EXPERIENCE WITH OFFSET COLLISIONS IN THE LHC

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Abstract

To keep the luminosity under control, some experiments require the adjustment of the luminosity during a fill, so-called luminosity levelling. One option is to separate the beams transversely and adjust the separation to the desired collision rate. The results from controlled experiments are reported and interpreted. The feasibility of this method for ultimate luminosities is discussed.

INTRODUCTION

Four major experiments take data at the LHC: two of them, ATLAS and CMS (at Interaction Point, IP, 1 and 5 respectively), are designed for high luminosity and pile-up $\mu \approx 20$ (number of inelastic interactions per crossing), while the other two experiments, Alice and LHCb (at IP 2 and 8), are designed for lower pile-up values ($\mu < 0.05$ and $\mu < 0.5$ respectively).

In 2010 LHCb managed to cope with up to $\mu_{max} < 2.5$ and $\approx 3 \times 10^{32}$ Hz/cm^{-2}. Given the nevertheless high target in integrated luminosity for the year 2011 (1 fb^{-1}), it was preferable to run whenever possible at a constant instantaneous luminosity, as close as possible to the maximum tolerable one, levelled down from the maximum deliverable from the machine which LHCb cannot tolerate. This motivated the need for a luminosity levelling technique.

In the early part of the run, an experiment was performed to demonstrate the feasibility of luminosity levelling by transversely displacing the beams by a small offset [1]. It was demonstrated that in the absence of strong long range interactions levelling by separation can be performed. The experimental conditions, the procedure and the results are discussed in this document.

Levelling by separation has since become an operational procedure and algorithms and applications have been developed so to help the automation of the process. The algorithms and the application are here briefly introduced.

It is worth noting that similar conditions are required by the Alice experiment and similar procedures are successfully applied.

EXPERIMENTAL SETUP

An experiment was performed to first test whether the luminosity in IP8 can be controlled by a finite, transverse offset in order to optimize the event pile up. The test was performed on March 24th 2011 as an end-of-fill study on fill 1647.

The required separation is in the range 0 - 2 σ [2]. The test was done to evaluate possible side effects such as: bad life time and beam losses, emittance growth, orbit changes or coherent motion, effects on other experiments. This test was performed with train of bunches (24 bunches per train) spaced by 75 ns, for a total of about 200 bunches per ring. The emittance during the test was $\approx$ 2.5 μm.

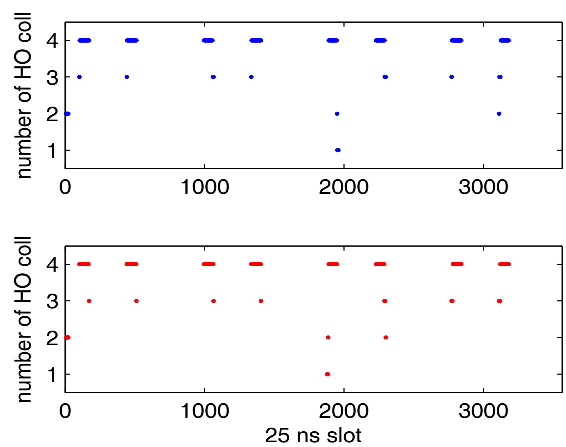

Figure 1: Number of head-on collisions as function of 25 ns slot number (beam 1 blue, top; beam 2 red, bottom).

Figure 1 shows the number of head on collision for all bunches as a function of the slot position of the bunches. Most bunches experience the maximum number of 4 head-on collisions although bunches with fewer collisions are present due to the asymmetries of the collision and filling schemes. Although long range encounters were present, the separation in this test was large enough (larger that 12 σ) that their effect can be considered irrelevant.

During the test the bunches were separated in steps of 0.5 σ in the vertical plane, starting from the optimized collision, i.e. exactly head-on. The decrease in instantaneous luminosities and variations in beam parameters were observed.

EXPERIMENTAL RESULTS

The result of the separation scan is shown in Figure 2 where the luminosity in IP8 is plotted in black as a function of time. The steps of the separation scan (5 steps in total) are clearly visible. The luminosity reduction for the final step (corresponding to a 2.5 σ separation) was larger than 3. At each step the beams were kept for about 20 minutes to observe possible problems, e.g. for beam lifetime or losses. After the final step the instantaneous luminosity was optimized again to the maximum achievable. In Figure 2 one can observe that the luminosity follows the original decay, without any visible deterioration.

