OBSERVATIONS OF BEAM LOSSES AT THE LHC DURING REDUCTION OF CROSSING ANGLE

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Abstract

Several machine development studies have been performed in 2016 at the LHC in order to evaluate the effects of reducing the crossing angles in favour of defining the maximum achievable luminosity in the ATLAS and CMS experiments. At the end of the LHC proton-proton run at 6.5 TeV the reduction of the crossing angle from 370 μrad to 280 μrad was operationally implemented. The observation of beam losses and lifetimes during this process are analysed and discussed.

INTRODUCTION

During the 2016 physics run we have tested and quantified the impact of a reduced crossing angle on the beam and luminosity lifetimes [1–3]. This test goal was to explore the limits due to long-range beam-beam effects for a possible reduction of the crossing angle and therefore to define the minimum reachable β^* [4,5] to push for maximum peak and integrated luminosity in the LHC for RUN II. Moreover we wanted to quantify how the beam intensities and emittances are affected by a reduced crossing angle. The goal was to define the needed margins from the chaotic limit identified in previous experiments [6,7] to ensure large beam lifetimes. In this paper we will focus on the analysis of the losses at the primary collimators and correlate them to the observed tune shifts during the experiment.

LONG RANGE EXPERIMENT OBSERVATIONS

A summary plot of the experiment is shown in Figure 1 where the Beam 1 (blue line) and Beam 2 (red line) losses are plotted as a function of time during the machine development study. We have reduced in steps the crossing angles in IP1 and IP5 simultaneously to keep the passive compensation of tunes and chromaticity and observe only the effect of increased spread and orbit effects. The angles were reduced starting from 370 μrad down to 180 μrad, at each new step in angle we stayed steady for approximately 15-20 minutes to observe the losses evolution in time. One can notice that the losses show two different regimes. First, a fast loss due to scraping of tail particles because the bunches are getting closer to each other and second the loss rate is almost constant during our time range. As we were reducing the crossing angle we observe an increase of the peak loss (in the first regime), this indicates an increased diffusion rate of particles. It is visible from the crossing angle of 230 μrad corresponding to approximately 8.5 σ beam to beam separation. A detailed description can be found in [1,2].

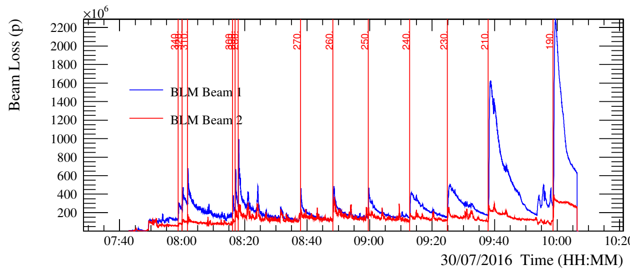

Figure 1: Measurement of beam loss in protons during Machine Development for Beam 1 in blue and Beam 2 in red.

The losses during the experiment were decomposed by applying an algorithm described in [8,9]. The losses are expressed in horizontal and vertical betatronic losses and as longitudinal type (due to off-momentum particles). Figure 2 shows the result of this decomposition for Beam 1. A clear vertical component is observed for Beam 1. A similar analysis for Beam 2 does not show this asymmetry between the planes and actually shows reduced losses for all crossing angles steps and larger losses in the horizontal plane, which is consistent with the different emittances during the experiment: 3 μm in the horizontal plane and 2.5 μm in the vertical plane.

Figure 3 shows the losses as a function of the crossing angle step. One can see that while for Beam 2 the losses are very small, below $5 \cdot 10^8$ protons/s and approximately constant for all the steps, for Beam 1 they increase after each step reaching the maximum rate of $2,1 \cdot 10^9$ protons/s.

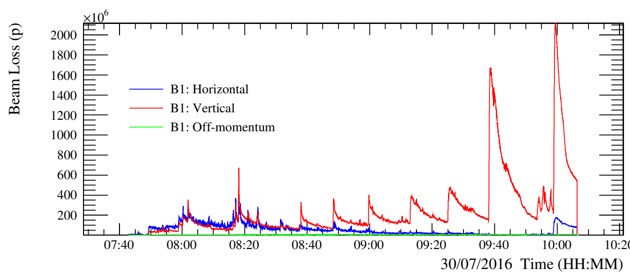

Figure 2: Beam 1 losses decomposed per plane (horizontal, vertical and off-momentum) during Machine Development.

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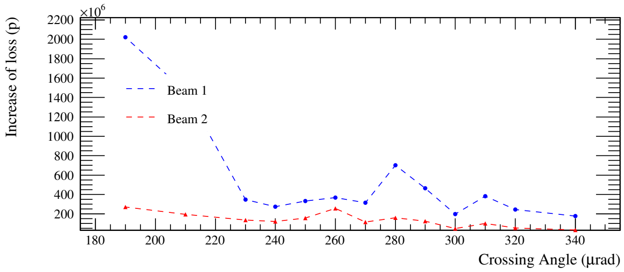

Figure 3: Increase of beam losses as function of crossing angle during Machine Development.

