IMPACT AND MITIGATION OF ELECTRON CLOUD EFFECTS IN THE OPERATION OF THE LARGE HADRON COLLIDER

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Abstract

In 2015 and 2016 the Large Hadron Collider has been routinely operated with 25 ns bunch spacing. With this beam configuration, electron clouds develop in a large fraction of the beam chambers, in spite of a very large electron dose accumulated on the surfaces. This posed several challenges to different aspects of the beam operation. In particular, the machine settings had to be optimized in order to mitigate coherent and incoherent effects of the electron cloud on the beam dynamics. A specifically designed feed-forward control had to be implemented and optimized in order to dynamically adapt the regulations of the cryogenic system to the strong heat load deposited by the electron cloud on the beam screens of the cryogenic magnets. At the same time, the data collected from the different accelerator subsystems (e.g. heat loads and evolution of the bunch by bunch beam parameters) allowed to significantly improve our models and understanding of these phenomena.

OPERATION IN THE PRESENCE OF ELECTRON CLOUD

Electron cloud effects caused important limitations to the performance of the LHC in 2015, the first year of luminosity production with 25 ns beams [1, 2]. Transverse instabilities and beam degradation were observed especially at injection energy. These could be mitigated by using the full performance of the LHC transverse feedback and operating with large chromaticity and octupole settings, while the tunes at injection had to be optimized to accommodate the large tune spread generated by the chromaticity, the octupoles and the e-cloud together [3].

Furthermore, the e-cloud was depositing a significant power on the beam screens of the cold magnets, which constituted a significant heat load for the LHC cryogenic system [4]. In order to cope with rapid changes of the heat load, especially when injecting beam and during acceleration, a feed-forward control had to be developed that automatically regulates the beam screen cooling circuits based on the measured properties of the circulating beams [5].

A reduction of the heat load per beam particle due to beam induced scrubbing could be observed over the year, nevertheless the heat load was still limiting the total intensity in physics at the end of the 2015 run.

During the 2015-16 Year-End Technical Stop (YETS) most of the machine was kept under vacuum. For this reason only a partial de-conditioning of the beam screen surfaces occurred. Therefore, the end-2015 situation could be rapidly recovered with only one day dedicated to scrubbing at injection energy [2]. After that, by applying the solutions found in 2015 to preserve the beam stability and handle the heat loads, the total number of bunches in collision could be rapidly increased to 2040 bunches per beam in trains of 72 bunches without significant limitations from e-cloud.

Problems encountered in the LHC injectors prevented to inject longer bunch trains. It was decided instead to increase the beam brightness to gain in luminosity. This could be done using a different production scheme in the PS accelerator called Batch Compression Merging and Splitting (BCMS) [6]. With this configuration each injection into the LHC consisted of two trains of 48 bunches (with a 225 ns gap between the two) and the number of bunches at 6.5 TeV could be increased to 2220, exceeding the LHC design luminosity [7].

During the entire 2016 run, high chromaticity and octupole settings were still needed in order to preserve the transverse emittances at injection energy. In fact, the octupole current had to be increased when moving to brighter beams in order to keep similar tune spreads. Dedicated experiments with different filling patterns confirmed that the observed instabilities are driven by e-cloud. Moreover the fact that a similar blow-up occurred both in the horizontal and in the vertical planes points to the e-cloud in the quadrupole magnets as the main source of instability. These observations are discussed in more details and compared against numerical simulations in [8].

CONDITIONING OF THE ARC BEAM SCREENS

Figure 1 shows the heat load measured at high energy in the eight arcs for all physics production fills in 2015 and 2016. In the bottom plot the data have been normalized to the total intensity of the circulating beams.

Over the 2015 run, a decrease of the normalized heat load (on average by a factor of two) could be observed, due to conditioning of the beam screen surfaces. This process continued at the beginning of the 2016 run, with some further margin gained with respect to the available cooling capacity (160 W for each 53 m long arc half-cell, consisting of three main dipoles and one short straight section), while the normalized heat loads stayed practically constant over the rest of the run. These observations are confirmed by dedicated reference fills performed to better disentangle the conditioning effect from other changes of the beam configuration [2].

