

IMPACT OF LONG RANGE BEAM-BEAM EFFECTS ON INTENSITY AND LUMINOSITY LIFETIMES FROM THE 2015 LHC RUN

M.Crouch¹, T.Pieloni², R.B. Appleby¹, D. Banfi³, J. Barranco Garcia³, R. Bruce², X. Buffat², B.D. Muratori⁴, M. Pojer², B. Salvachua², C.Tambasco^{2,3}, G. Trad²

¹University of Manchester and The Cockcroft Institute, UK

²CERN, Geneva, Switzerland

³EPFL, Lausanne, Switzerland

⁴Daresbury Laboratory, STFC and The Cockcroft Institute, UK

Abstract

Luminosity is one of the key parameters that determines the performance of colliding beams in the Large Hadron Collider (LHC). Luminosity can therefore be used to quantify the impact of beam-beam interactions on the beam lifetimes and emittances. The High Luminosity Large Hadron Collider (HL-LHC) project aims to reach higher luminosities, approximately a factor of 7 larger than the nominal LHC at peak luminosity without crab cavities. Higher luminosities are achieved by increasing the bunch populations and reducing the transverse beam sizes. This results in stronger beam-beam effects. Here the LHC luminosity and beam intensity decay rates are analysed as a function of reducing beam separation with the aim of characterising the impact of beam-beam effects on the luminosity and beam lifetime. The analysis and results are discussed with possible application to the HL-LHC upgrade.

INTRODUCTION

Contrary to the head-on beam-beam effects, the long-range beam-beam interactions are expected to play an important role in the LHC and HL-LHC performance and determining the choice of the parameters [1]. A key parameter that determines the strength of the long-range interaction is the local beam separation at the parasitic encounters. Usually the separation is measured in units of the RMS beam size at the corresponding encounter. To provide a comparison between different configurations, a normalised separation at the first long-range beam-beam encounter in the drift space is used. In the paraxial approximation at the two low β experiments, ATLAS and CMS, the normalised separation is expressed as

$$d_{sep} = \sqrt{\frac{\beta^* \gamma_r}{\epsilon_n}} \alpha, \quad (1)$$

where β^* is the β function at the IP (Interaction Point), γ_r is the relativistic factor, ϵ_n is the normalised emittance and α is the crossing angle. The long range beam-beam effects define the minimum achievable crossing angle at the experimental point and therefore impose a limit on the maximum luminosity for the defined optics. The long range effects can lead to various effects such as particle losses, emittance growth and orbit effects. Describing how these effects depend on the separation d_{sep} will help define the necessary

margins in terms of separation needed for further parameter choices in the LHC and for a possible high luminosity upgrade scenario.

ANALYSIS

To study the effects of the long-range beam-beam interactions, an experiment was performed during the LHC physics run in 2015 [2]. In this experiment the normalised beam separation is reduced by reducing the crossing angle α , whilst holding the remaining parameters in equation 1 constant, as done in previous studies [3–5]. In the experiment, the LHC was set up with 1 single train of 48 bunches per beam, spaced 25 ns apart, with approximately 1.1×10^{11} protons per bunch and transverse emittances of approximately $2.4 \mu\text{m}$. The trains collided in IP1 and IP5 at 6.5 TeV, leading to a maximum of 34 long-range encounters per IP for nominal bunches, while bunches at the head or tail of the train experience 17 long-range encounters. The crossing angles at IP1 and IP5 were reduced simultaneously in steps of approximately 1σ . The crossing angle was reduced from the operational value of $\alpha = 290 \mu\text{rad}$ to a minimum crossing angle of $\alpha = 118 \mu\text{rad}$. A detailed description of the machine study procedure can be found in [2].

However unlike [3–5], the crossing angle remained fixed for approximately 10 – 15 minutes to allow for the cleaning of the bunch tails at every crossing angle step and to observe the beam intensity and luminosity lifetimes. At each of the crossing angle steps the intensity and luminosity lifetimes were monitored and the impact of the crossing angle was analysed.

