Beam parameters observations during the second high pile-up collisions fill in 2011

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Summary

On the 25th of October 2011, a physics fill (fill nr. 2252) was dedicated to providing ATLAS & CMS with high pile-up collisions. A peak pile-up (number of inelastic interactions per crossing) $\mu$ of almost 35 was achieved. Part of the test was also to bring the pile-up to values $< 0.5$ and this was achieved by separating the beams in steps. The Head-On collisions were restored after each IP separation to study its effects. In this note observations of the beam parameters evolution (bunch current, emittances and length) are presented. Some conclusions are drawn and suggestions for future MDs are discussed.

1 Motivation

After the first high pile-up physics fill (fill nr. 2201), further test were requested by the experiments to check whether multiple high pile-up collisions can be effectively processed. In this note, we report on the beam parameter evolution we observed parasitically during this second high pile-up fill.

2 Experimental Setup

The filling scheme $Single_{11b+1small_{10}_{_1}_{_1}_{_1}}_{HighPileUp}$ was used to inject into the LHC rings 11 high intensity bunches per beam, roughly equally spaced by $\sim 8 \mu s$ (in addition to a low intensity pilot bunch). The SPS provided bunches of $\sim 2.3 \cdot 10^{11}$ ppb (Fig. 1) with an average normalized emittance of $\sim 2.5 \mu m$.

In Fig. 2, the number of Head-On (HO) and the Long Range (LR) collisions of every bunch is shown.
At the flat top energy (3.5 TeV) the beams were brought in collision in ATLAS and CMS according to the standard operational cycle. The machine was in the standard configuration:

- $\beta^* = 1$ m in IP 1/5 and $\pm 120 \mu$rad crossing angle,
- $\beta^* = 10$ m in IP 2 and $\pm 80 \mu$rad crossing angle,
- $\beta^* = 3$ m in IP 8 and $\pm 250 \mu$rad crossing angle.

In Fig. 3 the time evolution of the beam current, energy, $\beta^*$ and the luminosity in IP1 and IP5 over the fill is shown.

Figure 2: Number of HO and LR collisions per bunch for the used filling scheme “Single_11b+1small_10_1_1_HighPileUp”.

Figure 1: Initial bunch intensity for beam 1 (blue) and beam 2 (red).
Figure 3: The beam intensity evolution (beam 1 blue curve, beam 2 red curve) is plotted along with the $\beta^*$ function in IP5 (cyan curve), the beam energy (in magenta) and the luminosity measured by CMS (green curve) and ATLAS (light blue) for the whole fill.

The bunch transverse emittances were measured with the Wire Scanners (WS) during the injection plateau, during the energy ramp, at the start of collisions, before starting the beam separations and at the end of the fill (Fig. 4). The uncertainties on the optical function (beta) values during the ramp compromise the reliability of the calculated emittances from the measured beam size.

Figure 4: The normalized bunch emittances measured by the WS at the injection plateau, at the start of collisions and at the end of the stable beams mode.
However as shown in Fig. 5, an emittance growth was observed from injection to collisions especially for beam 1 (∼80% in the horizontal plane and ∼40% in the vertical plane); while for beam 2 the increase was smaller (∼10% in the horizontal plane and ∼15% in the vertical plane). As a cross-check and assuming round beams, a mean value of the normalized emittance at the start of the Stable Beams (SB) mode of ∼3.5 µm may be derived from the initial luminosity.

![Figure 5: Examples for horizontal and vertical normalized emittances measured with the WS for 1 bunch per ring. Both beams and both planes show an emittance growth from injection to collisions.](image)

After ∼100 minutes in SB mode, the beams were re-separated in three different phases, as explained in Tab. 1 and shown in Fig. 6:

![Figure 6: ATLAS and CMS instantaneous luminosity during the separation phases.](image)

- Five separation steps in the horizontal plane of IP 5 reducing the luminosity from ∼44 Hz/µbarn to ∼10 Hz/µbarn,
- Eleven separation steps in the vertical plane of IP 1 reducing the luminosity from ∼43 Hz/µbarn to ∼0.08 Hz/µbarn,
- Two separation steps in the horizontal plane of IP 5 reducing the luminosity from \(\sim 41 \text{ Hz}/\mu\text{barn}\) to \(\sim 1.23 \text{ Hz}/\mu\text{barn}\).

After each separation, the instantaneous luminosity was re-optimized to its maximum value in the considered IP.

