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MD 385: Long range beam-beam interaction and the effect on the beam and luminosity lifetimes

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Abstract

Identifying the minimum crossing angle achievable in the LHC is a key parameter to identify the collider luminosity reach. In this note, we summarise the observations collected during a dedicated experiment performed in 2015, where the strength of the long range beam-beam interaction is varied by reducing the crossing angle at IP1 and IP5. The crossing angle and the impact of the long range beam-beam interaction is analysed with respect to the beam and luminosity lifetimes. The effect of reducing Landau octupoles, initially operating at 476 [A] and high chromaticity values (15 units) are also shown. The minimum crossing angle achievable with collisions is identified, together with the impact on beam and luminosity lifetimes.

Keywords: CERN LHC, Beam Dynamics, Long Range Beam-Beam Effects, Beam lifetime

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Contents

1 Introduction

The aim of this study was to determine the minimum crossing angle achievable in the LHC, as done in the past [1–3] and to quantify the impact of the long range beam-beam effect on the intensity and luminosity lifetimes. The data for this machine study was taken on $15/09/2015$ between $11 : 00$ and $17 : 00$ and the fill number is 4368.

The strength of the long range beam-beam effect is dependent on the normalised beam separation in the drift space. This separation can be approximated in the two low β experiments, ATLAS at IP1 and CMS at IP5, using

$$d_{sep} = \sqrt{\frac{\beta^{*}\gamma}{\epsilon_n}}\alpha, \tag{1}$$

where β^{*} is the β-function at the IP, γ is the relativistic factor, ϵ_n is the normalised emittance and α is the crossing angle. Thus, as in previous machine studies [1, 2], the strength of the long range interaction is increased by reducing the crossing angle and hence reducing the beam-beam long range separation. The beam parameters for this particular fill are given in table 1.

Parameter	Beam1/Beam2
Energy [TeV]	6.5
Bunch Intensity [10^{10} ppb]	$\sim 1/\sim 1$
β^{*} [m] [IP1/IP5]	0.8/0.8
H Emittance ϵ [μm]	3.5/3.5
V Emittance ϵ[μm]	2.5 / 2.5
Bunch Spacing [ns]	25
# (LR) Colliding Bunches	48
Half crossing angle $\alpha/2$ [μrad]	145 $\rightarrow$ 59

Table 1: Beam parameters for the long range machine study.

1.1 Machine study description

In this machine study, a train of 48 bunches for both beams were injected and brought into collision at flat top energy (6.5 TeV) in IP1 and IP5 only, with two additional bunches at the beginning of the trains used as reference. The bunch trains were ramped up to flat top energy through the standard operational cycle of a physics fill in the LHC. The first reference bunch only underwent head on collisions, the second reference bunch was a non colliding bunch, while the train of 48 bunches experienced both head on and long range collisions in IP1 and IP5. The crossing angle at IP1 and IP5 was reduced in steps simultaneously. The crossing angle remained fixed for approximately $10 - 15$ minutes so that beam lifetime measurements could be made. The half crossing angles investigated were,

$$145 \rightarrow 130 \rightarrow 117 \rightarrow 112 \rightarrow 106 \rightarrow 96 \rightarrow 87 \rightarrow 79 \rightarrow 72 \rightarrow 65 \rightarrow 59 \quad [\mu rad].$$

For each crossing angle step the beam intensity and luminosity lifetimes were monitored and the impact on these two parameters were analysed. In addition, at the end of the crossing angle scan, the impact of the machine chromaticity and Landau octupoles on the beam and luminosity lifetimes was investigated.

The machine chromaticity was reduced from 15 units to 2 units and the current in the Landau octupoles was reduced from 476A to 0A. The impact of these parameters on the luminosity and intensity lifetimes are discussed.

At each crossing angle step the decay constant λ, was calculated by fitting the intensity and luminosity data with a c variable simple exponential decay function over the duration of the time spent at each step. This is the same fitting method that has been used in previous studies [4] and is shown to well describe the luminosity decay during physics fills at collision. Other fitting algorithms were also tested and have shown similar conclusions [4]. The fitting model used in this analysis is given by,

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

where the decay constant λ is the inverse of the lifetime τ, t is the time and N is either the luminosity or the intensity.

