Probing the behaviour of high brightness bunches in collision at 6.5 TeV and the interplay with an external source of noise (MD1433)

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Summary

The results of an experiment aiming at colliding high brightness bunches at 6.5 TeV in the LHC and probing the interplay between external noise and head on beam-beam interaction are presented. The colliding bunches are shown to have a burn off dominated lifetime, but they experience a significant emittance growth, possibly resulting from the transverse feedback noise with non standard settings. While several features remain to be understood, the effect of noise on colliding beams seems compatible with the so-called weak-strong model.

Contents

1 Introduction ................................... 1
2 Experimental setup ................................. 2
3 Results ........................................... 3
  3.1 Beam stability .................................. 3
  3.2 Behaviour of high brightness bunches in collision .......... 5
  3.3 Effect of noise ................................ 9
    3.3.1 Bunch intensities .......................... 9
    3.3.2 Emittances ............................... 9
4 Conclusion ..................................... 15
5 Acknowledgements ............................... 15

1 Introduction

An external source of noise, e.g. due to power converter ripple or ground vibrations, on a beam with a tune spread results in emittance growth. In the HL-LHC, the crab cavities are a potential source of noise
in the transverse plane. The tolerances for the design of those cavities are based on a given maximum emittance growth and therefore on a beam dynamics model [1]. Conservatively, the weak-strong model [2] was preferred to set the tolerances over the strong-strong model [3]. While in principle more accurate, the strong-strong model is very sensitive to the machine and beam configuration [4]. In particular it is sensitive to the position of the coherent beam-beam modes with respect to beam’s incoherent spectrum, which in turn are dependent on both machine and beam parameters (bunch brightness, phase advance between interactions points, collision scheme). Simulations suggest that, while the growth predicted by the strong-strong model is significantly lower than the one predicted by the weak-strong model in very specific configurations, in most realistic configurations the predictions of the strong-strong model are as high as those of the weak-strong model [5]. The transverse damper (ADT) plays a key role in those models, as it prevents emittance growth due to decoherence and also generates a noise due to the finite resolution of its pickups.

The experiment conducted aims at testing the accuracy of both models in a simple configuration, i.e. single bunches colliding head-on in the two main experiments at top energy (6.5 TeV). Similar experiments were performed at injection (450 GeV), the results indicated an additional source of emittance growth which could not be explained within the models [6–8].

2 Experimental setup

In order to probe a wide range of parameters in a reasonable amount of time, bunches with different intensities and similar transverse emittances were injected. The transverse feedback (ADT) was set with different damper gains for different bunches, as illustrated in Fig. 1. There were 9 bunches with three different intensities, referred to as low, intermediate and high brightness respectively. The first three bunches, one per family, are non-colliding bunches and experience the full ADT gain. The second group of three are colliding in IPs 1 and 5, they also experience the full ADT gain. The last group of three bunches are also colliding in IPs 1 and 5, however their damper gain is reduced by a factor 4.

The first fill was performed as the regular physics fills up to the establishment of collision in IPs 1 and 5.

Figure 1: Schematic of the filling scheme: the blue and red bars correspond to non-colliding bunches of beam 1 and 2 respectively, the black lines correspond to bunches colliding in IPs 1 and 5. The damper gain is maximum for the first 6 bunches and lower by a factor 4 on the last 3 (dashed black line).
The attenuators of the ADT pickup signals were set to high intensity settings, reducing their resolution for the bunches with smaller intensities. Transverse instabilities were observed at flat top and during ADJUST, as a result the second fill was performed with increased strength of the octupole (470 A to 570 A) and increased gain (50 turns to 25 turns damping time), the instabilities were no longer observed.

