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ANALYSIS OF THE ELECTRON CLOUD OBSERVATIONS WITH 25 ns BUNCH SPACING AT THE LHC

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Abstract

Electron Cloud (EC) effects have been identified as a major performance limitation for the Large Hadron Collider (LHC) when operating with the nominal bunch spacing of 25 ns. During the LHC Run 1 (2010 - 2013) the luminosity production mainly used beams with 50 ns spacing, while 25 ns beams were only employed for short periods in 2011 and 2012 for test purposes. On these occasions, observables such as pressure rise, heat load in the cold sections as well as clear signatures on bunch-by-bunch emittance blow up, particle loss and energy loss indicated the presence of an EC in a large portion of the LHC. The analysis of the recorded data, together with EC build up simulations, has led to a significant improvement of our understanding of the EC effect in the different components of the LHC. Studies were carried out both at injection energy (450 GeV) and at top energy (4 TeV) aiming at determining the energy dependence of the EC formation and its impact on the quality of the proton beam.

INTRODUCTION

Electron Cloud (EC) effects were observed at the LHC during the first three years of beam operation (Run 1, 2010–2012), becoming more and more severe while reducing the bunch spacing [1]. EC effects with 50 ns beams could be successfully mitigated through beam induced scrubbing and this bunch spacing could be used for most of the integrated luminosity production with 7–8 TeV Center of Mass (CoM) energy in 2011–12. After the 2013–14 machine shutdown (LS1) the LHC will be able to run at 13–14 TeV CoM energy and it will be necessary to move to the design bunch spacing of 25 ns in order to reach the design luminosity within the pileup limits accepted by the LHC experiments. Up to now, the 25 ns beam has been used only for test purposes, and as expected from simulation studies, due to the lower multipacting threshold, EC effects proved to be significantly more severe compared to the 50 ns case. Therefore, several experimental studies have been performed at the LHC with this bunch spacing in order to characterize the EC formation in the machine and its impact on the performance.

Beams with 25 ns spacing were injected into the LHC for the first time in 2011 and the first scrubbing tests with 25 ns beams at 450 GeV took place towards the end of the same year. More extensive studies were performed in 2012 when the last two weeks of the run were devoted to machine operation with 25 ns bunch spacing. This period featured three main stages: 1) a 3.5 days scrubbing run, during which the LHC was regularly filled with a large number of bunches with 25 ns spacing (up to 2700 bunches per ring) in order to decrease as much as possible the Secondary Electron Yield (SEY) of the beam chambers via beam induced scrubbing; 2) Machine Development (MD) fills with 25 ns beams at 4 TeV aiming at studying EC, beam-beam and other performance limitations with this bunch spacing; 3) a pilot physics run, during which the LHC experiments could collect data with 25 ns beams at 4 TeV. The main results of these activities with respect to EC effects will be summarized in the following while a more comprehensive description can be found in [2].

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SCRUBBING AT INJECTION ENERGY

Beam induced scrubbing proved to be effective for mitigating EC effects in the LHC achieving a full suppression of the EC in the cryogenic arcs for 50 ns beams and an important reduction with 25 ns beams. During the 2012 Scrubbing Run with 25 ns beams, a decrease of the SEY was seen in a substantial abatement on the heat load in the cryogenic sections and on the dynamic pressure rise in the room temperature sections. The reduction of the EC density in the beam chambers also reflected on beam quality observations. In the beginning, in order to control EC induced instabilities, high chromaticity settings ($Q'_{x,y} \simeq 10$) had to be used and large gaps had to be left between the injected trains of 72 bunches. Later on, the chromaticity could be lowered to $Q'_{x,y} \simeq 6$ and the LHC could be filled with about 2700 bunches per ring in trains of 288 bunches without triggering instabilities. A steady improvement, especially in the first stages of the Scrubbing Run, could be observed also on the beam lifetime and on the transverse emittance preservation.

The effect of the EC on the beam could be monitored through the bunch-by-bunch energy loss, as estimated from the RF synchronous phase shift. The signature of the EC buildup, with the energy loss growing along the bunch trains and saturating towards the tail, could be easily recognized in the measurement. In Fig. 1 we compare energy loss measurements, taken typically after each injection, during the first scrubbing fill (top) and during a fill performed after two days of scrubbing (bottom). A reduction by a factor of two on the peak energy loss can be observed, as a consequence of the SEY decrease.