During the experiment an unexpected tune shift was also observed for the bunches with long-range interactions. The magnitude of the shift depends on the crossing angle and has reached at the end of the angle scan a $\Delta Q = 0.006$. This is put in evidence in Figure 4 where the vertical frequency spectra of Beam 1 as a function of time and the angle steps are shown. The vertical tunes were shifted to larger values reaching almost $Q_y = 62,326$ very close to the third order resonance which is known to drive fast incoherent losses. The behaviour of the horizontal plane seems to go in different direction for the shift sign. This observation has been confirmed also in another independent study using beam transfer function measurements to quantify the effect and presented in [10]. Figure 5 shows the expected beam transverse footprint for different crossing angles.

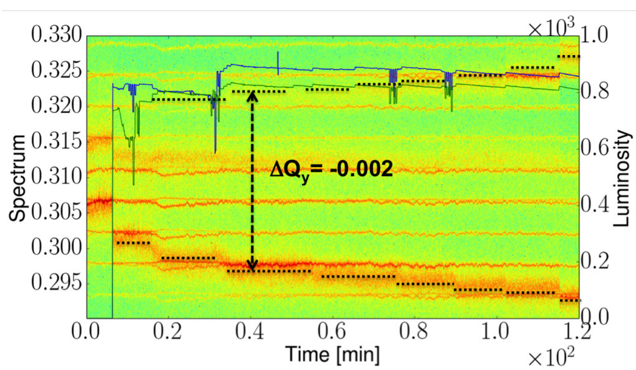

Figure 4: Beam vertical frequency response and ATLAS and CMS luminosity as a function of time during the crossing angle scans of Fill 5137. The tune shifts per angle change are highlighted with black dashed lines.

The observation of the tune shift is only on the bunches colliding long range, however in regular operation this effects are not visible since the tunes are measured on non-colliding bunches. Therefore it is fundamental for a good control of the losses to have the possibility to measure a subset of bunches with full long-range encounters, more representative of the beam tunes.

It is then confirmed that the losses observed at the collimators during the experiment (Figure 2, mainly in the vertical plane) are mainly due to the tune shift approaching the third order resonance. This observation points to losses observed during the long-range test were not only due to the long-range beam-beam effects but also to the actual tune change that was not corrected. It would be important to disentangle between the contribution to the loss rates of the tune shift from the one from the long-range increased spread. The opposite signs of the tune shifts observed, negative for the vertical and positive for the horizontal plane, point to a dependency on the long ranges interactions and can be explained by a loss of the passive compensation with the horizontal/vertical crossing schemes of ATLAS and CMS [11].

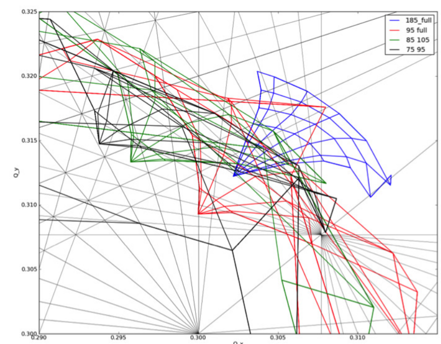

Figure 5: Beam transverse footprint for different crossing angles with a 20% asymmetry in the beam-beam separations of IP1 and IP5.

CROSSING ANGLE CHANGE DURING LHC OPERATION

In the first part of the Run in 2016 the crossing angle in IP1 and IP5 was 370 μrad. Based on the results on the beam tests described in the previous section [12], the 15th September 2016 a new crossing angle of 280 μrad was deployed operationally. Beam losses and beam lifetime were monitored regularly during the LHC fills with the new crossing. Figure 6 shows an example of the beam lifetime (in hours) for Beam 1 (blue line) and Beam 2 (red line) during the change of crossing. During this process, systematically, a dip in lifetime below 10 h was observed in each fill for Beam 1 only. The lifetime of Beam 2 was always very good close to 1000 h. The same algorithm used in the experiment was used in operation to decompose the beam losses during regular fills. Figure 7 shows the result of the decomposition. The dip in beam lifetime corresponds to the maximum loss for Beam 1 with a dominant vertical component.

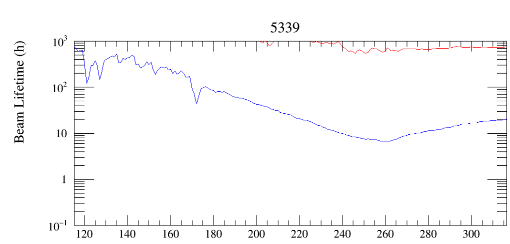

Figure 6: Beam lifetime during crossing angle change.