Once in collision, Gaussian white noise was injected in both transverse planes of both beams, increasing in steps the strength of the excitation. The bunch intensities, emittances and luminosities were monitored in steady phases of about 10 to 15 minutes. The excitation amplitude is given by the peak voltage, \( V \), at the ADT kicker. The RMS kick amplitude is given by:

\[
\Delta x'_{\text{rms}} = \frac{2V}{6.6 \cdot d \cdot E},
\]

where \( L = 6 \, \text{m} \) is the length of the ADT kicker, \( d = 52 \, \text{mm} \) is the gap between the kicker plates and \( E = 6.5 \, \text{TeV} \) is the beam energy. The noise is normalised to the divergence of the beam at the location of the kicker:

\[
\delta_{\text{rms}} = \Delta x' \sqrt{\frac{\gamma \beta}{\epsilon}},
\]

with \( \epsilon \) the normalised bunch emittance, \( \gamma \) the relativistic factor and \( \beta \) the corresponding optical function at the location of the kicker (Tab. 1).

### Table 1: \( \beta \) function at the damper kickers.

<table>
<thead>
<tr>
<th>Beam 1</th>
<th>Beam 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Horizontal</td>
<td>Vertical</td>
</tr>
<tr>
<td>272.4 m</td>
<td>218.9 m</td>
</tr>
</tbody>
</table>

3 Results

3.1 Beam stability

The octupole strength required to stabilise the high brightness bunches based on simulation is 320 A [9]. In previous MDs in similar conditions but reduced beam energy, those high brightness bunches became unstable at flat top [10, 11]. With \( I_{\text{oct}} = 470 \, \text{A} \), the three high brightness bunches of beam 1 became unstable at the end of the squeeze during the first fill, showing a discrepancy of a factor above 1.5 with the predicted octupole threshold. The resulting emittance growth is visible at minute 50 in both planes in Fig. 2. Similar bunches of beam 2 did not experience this instability. Two medium intensity bunches became unstable in the vertical plane of beam 1 during and after the modification of the crossing angle bump (so-called TOTEM bump), before the beams were brought into collision. As a consequence, the second cycle was performed with an increased octupole strength (570 A) in both planes and beams, the gain of the ADT was also increased from 50 to 25 turns. The high brightness non-colliding bunch was also removed from the filling scheme, in order to prevent losses due to instabilities of these bunches when reducing octupole and feedback gain during the experiment.

The beams could be brought into collision without coherent instabilities in the second fill. The medium intensity non-colliding bunch became unstable in the vertical plane of beam 1 when reducing the ADT gain from 25 to 50 turns (scan 4 in Tab. 2), visible at minute 360 in Fig. 2. The two non-colliding bunches of beam 2 became unstable in the horizontal plane when reducing the chromaticity from about 10 to 5 units (scan 5), the emittance blow up is visible at minute 400. The same bunches became unstable again about 40 minutes later, when reducing the octupole current from 570 to 188 A (step 6).

While the non-colliding bunches seems slightly less stable with respect to predictions, the stability of the colliding bunches of both beams through the experiment, even when reducing the octupole current, chromaticity and ADT gain, is in agreement with the expected strong stability due to Landau damping from the large head-on beam-beam induced tune spread.
Figure 2: Emittance of the different bunches through the two cycles. The blue, green and red lines correspond to low, medium and high intensity bunches respectively. Left plots show the behaviour of the non-colliding bunches, middle and right plots correspond to colliding bunches with full and reduced gain respectively.
Figure 3: Measured bunch intensities when bringing the beams into collision (left plot). The green and blue lines correspond to the high intensity bunches of beam 1, the cyan and red lines to the ones of beam 2. The beams are brought into collision between minutes 70 and 75, including the optimisation of the orbit at the IP. The difference in intensity decay rates obtained with the corresponding fits before and after the separation bumps as a function of the luminosity estimated based on measured machine and beam parameters are compared to the expectation for a burn-off dominated beam (black curve on the right plot).

The possibility to bring such single bunches in collision represents a major achievement since their brightness is higher than the HL-LHC target bunch brightness by \( \approx 40\% \).

