LUMINOSITY AND LIFETIME MODELING AND OPTIMIZATION

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Abstract

During Run 2, the continuous monitoring of the luminosity evolution has revealed the existence of lifetime degradation sources, beyond burn-off. By employing a bunch-by-bunch analysis, beam-beam effects but also electron cloud have been identified as significant contributors to these additional losses. In order to mitigate these effects and improve performance, multi-parametric Dynamic Aperture (DA) simulations have been used as a guide to establish the optimum machine parameters during operation. The impact of the reduction of chromaticity and octupole current, as well as the crossing angle anti-leveling and levelling techniques of 2018 are further detailed.

INTRODUCTION

Luminosity is an important indicator of the performance of a collider, defined as the number of events per second normalized to the interaction cross section [1]. One of the main mechanisms that affect the delivered luminosity are the beam losses [2]. Studies during Run 1 and 2, based on experimental observations and the luminosity model, revealed the existence of losses, which are above burn-off [3], an effect that indicates the presence of additional diffusion mechanisms, such as electron-cloud and noise.

To this end, important information can be extracted by monitoring the luminosity evolution along the years. In Run 2, a variety of beam flavors, levelling techniques, β^* values and the introduction of the Achromatic Telescoping Squeezing (ATS) optics [4] were incorporated in operation. The comparison between different beam and machine configurations is performed through an automatic bunch-by-bunch (bbb) and Fill-by-Fill (FbF) performance follow-up tool [5], based on the extracted data from the logging system (CALS) [6]. The combination of the monitoring tool with the luminosity model, underlines a sensitivity of the additional losses on the machine configuration, as well as a lifetime asymmetry between Beam 1 and Beam 2. The aim of this paper is to identify the source of these losses by studying the most impacted beam modes in the cycle and to investigate the cause of the lifetime imbalance between the two beams.

The paper is divided in four sections. First, an overview of the lifetime at Stable Beams (SB) for 2017 and 2018 is presented. The bunch classification needed for the analysis, driven by the bbb variations observed across the Fills, is defined in the second section. Next, the impact of the β^* reduction on the losses during squeeze is depicted and the tune optimizations applied in 2018, based on Dynamic Aperture (DA) studies [7], are shown. The impact of the levelling and anti-leveling techniques on the lifetime at SB is discussed in the last section along with preliminary indications concerning the asymmetry of the two beams.

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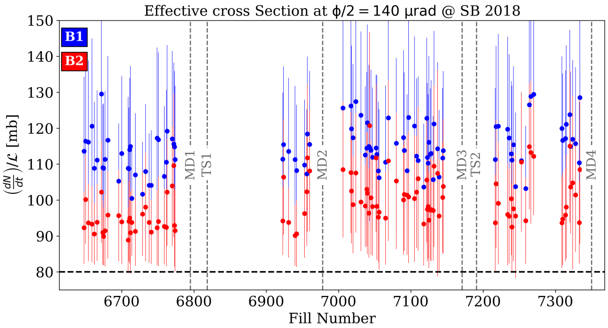

Figure 1: Effective cross section for Beam 1 (blue) and Beam 2 (red) as a function of the Fill number for $\phi/2 = 140\ \mu$rad. The inelastic cross section of the proton-proton collisions is represented by the black dashed lines.

STABLE BEAMS LIFETIME OVERVIEW

In 2018, LHC operated with a beam energy of 6.5 TeV, with the Batch Compression Merging and Splitting (BCMS) scheme and a nominal bunch spacing of 25 ns [8]. To regain some of the luminosity lost due to burn-off, the crossing angle was gradually reduced with decreasing beam intensity at collision [9]. The beams were squeezed to a β^* of 30 cm and then further reduced to 25 cm during SB in order to maximize the integrated luminosity.

Using the performance follow-up tool, the average effective cross section, defined as the loss rate normalized to the measured luminosity, is computed for the proton physics Fills of 2018. Due to the variation of the crossing angle during the anti-leveling, for a consistent comparison between the Fills, a specific value of the crossing angle is selected. Figure 1 depicts the effective cross section of Beam 1 (blue) and Beam 2 (red) as a function of the Fill number for a half crossing angle of 140 μrad. The inelastic cross section of proton-proton collisions (~81 mb) is illustrated (black dashed line). The vertical lines with TS and MD labels correspond to the Technical Stops and Machine Development dedicated Fills, respectively. Reviewing the results yields that losses beyond the burn-off limit are systematically present for both beams. It must be noted however, that this effect is more significant for Beam 1.

