ELECTRON CLOUD OBSERVATIONS DURING LHC OPERATION WITH 25 ns BEAMS

*K.Li ,H.Bartosik,G.Iadarola,L.Mether,A.Romano,G.Rumolo,M.Schenk,CERN,Geneva,Switzerland

Abstract

While during Run 1 (2010-2012) of the Large Hadron Collider (LHC) most of the integrated luminosity was produced with 50 ns bunch spacing, for the Run 2 start-up (2015) it was decided to move to the nominal bunch spacing of 25 ns. As expected, with this beam configuration strong electron cloud effects were observed in the machine, which had to be mitigated with dedicated scrubbing periods at injection energy. This enabled to start the operation with 25 ns beams at 6.5 TeV, but e-cloud effects continued to pose challenges while gradually increasing the number of circulating bunch trains. This contribution reviews the encountered limitations and the mitigation measures that where put in place and will discuss possible strategies for further performance gain.

INTRODUCTION

While most of the luminosity production for the LHC Run 1 was performed with 50 ns bunch spacing, for Run 2 it was decided to move to the design value of 25 ns. Tests performed before the shutdown as well as simulation studies showed that electron cloud (e-cloud) effects could pose important challenges to the operation of the machine [1–3].

For this reason it was decided to start the operation with roughly nominal beam parameters (typically $1.1{\times}10^{11}$ p/bunch with transverse emittances of about 2.5 μm), postponing to a later stage the exploitation of high brightness beam variants available from the injectors. Moreover, a significant time of the machine schedule was devoted to scrubbing runs for the mitigation of the e-cloud.

After a first period of commissioning with low intensity beams, a first scrubbing run took place in the period 24 June – 5 July 2015, with the aim of preparing the machine for a first intensity ramp-up in physics with 50 ns beams. With this bunch spacing only about 450 bunches per beam could be accelerated to 6.5 TeV, due to radiation to electronics faults in the Quench Protection System (fixed during the following Technical Stop) [4].

A longer scrubbing period took place in the period 25 July – 10 August, aiming at enabling physics production with 25 ns beams. After that, the LHC was operated mostly with 25 ns bunch spacing for the rest of the proton run, with a gradual increase of the beam intensity during this period.

SCRUBBING AT 450 GeV

After the Long Shutdown 1 (LS1), the Secondary Electron Yield (SEY) of the LHC beam screens was found to be reset to the values observed at the beginning of Run 1. This is not surprising, since most of the machine was exposed to air. In fact, e-cloud induced instabilities were observed even with 50 ns beams, which were used routinely for physics production before the shutdown, without major problems from the e-cloud.

Figure 1 (top) shows the beam intensity evolution during the scrubbing periods. Apart from an initial short period with 50 ns bunch spacing (~2 days), the scrubbing was mainly performed with 25 ns beams [5]. The main limitations encountered during these periods were, initially, violent e-cloud instabilities which led to beam dumps or strong beam quality degradation and considerably hampered efficient scrubbing to take place. This improved with time as the machine settings could be optimized and gradual scrubbing did occur. In addition, technical limitations had to be dealt with such as strong pressure rises at the injection kicker (MKI) as well as vacuum spikes at the damaged injection absorber (TDI) in Point 8 (see [6]) which limited the total number of bunches in beam 2 throughout the scrubbing. Finally, there was the limitation imposed by the cryogenics system suffering from strong transients on the beam screen temperature during injection which would lead to loss of the cryogenic conditions. Hence, it was not possible to inject at the maximum speed allowed by the SPS repetition rate.

Despite these limitations the intensity in the machine was gradually increased up to about 2400 bunches. The scrubbing efficiency was optimized based on observations and monitoring of the heat loads and bunch-by-bunch energy loss [7].

The evolution of the SEY of the beam screens in the main dipoles could be reconstructed by comparing heat load measurements with PyECLOUD buildup simulations (as described in [1]) and is shown in Fig. 1 in the bottom plot. The SEY reduction is much faster at the early stages of the scrubbing process when the SEY is larger, which is a known feature of the surface behavior [8]. Nevertheless, an evident improvement of the beam quality was observed even in the later stages.

INTENSITY RAMP-UP WITH 25 ns BEAMS AT 6.5 TeV

Despite the fact that full suppression of the e-cloud was not achieved, the scrubbing runs provided sufficient mitigation to control the beam degradation at 450 GeV and start the intensity ramp-up with 25 ns beams at 6.5 TeV.