### 3.2 Behaviour of high brightness bunches in collision

The luminosities obtained from the online lumimeters were in disagreement with the estimation based on the measured machine and beam parameters using:

\[
L_{\text{tot}} = \frac{N_1 N_2}{2\pi} \left( \frac{1}{\sqrt{\sigma_{1,H}^2 + \sigma_{1,V}^2}} + \frac{1}{\sqrt{\sigma_{2,H,eff}^2 + \sigma_{2,V,eff}^2}} \right),
\]

with \( f_{\text{rev}} \) the revolution frequency, \( N_1 \) and \( N_2 \) the intensities of the two colliding bunches, \( \sigma_{k,i} \) the beam size at the IP of beam \( k \) and plane \( i \) and the corresponding effective beam size due to the crossing angle \( \theta \):

\[
\sigma_{i,\text{eff}} = \sigma_i \sqrt{1 + \left( \frac{\sigma_s}{\sigma_i} \tan(\theta/2) \right)^2},
\]

where \( \sigma_s \) is the r.m.s. bunch length. The two terms in Eq. 3.1 correspond to the contribution of the IPs 1 and 5 with a crossing angle in the vertical and horizontal plane respectively. The measured bunch by bunch decay rates are however in reasonable agreement with the expected luminosity burn-off (Fig. 3), assuming an inelastic cross section of 80 mb. Nevertheless, the beam-beam induced tune shifts measured with the BBQ (Fig. 4) are systematically lower than the ones estimated from the machine and beam parameters, suggesting that the measured emittance are underestimated. This effect is detailed in Sec. 3.3.2. In particular, the maximum pile up of 184 events per bunch crossing seems overestimated, a value of \( \approx 160 \) would be compatible with the measured beam-beam induced tune shift and decay rates. This overestimation of the luminosity based on measured machine and beam parameters is visible in Fig. 3, where the loss rate of the different bunches is on average lower than the one estimated based on the burn off.

The discrepancy with ATLAS online lumimeters was later understood thanks to tests with high pile up, when both the lumimeter and the detector could acquire data, allowing for a calibration of the lumimeter in the high pile up regime. After the calibration, the measured luminosities at ATLAS were in agreement.
Figure 4: Spectrogram in the horizontal plane of beam 1 from the BBQ turn-by-turn data, showing 3 main lines (left arrows) appearing when the beams are brought into collision (at minute 5.1) shifted respectively by -0.018, -0.012 and -0.007 with respect to the machine tune (right arrow).

throughout the experiment with the estimation based on machine and beam parameters within about 10% [12, 13].

The evolution of the transverse emittances when bringing the beams into collision is shown in Fig. 5, one observes a fast variation of the emittances at the moment when the beams are brought into collision. Figure 6c suggests that this effect varies linearly with the total beam-beam tune shift that the bunch experiences:

$$\Delta Q_i = \frac{r_0 N \beta}{2 \pi \gamma} \left( \frac{1}{\sigma_{i,\text{eff}}(\sigma_{i,\text{eff}} + \sigma_j)} + \frac{1}{\sigma_i(\sigma_i + \sigma_{j,\text{eff}})} \right), \quad (3.3)$$

where $i$ refers to a given plane, $j$ to its counterpart, $N$ is the bunch intensity and $r_0$ the classical proton radius. All quantities used to compute the tune shift refer to the bunches with which the one under consideration is colliding. This effect could be the result of a modification of the $\beta$ function at the location of the BSRT induced by the strong beam-beam interactions or by a modification of the particle distribution in the beam. The fact that the variation develops within a time scale of minutes favours a modification of the distribution due to different diffusion mechanisms. In particular, both the presence of beam losses and an emittance exchange mechanism between the transverse planes could explain the apparent reduction of the emittance in the vertical plane.