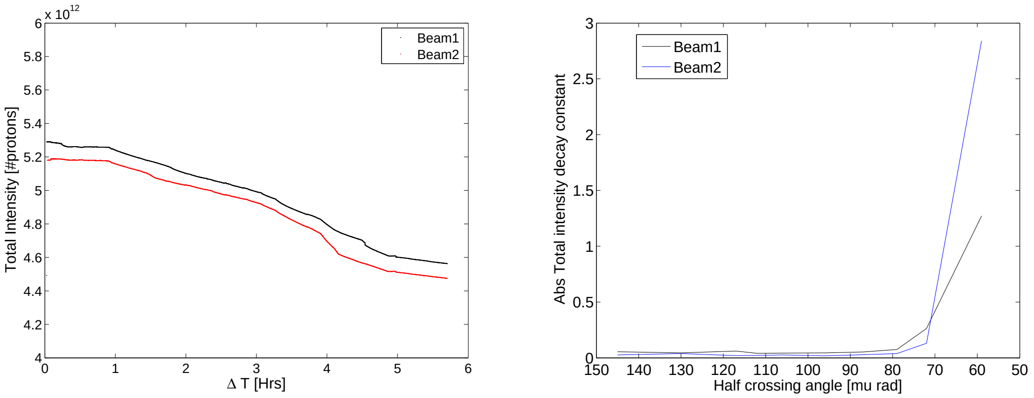
2 Results

In this section the initial results from the machine study are presented. In section 2.1 the impact of crossing angle on beam intensity and luminosity lifetime is analysed. Following this, in section 2.2, the intensity and luminosity lifetimes for each bunch are studied as a function of crossing angle and bunch slot. Finally in section 2.3, the impact of reducing both the chromaticity and the Landau octupole currents on the intensity and luminosity lifetimes are studied and presented.

2.1 Beam Intensity and Luminosity

2.1.1 Beam intensity lifetime

Figure 1(a) shows how the total beam intensity varied over the duration of the machine study. From this the intensity decay constant was calculated by fitting equation 2 at each half crossing angle step. The beam intensity lifetime decay constant was calculated and plotted in Figure 1(b) as a function of the half crossing angle. The beam intensity lifetime remains approximately constant until a half crossing angle of 70 − 80 μrad is reached, at this point the beam intensity lifetime begins to reduce.



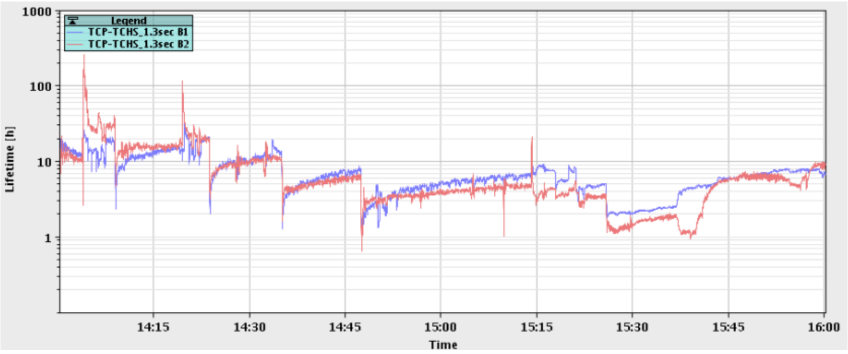
(a) (b)

Fig. 1: (a) shows the total beam intensity for beam 1 (black) and beam 2 (red) over the duration of the machine study. (b) shows the intensity decay constant calculated and plotted against the half crossing angle.

The beam lifetime corresponds qualitatively to the losses seen on the TCP collimator shown in Figure 2. Significant losses are seen between the crossing angles 79 $\mu rad \rightarrow$ 59 μrad, with both beam intensity lifetimes dropping below 10 hours.

2.1.2 Beam Luminosity lifetime

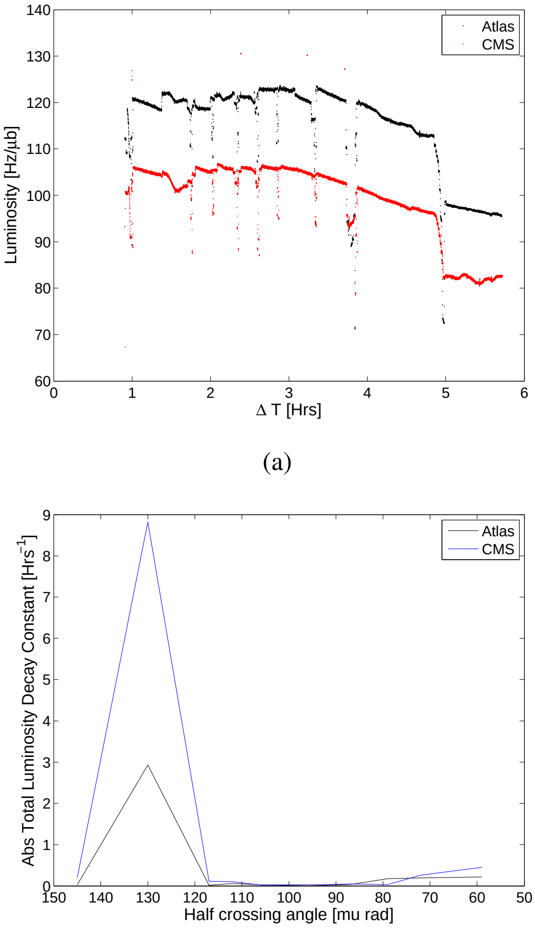
From Figure 3 the total luminosity from ATLAS and CMS is plotted over the duration of the machine study. The total luminosity lifetime was calculated again using the fitting model given by Eq. 2 and plotted against the crossing angle steps in Figure 3 (b). The luminosity (unlike the intensity) is subject to apparent reductions due to transverse offsets between the two beams. The offset leads to a reduction in luminosity due to a geometrical factor. This could lead to spurious results if this is not excluded from the fitting process. An example of such spurious reductions in luminosity is shown in Figure 3 (a). At approximately 1.5 hours into the machine study, there is a sharp drop in luminosity. This is due to a