In Fig. 2 the normalized heat loads over the two years are plotted as a function of the integrated heat load, which is an indicator of the electron dose accumulated on the beam screens. It can be noted how the different sectors start from significantly different values, and this difference is preserved throughout the conditioning process, in spite of the very

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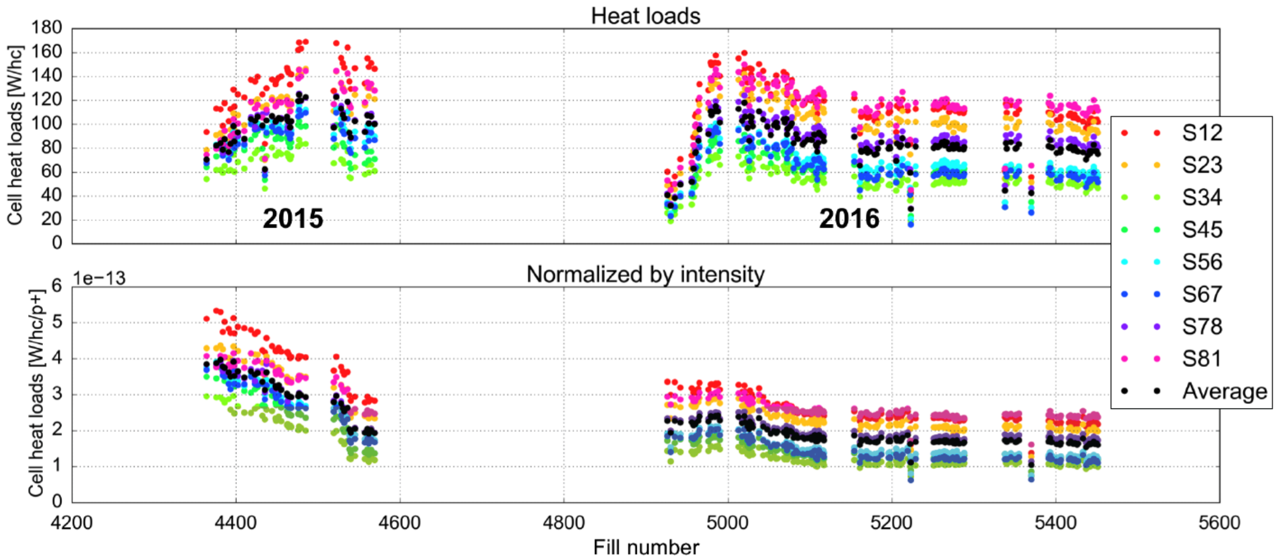

Figure 1: Top: heat load measured at high energy for all the fills with 25 ns bunch spacing in 2015 and 2016. Bottom: the same data normalized to the intensity of the circulating beam.

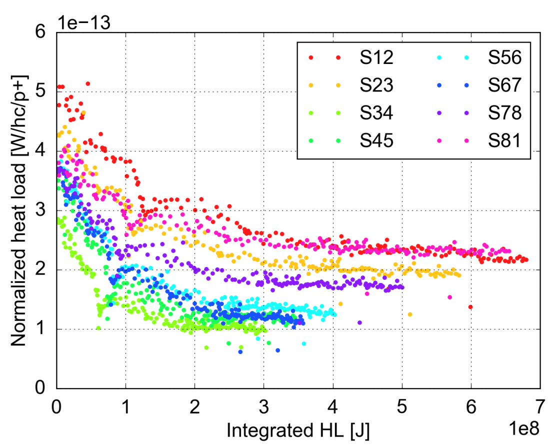

Figure 2: Normalized heat load at high energy as a function of the integrated heat load accumulated on the beam screens.

different accumulated heat loads. This behavior is still unexplained, since the different sectors are by design identical.