Comparing Figs. 6a and 6b, one observes an important correlation of the increase of the emittance growth once the beams are colliding with both the bunch brightness and the beam-beam tune shift experienced by the bunch, which depends on the colliding bunch brightness. This double correlation is inherent to the symmetric filling schemes. A significant increase of the emittance growth rate is observed in the horizontal plane of the two beams, whereas a reduction is observed in the vertical. Similarly, both these phenomenon could be explained by either the combination of stronger IBS in the horizontal plane with losses in the vertical plane, or due to an emittance exchange mechanism. The latter was observed in strong-strong simulations when the frequency of the vertical $\pi$-mode overlaps with the horizontal incoherent tune spread [5]. Further simulation studies are needed in order to perform a quantitative comparison with the measurements.
Figure 5: Measured transverse emittances (BSRT) when bringing the beams into collision for the two high intensity bunches of each beam. The beams are brought into collision between minutes 70 and 75, including the optimisation of the orbit at the IP. The value obtained with the corresponding fits before and after the separation bumps are reported in Fig. 6.

<table>
<thead>
<tr>
<th>Fill number</th>
<th>Scan number</th>
<th>Full ADT damping time [1/turn]</th>
<th>Chromaticity</th>
<th>Octupole current [A]</th>
<th>ADT kicker Voltage [V]</th>
</tr>
</thead>
<tbody>
<tr>
<td>5367</td>
<td>1</td>
<td>50</td>
<td>15</td>
<td>470</td>
<td>0, 32, 48, 64</td>
</tr>
<tr>
<td>5367</td>
<td>2</td>
<td>25</td>
<td>15</td>
<td>470</td>
<td>64</td>
</tr>
<tr>
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<td>3</td>
<td>25</td>
<td>15</td>
<td>570</td>
<td>0, 32, 48, 64</td>
</tr>
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<td>4</td>
<td>50</td>
<td>15</td>
<td>570</td>
<td>0, 32, 48, 64</td>
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<td>10</td>
<td>570</td>
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<tr>
<td>5368</td>
<td>6</td>
<td>50</td>
<td>5</td>
<td>570</td>
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<tr>
<td>5368</td>
<td>7</td>
<td>50</td>
<td>5</td>
<td>188</td>
<td>0, 64</td>
</tr>
</tbody>
</table>

Table 2: Machine parameters during the noise amplitude scans.
Figure 6: Measured variation of the emittance and of the corresponding variation of the growth rate when bringing the beams into collision for the colliding bunches in the high ADT gain window (25 turns).
3.3 Effect of noise

Two ramps could be performed, the settings of the different noise amplitude scans are summarised in Tab. 2. The evolution of the intensity, decay rates, emittance and emittance growth rates during those scans are discussed in the following. The data points where coherent instabilities affected the emittance of one of the two beams or planes were filtered out. Since the high intensity bunches became unstable during the first cycle, data are available only for non-colliding bunches and medium intensity bunches.

3.3.1 Bunch intensities

The bunch intensities during the experiment are shown in Fig. 7, focusing on scan 1, 3 and 4 with the largest beam-beam tune shift. The corresponding decay rates are reported in Fig. 8, including a correction of the estimated luminosity burn off. As mentioned previously, the burn off seems to be slightly overestimated, leading to negative decay rate. The noise does induce significant losses, with an apparent quadratic dependence on the noise amplitude. The losses are greater during the scan 4, despite the reduced beam-beam tune shift, indicating a dependence on the ADT gain, reduced by a factor 2 during the 4th scan with respect to the 3rd. This effect is also visible in beam 1 during scan 4 (Fig. 8e), as the colliding bunches with reduced damper gain (dashed lines) are consistently suffering more than other bunches.

3.3.2 Emittances

As mentioned previously, the luminosity decay rate observed indicate that the luminosity computed based on measure emittances and intensities is overestimated. The beam-beam tune shift measured with the BBQ (Fig. 4) is compatible with the ones estimated for beam 1 (start of scan 3 in Fig. 10c and 10d), but incompatible with the estimated values of $\Delta Q_{tot} = -0.028$ in the vertical plane of beam 1. This difference is visible in the measured emittances (Fig. 9) suggesting that the emittances of beam 2 are underestimated by about 35%.