(a)

Fig. 2: (a) Intensity lifetime in hours as calculated from the uncalibrated collimators for the half crossing angles of $87\ \mu rad \rightarrow 59\ \mu rad$.

significant orbit drift shown in Figure 4, which leads to a transverse offset between the two colliding beams. Due to these orbit drifts, the luminosity at both IPs needed to be re-optimised throughout the experiment since a full head on collision was lost. This re-optimisation of luminosity could lead to a significantly larger decay constant λ being calculated.

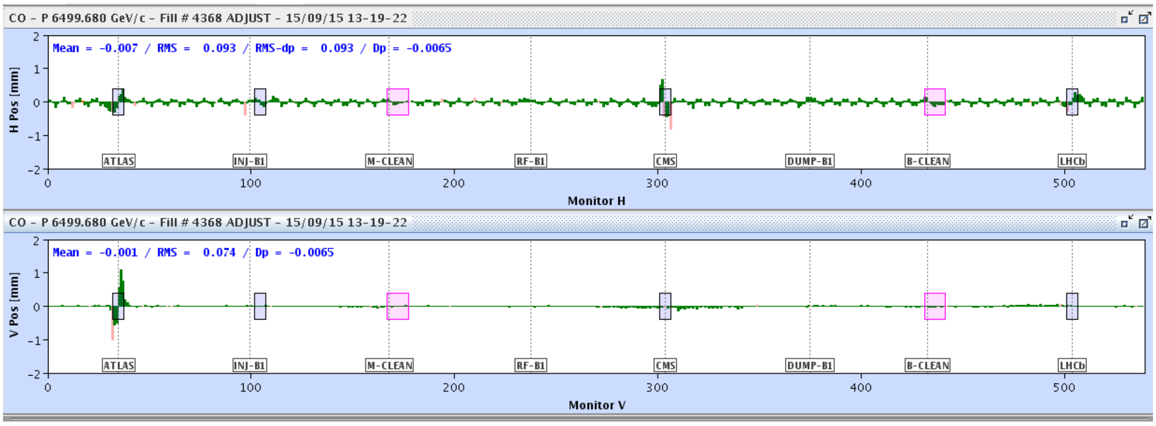


(a)

(b)

Fig. 3: (a) The total luminosity obtained from both ATLAS and CMS over the duration of the machine study. (b) shows the luminosity decay constant as a function of the crossing angle

An example of this can be seen in Figure 3(b) at a half crossing angle 130 μrad. The value of λ at the second crossing angle is not due to any coherent mechanism but is due to the transverse offset



(a)

Fig. 4: Shows the significant orbit drift that occurred at the second crossing angle 130 μrad.

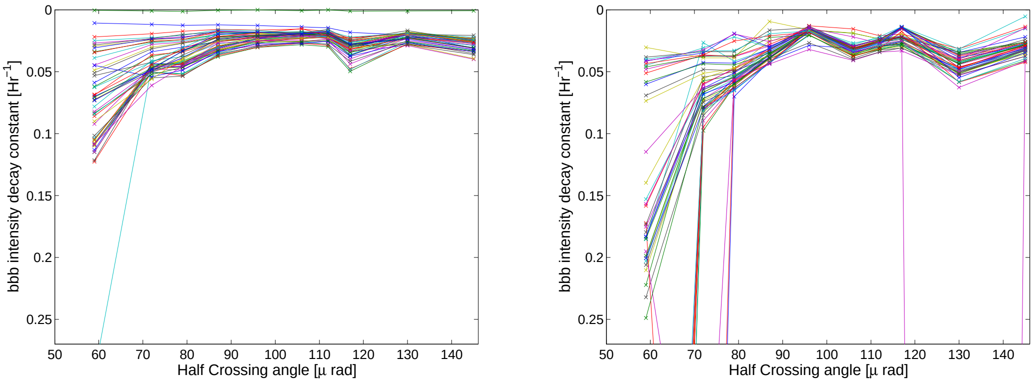
between the two colliding beams and is a product of the re-optimisation of luminosity. The results from re-optimisation of the luminosity are disregarded.