To calculate the intensity and luminosity decay constants an exponential decay model was used to fit the intensity and luminosity data. The exponential decay model was of the form

$$N(t) = N_0 e^{(-\lambda t)} + c(t) \quad (2)$$

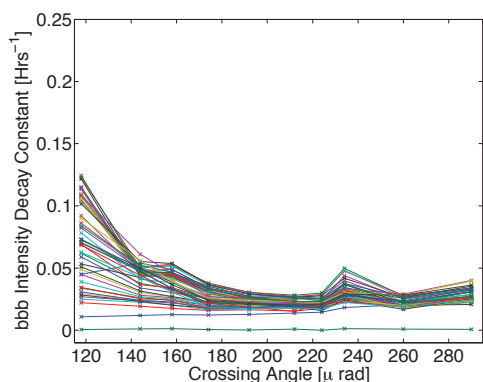
where $N(t)$ represents the data being fitted, for either the intensity or the luminosity data, λ is the decay rate which relates to the lifetime by $\lambda = \frac{1}{\tau}$, t is the time and finally the constant c accounts for the finite time over which the model is fitted. Other luminosity decay models were tested for the LHC data, as described in [6], however equation 2 was found to be appropriate for this data and fitted the intensity and luminosity data well. The decay constants were then calculated at each crossing angle step.

OBSERVATIONS

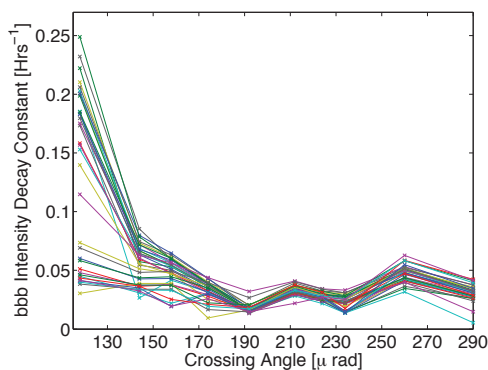
Throughout the experiment, the beams were subject to significant orbit drifts which required the re-optimisation of the luminosity at most crossing angle steps. To avoid spurious results when the offsets were large, the offsets were not included in the decay rate calculation.

Bunch by Bunch Intensity Lifetimes

The decay constant calculated for the bunch by bunch intensities were plotted as a function of the crossing angle in Fig. 1 for beam 1 (a) and beam 2 (b). There is no measurable reduction of intensity lifetimes until a crossing angle of 170–190 μrad is reached. At this point, some bunches appear to be affected more strongly by the crossing angle, with beam 2 lifetimes suffering more due to the crossing angle reduction.



(a) Beam 1

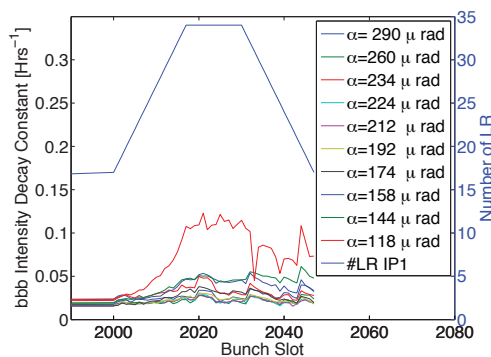


(b) Beam 2

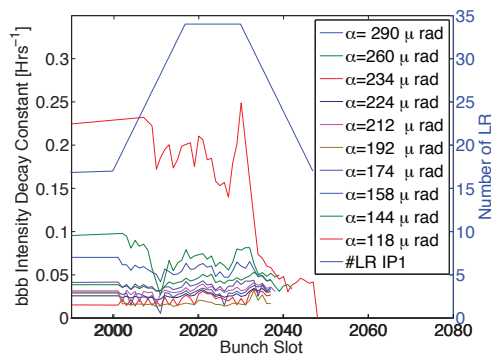
Figure 1: The bunch by bunch (bbb) intensity decay constant calculated for beam 1 (a) and beam 2 (b).

