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ANALYSIS ON BUNCH-BY-BUNCH BEAM LOSSES AT 6.5 TeV IN THE LARGE HADRON COLLIDER

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Abstract

In 2018, a large fraction of the physics data taking at the Large Hadron Collider has been performed with a beam energy of 6.5 TeV, the nominal bunch spacing of 25 ns and beta functions at the high luminosity interaction points of 30 cm. In order to maximize the integrated luminosity, the crossing angles are gradually reduced as the beam intensity reduces due to luminosity burn-off. In these conditions the beam lifetime is visibly affected by collective effects and in particular by beam-beam interaction and electron cloud effects. By analysing the beam losses at a bunch-by-bunch level, it is possible to disentangle the contributions from different effects and to assess the impact on the losses of changes applied to the machine configuration.

BEAM LOSSES DURING THE BETATRON SQUEEZE

At the Large Hadron Collider (LHC), during the energy ramp that accelerates the beam to 6.5 TeV, the optical beta functions at the high-luminosity interaction points (β^*) are gradually reduced down to 1 m. Before bringing the beams in collision, β^* is further reduced down to 30 cm in a dedicated *betatron squeeze* process which lasts approximately 10 minutes. The last portion of this optics manipulation is made using a telescopic method [1, 2].

The blue line in Fig. 1 shows the beam lifetime recorded over several luminosity fills at the beginning of the 2018 run. It can be noticed that the beam lifetime reduces significantly towards the end of the process, especially for β^* smaller than 40 cm. In this contribution, we refer always to the beam circulating clockwise (Beam 1). The same features are observed also on the other beam but in a less pronounced fashion. The origin of this asymmetry has not been identified yet and is presently under investigation.

The origin of such degradation of the beam lifetime is believed to be a reduction of the machine Dynamic Aperture (DA) provoked by the reduction of β^*. The dominant non-linear effects inducing the reduction of the DA are the Beam-Beam Long-Range (BBLR) interactions and electron cloud (e-cloud) effects. Both these effects are expected to act differently on different bunches within the beam [3, 4].

In order to optimize the beam lifetime, the fractional betatron tune settings over the squeeze process were changed from $(Q_x, Q_y) = (0.31, 0.32)$ to $(0.305, 0.315)$ to increase the DA as illustrated in Fig. 2 [5, 6]. This modification was

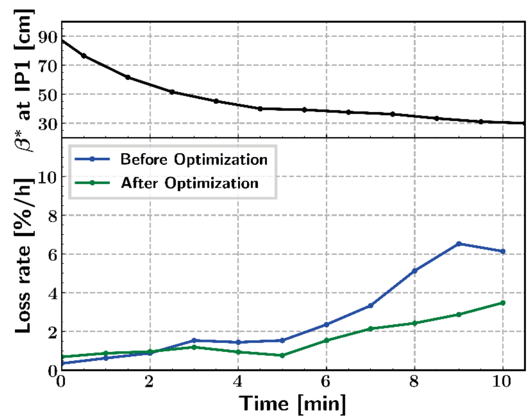

Figure 1: Top: β^* evolution during the betatron squeeze process. Bottom: beam loss rate during the betatron squeeze before and after the lifetime optimization.

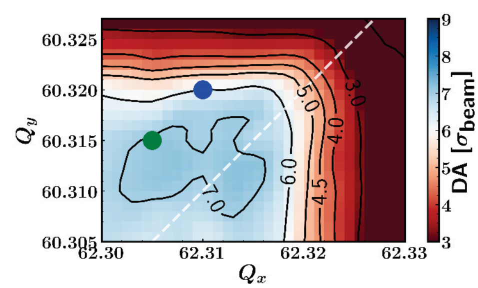

Figure 2: Simulation of DA as a function of the betatron tunes. Dots represent the chosen tune settings.

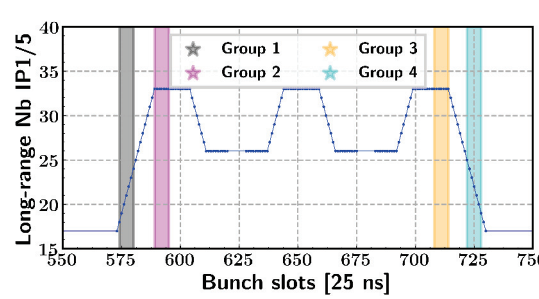

Figure 3: Number of BBLR interactions at each of the high-luminosity interaction points for the different bunches of a circulating bunch train. Groups of bunches that are analyzed in detail are highlighted in different colours.

based on tracking simulation studies including magnetic non-linearities from the machine lattice and beam-beam effects, but not e-cloud effects [7].