Similarly, Figure 3(b) shows that there is no significant change in the luminosity decay constant at both IPs until the half crossing angle is 79 μrad and below. This agrees with the total beam intensity data and the losses recorded on the TCP collimators, shown in Figure 2.

2.2 Bunch by bunch lifetimes

2.2.1 Bunch by bunch intensity

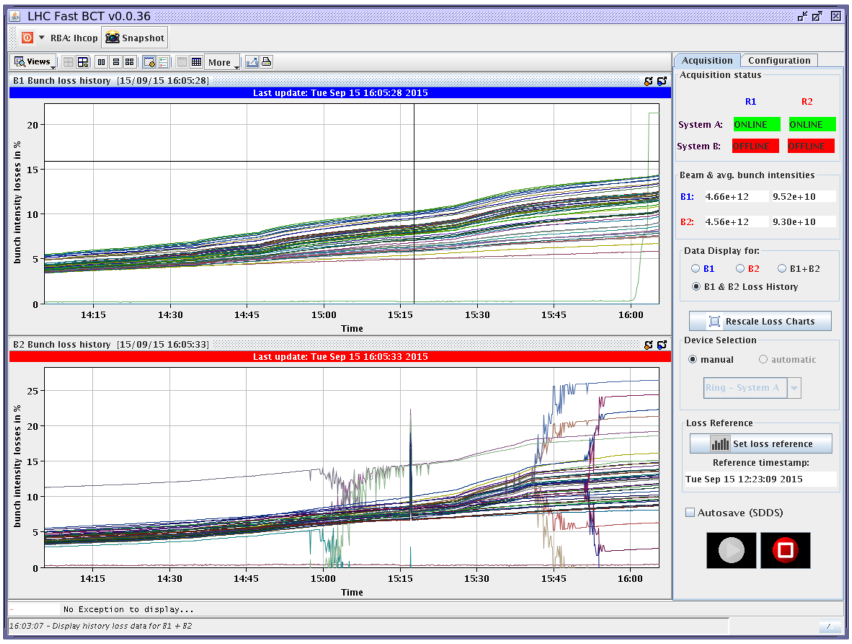
The bunch by bunch (bbb) intensity was analysed over each crossing angle change and the bunch intensity lifetimes were compared as shown in Figure 5. From this figure, it can be seen that like the total intensity and luminosity data, reducing the half crossing angle does not have a significant effect for half crossing angles above approximately 80 μrad. For crossing angles smaller than this, different bunches are affected differently. In beam 1, at a half crossing angle of 59 μrad the bunch intensity lifetime varies between 30-8 hours, whereas bunches in beam 2 seem to be effected more, with the majority of bunches experiencing intensity lifetimes less than 10 hours. A number of the bunches in the second beam experience intensity lifetimes as small as 4 hours. The beam 2 bunch by bunch intensity data is not as clean as the beam 1 data, due to measurement issues. This can be seen in figure 6.



(a) *Beam 1* (b) *Beam 2*

Fig. 5: Bunch by bunch intensity decay constant as a function of crossing angle for beam 1 and beam 2.

A similar trend can be seen in the BCT data shown in Figure 6, with the bunches in beam 2 experiencing smaller bunch intensity lifetimes than that of the bunches in beam 1. Analysing bunch intensity lifetimes as a function of the bunch slot shows that intensity lifetimes correspond strongly to



B1 Bunch loss history [15/09/15 16:05:28]

Last update: Tue Sep 15 16:05:28 2015

B2 Bunch loss history [15/09/15 16:05:33]