Each bunch is affected by different emittance growth mechanisms due to their different intensities (IBS, different noise from the ADT), these effects are visible when bringing the beams into collision. Here we rather discuss the variation of the emittance growth rate as a function of different parameters, in order to isolate its contribution.
Figure 8: Bunch intensity decay rates during the different scans, the contribution from the estimated luminosity burn off has been subtracted based on Eq. 3.1 and an inelastic cross section of 80 mb. The blue, green and red lines correspond to low, medium and high intensity bunches respectively. The dotted lines show the behaviour of the non-colliding bunches while the solid and dashed lines correspond to colliding bunches with full ADT gain and reduced gain respectively.
Figure 9: Emittance measured with the BSRT during the different scans. The blue, green and red lines correspond to low, medium and high intensity bunches respectively. The dotted lines show the behaviour of the non-colliding bunches while the solid and dashed lines correspond to colliding bunches with full ADT gain and reduced gain respectively. Note that the time axis is broken in between the two fills.

Figure 10: Beam-beam tune shift experienced by the beam indicated, i.e. induced by the other beam on a given plane during the different scans. The blue, green and red lines correspond to low, medium and high intensity bunches respectively. The solid and dashed lines correspond to colliding bunches with full ADT gain and reduced gain respectively. Note that the time axis is broken in between the two fills.
Figure 11: Variation of the emittance growth rate when introducing noise measured with the BSRT during scan 1 (Tab. 2). The blue, green and red lines correspond to low, medium and high intensity bunches respectively. The dotted lines show the behaviour of the non-colliding bunches while the solid and dashed lines correspond to colliding bunches with full ADT gain and reduced gain respectively.

Set up (Scans 1 and 2)

The first scan (Fig. 11) was performed despite the coherent instabilities that deteriorated the beam quality in order to verify the availability of the excitation using the ADT and define empirically at which noise amplitudes the effect become measurable. The results shown in Fig. 11 indicated that all beams and planes are affect by the noise as expected, emittance growth in the order of 10%/h are measurable within steps of 10-15 minutes of excitation. During scan 2, the ADT filters were adjusted to improve the effective gain by a factor two, this setup was then used over the next cycle.

Impact of the damper gain (Scans 3 and 4)

The highest beam-beam tune shift were achieved during the first scan of the second fill. As expected the non-colliding bunches experience a reduced emittance growth with respect to colliding bunches in all configurations (Fig. 12). The bunches experiencing a reduced damper gain (dashed lines, $\tau \approx 100$ turns) show a larger emittance growth, demonstrating the beneficial effect of the ADT in the presence of an external source of noise. Due to this effect, the difference in growth rate between bunches of different brightness is expected to be reduced at large ADT gain (solid lines), which is consistently observed in all the planes and beams. The bunches with reduced damper (dashed lines) show a brightness dependent increase of the growth rate. The effect is however not equivalent in the different planes and beams, in particular in the vertical plane of beam 2, bunches with highest brightness, and therefore beam-beam tune shift, grow less than the brighter ones. Such an effect may be due to different configurations of coherent beam-beam modes, since the two planes and beams have different phase advances between interactions points. Further numerical studies are required to quantify this effect.

While reduced due to the degradation of the beam quality during the scan 3, the total beam-beam tune shift of the highest brightness bunches during scan 4 remains at $\approx -0.013$. While the largest tune shift is still significant, the difference in brightness, and therefore in beam-beam parameters, between the different bunches has greatly reduced. As a consequence the behaviour of the difference bunches become...
Figure 12: Variation of the emittance growth rate measured when introducing noise during scan 3 (Tab. 2). The blue, green and red lines correspond to low, medium and high intensity bunches respectively. The dotted lines show the behaviour of the non-colliding bunches while the solid and dashed lines correspond to colliding bunches with full ADT gain and reduced gain respectively.