The LHC beam is made of several trains injected individually into the machine, separated by gaps of 800 ns. Each

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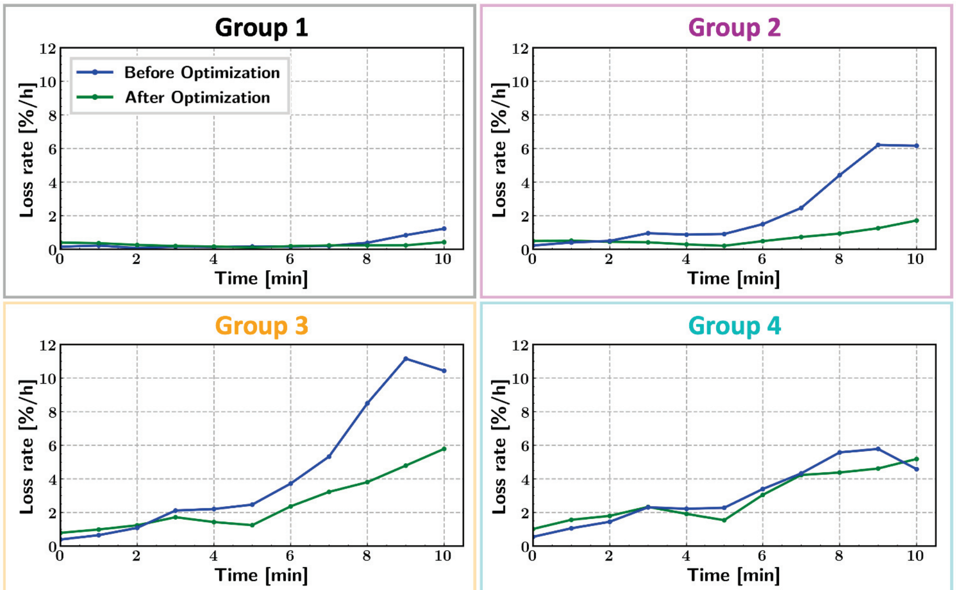

Figure 4: Loss rate measured for the groups of bunches illustrated in Fig. 3, before and after the optimization (average over several fills).

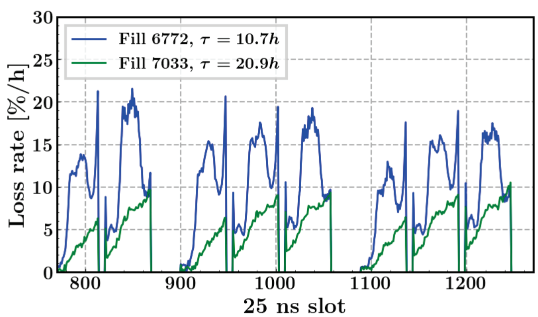

Figure 5: Bunch-by-bunch loss rate for three consecutive bunch trains at β^*= 33 cm, for two fills performed before and after the lifetime optimization.

train is made of three batches of 48 bunches separated by gaps of 200 ns. Due to this feature and to the fact that the two beams interact with each other only in a short section of the collider around the interaction point, the number of beam-beam interactions is different for different bunches.

Figure 3 shows the number of BBLR interactions experienced by each bunch within one of the LHC trains. The largest number of interactions is experienced by the bunches in the central part of the three batches. The effect of the e-cloud instead is expected to be smaller for the bunches at the head of the train and significantly stronger for the bunches at the tail.

In light of these features, we analyze in detail four groups of bunches (indicated by different colours in Fig. 3):

Group 1: Bunches at the head of the leading batch, which experience a small number of BBLR interactions and reduced e-cloud effects;

Group 2: Bunches at the center of the leading batch, which experience the maximum number of BBLR interactions and reduced e-cloud effects;

Group 3: Bunches at the center of the trailing batch, which experience the maximum number of BBLR interactions and stronger e-cloud effects;

Group 4: Bunches at the tail of the trailing batch, which experience a small number of BBLR interactions and stronger e-cloud effects.

The blue lines in Fig. 4 show the loss rate measured for these four groups of bunches during the betatron squeeze averaged over several fills at the beginning of the 2018 run. As expected, the bunches of Group 1, which experience a small number of BBLR interactions and reduced e-cloud effects, are those showing the best lifetime. It is also possible to notice that the bunches in Group 2, which experience the maximum number of BBLR interactions but reduced e-cloud, show a significantly better lifetime than the bunches in Group 3, having the same number of BBLR interactions but stronger e-cloud. The lifetime of the bunches in Group 4 is also relatively poor, in spite of the fact that they experience a smaller number of BBLR interactions. These observations indicate a strong role of the e-cloud in the observed losses. The blue line in Fig. 5 shows the bunch-by-bunch loss rate for three consecutive bunch trains at β^*= 33 cm for one of the fills in the same period. Higher losses can be observed for the bunches at the center of the batches, which are the ones experiencing the largest number of BBLR interactions.

The green lines in Fig. 4 show the measured loss rates averaged over several fills during the betatron squeeze, after the change was applied. A significant improvement is observed especially for the bunches in Groups 2 and 3, for which the number of BBLR interactions is maximum. The overall effect of the optimization on the total beam loss rate is visible in Fig. 1. The effect of this modification can be observed, for the different bunches along the train, in Fig. 5. The overall lifetime improves by a factor of two. The losses

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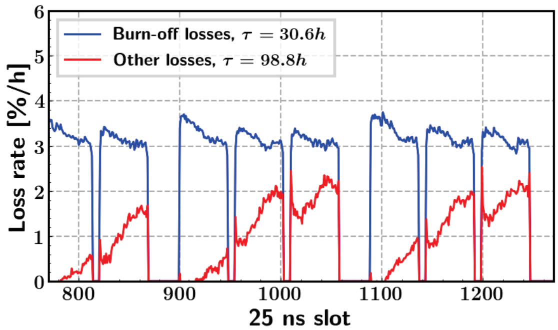

Figure 6: Bunch-by-bunch loss rate decomposition for three consecutive bunch trains 5.5 h after the start of collisions.

