ELECTRON CLOUD AND SCRUBBING STUDIES FOR THE LHC

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Abstract

Electron cloud build-up resulting from beam-induced multipacting is one of the major limitations for the operation of the LHC with beams with close bunch spacing. Electron clouds induce unwanted pressure rise, heat loads on the beam screens of the superconducting magnets and beam instabilities. Operation with bunch spacing of 50 ns in 2011 and 2012 has required decreasing the Secondary Electron Yield of the beam screens below the multipacting threshold for beams with this bunch spacing. This was achieved by continuous electron bombardment induced by operating the machine with high intensity beams with 50 and 25 ns spacing during dedicated periods at injection energy (450 GeV) and at top energy (3.5 and 4 TeV). The evolution of the Secondary Electron Yield during these periods, in different sections of the machine, can be estimated by pressure rise, heat load and by bunch-by-bunch RF stable phase measurements. The experimental information on the scrubbing process will be discussed and a possible “scrubbing strategy” to allow the operation with 50 ns and 25 ns beams after the Long Shutdown in 2013-2014 will be presented.

INTRODUCTION

Electron Cloud (EC) effects are among the major limitations to the operation of the Large Hadron Collider (LHC) with tight bunch spacing. Heat load on the cryogenic sections, vacuum pressure rise and detrimental effects on the beam due to its interaction with the EC have been observed both with 50 ns and 25 ns bunch spacing and had to be mitigated through beam induced scrubbing. An overview of EC observations and studies over the last two years will be presented in the following. More details can be found in [1, 2] and references therein.

THE 2011 EXPERIENCE

In 2011, the LHC suffered from EC effects both at the beginning of the run with 50 ns beams and then later, during all Machine Development (MD) sessions with 25 ns beams. The EC 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. This lowered the maximum Secondary Electron Yield (in the following SEY, or $\delta_{\max}$) in the dipoles from an estimated initial value of about 2.3 to slightly below 2.2 (see Fig. 1), which was sufficient to guarantee an EC 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, and both heat load in the arcs and emittance growth on the bunches located at the tails of the trains were observed. In a following MD session (26 August), there was an attempt to inject trains of 48 bunches but, due to the strong EC, the beam became unstable quickly after injection and was dumped after a few hundreds of turns due to fast beam losses or large orbit excursions. The pattern of the instability over the bunch train could be successfully reproduced by means of combined PyECLOUD-HEADTAIL simulations [2]. The next short MD session with 25 ns beams (7 October) consisted of injection tests with up to 288 bunches (using high chromaticity settings, i.e. $Q' \approx 15-20$, to control the instabilities) and a store of a few hours with 60 bunches per beam at 3.5 TeV for the first data collection by the LHC experiments with 25 ns beams. It was only during the two last MD sessions, which took place on 14 and 24-25 October, 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. At this stage the beams exhibited much reduced degradation with respect to the beginning of the 2011 run, although the heat load in the arcs, as well as bunch by bunch energy loss (see Fig. 2), lifetime and emittance evolution still indicated the presence of a significant EC in the LHC.

25 ns BEAMS IN THE LHC IN 2012

Thanks to beam scrubbing from the 2011 MD sessions with 25 ns beams, which provided a safe enough margin to guarantee EC free operation with 50 ns beams, the LHC quickly became productive for physics with 50 ns beams without suffering any major limitation due to EC. The first injection tests of 25 ns beams in 2012 were made on 10 July. The time evolution of the beam losses as well as a strong emittance growth on the trailing bunches of the train clearly revealed a degradation of the beam quality with respect to 2011 for very similar beam parameters and machine settings. From the heat load measurements it could indeed be 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 (few hours). The deterioration with respect to the last value determined from heat load data in 2011 suggests that, although the arcs were not opened to