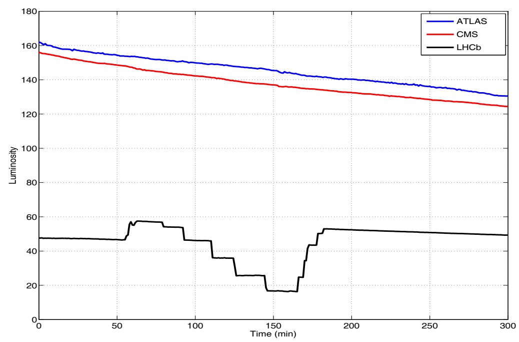

Figure 2: Luminosity in IP8 during levelling scan, also shown luminosity in IP1 and IP5 during scan. The first step up in LHCb luminosity corresponds to the start of the experiment (fully head-on).

In order to assess possible effects on the other experiments, in Figure 2 we also show the luminosities in IP1 and IP5 during the separation scan, in blue and red traces. IP1 and 5 were kept head-on for the length of the whole experiment. No effect on IP1 and IP5 luminosities was observed during the scan.

The emittances measured by the synchrotron light telescope were monitored during the scan, and again no visible effect was seen when the two beams were offset in IP8 [1].

INTERPRETATION

The luminosity levelling using a parallel offset in IP8 seemed to have very little effect on: lifetimes, emittances and beam losses, or luminosity in the other experiments.

To explain this behaviour, one can look at the resulting tune shifts, i.e. detuning with amplitude, during this scan. Since the other interaction points have not been affected and the long range contribution was irrelevant, it is sufficient to compute the effect of the central collision in IP8 as the scan was performed. To understand the expected tune spread, the beam-beam force for round beams is shown (see Figure 3). The tune change is obtained by phase averaging over the slope of the force and shown in Figure 4 for small amplitude and in Figure 5 for large amplitude particles. The resulting tune shift is smaller for large amplitude particles (as well known).

In the case of separated beams (or offsets) the averaging has to be done at the position of the separation, see Figure 6 for small amplitude particles. In Figure 6 we separated the beams such that the offset corresponds to the maximum of the beam-beam force, i.e. around a separation of $\approx 1.6\ \sigma$. Contrary to the head-on case, the slope of the force on the maximum is zero and the tune shift vanishes.

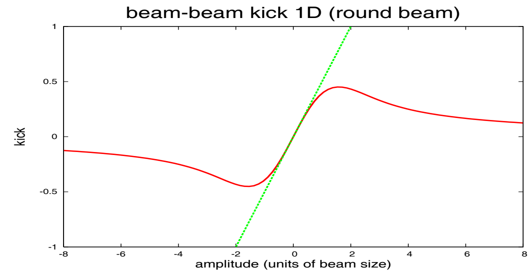

Figure 3: Beam-beam kick for round beam.

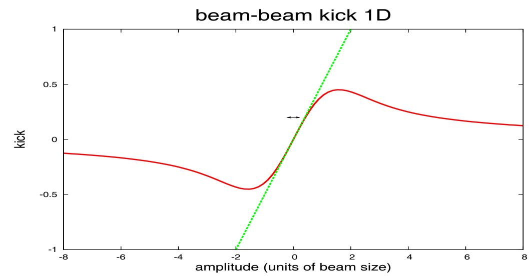

Figure 4: Beam-beam kick for round beam. Averaging for small amplitude particles.

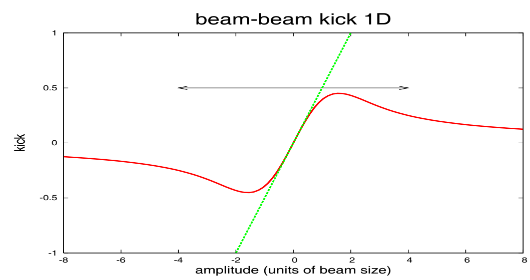

Figure 5: Beam-beam kick for round beam. Averaging for large amplitude particles.

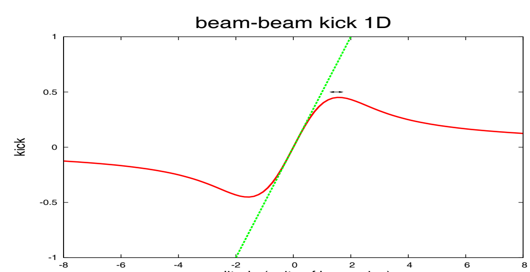

Figure 6: Beam-beam kick for round beam with offset collision. Averaging for small amplitude particles.