Heat load measurements from the cryogenic system showed that a large part (up to 80%) of the energy lost by

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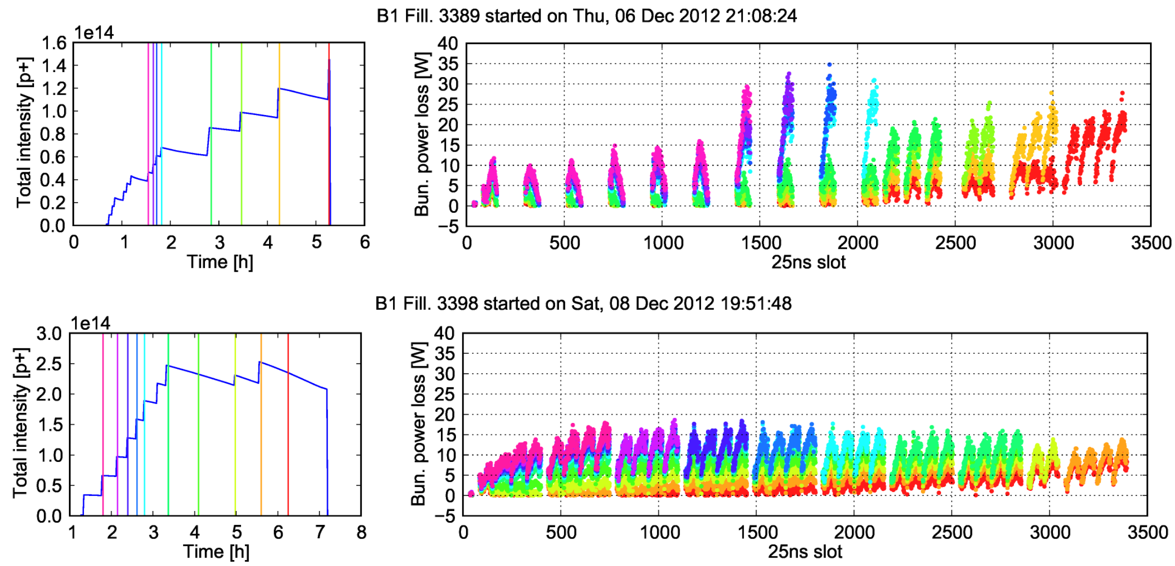

Figure 1: Total beam intensity and bunch-by-bunch energy loss measurements for beam 1 during two different fills of the 2012 scrubbing run with 25 ns beams. The different traces in the right plots correspond to different times indicated by vertical bars in the left plots (for the first six trains in the top plot, data acquired right after the corresponding injection were not available).

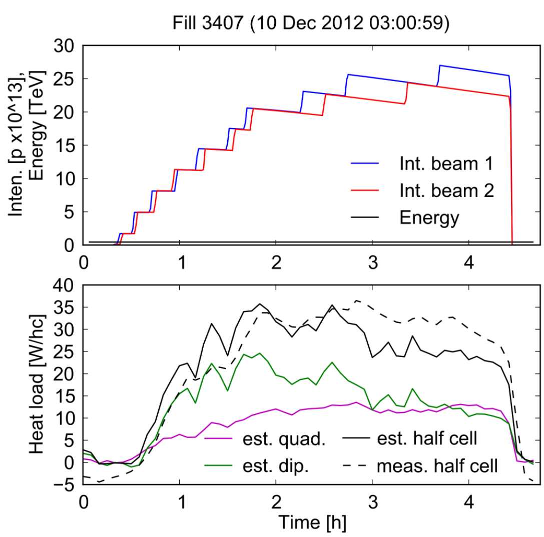

Figure 2: Heat load measured in the SAM quadrupoles and dipoles rescaled to the lengths of the magnets in a regular LHC arc half-cell (purple and green), their sum (black continuous), and values measured in the LHC arcs (black dashed).

the beam was deposited on the beam screens of the cryogenic arcs. The comparison of the measured heat load with the estimated beam induced heating due to synchrotron radiation and to the impedance of the beam screen, confirmed that a strong contribution from EC was present during all the tests with 25 ns beams. In the LHC arcs each beam screen cooling circuit extends over a full half cell (three 15 m long dipoles and one 3.1 m long quadrupole plus multipoles), hence the individual contributions of the different magnets to the heat load cannot be separately measured. In order to disentangle the contributions from dipoles and quadrupoles we decided to use the information coming from the heat load measurements in the Stand Alone Modules (SAM) installed in the straight sections, which are magnets equipped with a dedicated cryostat for which heat load detection is available. In particular we considered the matching quadrupoles Q5 on both sides of the Insertion Regions (IRs) 1 and 5 and the separation dipoles D3 of the IR 4. We rescaled the measured values to the lengths of the magnets in a regular LHC arc half-cell in order to estimate the respective contributions to the total heat load. The results of this procedure for the last fill of the 2012 Scrubbing Run are shown in Fig. 2. The total estimated heat load is shown by the continuous black curve and is consistent with the average value measured in the LHC arcs (dashed black line). We notice that, despite being a small portion of the total arc length, the quadrupoles give a significant contribution to the heat load. This feature was expected from EC buildup simulations, which showed that the quadrupoles have a much lower multipacting threshold compared to the dipoles. Figure 2 also shows that the heat load in the dipoles is much more sensitive to beam degradation since the dipole contribution is larger than the one from the quadrupoles at the beginning of the fill, when the beam parameters are close to nominal. The two become roughly equal at the end of the fill, when transverse blowup and particles losses had already occurred on many bunches of the beam. This is because the SEY in the dipoles is very close to the multipacting threshold and therefore small changes in the beam parameters can have a strong impact on the EC buildup.