Last update: Tue Sep 15 16:05:33 2015

Acquisition status

	R1	R2
System A:	ONLINE	ONLINE
System B:	OFFLINE	OFFLINE

Beam & avg. bunch intensities

B1:	4.66e+12	9.52e+10
B2:	4.56e+12	9.30e+10

Data Display for:
○ B1 ○ B2 ○ B1+B2
● B1 & B2 Loss History

Device Selection
● manual ○ automatic
Ring – System A

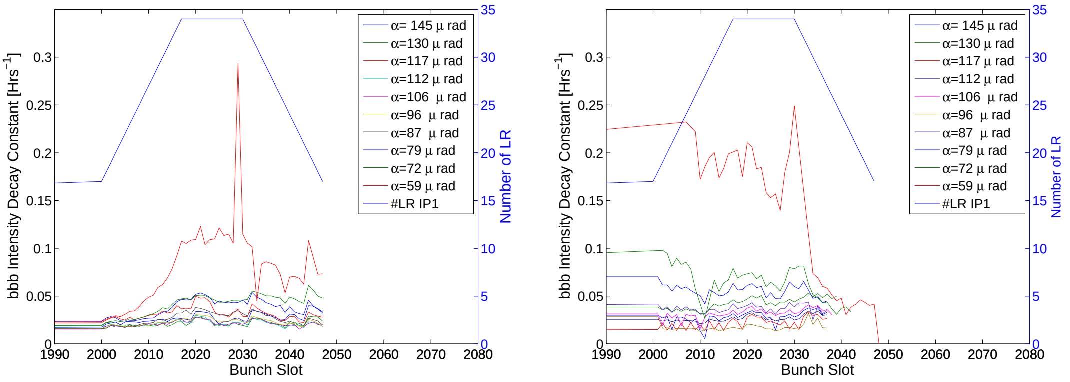
Loss Reference
Reference timestamp:
Tue Sep 15 12:23:09 2015

☐ Autosave (SDDS)

```
No Exception to display...
16:03:07 - Display history loss data for B1 + B2
```

Fig. 6: Losses recorded by the BCT data, showing that only the non colliding bunch becomes unstable when the octupole current and chromaticity is reduced for a fixed half crossing angle of 59 μrad. Some of the measurement issues can be seen in the beam 2 data.

the number of long range interactions that a bunch experiences, this can be seen in Figure 7. Bunches in the centre of the train experience the most long range interactions, which in turn leads to bunch intensity lifetimes less than 10 hours at a half crossing angle of 59 μrad, whereas bunches at the beginning or end of the train do not experience a large number of long range interactions. The lifetime for these bunches remains approximately 30 hours irrespective of the half crossing angle. An asymmetry between the head and tail of the train is also observed, the cause of this asymmetry is still under investigation but could possibly arise due to closed orbit effects caused by the long range beam-beam interactions.



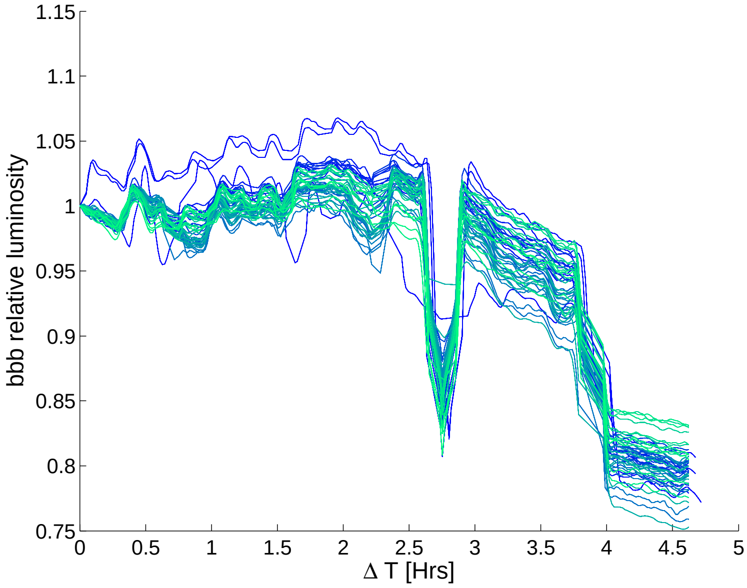
(a) (b)

Fig. 7: Shows how the bunch intensity decay constant varies with the bunch slot and the number of long range interactions for different half crossing angles. Figure (a), shows the variation of intensity lifetimes as a function of bunch slot for beam 1 and figure (b) shows the variations in intensity lifetime with bunch slot for beam 2.

2.2.2 Bunch by bunch luminosity.

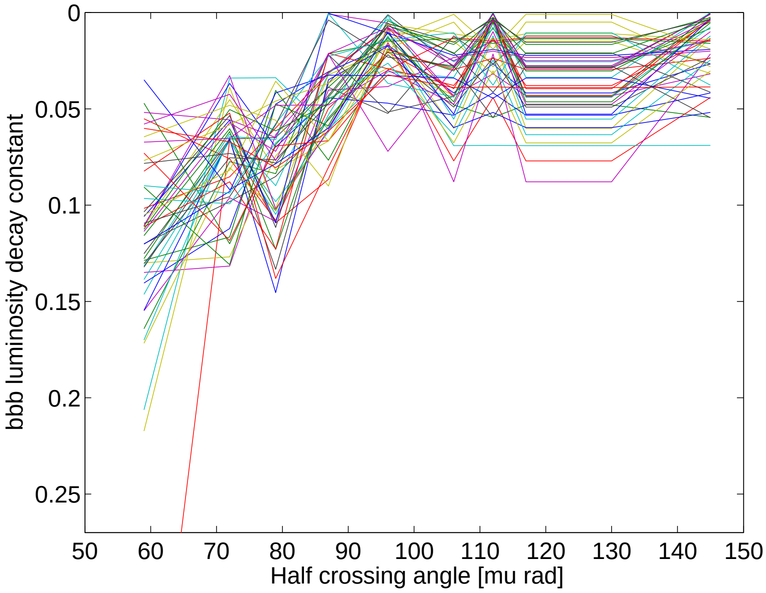
The bunch by bunch luminosity data from ATLAS was also analysed as shown in Figure 8. The orbit drift leading to re-optimisation is apparent in this data, most obviously at approximately 2.5 hours into the machine study. The orbit drifts introduce a transverse offset between the colliding beams, requiring luminosity re-optimisation at most of the crossing angle steps. When fitting the luminosity to determine the bunch by bunch luminosity lifetimes, these orbit drifts and re-optimisations needed to be avoided otherwise the luminosity lifetimes would be much larger than anticipated. An example of this can be seen in figure 9 at the half crossing angle 130 μrad and 106 μrad. At these crossing angles the decay appears to be larger than expected, and does not correspond with the intensity loss data.