<table>
<thead>
<tr>
<th>SEPARATION STEP</th>
<th>Percentage of the initial luminosity before separation at:</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>Phase 1</td>
</tr>
<tr>
<td>IP 5</td>
<td>100%</td>
</tr>
<tr>
<td>(44 Hz/\mu barn)</td>
<td>(43.16 Hz/\mu barn)</td>
</tr>
<tr>
<td>0</td>
<td>100%</td>
</tr>
<tr>
<td>1</td>
<td>83%</td>
</tr>
<tr>
<td>2</td>
<td>64%</td>
</tr>
<tr>
<td>3</td>
<td>49%</td>
</tr>
<tr>
<td>4</td>
<td>37%</td>
</tr>
<tr>
<td>5</td>
<td>23%</td>
</tr>
<tr>
<td>6</td>
<td>-</td>
</tr>
<tr>
<td>7</td>
<td>-</td>
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<tr>
<td>9</td>
<td>-</td>
</tr>
<tr>
<td>10</td>
<td>-</td>
</tr>
<tr>
<td>11</td>
<td>-</td>
</tr>
</tbody>
</table>

Table 1: Luminosity reduction during the three phases of beam separations. In addition to the starting luminosity value at the beginning of each step, at each step the new value of the measured luminosity is expressed in terms of percentage of the initial one.

3 Beam Parameter Evolution

3.1 Beam Intensity

3.1.1 Before the beams separation

The intensity evolution of both beams was observed since the start of collisions and plotted in Fig. 7 and 8. Normalizing the bunch intensity curves to the initial value at the start of collisions, allows to identify three groups of behaviours according to the number of HO collisions the bunches experience (3 HO, 2 HO, 1 HO).

Analysing the intensity data for the first 1.8 hours, it is possible to disentangle the separations effects from the initial evolution of the bunch parameters.
For most bunches a linear decrease in intensity is observed during the considered time period; a linear fit is applied to the measured intensities and the slopes corresponding to the loss rates are shown in Fig. 9. The highest losses are observed for bunches experiencing 3 HO collisions while the lowest losses are for bunches with 1 HO collision only.

It is interesting to observe that bunch 995 in beam 1 (b995B1) lost less than bunch 992 in beam 2 (b992B2), even though both collide only in IP 2 and IP 8 respectively. The luminosity burn-off protons are three times higher for b995B1 than b992B2 since the measured luminosity in LHCb is almost three times greater than the one measured in ALICE.

The same phenomenon is seen comparing the loss rates of the intensity of bunch 101 in both beams which collide in IP 125/158 respectively. Assuming that the burn-off rate in IP 1 & 5 for both is almost the same, since the luminosity in IP8 is higher than in IP2 the expected losses rate for bunch 101 in beam 1 would be smaller than for bunch 101 in beam 2. This is in contradiction with the observation.

In order to investigate the difference between the slopes of the intensity of these two bunches, the burn-off proton loss rate calculated from the instantaneous luminosity measured in the IPs was subtracted from the total losses. We call this ‘residual losses’.

Hence, the total and residual losses are shown in Fig. 10 for beam 1 and Fig. 11 for beam 2.
Figure 9: Slopes from linear fits of the bunch intensity decays for the first 100 minutes.

Figure 10: B1: On the left, the total proton losses per bunch per minute from the start of collisions. On the right, additional proton losses per minute with respect to the burn-off.

Figure 11: B2: On the left, the total proton losses per bunch per minute from the start of the collisions. On the right, additional proton losses per minute with respect to the burn-off.

Looking at the residual losses, it can be seen that for beam 2 the differences in losses between $b_{101}B_{2}$ and the others is due mainly to the burn-off protons. For beam 1 this is
not the case; the extra losses seen in the first 60 minutes in collisions for \( b101B1 \) are not justified by the luminosity burn-off as shown on the right side of Fig. 10.

Note also that \( b992B2 \) colliding in IP 2 with \( b101B1 \): the additional losses resulting after the subtraction of the burn-off are higher than for all the other bunches.

### 3.1.2 After the beams separation

We divide the observation of losses during the separation according to the three phases mentioned in Tab. 1. Similarly to what done in 3.1.1, the loss trend can be organized in families (according to the collision scheme) for all the steps.

#### - Separation phase 1 (IP 5)

The first separation step in IP 5 had an effect on the luminosity in IP 1, where a drop of 3.5% was observed. No significant change in the intensity evolution of all the bunches in both beams except for:

- bunch 101 in beam 1 (having 3 HO: IP 1 & 5 with bunch 101 in beam 2, IP 2 with bunch 992 in beam 2),
- bunch 992 in beam 2 (having 1 HO: IP 2 with bunch 101 in beam 1).

![Figure 12: The evolution of some bunches normalized intensity during the three scans in the IPs. The concerned bunches are: b101B1 colliding in IP 1, 5 with b101B2 and IP 2 with b992B2; and b995B1 colliding in IP 8 with b101B2.](image)

An increase in the loss rate is observed for \( b101B1 \) since the first separation step as shown in Fig. 12. For the \( b992B2 \), a sudden increase in losses is seen in the first and last steps of the separation. Note that at the end of the fifth step, once the beams are put back in HO collisions in IP 5, the losses rate for \( b992B2 \) returned at the value it had before the beams manipulation as seen in Fig. 13. In order to explain and understand the link between the behaviour of \( b992B2 \), colliding only in IP 2 and the separations
in IP 5 it is important to consider the LR collisions this bunches is experiencing in IP 5 with b995B1.