LOSSES IN 2017 AND 2018

An increase in losses was observed between the 2017 and 2018 run. For a consistent comparison between the two,

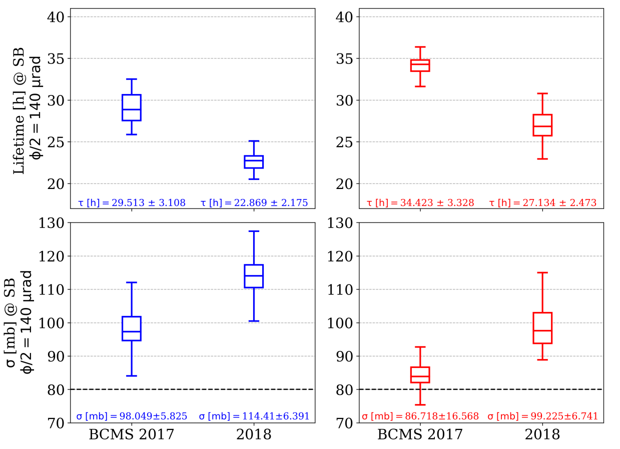

Figure 2: Average lifetime (top) and effective cross section (bottom) for B1 (blue) and B2 (red) at SB computed from the BCMS Fills in 2017 and 2018.

only the BCMS Fills of 2017 (Fills 5830-6165) have been included in the analysis. Figure 2 shows the average lifetime (top) and the effective cross section (bottom) for Beam 1 (left) and Beam 2 (right) in 2017 and 2018. The error bars correspond to one standard deviation. These observations reveal a reduction of 22.5% and 21.2% in lifetime and an increase of 16.7% and 14.4% in effective cross section for Beam 1 and Beam 2, respectively, in 2018. The main modification in the machine configuration between the two runs is that in 2017 the machine was mainly operating with a β^* equal to 40 cm in the high luminosity interaction points which was reduced to 30 cm in 2018.

BUNCH CLASSIFICATION

In order to disentangle the impact of several effects on the loss rate, the introduction of a bunch classification is necessary. Figure 3 presents the contribution of burn-off (green) and additional losses (red) on the bbb loss rate [10]. This decomposition reveals accumulating losses along the trains, patterns compatible with the presence of electron cloud. To study these bbb variations and individually assess the contribution from beam-beam effects and electron cloud, the following bunch classes are defined:

1. Pacman: Bunches at the start of the batch, with limited long-range encounters.
2. LR: Bunches which experience the maximum number of long-ranges in IP1 and 5.
3. LR-ecloud: Bunches affected both from beam-beam effects and electron cloud.
4. Pacman-ecloud: Bunches at the end of the batch, encountering the minimum number of long ranges and the maximum impact from electron cloud.

The position of the classes as a function of the number of the long range encounters in the two IPs is illustrated in Fig. 4 for a single batch and a color code is assigned to each group. In the next sections, an average over seven bunches is

Figure 3: Bunch-by-bunch loss rate for Beam 1 at 4.2 h in SB for Fill 6666 [10].

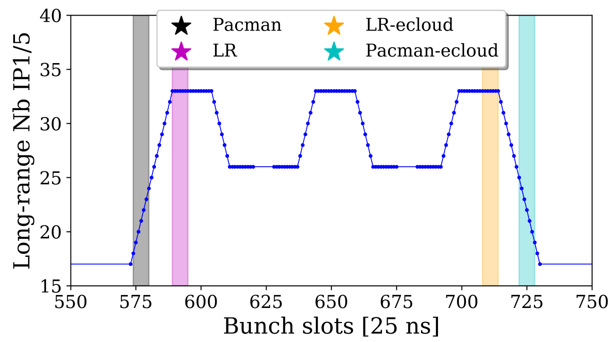

Figure 4: Position range of the different classes as a function of the number of long range encounters in IP1 and IP5.

performed per class and only the batches consisting of 144 bunches are considered.

SQUEEZE

In the 2018 run, a reduction of lifetime was reported during the telescopic part of the squeeze, which was not visible during the BCMS Fills of 2017 [11, 12]. Figure 5 shows the average lifetime over all 2018 proton Fills as a function of the β^* steps. The imbalance between the two beams is already visible during this beam mode, with Beam 1 reaching the start of SB with a lower lifetime. Furthermore, for $\beta^* < 40$ cm an abrupt lifetime reduction is observed for both beams. These losses were not present in 2017 as the β^* was limited to 40 cm (vertical dashed line). Through this observation a correlation of the losses with the β^* reduction is established.