Figure 9 shows the bunch by bunch luminosity decay constant as a function of the half crossing angle. Excluding the re-optimisation of luminosity at the half crossing angles 130 μrad and 106 μrad, once again a similar trend is observed as seen in the intensity data. For half crossing angles above 79 μrad there is no strong dependence on the half crossing angle, however below this crossing angle an increase in the bunch by bunch luminosity decay constant can be seen as the beam separation is reduced.



(a)

Fig. 8: The relative bunch by bunch luminosity data as recorded by the ATLAS experiment over the duration of the machine study.



(a)

Fig. 9: The bunch by bunch luminosity decay constant as a function of the half crossing angle.

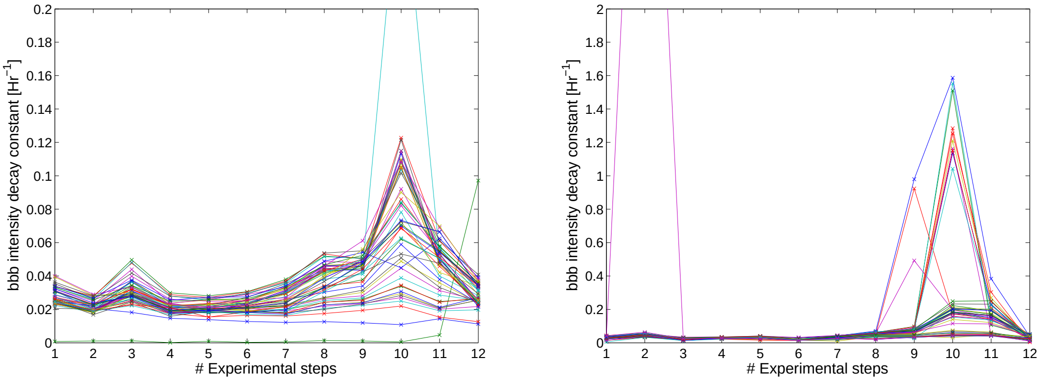
2.3 Octupole and Chromaticity

At the smallest crossing angle of 59 μrad, both the chromaticity and octupole current were reduced in an attempt to improve the intensity and luminosity lifetimes. The experimental steps $1 \rightarrow 12$ are described in table 2

Step #	Action applied
$1 \rightarrow 10$	α_{half} : $145 \rightarrow 59$ $[\mu rad]$
11	$Q' = 15 \rightarrow 2$ units
12	$Q' = 2, J_{oct} = 476A \rightarrow 0A$

Table 2: Experimental steps.

At the 11^{th} experimental step, the half crossing angle was fixed at 59 μrad and the chromaticity was reduced by a total of 13 units, from 15 units to 2 units and the intensity and luminosity lifetimes were observed. Then at the 12^{th} experimental step, with the same half crossing angle and chromaticity, the octupole strength was decreased from 476A to 0A and the intensity and luminosity lifetimes were observed.



(a) *Beam 1* (b) *Beam 2*

Fig. 10: The bunch by bunch intensity decay constant as a function of the experimental steps

Reducing the chromaticity from 15 units to 2 units shows a significant improvement in bunch intensity lifetime in beam 1. The lifetime improves for bunches in beam 1 from $\lambda^{-1} < 10$ hours to a lifetime of $\lambda^{-1} \sim 20$ hours. The bunches in the second beam did not see such a large improvement for the majority of the bunches, until a tune correction of $Q_{B2\ V} = +0.001$ and $Q_{B2\ H} = +0.002$ was applied. The chromaticity reduction appears to improve the bunch by bunch intensity lifetime of bunches that experience a high number of long range interactions.