ENERGY RAMP AND 4 TeV STORES

Despite not being sufficient to fully suppress the EC at injection energy, the conditioning accumulated during the 2012 scrubbing run was sufficient to allow ramping for the first time beams with 25 ns spacing up to 4 TeV. Several fills

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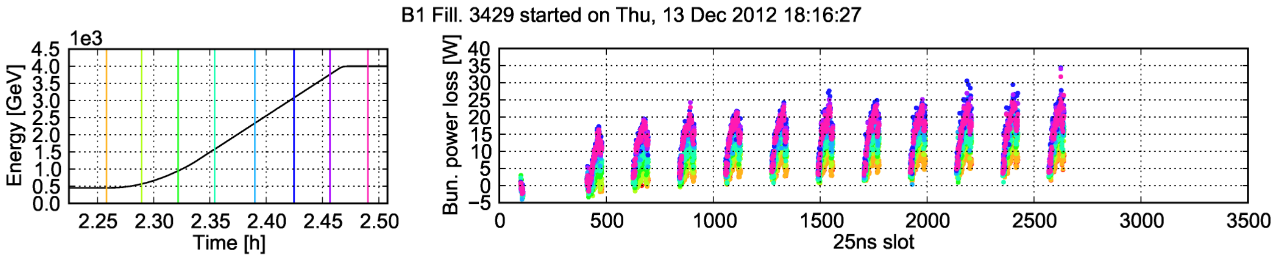

Figure 3: Beam energy and bunch-by-bunch energy loss measurements for beam 1 during the energy ramp of a fill with about 800 bunches with 25 ns spacing. The different traces in the right plot correspond to different times indicated by vertical bars in the left plot.

at 4 TeV were performed for MD purposes and for a pilot physics run, during which the four LHC experiments could collect data from p-p collisions with 25 ns bunch spacing.

As in all the other tests with 25 ns beams, the heat load exceeded by a large factor the value expected just from the synchrotron radiation and the beam screen impedance contributions. Moreover a strong enhancement could be observed between injection energy (450 GeV) and top energy (4 TeV). Because of the slow time response of the cryogenic system, we could not use the heat load measurement to resolve the behavior of the EC induced heat load on the energy ramp. Instead, this could be achieved by observing the beam energy loss from the stable phase measurements, as shown in Fig. 3, from which we could notice that the enhancement of the energy loss is much less pronounced on the first bunches of the circulating batches (as expected for EC effects). Since an increase in energy loss is observed even in the very first part of the energy ramp, the increase in primary electrons due to photoemission along the arc dipoles, which should become non negligible only when the beam energy reaches about 2 TeV, cannot be the only mechanism driving the observed enhancement. Most likely the impact on the EC buildup of other mechanisms like bunch length and transverse beam size reduction is also non negligible, especially in the dipole magnets where the SEY at the moment of the experiment was very close to the multipacting threshold estimated for the injection energy.

Despite the strong EC activity observed during the high energy stores, there were no signs of important beam degradation at top energy that could be ascribed to EC effects. This is not completely surprising, since at higher energies the beam tends to become less sensitive to transverse kicks due to the larger longitudinal momentum (increased "beam rigidity"). Indeed the transverse emittance blowup observed with 25 ns beams during the high energy stores looks very similar to the one observed with 50 ns, for which no EC buildup was occurring in the LHC arcs. This suggests that also in the 25 ns cases the blowup during collision is driven by other mechanisms than EC. This is also confirmed by bunch by bunch emittance measurements. Figure 4 shows the emittances estimated from the luminosity at different moments of a physics fill performed with 396 bunches with 25 ns spacing. We can notice the typical EC signature on the transverse emittances along the train already on the first trace, which was taken right after the beams were brought in collision. Actually, using transverse emittance measurements from the synchrotron radiation telescope, we could verify that the blowup had occurred mainly at injection energy. During the high energy stores (when beams were colliding in all the Interaction Points) we notice a completely different behavior since the transverse blow up is stronger for the bunches at the head of the bunch trains, even if they experience a much weaker interaction with the EC. This again goes in the direction that the transverse blowup observed at high energy is driven by other mechanisms than EC.

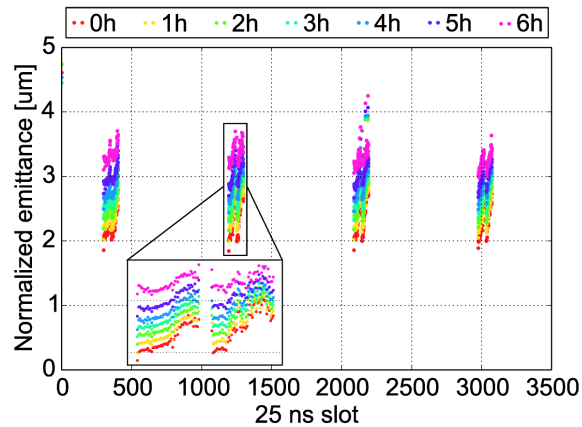

Figure 4: Bunch-by-bunch transverse emittances estimated from luminosity at the ATLAS experiment during a fill with 396 bunches with 25 ns spacing. Different traces correspond to different moments during the store.

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