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ELECTRON CLOUD OBSERVATIONS AND MITIGATION FOR THE LHC RUN 3

L. Mether*, B. Bradu, G. Iadarola, S. Johannesson[1], K. Paraschou, G. Rumolo, L. Sabato[1],
CERN, Geneva, Switzerland
[1] also at EPFL, Lausanne, Switzerland

Abstract

When operated with the nominal bunch spacing of 25 ns, the Large Hadron Collider (LHC) suffers from significant electron cloud effects. During the second operational run (Run 2) of the LHC, beam-induced conditioning allowed a satisfactory exploitation of 25 ns beams for luminosity production but could not fully suppress electron cloud formation. It has since been understood that this limitation was due to a degradation of some of the beam screen surfaces that occurred with beam operation after air exposure during the first long shutdown period. In the LHC Run 3, several electron cloud effects are expected to become even more important due to the increase in bunch intensity foreseen during the run. In addition, the beam screens have again been exposed to air during the preceding shutdown period, leading to a reset of most of the conditioning acquired in Run 2 and opening the possibility for further degradation. In this contribution, we describe the experimental observations of electron cloud effects during operation with beam after the start of Run 3 in 2022 and discuss their implications for future operation and mitigation strategies for the remainder of the run.

INTRODUCTION

The LHC has been routinely operated with beams with 25 ns bunch spacing since the beginning of Run 2 in 2015. Throughout this time, electron cloud effects have been present during standard machine operation for luminosity production [1–3]. Among the main experimental observations of the electron cloud are transverse instabilities and emittance growth occurring at injection as well as additional heat load on the beam screens of the cryogenic magnets, up to six times larger than expected from beam induced impedance and synchrotron radiation alone. A reduction in these effects could be observed during the first few months of operation in Run 2, indicating the beam-induced conditioning of the beam screen surfaces, i.e. the lowering of the secondary emission yield (SEY) of the surface due to bombardment by the electron cloud itself [4, 5]. However, little to no evolution was observed after the first months and over the majority of the run, while electron cloud effects remained evident.

Contrary to expectation, the heat loads measured on the beam screens showed large variations between the eight arcs of the machine, as well as between individual half-cells, magnets and apertures. Comprehensive studies of the behaviour of the heat loads with different beam and machine configurations together with electron cloud simulations identified an alteration of the SEY of some of the beam screen surfaces as the most likely cause for the observed heat loads [6]. The hypothesis was later supported by surface analysis conducted on beam screens extracted from the LHC after Run 2. Surfaces from beam screens with high measured heat loads, which showed both a low carbon content and the presence of cupric oxide (CuO), instead of the cuprous oxide (Cu_2O) found on beam screens with low heat loads, also showed larger SEY and slower conditioning with electron bombardment at room temperature than beam screens with low measured loads [7, 8].

A comparison of the heat loads measured during Run 2 to heat loads measured during first tests with 25 ns beams shortly before the start of the first long shutdown, which showed a much lower average and no significant difference between the eight arcs, suggests that this surface alteration occurred during or after the shutdown [6, 9]. While the precise origin and process of degradation is not fully understood, the risk remains that further degradation could occur trough the same mechanism as a consequence of air exposure during subsequent shutdowns.

SCRUBBING RUN

In 2022, the LHC was brought back into operation after its second long shutdown period (LS2). Since most of the beam chambers and in particular the arc beam screens were exposed to air during LS2, the conditioning acquired over Run 2 was lost. In order to condition the beam screens sufficiently to allow for standard operation, a dedicated scrubbing run took place, during which successive fills were stored at injection energy (450 GeV) for long periods of time for beam-induced conditioning. The reset of the SEY was observed clearly when the first trains of bunches were injected into the ring. Due to violent transverse instabilities and fast beam losses, it was initially not possible to store trains of more than 12 bunches, as seen in Fig. 1, even with stabilization from strong chromaticity, octupoles and the transverse feedback system. Over the scrubbing run, the train length could gradually be increased up to 288 bunches and in total 2748 bunches/beam could be stored with reasonable beam quality, indicating a strong reduction of the SEY of the surfaces.

A reconstruction of the SEY evolution during the scrubbing run was made by comparing the measured heat loads in each half-cell of the machine to the expected heat load for different SEY, based on electron cloud simulations of the main arc elements (dipoles and quadrupoles) with the