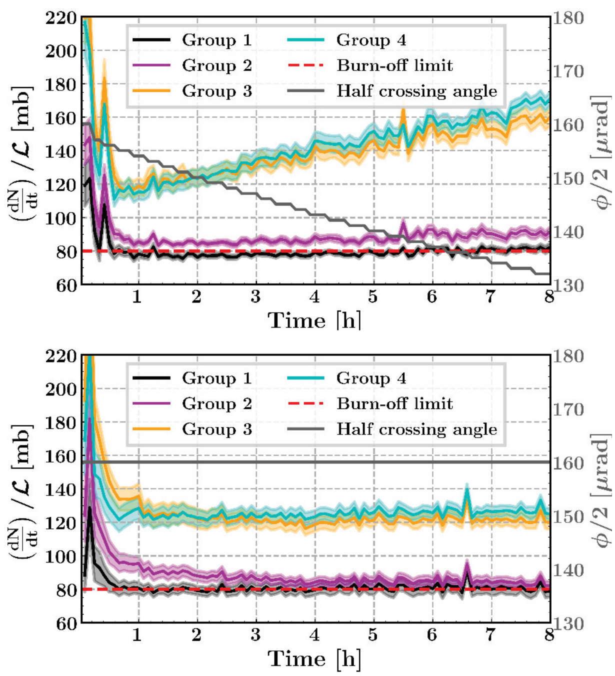

Figure 7: Effective cross sections during the time spent in collision for selected groups of bunches as illustrated in Fig. 3 during a typical fill with gradual crossing angle reduction (upper plot) and a test fill with constant crossing angle (lower plot).

in the bunches at the center of the batches (driven by BBLR interactions) strongly decrease, while a trend of increasing beam losses along the batches persists, which is a typical signature of e-cloud effects.

BEAM LOSSES IN COLLISION

Beam losses are observed also during the luminosity production beam stores. Also in this case, different bunches exhibit different behaviour. In collision, a significant fraction of the losses comes from luminosity burn-off at the interaction points. This can be easily estimated from the luminosity measurements assuming a burn-off cross section of 80 mb due to the proton-proton inelastic cross section at 13 TeV center of mass energy [8].

Figure 6 shows the loss rate decomposition for a typical luminosity fill from 2018. The blue trace represents the burn-off losses estimated from the bunch-by-bunch luminosity measured by the LHC experiments, while the red curve represents the additional losses, obtained by subtracting the estimated burn-off rate from the measured loss rate. The signature of e-cloud is clearly recognizable as the additional losses are increasing along the bunch trains. For the first bunches of the trains the losses are fully dominated by burn-off. Instead, the additional losses are comparable to the burn-off losses for the bunches at the tails of the trains. This has a significant impact on the integrated luminosity collected from those bunches [9].

The evolution of the beam losses during a typical luminosity store is shown in Fig. 7 (top) for the four groups of bunches identified in Fig. 3. The losses are normalized to the measured luminosity from the corresponding bunches, in order to obtain an *effective cross section* ($\sigma_{\mathrm{eff}} = \left|\frac{dN}{dt}\right| / \mathcal{L}$ where N is the bunch population and $\mathcal{L}$ is the bunch luminosity). The effective cross section coincides with the burn-off cross section when no additional losses are present.

Figure 7 (top) shows significant additional losses on all bunch groups in the first 0.5 h after the start of collisions. This could be caused by particles lost due to the sudden decrease of the DA introduced by the head-on beam-beam interactions. After this initial stage, the bunches in Groups 1 and 2, which experience weaker e-cloud effects, show losses very close to the burn-off limit, while the bunches in Groups 3 and 4, which are exposed to stronger e-cloud, show significantly larger losses.

On the bunches in Groups 3 and 4 the effective cross-section increases during the fill. This increase is driven by the gradual reduction of the crossing angle between the beams at the interaction points, which is applied during the fill to increase the luminosity. Figure 7 (bottom) shows a test during which the crossing angle was kept constant for the entire fill. It can be noticed that in this case the effective cross section for Groups 3 and 4 remains practically constant.

CONCLUSIONS

The analysis of the beam losses at a bunch-by-bunch level allows identifying the main sources of the observed beam degradation. In particular, it is possible to identify clear patterns generated by BBLR interactions and e-cloud effects. During the betatron squeeze, it was possible to mitigate the losses by modifying the betatron tune settings. In collisions the losses were found to be correlated with the crossing angle changes applied during the fill. Next steps include the development of tracking simulation tools for e-cloud effects and the study of losses and DA with them.

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