Assuming a normalised emittance of $2.4 \mu\text{m}$, one can deduce that no measurable losses are observed for separations d_{sep} in the range of $14 - 8.5 \sigma$. The onset of losses starts at a normalised separation $d_{sep} = 7.5 - 8.5 \sigma$. Below this separation, the losses become important, bringing the beam lifetimes below 10 hours for a beam-beam separation of 5.5σ for beam 1 and 6.5σ for beam 2.

Plotting the decay constant as a function of the bunch slot and comparing to the number of long range interactions, one can determine which bunches are effected more strongly



(a) Beam 1



(b) Beam 2

Figure 2: The bunch by bunch (bbb) intensity decay constant as a function of bunch slot and the number of long range interactions.

by the reduction of crossing angle. Figure 2 shows that the bunch intensity decay rates correspond strongly to the number of long range beam-beam interactions. The intensity lifetimes suffer more for bunches that experience a higher number of long range interactions, such as bunches at the centre of the train, whereas bunches at the head or tail of the train experience less long range interactions and hence have better lifetimes.

From simulations [7], a reduction in the dynamic aperture due to the long-range beam-beam interaction was expected leading to increased losses with crossing angle reduction. This is confirmed by the results shown in Fig. 1 and Fig. 2.

Luminosity Lifetimes

Plotting the bunch by bunch luminosity lifetimes as a function of crossing angle, one sees a similar trend as found in the intensity data. Figure 3 shows how the luminosity lifetimes for bunches in the centre of the train reduce with crossing angle. Once again, there appears to be no significant impact from the crossing angle reduction until a crossing angle of 170 – 190 μrad is reached. For crossing angles smaller than this, the lifetimes begin to deteriorate quickly, with the lifetimes for most of these bunches falling to less than 10 hours, which corresponds to a beam-beam separation of 6.5σ .

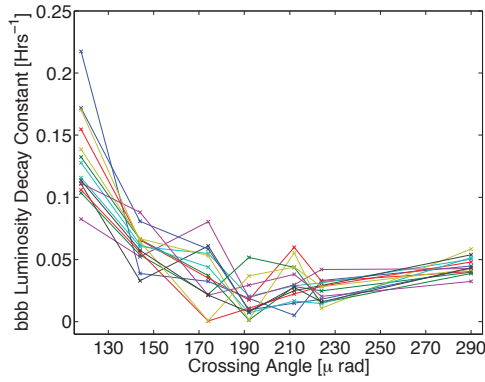


Figure 3: Bunch by bunch (bbb) luminosity decay rate per hour as a function of crossing angle for bunches in the centre of the train. The luminosity data is provided by the ATLAS detector.

Scaling Laws

From this observation, one can extract empirical scaling laws to describe the impact of the crossing angle and number of long-range beam-beam interactions on the intensities and luminosity lifetimes, which can in turn be related to dynamic aperture studies [7].

To obtain empirical scaling laws between the crossing angle and the decay rates, a number of non linear models were fitted to the data. The lifetimes appears to behave linearly for crossing angles above about $200 \mu rad$. When the crossing angle α is smaller than about $200 \mu rad$, the decay constant behaves more like a 2^{nd} order polynomial, giving an empirical relationship between the lifetimes, beam-beam separation and crossing angle as

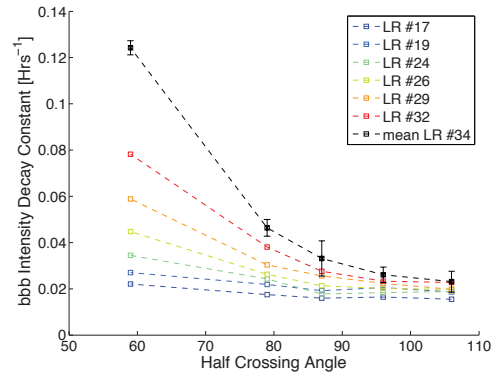
$$\lambda \propto \frac{1}{\alpha^2} \propto \frac{1}{d_{sep}^2}.$$

This relation points to a dependency of the loss rate to the beam-beam tune spread, since this goes to a first approximation like $\Delta Q = d_{sep}^{-2}$.