Nevertheless, the accumulated conditioning should allow to further increase the number of bunches for the 2017 run, when the limitations from the injector complex will be removed. In particular, it should be possible to operate with the maximum number of bunches allowed by the BCMS scheme (i.e. 2556 bunches) for bunch intensities up to $1.2{\times}10^{11}$ p/bunch [9].

EFFECT OF BEAM PROPERTIES

The data collected on the LHC subsystems during physics operation and in dedicated tests allow studying experimentally how different beam properties influence the e-cloud formation. This will be briefly discussed in the following subsections.

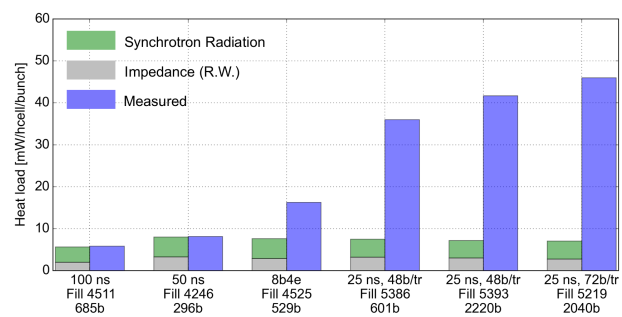

Figure 3: Heat loads measured at high energy with different filling patterns in one of the LHC arcs (S23). The expected values from impedance and synchrotron radiation (calculated as described in [11]) are shown for comparison.

Effect of the Filling Pattern

A characteristic feature of e-cloud effects is the strong dependence on the bunch spacing [10]. Figure 3 shows the heat load at high energy (normalized to the number of bunches) measured in one of the LHC arcs with different filling patterns (more information can be found in [12]). For bunch spacings of 100 ns and 50 ns, the measured heat loads agree very well with the expectations from impedance and synchrotron radiation.

With 25 ns bunch spacing the heat load is instead much larger due to the strong contribution from the e-cloud. With this bunch spacing, the heat load per bunch changes only by a small amount when comparing trains of 48 bunches against trains of 72 bunches and when the ring is filled only partially (see comparison between 2220 bunches and 601 bunches in Fig. 3).

An intermediate situation is observed with the “8b+4e” pattern, which is made of short trains of eight 25-ns spaced bunches interleaved by four empty slots [6] in order to mitigate the e-cloud formation. With this scheme the maximum number of bunches in the LHC is limited to about 70% of

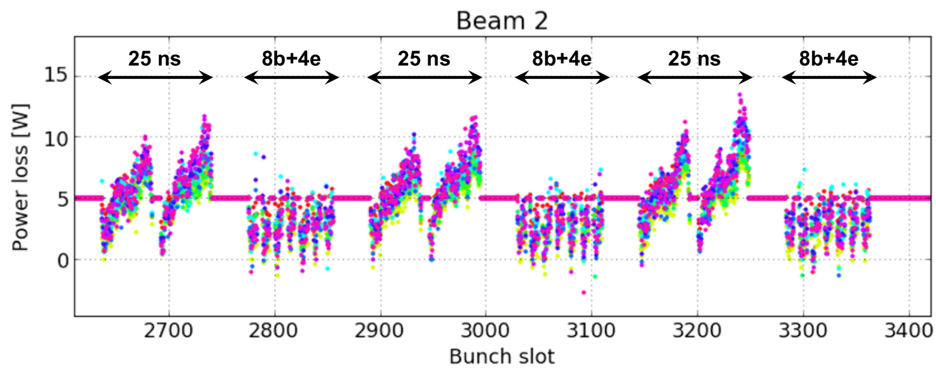

Figure 4: Bunch-by-bunch energy loss, measured using the RF stable phase, during a test fill combining 8b+4e trains of 56 bunches and 25 ns trains of 48 bunches in the same filling pattern (Data courtesy of J. Estaban Muller).