A bbb analysis reveals a lifetime reduction for bunches at the center and tails of the trains, patterns compatible with long-range and electron cloud effects. Figure 6 (left) depicts the evolution of the β^* (blue) and the octupole current (black) and a color code is assigned to the lifetime (right) as a function of the bunch position. Similarly to the previous observations, the impact on lifetime becomes more significant with the reduction of β^*. In addition, these patterns are more pronounced in Beam 1 (top), while Beam 2 (bottom) is less affected.

A class decomposition of the average losses over all Fills during squeeze summarizes the contribution of the different

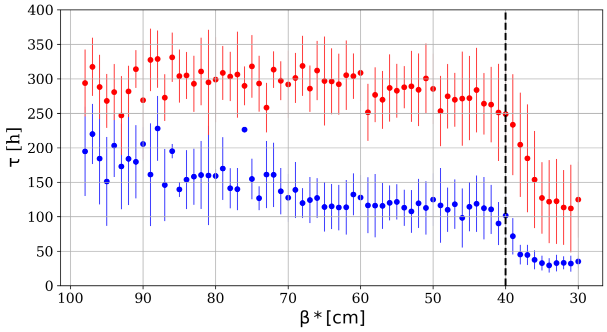

Figure 5: Average lifetime of the 2018 proton Fills as a function of the β^* steps during squeeze in 2018 for Beam 1 (blue) and Beam 2 (red). The black dashed line indicates the minimum β^* value in squeeze 2017.

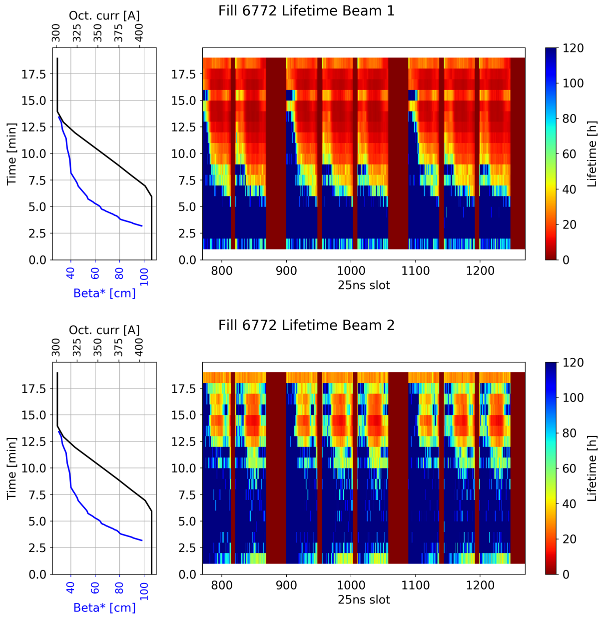

Figure 6: Bunch-by-bunch lifetime of Beam 1 (top) and Beam 2 (bottom) during squeeze and the evolution of the β^* (blue), as well as the octupole current (black).

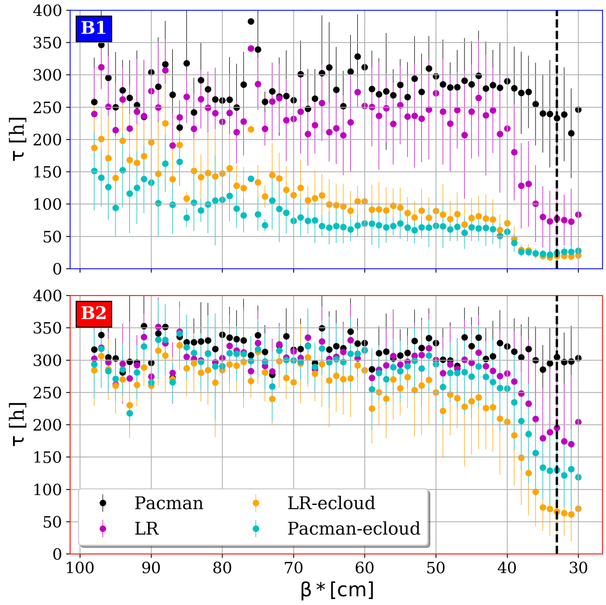

Figure 7: Class decomposition of the lifetime reduction during squeeze for Beam 1 (top) and 2 (bottom).

bunch types. Figure 7 presents the average lifetime as a function of the β^* for the various classes. These results show that no significant impact is observed in the Pacman class during squeeze. Although a reduction is observed for the LR class, the main contributors are the bunches which are also affected by electron cloud.