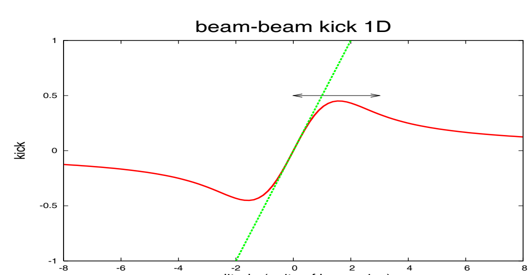

Figure 7: Beam-beam kick for round beam with offset collision. Averaging for large amplitude particles.

The averaging for large amplitude particles (Figure 7) shows another feature: the particle samples positive as well as negative slopes and the expected tune change is small.

As a conclusion of this qualitative argument one must expect that the tune spread (i.e. footprint) becomes small in the plane of separation when the beam separation corresponds to the maximum beam-beam force (round beams only). Quantitatively this can be obtained by particle tracking and the results are shown in Figure 8. Figure 8 shows tune footprints for different beam separation (in the case of the simulation in the horizontal plane) and indeed the spread becomes small when the separation is close to 1.6 σ.

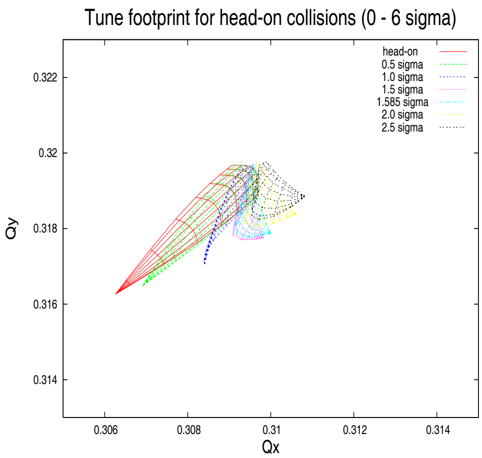

Figure 8: Head-on tune footprint for different horizontal offsets.

OPERATIONAL PROCEDURES

An algorithm and an application were developed to fully exploit the potential of the levelling by separation and provide LHCb with approximately constant instantaneous luminosity [4]. The algorithm makes sure that the separation is decreased in steps as long as the instantaneous luminosity is below the target (within a few percent tolerance which can be defined by the user). The step size as a fraction of the beam size σ is defined by the user or suggested by the experiment directly. An audible voice alarm is triggered when a levelling step is required.

In Figure 9 (top plot), the instantaneous luminosities for ATLAS, CMS and LHCb are shown for a recent physics fill: while for LHCb the target is levelled to the desired value, for ATLAS and CMS the luminosity decays naturally due to emittance growth and intensity decrease. Occasional steep changes are given by luminosity optimizations and orbit corrections that compensate for small drifts.

Figure 9 (bottom plot) shows the LHCb luminosity target and the delivered instantaneous luminosity during the first two hours of a the same physics fill. It is possible to see how by decreasing the separation with small steps, the target is approached and smoothly reached.

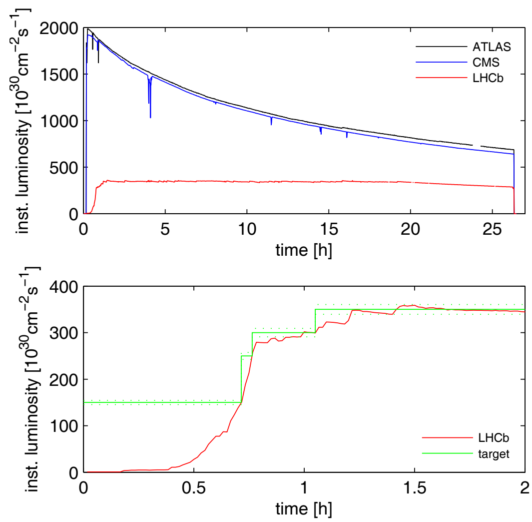

Figure 9: Top: example of IP1, 5 and 8 instantaneous luminosity during fill 2006. Bottom: LHCb instantaneous luminosity and target (with 3% acceptance boundaries for the same fill, first 2 hours. Note that the steps are driven by the experiment.

CONCLUSIONS

It was demonstrated that the luminosity can be successfully levelled using transverse offsets without significant effects on the beam or the performance of the other experiments. The result can be understood at least qualitatively analysing the expected tune spread of the separated collision. The experiment was done without very significant long range beam-beam interaction and the presence of strong parasitic contributions may change the picture slightly. This will be tested once 25 ns spaced bunches are be available for collisions in the machine.

Luminosity levelling is now operational for LHCb and Alice physics production. An application that drives it according to experiment defined parameters is used by the LHC shift crews. LHCb has so far integrated over 0.7 fb^{-1}, making the target for the year in reach.

ACKNOWLEDGEMENTS

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REFERENCES

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