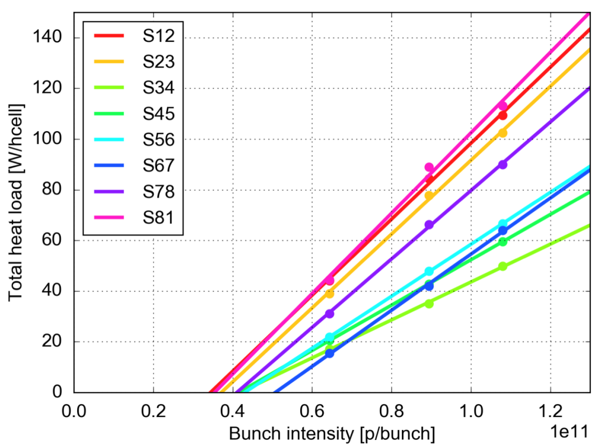

Figure 5: Heat load at high energy measured in the LHC arcs in three dedicated fills with different bunch intensities. A linear fit of the data for each arc is also shown.

what can be achieved with the standard 25 ns pattern. Figure 3 shows that with this configuration the measured heat load per bunch is larger than the expectation from impedance and synchrotron radiation but still significantly reduced compared to longer 25 ns bunch trains.

In 2016, the possibility was investigated of combining 8b+4e trains with standard 25 ns trains within the same filling scheme in order to adapt the heat load to the available cooling capacity while maximizing the number of bunches. This could be successfully tested in a Machine Development session. A hybrid filling scheme with 1908 bunches was used, consisting of 55% of 25 ns beam and of 45% of 8b+4e beam, resulting in 15% less bunches than the equivalent standard filling scheme. In these conditions a 40% reduction of the heat load could be observed in the most critical sector of the machine [13]. Measurements of the bunch-by-bunch power loss, estimated by the RF stable phase [14], confirmed that a significant e-cloud is developing exclusively around the 25 ns trains, as shown in Fig. 4.

Effect of the Bunch Intensity

The dependence of the heat load at 6.5 TeV on the bunch intensity was investigated with three dedicated fills performed in a Machine Development session. The results

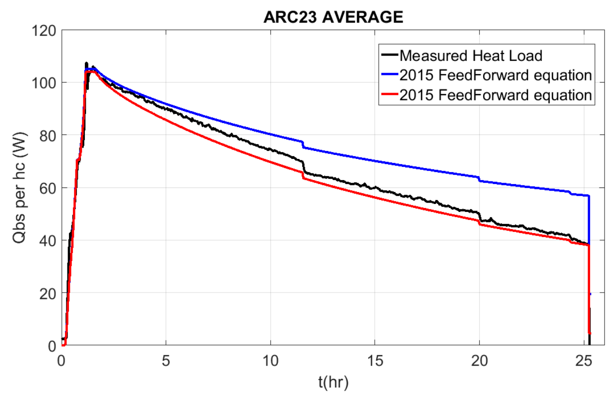

Figure 6: Heat load measured at high energy in one of the LHC arcs (S23) compared against the evaluation used for the feed-forward loop in 2015 and 2016.

of these measurements for the eight LHC arcs are shown in Fig. 5 together with a linear fit of the data. The intensity threshold for the e-cloud formation can be clearly identified in the region between 0.3×10^{11} p/bunch and 0.5×10^{11} p/bunch. More details can be found in [15].

The presence of such an intensity threshold was initially not taken into account in the definition of the feed forward algorithm for the cryogenics regulations, which simply assumed a linear dependence on the bunch intensity, calibrated around the nominal value of 1.1×10^{11} p/bunch [5]. As shown by the blue curve in Fig. 6, this led to a significant overestimation of the heat loads at the end of very long fills, when the intensity decreased significantly due to luminosity burn-off. In these cases the feed-forward was significantly over-cooling the beam screens. This was corrected in 2016 by introducing an intensity threshold in the feed-forward model, which allows for a better modeling of the heat load decrease during long fills (see red curve in Fig. 6).

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