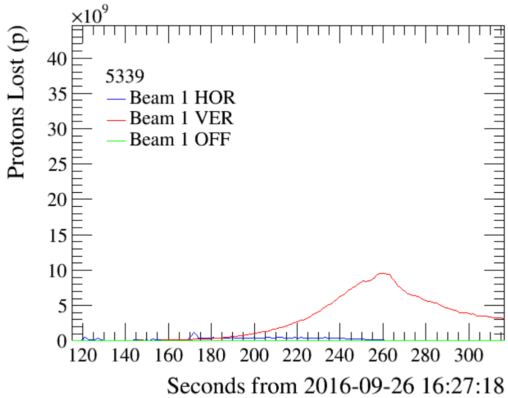

Figure 7: Protons lost per plane for Beam 1 during crossing angle change.

Because the tunes at the LHC are only measured in the non-colliding beams the tune shift was not observed, however a tune shift of the order of few 10^{-3} for Beam 1 vertical tune was incorporated smoothly during several fills. Figure 8 shows the minimum beam lifetime as a function of the shift of Beam 1 vertical tune. A clear improvement on the lifetime is observed as we shift the vertical tune brining it away from the third order resonance.

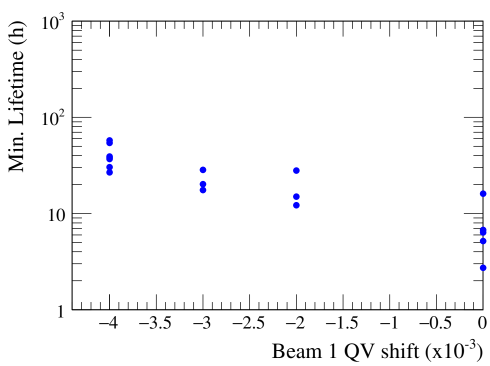

Figure 8: Minimum beam lifetime during change of crossing angle as function of the vertical tune shift for Beam 1.

BUNCH BY BUNCH LOSSES AND LONG-RANGE

An analysis of the bunch by bunch losses measured by the diamond detectors [13] for the two physics fills where the reduction of crossing angle is applied (Fill 5339) and when a tune correction is applied (Fill 5340) is shown in Figure 9 over 2 minutes range during two intervals: at the end of the angle change (black dots) and before the head-on collision. One can notice the long-range scraping (bunch by bunch typical pattern) on losses when the crossing angle is reduced, as also observed during the dedicated experiment and before the head-on collisions at the experiments (red dots). It is clear that long-range effects appear at the reduction of the angles as observed during the experiment as sharp losses with long-range patterns and they disappear before going into collision in these two cases. The tune correction applied has reduced drastically the long-range losses as well as the long-range signature. In collision no pattern is observed.

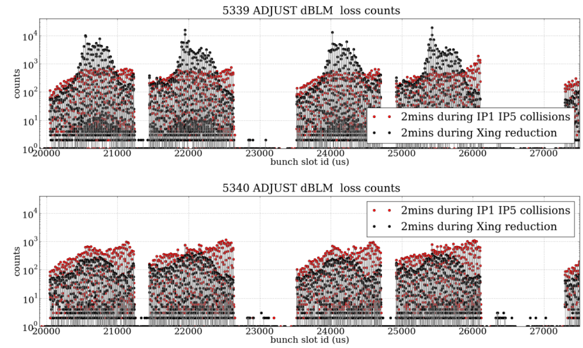

Figure 9: Bunch by bunch loss counters as a function of the bunch position in μs from diamond detectors over 2 minutes time interval at the reduction of crossing angle and before head-on collisions in IP1 and IP5 for two physics fills 5339 and 5340.

CONCLUSION

During the long-range crossing angle scan important losses have been observed in Beam 1 only and have been identified with losses in the vertical plane. The losses are strongly correlated to an unexpected tune shift with amplitude correlated to the crossing angles. The tune shift appears only on bunches undergoing long-range interactions not on the single head-on colliding bunch. This points to the long-range interactions as a possible source of such shift which is not visible during standard physics fills since the tune measurement is locked on non-colliding bunches. During the operational implementation of the reduced crossing angle losses have appeared on Beam 1 with long-range patterns during the angle reduction bringing the beam lifetime below 10 h. A vertical tune shift has been applied to compensate for the unexpected one measured during two independent experiments and lifetimes have increased drastically above 10 h and long-range pattern is reduced already before collisions. Optimising further the tunes has brought a larger improvement of the lifetimes above 20 hours. To optimise the beam-beam effects and consequently the beam lifetimes tune measurements on colliding bunches with full number of long-range encounters together with the diamond bunch by bunch losses should be used to disentangle between the contributions of the different beam-beam effects as for example scraping of tail particles and diffusive mechanisms.

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