At experimental step 12 and at the same fixed half crossing angle of 59 μrad, the Landau octupole current was reduced from 476A to 0A in addition to the chromaticity reduction. The bunch by bunch intensity lifetime improves in both beams from $\lambda^{-1} < 10$ hours to $\lambda^{-1} > 20$ hours as shown in Figure 11.

With the chromaticity and Landau octupole current reduced, the half crossing angle can be reduced to 59 μrad without any significant reduction in the bunch intensity lifetimes, this is mirrored in the total beam intensity and luminosity data as well as the bunch by bunch luminosity data, as seen in Figure 12. This allows the LHC to achieve a much smaller crossing angle, without having a significant impact on the lifetimes of the beams.

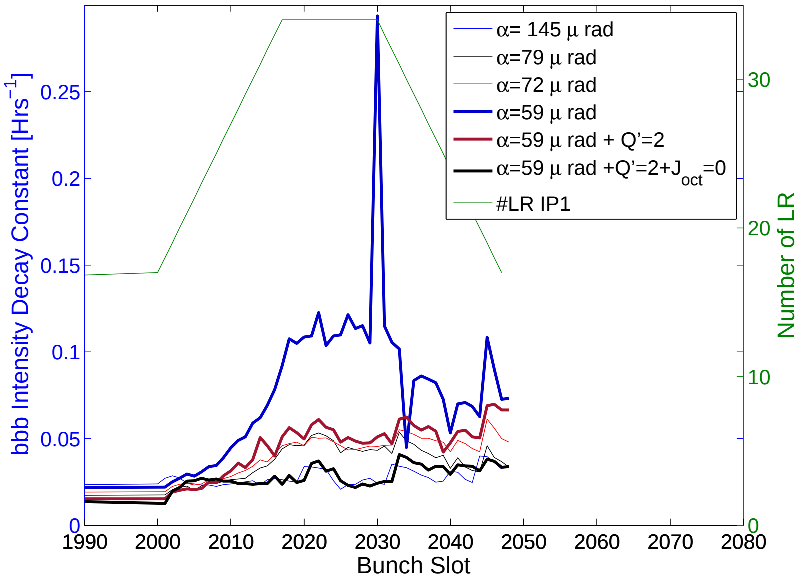
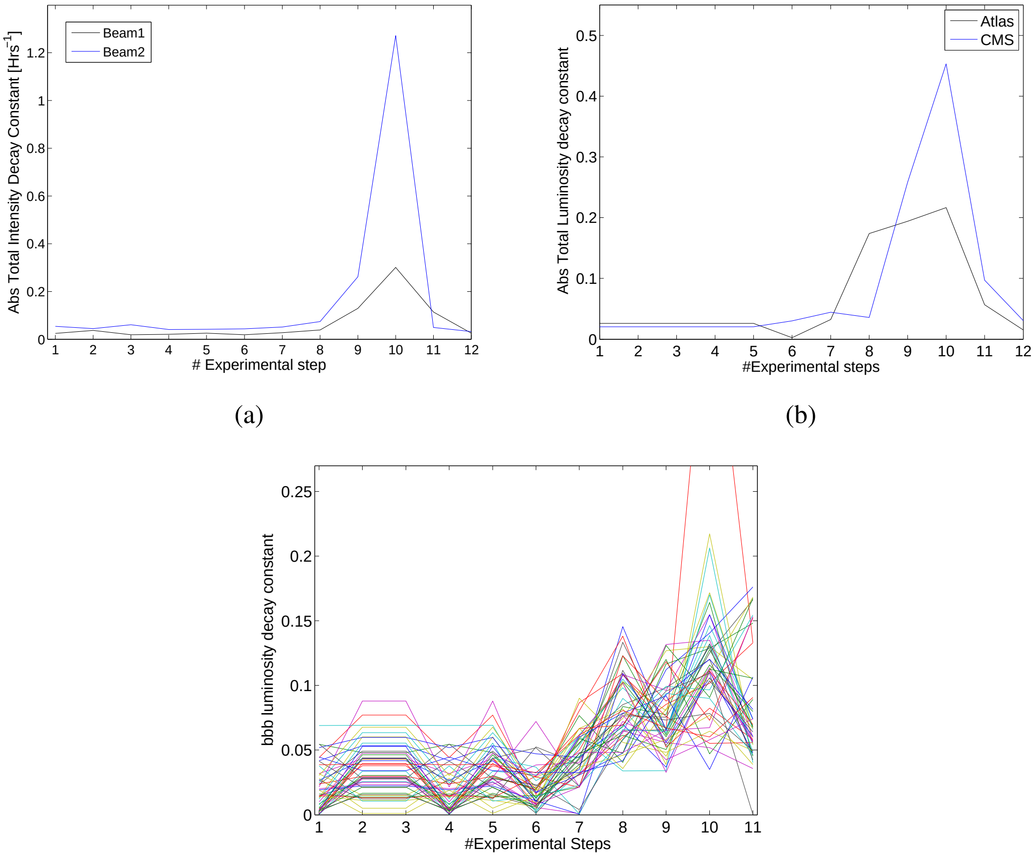


Fig. 11: Bunch by bunch intensity decay constant as a function of bunch slot compared to the number of long range interaction. The improvement of bunch intensity lifetime with chromaticity down 13 units and the octupole current to 0A is highlighted.