For the mitigation of the beam-beam effects, tune optimizations during squeeze were applied in 2018, based on the results of DA simulations. These results are obtained by computing the minimum DA for each pair of horizontal and vertical tunes in the vicinity of the nominal working point (Q_x, Q_y)=(0.31,0.32). The optimal working point is defined as the pair that leads to the maximization of the minimum DA. The results suggest that operating closer to the diagonal can have a beneficial impact on the beam lifetime [13]. In 2018, the first tune optimization was conducted after TS1 and a second modification was applied after MD2. Figure 8 shows the bbb loss rate for the two beams at the nominal value of the working point (top) and after the second tune optimization (bottom), where the working point is moved to (0.305,0.315). Although the dependence on the long range encounters is less pronounced, the electron-cloud patterns are still present. This can be explained by the fact that only the Pacman and LR classes are currently simulated and effects such as electron cloud are not considered. In normal operation, the majority of the bunches can be identified as LR-ecloud types. Effects such as electron cloud, noise and magnet imperfections introduce additional non-linearities, that further limit the minimum DA and hence, the beam lifetime. The tune optimizations proved to be beneficial for the LR and LR-ecloud classes, where an improvement in lifetime by a factor of 1.3, 0.4 and 3.1, 1.8 for each class and beam, respectively, is observed. As a next step, the octupolar current was decreased, aiming to reduce the tune spread and to provide additional margins in the DA, which did not lead to any significant improvement in terms of lifetime.

STABLE BEAMS

In 2018, the contribution of the extra losses as a luminosity degradation mechanism was comparable to the emittance blowup, an effect which was not observed during the previous years [14]. Figure 9 presents the average evolution of the effective cross section in 2018 for Beam 1 (top) and Beam 2 (bottom) and the spread corresponds to one standard deviation. A comparison with the burn-off limit (black dashed line) indicates that extra losses are observed in the first few hours of SB. In 2017, these losses decay and reach the burn-off limit, an effect that was not observed in 2018.

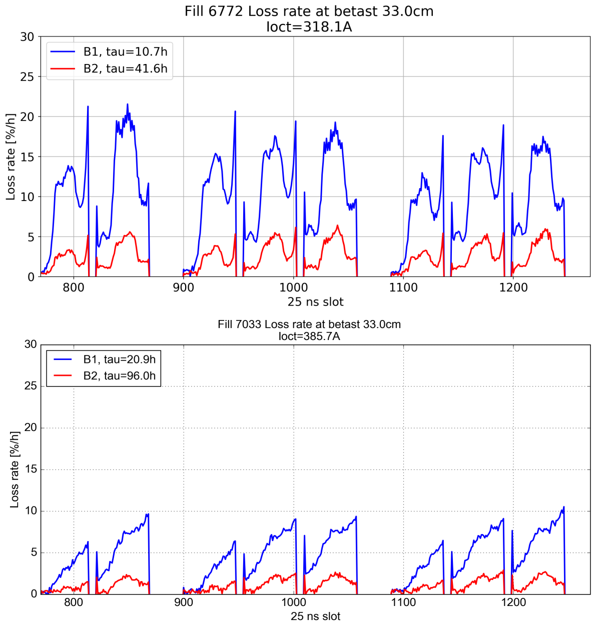

Figure 8: Bunch-by-bunch loss rate for Beam 1 (blue) and Beam 2 (red) at the nominal working point (top) and after the second tune optimization (bottom).

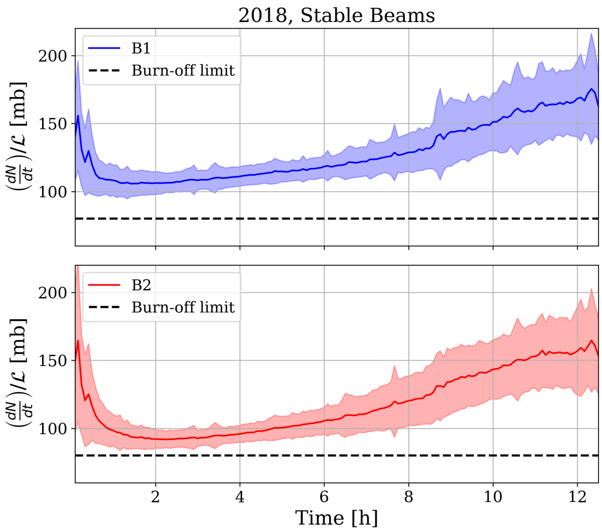

Figure 9: Evolution of the effective cross section in 2017 (top) and 2018 (bottom) for Beam 1 (blue) and Beam 2 (red). The black dashed line represents the burn-off limit.