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* lotta.mether@cern.ch

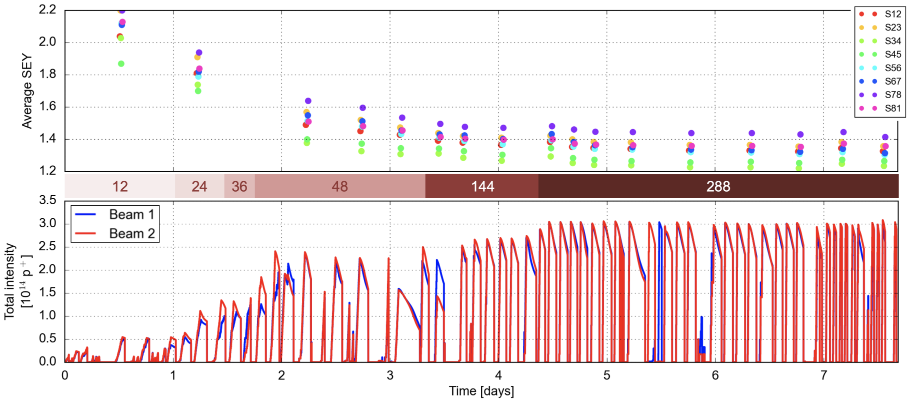


Figure 1: Evolution of the SEY (top), bunch train length (middle) and beam intensity (bottom) during the scrubbing run.

PyECLOUD code [10], as shown in Fig. 1. The average SEY at the beginning of scrubbing was above 1.8 in all sectors and decreased to 1.4 or below over the scrubbing run, as implied by the improvement in beam stability and lifetime.

2022 OPERATION

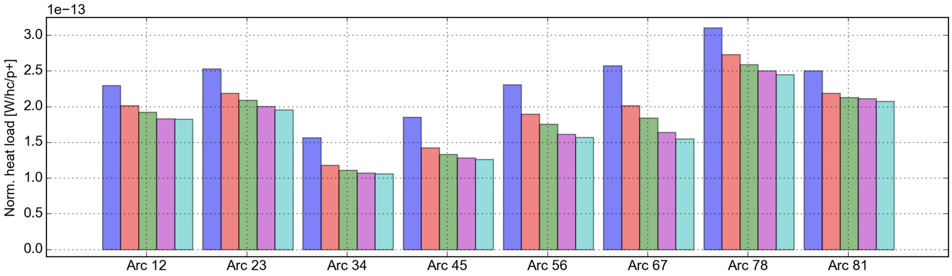
After the scrubbing run, the LHC beams were brought into collision for luminosity production at 6.8 TeV with a gradually increasing number of bunches, starting with around 300 bunches/beam. The bunch intensity was kept at or below 1.2×10^{11} p^+, with the intention to gradually increase the intensity up to 1.4×10^{11} p^+ once the full machine, i.e. 2748 bunches/beam injected in trains of 5×48 bunches, had been reached. From the beginning of the scrubbing run and throughout the intensity-ramp-up, the highest average heat load was systematically measured in one of the eight arcs, namely sector 78 [11, 12]. Notably, the heat loads in this particular sector were of an intermediate magnitude in Run 2 [2]. A few weeks into the intensity ramp-up, with around 2200 bunches/beam, the heat load in sector 78 reached close to the cooling capacity available for this sector from the cryogenic system, around 195 W/half-cell [13, 14]. From this point on, the increase in number of bunches and bunch intensity was limited by the heat load in this sector [15].

In order to reduce the heat load per bunch so that the number of bunches could be increased, it was necessary to either decrease the bunch intensity or change the bunch train pattern to limit electron cloud production. Since the electron cloud fully builds up in an estimated 20-30 bunch passages [16], the total amount of electron cloud can be reduced by reducing the length of the individual bunch trains. By switching from trains of 48 to trains of 36 bunches it was possible to inject around 2450 bunches/beam (close to the maximum number of bunches possible with this train pattern) without lowering the bunch intensity. Over the remaining two months of operation in 2022, this bunch pattern was used and the bunch intensity could gradually be increased up to nearly 1.5×10^{11} p^+ at the start of collisions, while keeping the heat load in sector 78 at the limit of the available cooling capacity. The intensity increase was possible in part due to the continued conditioning of the surfaces and in part due to the modification of other beam parameters, in particular the bunch length which was gradually increased from 1.1 to 1.3 ns over the same period.

The beam screen heat loads are the best quantitative measure of the amount of electron cloud in the LHC. Whereas it is evident, based on the evolution of the heat loads during 2022 operation, that further conditioning of the beam screens has taken place, it is difficult to estimate the precise amount and pace of conditioning, due to the constant change in beam parameters over the same period. Figure 2 shows a comparison of the heat loads between five fills over the year, sampled at different times within the fill, such that the bunch intensities and lengths have similar values. The comparison suggests that the beam screen conditioning has tapered off, as expected with accumulated electron dose, and that significant further conditioning is unlikely to occur, leaving several sectors with higher heat loads than expected, based on their state in Run 2 [15]. An independent observation of the worsened machine state is the fact that stronger mitigation measures in the form of high chromaticity and octupole currents were required in 2022 than in Run 2, despite the expected favorable scaling of beam stability with increasing bunch intensity [17]. In conclusion, the observed electron cloud effects in 2022 strongly indicate that further beam screen degradation has occurred as a consequence of LS2.