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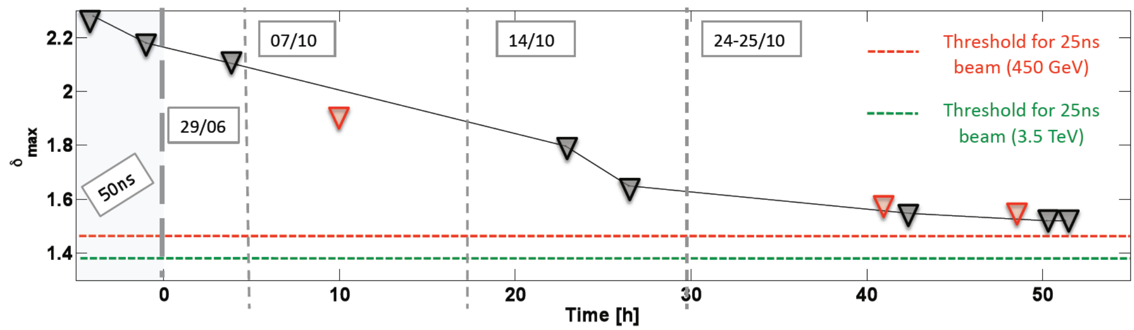

Figure 1: Evolution of $\delta_{\max}$ on the the beam screen in the dipole magnets in 2011, estimated comparing the measured heat load against PyECLOUD simulations. The first two points were measured with the 50 ns beams during and after the scrubbing run, the others with 25 ns beams during the tests with this spacing. The black (red) points are evaluated with two beams (one beam) in the ring.

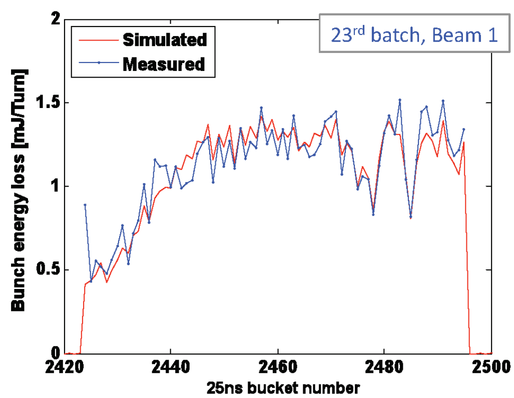

Figure 2: Bunch by bunch energy loss on a bunch train with 25 ns spacing estimated from the stable phase shift measurements (25 Oct. 2011) and from PyECLOUD build up simulations.

air during the winter shutdown 2011-2012, a deconditioning of the inner surface of the beam screen has occurred. However, it is encouraging that a value of $\delta_{\max}$ of about 1.55 could be quickly recovered after a very short scrubbing period.

Between 6 and 10 December, a scrubbing run with 25 ns beams at injection energy was carried out in order to further reduce the SEY over the whole machine and enable the LHC to be eventually ramped to 4 TeV with 25 ns beams for machine studies and a pilot physics run with this bunch spacing. The operation during this period was rather smooth since no fundamental showstoppers were found and, thanks to the excellent machine availability, a significant scrubbing dose could be maintained all along the scrubbing run. During the fist scrubbing fill with trains of 72 bunches from the SPS, the quality of the beams could be seen to improve significantly from injection to injection and the chromaticity could be lowered in steps down to $Q' \approx 7$ without triggering EC instabilities. From the second fill onwards, it was decided to switch to trains of 288 bunches per injection in order to 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} protons ($\sim$84% of the design value) was stored for Beam 2. Several stores with full machine then took place over the scrubbing period. Beam observations and heat load measurements indicate that the scrubbing process successfully carried on over the first 60 – 70 hours but later slowed down. This can be noticed, for example, in Fig. 3 where we show the average lifetime of the beam after a one hour store considering only the last five bunches of each bunch train (i.e. those most affected by EC effects). The reasons of this behavior are presently under investigation. Possible explanations include, for instance, the existence of other regions of the arcs (e.g. the main quadrupoles) 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).