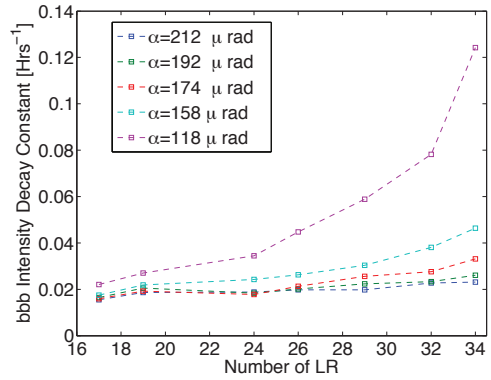
The dependency with the number of long range is shown in Fig. 4, for different crossing angles. For larger crossing angles the dependency is linear with the number of interactions and the losses are small. However as the separation is reduced to 6.5σ , which corresponds to a crossing angle of $\alpha = 118 \mu rad$, the decay rate with crossing angle becomes non linear and appears to scale with the number of long range interactions. Further investigations of the scaling are required to properly describe the dependency and this is ongoing.

DISCUSSION AND OUTLOOK

This article briefly summarises results from a machine study recently undertaken in the LHC to investigate the long range beam-beam limit [2]. Determining the minimum crossing angle achievable in the LHC is vital to maximise the luminosity reach. Understanding the loss rate dependency



(a)



(b)

Figure 4: (a) Bunch by bunch intensity decay rates per hour as a function of the crossing angle for different families of bunches undergoing different number of long-range (LR) encounters as expressed in the legend. (b) Bunch by bunch decay rate per hour as a function of the number of long-range (LR) interactions for different crossing angles with values given in the legend.

on the long-range beam-beam strength is fundamental to HL-LHC studies. This analysis shows that the beam intensity and luminosity lifetimes deteriorate while reducing the crossing angle. In general and for unknown reasons, beam 2 suffers more than beam 1, pointing to some difference between the two beams (working point, emittances etc). The bunch by bunch intensities and luminosity lifetimes begin to experience an effect from the crossing angle at approximately $170 - 190 \mu rad$. This corresponds to a beam-beam separation at the first long range beam-beam encounter of $7.5 - 8.5 \sigma$, whilst assuming a normalised emittance of $2.4 \mu m$. At crossing angles below this value, the lifetimes in both the luminosity and intensity fall below 10 hours. The loss rates show a clear pattern that depends on the number of long-range beam-beam interactions. Preliminary empirical scaling laws indicate that the intensity decay rates appear to scale with beam-beam separation like $\lambda \propto \frac{1}{d_{sep}^2}$.

ACKNOWLEDGEMENTS

The authors would like to thank the operators of the LHC and everyone that enabled the data to be taken during the machine study. This research is supported by the High Luminosity LHC project.

REFERENCES

- [1] W. Herr *et al.*, “Long-range beam-beam effects in the LHC”, in *Proc. ICFA Mini-Workshop on Beam-Beam Effects in Hadron Colliders*, CERN, Geneva, Switzerland, 18-22 March 2013, CERN-2014-004, pp. 87–92.
- [2] M. Crouch *et al.*, “Long range beam-beam interaction and the effect on the beam and luminosity lifetimes”, CERN, Geneva, Switzerland, CERN-ACC-Note-2016-0019.
- [3] R. Assman, *et al.*, “Results of long range beam-beam studies - scaling with beam separation and intensity”, CERN, Geneva, Switzerland, CERN-ATS-Note 2012-070 MD.
- [4] R. Alemany, “Results of long range beam-beam studies and observations during operation in the LHC”, CERN, Geneva, Switzerland, CERN-ATS-Note-2011-120 MD.
- [5] M. Albert *et al.*, “Head-on beam-beam collisions with high intensities and long range beam-beam studies in the LHC”, CERN, Geneva, Switzerland, CERN-ATS-Note-2011-058 MD.
- [6] A. Esmail-Yakas, “Effects of beam-beam interactions on luminosity decay rates at the LHC in 2012”, Masters thesis, Imperial College, London, 2015.
- [7] T. Pieloni *et al.*, “Beam-beam effects long range and head-on”, presented at the 6th Evian Workshop (EVIAN’15), Dec. 2015.