cloud instability, it could be avoided by running with larger chromaticity or injecting larger transverse emittances. A stable phase shift proportional to the total intensity was also measured, with slope double for 50 ns beams than for 75 ns beams, consistently with the pressure data.
In 2011 the electron cloud instability still affected the 50 ns beams all throughout the scrubbing run. For instance, Fig. 2 shows a snapshot of the bunch by bunch emittances of Beam 2 at 450 GeV for one of the fills that took place during the scrubbing run. From the third to the sixth batch, an anomalous horizontal emittance growth correlated with the bunch position in the batch is visible.

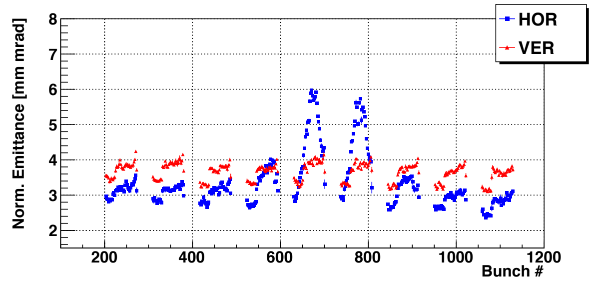

Figure 2: Bunch by bunch emittance snapshot at flat top.

Later on in the course of the run, no significant electron cloud instability and emittance growth was observed. Presently, the LHC is fully filled with 50 ns beams (1380 bunches per beam), which can be kept in collision for above 20 hours without developing any significant emittance growth pattern that could point to electron cloud.
The synchronous phase shift as a function of the beam total intensity was also re-measured in 2011 and its slope was found to decrease by more than an order of magnitude over the scrubbing run (see Fig 3). This is yet another proof of the efficiency of the scrubbing.

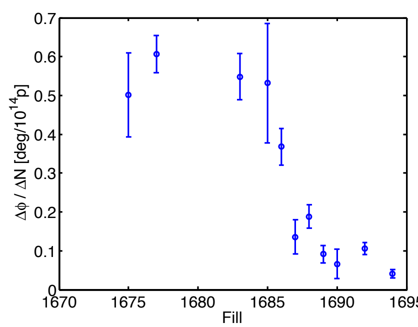

Figure 3: Evolution of the synchronous phase shift per unit of total stored current for 50 ns beams during the scrubbing run.

SUMMARY

Several observables pointed to the presence of an electron cloud in the LHC, when running with trains of closely spaced bunches. Since the electron cloud effects become more critical when reducing the bunch spacing, machine scrubbing has been applied to reduce their impact and ensure the smooth current operation with 50 ns beams. The same procedure could be attempted for the 25 ns operation, although the required SEY reduction will be more critical.

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