On the contrary, these losses continuously increase during the anti-leveling with visible spikes during the β^* levelling.

Start of Stable beams

The start of SB is the first regime of interest for the investigation of the beam losses. Figure 10 depicts the average initial lifetime over all bunches (green) in 2018 for Beam 1 (top) and Beam 2 (bottom). A reduction of the initial lifetime is observed compared to the period prior to TS1, especially for the LR (orange) and LR-ecloud (cyan) classes of Beam 2.

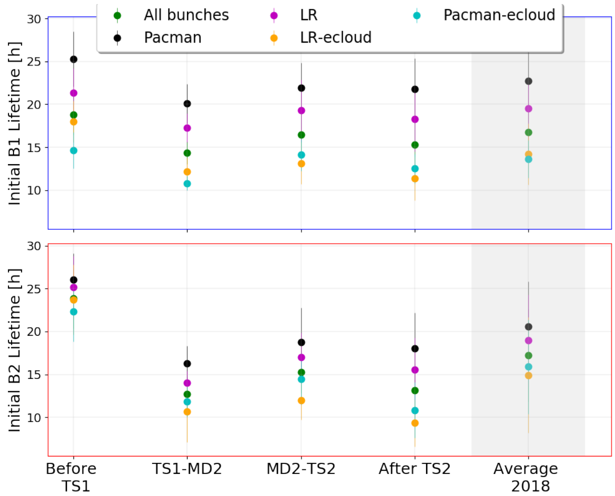

Figure 10: Average lifetime at the start of SB for Beam 1 (top) and Beam 2 (bottom) across the different tune optimizations.

This effect appears to be correlated with the tune modifications applied in squeeze. The classes that were optimized during squeeze reach the start of SB with a reduced lifetime. This indicates that although fewer losses are observed from the tune optimization at squeeze, these protons are eventually lost at the start of SB. Overall, the average regime (gray span) shows that the LR-ecloud and Pacman-ecloud classes exhibit the lowest lifetime at the start of SB.

Losses during the crossing angle anti-leveling

To investigate the increased losses during the anti-leveling, two Fills with similar machine conditions in terms of chromaticity and octupole current are compared. In the first case, the crossing angle is constant along the Fill. On the contrary, in the second case, the crossing angle variation is employed. Figure 11 presents the contribution of each class to the evolution of the effective cross section. In both cases, the major contributors are the bunch types that are affected by electron-cloud for both beams. For the first Fill (top), the losses remain constant in time, whereas in the later case (bottom), an increase is observed, mainly affecting Beam 1. Based on these observations, a correlation between the crossing angle variation and the losses due to electron-cloud, is established. It must be noted that despite the increase of losses due to the anti-leveling, a gain on the integrated luminosity is reported [13].

Figure 12 illustrates the class decomposition of the effective cross section for a half crossing angle of 140 μrad across the physics Fills of 2018. For both beams, the effective cross section of the Pacman class (black) is close to the burn-off limit. The LR class exhibits losses which are slightly above the expected level from collisions. Additional non-linearities, that are present in the LR-ecloud and Pacman-ecloud class, result in a lifetime discrepancy between Beam 1 (blue) and Beam 2 (red). For these classes, losses beyond the burn-off limit are observed, mainly affecting Beam 1.

Table 1: Burn-off corrected lifetime across 2018 pre-TS1 (chromaticity reduction), TS1-TS2 (smoother crossing angle variation), post-TS2 (octupolar current reduction).

	Burn-off corrected lifetime [h] @ $\phi/2$ = 140μrad in SB					
	Beam 1			Beam 2		
	Pre-TS1	TS1-TS2	Post-TS2	Pre-TS1	TS1-TS2	Post-TS2
Average	68.96	65.62	70.89	103.06	81.95	86.95
Pacman	191.95	196.87	195.17	193.38	192.92	188.77
LR	174.09	174.90	169.54	188.42	174.51	175.95
LR-ecloud	52.52	40.94	57.40	106.39	59.29	73.60
Pacman-ecloud	42.70	36.48	51.28	96.42	67.92	79.23