After the scrubbing run, about two days were devoted to machine studies with 25 ns beams at 4 TeV. During this period the number of bunches injected into LHC and ramped to 4 TeV was gradually increased from fill to fill up to 804 bunches. 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 parameters at top energy. Immediately afterwards, a short fill with the same filling pattern and lower intensity per bunch (around 9×10^{10} ppb) was also performed in order to investigate the heat load dependence on the bunch intensity. Probably due to photoelectrons, at 4 TeV the heat load measured in the arcs was significantly enhanced with respect to the value measured at 450 GeV with the same beam and stayed practically constant during the high energy stores. Bunch by bunch stable phase measurements confirm this behavior. The analysis of the heat load suggests that no 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 EC. Bunch by bunch losses were very small and emittances increased over the 8 hour store

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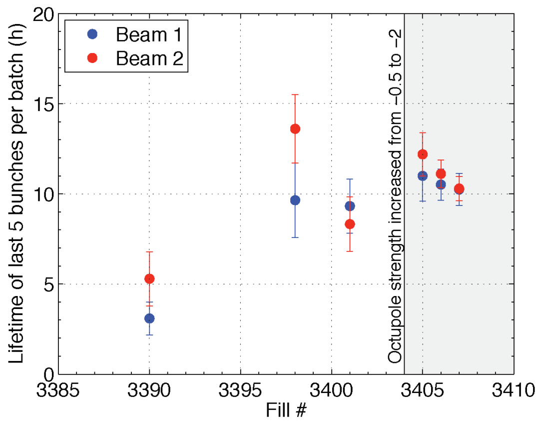

Figure 3: Beam lifetimes (after 1 hour store at injection energy, averaged over the last five bunches per 72-bunch train) as a function of the fill number during the scrubbing run. The shaded region is after a change of the octupole settings to control a fast instability on the first injected train.

by less than 10% uniformly along the train.

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 which took place from 15 to 17 December, just before the 2012 Christmas stop. 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, trains of multiples of 48 bunches from the SPS, normalized transverse rms emittance of $\sim$1.4 μm at injection into the LHC) [3]. The total intensity was ramped up through four successive fills with 108, 204, 396, 780 bunches (the last fill went successfully through acceleration and squeeze, but the beams were accidentally dumped while going in collision). The beam emittances at top energy during the collisions (averaged over the two transverse planes for Beam 1 and Beam 2) could be reconstructed from the luminosity data (see Fig. 4). The fills with 108 and 204 bunches, grouped in $\sim$25 μs spaced trains of 48 bunches, showed only a faint signature of the EC effect over the 48-bunch trains. The bunch by bunch emittances from the fill with 396 bunches clearly exhibit the typical EC pattern along the 2$\times$48-bunch trains, which appeared already at low energy. This could be related to the fact that in the latter case the build up of the first injected train generates a sufficiently high electron density in the chamber that is not completely reset before the passage of the next train.

FUTURE SCRUBBING SCENARIO

After the 2013-14 Long Shutdown, $\delta_{\max}$ of the beam screen in the arcs will likely be reset to values higher than 2.3, as it was before the 2011-2012 machine scrubbing. It will be necessary to envisage a scrubbing period 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 the arcs to a value close to the EC threshold. 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 margin to ensure EC 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. Based on the experience from 2011-12, 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 EC in the LHC and further scrubbing will have to be achieved then during the physics run implying a slow down of the intensity ramp-up process due to heat load, emittance blow up and poor lifetime.

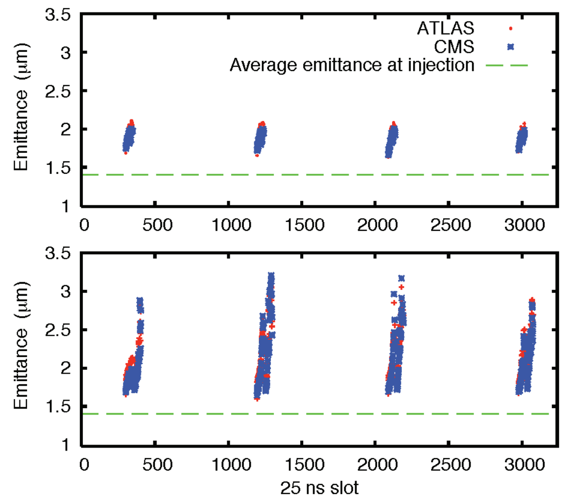

Figure 4: Snapshots of the bunch by bunch emittances from luminosity for the fill with 204 (top) and 396 bunches (bottom). The line of the measured emittances at injection is also drawn. Courtesy of M. Hostettler and G. Papotti.

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