One of the first consequences of the presence of a strong e-cloud in the machine, was the difficulty to ensure the beam stability at 450 GeV. High chromaticity and octupoles settings were required together with the full performance of the transverse damper [9–11]. As a consequence, however, these settings, in combination with the effects of the e-cloud,

---

* Kevin.Shing.Bruce.Li@cern.ch

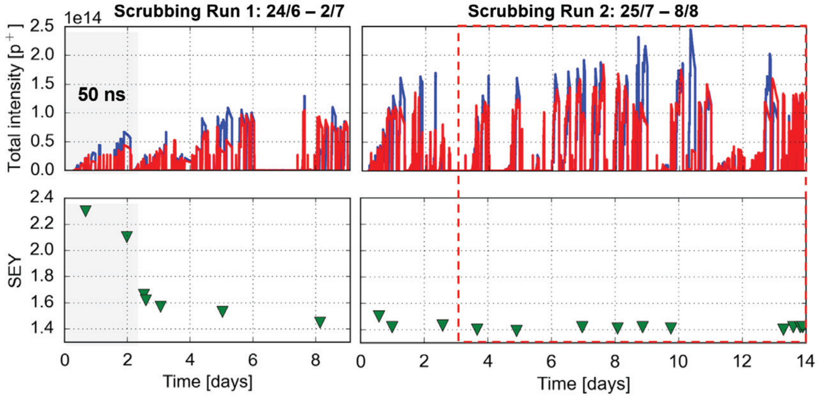

Figure 1: Evolution of the beam intensity during the scrubbing periods (top) and corresponding evolution of the SEY in the dipoles as estimated from simulations (bottom).

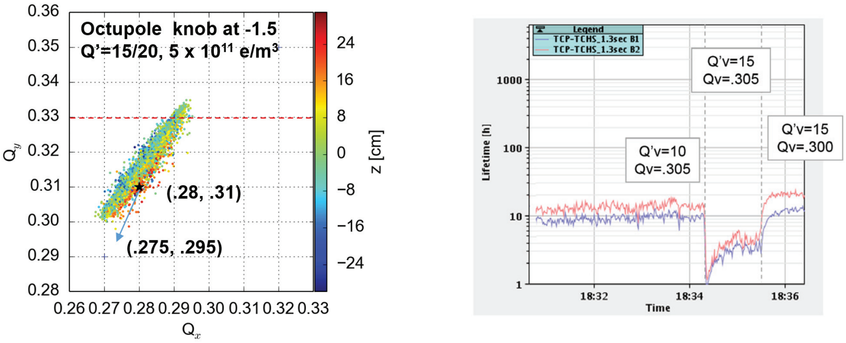

Figure 2: Left: tune footprint at 450 GeV as obtained from PyECLOUD-PyHEADTAIL simulations. Right: beam lifetime measured with 25 ns beams in the LHC for different settings of vertical tune and chromaticity. A drop is observed when the vertical chromaticity is increased by five units – the lifetime is recovered when the vertical tune is lowered by 0.005 units while keeping the chromaticity at 20 units.

induced a large tune footprint at 450 GeV potentially hitting the third order resonance at Q_y=59.33 as shown in Fig. 2 (left). The contribution of the different mechanisms (Q', octupoles, e-cloud) to the tune footprint has been studied in detail with PyECLOUD-PyHEADTAIL simulations as described in [12]. As a result, following a proposition that was already made in August at the early stage of intensity ramp-up with 25 ns, it was decided to operate with vertical tunes slightly lower than nominal (Q_y=59.295 instead of Q_y=59.31) which then, in fact, significantly improved the beam lifetime at 450 GeV. The effect of different tune and chromaticity settings on the beam lifetime is shown in Fig. 2 (right). With this, instabilities and beam degradation could be kept reasonably under control.

The e-cloud was still posing important challenges to the beam intensity ramp-up at 6.5 TeV due to the unprecedented heat loads on the beam screens of the cryogenic magnets. In order to allow for fine tuning on the regulations of the cryogenic systems, the intensity ramp-up had to be performed in small steps (∼ 150 bunches). Moreover, the injection speed had to be decreased in order to better control beam screen temperatures. Eventually, the limitations from transients on the heat loads could be improved by modifications introduced on the Cryo Maintain rules, allowing for larger temperature excursion, as well as by the continuous effort in improving of cryogenic feed-forward control [13].

By the beginning of October, the LHC could be operated with around 1450 bunches per ring with a total beam intensity of $1.5{\times}10^{14}$ p^+ per ring, approaching at this point, however, the limit of the available cooling capacity on the arc beam screens. To overcome this limitation, together with further conditioning of the beam screens also the beam parameters had yet to be further optimized. The bunch length was increased from 1.25 ns to 1.35 ns and the filling scheme was adapted in order to minimize the number of bunches at e-cloud saturation, based on the e-cloud risetime observed on the bunch-by-bunch energy loss from the RF stable phase shift [14]. In particular, the heat load could be controlled by increasing the spacing between the bunch trains and by reducing the length of the trains themselves. By the end of the proton run it was possible to operate with 2244 bunches per ring in short trains of 36 bunches, with bunch intensities of about $1.2{\times}10^{11}$ p/bunch.

The bottom plot in Fig. 3 shows the average heat load measured on the arc beam screens during the intensity ramp-up with 25 ns beams. A global reduction by a factor two

ISBN 978-3-95450-147-2

Figure 3: Evolution of the beam intensity (top), average heat load in the arc magnets (middle) and heat load normalized to the beam intensity (bottom) during the intensity ramp-up with 25 ns beams.

can be observed on the heat load per proton, as a combined effect of the accumulated scrubbing dose and of the tuning of the beam parameters.