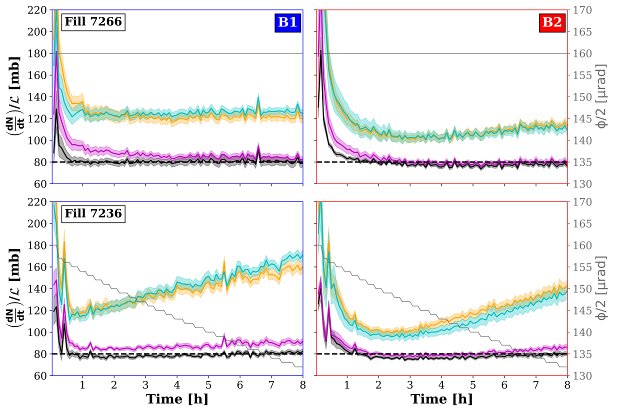

Figure 11: The impact of the crossing angle (gray) on the class decomposition of the effective cross section evolution for a Fill with a constant crossing angle (top) and with a crossing angle variation (bottom).

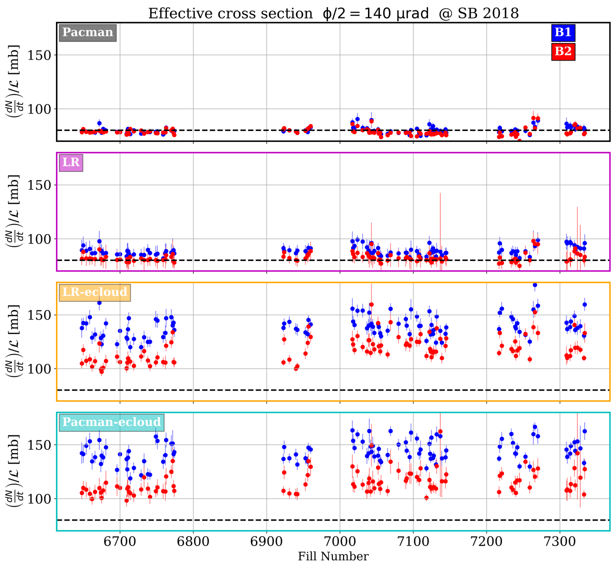

Figure 12: The effective cross section for the proton fills of 2018 at $\phi/2$ = 140 μrad for the different classes.

Dynamic Aperture optimizations in 2018

In 2018, a set of modifications in the machine configuration were applied aiming to improve the beam lifetime [13]. Based on multi-parametric DA simulations, the optimization of parameters such as chromaticity, octupolar current and crossing angle variation with respect to intensity were expected to be beneficial for the beam performance. For this reason, the chromaticity was reduced (from 15 to 7) and a smoother reduction of the crossing angle was applied. After TS2, these modifications were combined with a reduction of the octupolar current. Table 1 summarizes the impact of these steps on the burn-off corrected lifetime for each beam and class. The results show that no significant improvement is observed by these modifications. This can be explained by the fact that, as previously stated, the simulations aim at optimizing the classes Pacman and LR, which are already close to the burn-off limit. However, the dominating factors of beam losses are classes LR-ecloud and Pacman-ecloud, which are yet to be integrated in the simulation tools. Therefore, the development of a more complete model that accounts for these factors is necessary.

SUMMARY

An increased luminosity degradation due to beam losses was observed in 2018, compared to the rest of Run 2. An analysis based on the classification of the bunches, depending on their position in the trains, shows that beam-beam and electron cloud are the main contributors to this effect.

During the squeeze of the beams, a decrease of lifetime is observed for $\beta^* < 40$ cm, originating from bunch classes impacted by electron cloud, mainly affecting Beam 1. The tune optimizations appears to be beneficial for the mitigation of the long range losses.

During SB across Run 2, the Beam 1 lifetime was systematically lower than Beam 2 and, similarly to 2017, extra losses were observed in the first few hours of operation. However, in 2018 additional losses, induced by the crossing angle anti-leveling and the β^* levelling, were present. Despite the additional losses, these techniques are beneficial for the integrated luminosity.

Overall, in both beam modes, electron-cloud is a dominating factor of lifetime degradation and a correlation with the crossing angle and the β^* is established. Non-linearities introduced by beam-beam effects and electron cloud, contribute to the lifetime imbalance between the two beams.

To assess the impact of effects which are not included in the model, a correlation between the computed DA from simulations and the lifetime from experimental data is needed. On-going studies aim to explore the contribution of incoherent electron cloud and noise on the beam lifetime.

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