(a) (b)

(c)

Fig. 12: This figure shows the improvement in lifetimes at the 11^{th} and 12^{th} experimental steps. (a) shows the total beam intensity lifetime improvement. (b) shows the luminosity improvement as measured by ATLAS and CMS. (c) shows the improvement in bunch by bunch luminosity, note that there is no 12^{th} experimental step due to the short duration of time spent with zero octupole current.

3 Discussion and Outlook

An experiment to quantify the impact of the long range beam-beam separations on the beam intensity and luminosity lifetimes has been performed. The initial analysis shows how the beam intensity and luminosity lifetimes deteriorate from approximately 40 hours down to 4 hours as the crossing angle decreases. The degradation of the beam and luminosity lifetimes starts approximately at a half crossing angle of $80 - 90\mu rad$. This corresponds to a beam-beam separation at the first long range beam-beam encounter of $7.7 - 8.6\sigma$ assuming a normalised emittance of $2.4\mu m$, which results in lifetimes below 10 hours. The reduction of the lifetimes are visible in both the intensity and luminosity data. The minimum beam-beam separation achievable is $7.7 - 8.6\sigma$ with lifetimes at roughly 10 hours. Smaller crossing angles will lead to luminosity and intensity lifetimes of $8 - 4$ hours. An analysis of the bunch by bunch lifetimes show a strong correlation with the number of long range collisions for crossing angles below $80\mu rad$. An asymmetry between the head and tail of the bunch trains can also be seen, which is still under investigation but it could arise due to closed orbit effects from the long range beam-beam interaction. A detailed analysis or repeating the experiment with cleaner conditions could help clarify this observation.

At the smallest crossing angle of $59\mu rad$ the chromaticity and the Landau octupole current was reduced in two experimental steps. The reduction in chromaticity from $Q' = 15 \rightarrow Q' = 2$ units and a tune correction to beam 2 leads to an improvement in lifetimes from $4 - 8$ hours to above 10 hours. At the same crossing angle and chromaticity, the current in the Landau octupole was reduced from 476A $\rightarrow$ 0A and a further improvement in lifetimes was observed for bunches in the train, with the lifetimes returning to above 20 hours whilst reducing the beam-beam separation by about 2σ as also expected from simulations [5].

The non colliding bunch is the only bunch to go unstable with the chromaticity at $Q' = 2$ units and Landau octupole current at $J_{oct} = 0$A. This consequentially leads to an emittance blow up and a 20% reduction in intensity. Bunches colliding head on in IP1 and IP5 are stable with a chromaticity of 2 units and Landau octupoles at zero current. Serval uncertainties during the machine study have deteriorated the data, especially the large orbit drift which had a strong impact on the luminosity lifetimes. The main conclusions of the experiments have been presented in [5]. Repeating the machine study is essential to understand the luminosity reach of the LHC and the impact of the various parameters regularly used in operation, such as the chromaticity and octupoles.

3.1 Outlook

Further work will include extracting scaling laws of lifetimes as a function of the crossing angle with the aim of comparing to scaling from dynamic aperture studies. Further analysis of the non-colliding and head-on only bunches, along with a detailed analysis of the bunch by bunch emittances is ongoing. It may be possible to obtain bunch by bunch luminosity data from CMS, this would provide a good comparison to the data obtained from ATLAS and may also improve the luminosity analysis since CMS records data over more regular intervals than ATLAS. Analysis of the head tail asymmetry in the bunch train will also be investigated.

4 Acknowledgement

The authors would like to thank everyone involved in the long range machine study, especially the operators on shift for their time and expertise.

5 References

[1] R. Assman, et al., ’Results of long range beam-beam studies - scaling with beam separation and intensity’., CERN-ATS-Note 2012-070 MD.

[2] R. Alemany., ’Results of long range beam-beam studies and observations during operation in the LHC’., CERN-ATS-Note-2011-120 MD.

[3] M. Albert, et al., ‘Head-on beam-beam collisions with high intensities and long range beam-beam studies in the LHC’., CERN-ATS-Note-2011-058 MD.

[4] A. Esmail-Yakas., ’Effects of beam-beam interactions on luminosity decay rates at the LHC in 2012’., [Masters] Imperial College London; 2015.

[5] T. Pieloni, et al., ’Beam-Beam Effects Long Range and Head-on’, LHC Operational Workshop, EVIAN 2015