MITIGATION IN RUN 3

During 2023, the bunch intensity in the LHC will be increased up to 1.8×10^{11} p^+, which is foreseen to be the operational bunch intensity until the end of Run 3, in 2025 [18]. Given the state of the beam screens and the prospects for further conditioning by the end of 2022, it is clear that such intensities can only be achieved with further changes to the bunch train pattern due to the heat load in sector 78. Compared to simply cutting the bunch trains even shorter, a more powerful mitigation measure is provided by the “8b+4e” bunch pattern, which consists of trains of 56 bunches, where every 8 bunches are followed by 4 empty bunch slots [19]. Because the scheme introduces gaps already on the rising slope of the build-up, the electron cloud never reaches full



	01 Aug 2022	21 Aug 2022	15 Oct 2022	01 Nov 2022	25 Nov 2022
Fill	8079	8149	8274	8333	8484
T_sample [h]	1.50	3.18	5.10	6.90	7.70
Avg. int. (B1/B2) [p]	1.10e11/1.11e11	1.10e11/1.10e11	1.07e11/1.13e11	1.08e11/1.11e11	1.08e11/1.12e11
Bun.len. (B1/B2) [ns]	1.13/1.14	1.12/1.12	1.12/1.13	1.10/1.13	1.13/1.13

Figure 2: Comparison of the normalized heat load over 2022 operation, as represented by five fills separated by an equal dose of accumulated heat load. The heat loads are sampled at different times within the different fills, in order to find comparable bunch intensity and bunch length between fills.

saturation, leading to a strong reduction of electron cloud effects [20]. A test at the end of 2022 of the 8b+4e beam with bunch intensity around 1.7×10^{11} p^+ at collision energy confirmed a reduction by more than 70% of the electron cloud component of the heat load. The drawback of this scheme is the limitation of the total number of bunches to less than 2000 per beam. A better compromise is obtained with hybrid filling schemes, combining 8b+4e beam with standard 25 ns beam, which allow adjusting the amount of 8b+4e beam to match the heat load to the cooling capacity [4]. A hybrid filling scheme mixing 35% of 8b+4e beam with trains of 48 bunches, tested in the LHC in 2022, showed a 15% reduction in the heat load per bunch in sector 78 for a 4% reduction in the number of bunches.

Based on a cell-by-cell SEY map of the machine, obtained by comparing the measured heat loads in each half-cell to the heat loads expected from simulations with matching beam conditions, further simulations can be used to predict the expected heat load as a function of the bunch intensity for different bunch train patterns. Dedicated heat load measurements made with different bunch intensities at the end of 2022 show an excellent agreement with the predicted heat load dependence on bunch intensity, based on the SEY estimation from a physics fill performed around the same time, as shown in Fig. 3 for sector 78. Following this procedure, we can estimate the maximum number of bunches achievable with a given bunch intensity, or the maximum achievable bunch intensity with a given number of bunches, for different bunch train patterns. These estimates can in turn be used to calculate the integrated luminosity that can be reached for the different bunch train options.

In general, studies show that filling patterns that are strongly limited in bunch intensity give poor performance, even if they allow for a large number of bunches [21]. The best compromise between heat load and performance is predicted to be obtained with a hybrid scheme, with injections consisting of a single train of 8b+4e beam (25%) followed by up to five trains of 36 bunches (75%). This filling pattern allows for a similar total number of bunches as used in

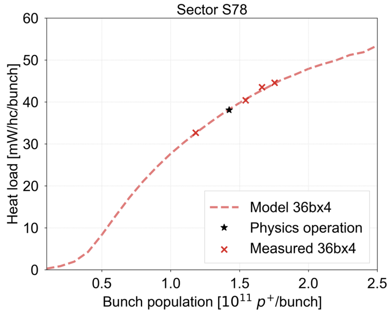


Figure 3: A comparison of the predicted dependence of heat load on bunch intensity (dashed curve) based on a physics fill (star) with measurements at different bunch intensity (crosses) for injections with 4 trains of 36 bunches.

2022, but is not expected to be limited in intensity below 1.8×10^{11} p^+/bunch and is therefore foreseen to be used for operation in 2023. If it proves successful, and it is confirmed that no significant further conditioning of the beam screens that would provide additional margin occurs, the same mitigation measure will likely be used throughout Run 3.

CONCLUSION

Observations during LHC operation in 2022 show stronger electron cloud effects than observed during most of Run 2, indicating that further degradation of the beam screens has occurred, as a consequence of the recent shutdown. Throughout 2022, the achievable number of bunches was limited by the heat load in sector 78. The limitation is expected to be more severe with the increase in bunch intensity foreseen as of 2023. It can be partly compensated by operating with the hybrid filling schemes identified as mitigation strategy and a good performance of the LHC can nevertheless be expected. On the other hand, the observations raise concern for the long-term performance reach of the LHC, if still further degradation cannot be avoided. For this reason, methods are under study for treating the beam screen surfaces to improve both their SEY and conditioning behaviour [7, 8].

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