The electron dose deposited on the beam screens over this period could be inferred combining heat load measurements and PyECLOUD simulations (providing information on the geometric distribution and energy spectrum of the electrons impacting on the beam screens). The result is shown in Fig. 4, which reports for comparison also the dose accumulated during the scrubbing run at the beginning of August. It appears evident that it would have been impossible to accumulate the same dose during a dedicated scrubbing run with a reasonable duration. Assuming that the behavior of the beam screen surfaces will be the same after future Long Shutdowns, the most efficient strategy will be to allocate a shorter scrubbing period, sufficient to achieve acceptable beam quality, and then accumulate further dose in parallel with physics (with the e-cloud defining the pace of the intensity ramp-up).

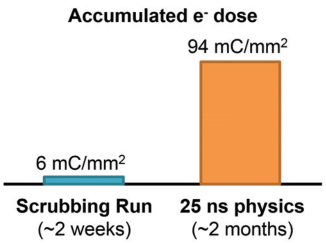

Figure 4: Electron dose accumulated in the arc dipoles during the second scrubbing period and during the physics intensity ramp-up. Only electrons with energies above 50 eV are considered, since they give a stronger contribution to the scrubbing process [8].

CONCLUSIONS

The 2015 experience has shown that scrubbing at 450 GeV allows to achieve sufficient mitigation for e-cloud instabilities and beam degradation occurring at low energy with 25 ns bunch spacing. Optimized machine settings involving chromaticity, Landau octupoles and transverse feedback together with a change of the working point enabled to preserve the good beam quality from injection to collision, in spite of the e-cloud still present in the machine (as witnessed by the heat load in the arcs). The cryogenics system required close follow-up and optimization of the Cryo Maintain rules together with the filling schemes employed to enable a reliable operation. This allowed the use of 25 ns beams for a large fraction of the luminosity production in 2015, with the positive side effect of accumulating a significant electron dose during the physics fills. This resulted in a reduction of the e-cloud induced heat load in the arc dipoles by roughly a factor of two in two months of operation.

The analysis also revealed the very large doses needed to observe an evolution of the heat loads at this stage. These are practically incompatible with a dedicated scrubbing run. Hence, for the future, only short scrubbing runs are foreseen with the aim of achieving sufficient beam quality to move towards luminosity production. The main scrubbing would then be performed parasitically during the physics runs.

ACKNOWLEDGMENTS

The authors would like to thank many colleagues from BE/ABP, BE/BI, BE/OP, BE/RF, EN/STI, TE/ABT, TE/CRG, TE/VSC for the fundamental support they provided throughout the presented studies, and G. Arduini and E. Metral for providing important input to this contribution.

REFERENCES

[1] G. Iadarola, "Electron Cloud studies for CERN particle accelerators and simulation code development", CERN-THESIS-2014-047 and references therein.

[2] G. Iadarola, G. Arduini, H. Bartosik and G. Rumolo, "Electron cloud and scrubbing in 2012 in the LHC" in Proceedings of LHC Operation Workshop Evian 2012, 18–20 December, 2012, Evian, France.

[3] G. Iadarola and G. Rumolo, "Scrubbing: Expectations and Strategy, Long Range Perspective", Proceedings of the Chamonix 2014: LHC Performance Workshop, Chamonix, 22–25 Sep 2014, France.

[4] S. Danzeca, "R2E - Is it still an issue", Proceedings of LHC Operation Workshop Evian 2016, 15–17 December, 2015, Evian, France.

[5] G. Rumolo, "Outcome of the scrubbing run", presented at LMC 19/08/2015.

[6] A. Lechner, "TDI", Proceedings of LHC Operation Workshop Evian 2016, 15–17 December, 2015, Evian, France.

[7] J. Esteban Müller and E. Shaposhnikova, "Synchronous phase measurements in the LHC for electron cloud observations", CERN-ACC-NOTE-2013-0007.

[8] R. Cimino et al., "Nature of the Decrease of the Secondary-Electron Yield by Electron Bombardment and its Energy Dependence", PRL 109, 064801 (2012).

[9] L. Carver, "Instabilities and Beam Induced Heating in 2015", Proceedings of LHC Operation Workshop Evian 2016, 15–17 December, 2015, Evian, France.

[10] D. Jacquet, "Injection", Proceedings of LHC Operation Workshop Evian 2016, 15–17 December, 2015, Evian, France.

[11] G. Kotzian, "ADT Post-LS1", Proceedings of LHC Operation Workshop Evian 2016, 15–17 December, 2015, Evian, France.

[12] A. Romano, "Effect of the e-cloud on the tune footprint at 450 GeV", presented at LBOC Meeting 27/10/2015.

[13] K. Brodzinski, "Cryogenics", Proceedings of LHC Operation Workshop Evian 2016, 15–17 December, 2015, Evian, France.

[14] G. Iadarola, "Heat load evolution, tests with different batch spacing and possible filling schemes for the next intensity steps", presented at LMC 07/10/2015.