Figure 13: Variation of the emittance growth rate when introducing noise during scan 4 (Tab. 2). The blue, green and red lines correspond to low, medium and high intensity bunches respectively. The dotted lines show the behaviour of the non-colliding bunches while the solid and dashed lines correspond to colliding bunches with full ADT gain and reduced gain respectively.
indistinguishable (Fig. 13). Nevertheless, the colliding bunches show a brightness dependent increase of the emittance growth rate in the vertical plane of the two beams. Also, the non-colliding bunches and the bunches with reduced damper gain stand out with the smallest and largest increase in growth rate respectively, as expected. A quantitative comparison of the measured increase of the emittance growth due to the external noise with theoretical models requires an accurate knowledge of the ADT gain and the excitation amplitude. A calibration of those quantities requires tests with beam that will be performed during the 2017 run. In the meantime, a variation of the relative error on those parameters allows for a first attempt to estimate the validity of the model. Figure 14 shows the relative difference between the measurements and the predictions from the theoretical weak-strong and strong-strong model, averaged over the data points of scan 3. It shows that the values estimated for the noise amplitude and the ADT gain lead to an average difference of about 100%. A reasonable agreement of about $\approx 30\%$ is found between the data and the weak-strong model predictions, considering that the effective damping time is overestimated by a factor $\approx 3$, a significant error that cannot be excluded based on data currently available. A similarly reasonable agreement of $\approx 40\%$ can be found with the strong-strong model prediction assuming that the noise amplitude is underestimated by a factor $\approx 2.3$, this error is however not compatible with the measured voltage at the ADT kicker. Similar conclusions are drawn from the data of scan 4.

Impact of chromaticity (Scans 5 and 6)

Due to the degradation of the beam quality due to coherent instabilities when reducing the chromaticity, only few data points are meaningful during the scan 5, in conditions similar to previous scan except for the chromaticity, which was reduced by 5 units. For both beams, the increase of emittance growth due to the presence of noise was reduced by a factor 1.5 to 2 in the horizontal plane and increased in a similar manner in the vertical plane. A single data point is left for the scan 6, with chromaticity reduced by another 5 units. The increase in growth rate was reduced by another factor $\approx 2$, except for the horizontal plane of beam 1, where the increase of the emittance growth remained unchanged (Fig. 15). The observed impact of chromaticity does not follow the naive expectation, in which the reduction of the chromatic spread would lead to a reduction of the emittance growth. It could be explained by a modification of the coherent modes by the chromaticity [14], a quantitative comparison requires further simulation studies.

Impact of the octupole strength (Scan 7)

The beam quality after the reduction of the octupole strength is too low to be reasonably considered.
Figure 15: Variation of the emittance growth rate when introducing noise during scans 5 (crosses) and 6 (dots) Tab. 2). The blue, green and red lines correspond to low, medium and high intensity bunches respectively. The dotted lines show the behaviour of the non-colliding bunches while the solid and dashed lines correspond to colliding bunches with full ADT gain and reduced gain respectively.

4 Conclusion

High brightness bunches with an intensity just below $2 \cdot 10^{11}$ protons within an emittance of 1.5µm were brought into collision, along with bunches of lower brightness. The high brightness bunches became unstable in a first attempt with 470 A in the octupoles, but remained stable through the cycle in a second attempt with 570 A. When brought into collision, those high brightness bunches experiences a fast emittance growth within the first minutes in collision with a linear dependence on the beam-beam tune shift. Afterwards, a steady increase of the emittance is observed with a rate higher than in absence of collision, the difference between the planes remains to be understood. The intensity decay rate of the bunches in collision is compatible with luminosity burn off, corresponding to a pile up to 160 events per crossing.

Overall the measured contribution of the interplay between beam-beam effects and external noise to the emittance growth seems in agreement with the weak-strong model, provided that there exists a significant difference between the expected and effective ADT gain by a factor 3 to 4, justifying dedicated measurements in the future. The difference between beams and planes, as well as a non trivial dependence on chromaticity, reveals important effects that were observed in strong-strong simulations. Quantitative comparisons with simulations are needed to shed light on the underlying mechanisms.

5 Acknowledgements

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References