Figure 13: The evolution of the normalized intensity of b992B2 during the first separation phase in IP 5.

- **Separation phase 2 (IP 1)**
  b995B1, b992B2 having one HO collision in IP 8 and 2 respectively were not affected by the steps of this separation. For the 3 HO collisions family, it can be observed that b101B1 experienced higher loss rate at half total separation and kept this loss regime until the beams were brought back into HO collision; bunch B2 – b101 entered a higher loss regime since the first separation step and maintained this rate once back into the initial situation of fully HO collisions. The slopes of the intensity evolution for all the other bunches (2 HO families) depend on the value of the separation between the beams: lower losses were observed for higher separations. It is worth observing that the bunch losses for both families in beam 1 and beam 2 colliding in IP 1 and 5 at zero separation were higher at the end of this phase (especially for beam 1).

- **Separation phase 3 (IP 5)**
  No clear variation in the intensity decay was observed for the bunches having 1 HO and 3 HO in both beams, while for all the other bunches, the losses were decreasing for an increasing beam separation. Again for some bunches in beam 1 having 2 HO, the initial loss rate was not restored at the end when the beams were brought to HO collisions: higher losses were still observed in the end.
### 3.2 Transverse Emittances

The beam sizes measured by Beam Synchrotron Light Telescopes (BSRT) were corrected with the correction factors shown in Tab. 2. These factors were calibrated with the measured emittances by the WS at the end of the squeeze and during the SB mode (before the separation phases) and at its end [1].

<table>
<thead>
<tr>
<th>Correction factor</th>
<th>Horizontal plane</th>
<th>Vertical plane</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Beam 1</strong></td>
<td>0.45</td>
<td>0.39</td>
</tr>
<tr>
<td><strong>Beam 2</strong></td>
<td>0.38</td>
<td>0.41</td>
</tr>
</tbody>
</table>

Table 2: Correction factor used to calibrate the BSRTs measurements for both planes of each beam.

The aim was to observe the relative changes in emittance evolution during the beam separation in the IPs, since the uncertainty on the correction factors used to calibrate the BSRT allows mainly the study of the relative emittances differences per bunch. The bunches can be classified in three categories:

- bunches presenting a higher growth rate in the vertical plane during the separation phases: \( b_{101}B_2, b_{421}B_2 \) and \( b_{1061}B_1 \) (see Fig. 14),

![Figure 14: Vertical emittances of bunches 101-421 (beam 2) showing a continuous smooth increase in the emittance while separating the beams in IP5.](image)

- bunches presenting sudden blow-up throughout the separation steps: \( b_{101}B_1, b_{421}B_1, b_{992}B_2 \) and \( b_{1061}B_2 \) (see Fig. 15).

- bunches not affected by the separation steps (see Fig. 16),

The sudden increases in emittance were observed mainly in the vertical plane during the steps of the first CMS separation (recall that in IP 5 the vertical plane is the separation plane).
Figure 15: Vertical blow-up of the vertical emittance of bunches 101-421 (beam 1) and bunches 992-1061 (beam 2) while separating the beams in IP 5.

Figure 16: Intensity and transverse emittances of the bunches $b_{2341}B1$ and bunch $b_{1701}B2$. No big effects were observed on these parameters due to the beams separation.
3.3 Bunch Length

3.3.1 Beam 1

Figure 17: Bunch length evolution for the bunches in beam 1 throughout the SB mode.

Analysing the initial bunch length at the declaration of the SB mode, as extracted from the LHC Beam Quality Monitor (BQM) [2], showed a wide spread in the initial value as presented in Fig. 17. To try to understand the effect of the initial bunch length on the evolution of other bunch parameters, especially the intensity, only the nine bunches with two HO collisions were considered in this analysis (to disentangle the collision scheme from the loss observations).

Figure 18: Beam 1 total bunch length growth with respect to its initial value. The yellow color indicates the shortest bunches in the train, while the green indicates the longer one. All the other bunches are plotted in blue.
A percentage of the growth was calculated for every bunch as shown in Fig. 18 and a correlation was observed between higher growth rates and the initial shorter bunch length. This is consistent with what shown in Fig. 17, where despite the initial spread in the length, all bunches converge to the value of $\sim 9.5\text{cm}$ after 4 hours in collisions.

Fig. 19 presents a scatter plot showing the correlation between the initial bunch length and the loss slopes, confirming what stated above.

The bunch length at the SPS extraction and at different times in the LHC cycle are shown in Fig. 20. Not only a large scatter in the values is seen at the SPS, it was also observed that bunches staying less time in the LHC at injection energy are the shortest later in the cycle (prepare ramp, flat top, start of collisions).

Figure 19: Correlation between initial bunch length and the linear loss rate of the 9 bunches in beam 1 colliding only in IP 1 and 5.

Figure 20: Different measurements of the bunch length in beam 1 showing its evolution from the SPS to the collisions in the LHC.
3.3.2 Beam 2

We only highlight the bunch length evolution of beam 2. It is worth pointing out the behaviour of $b992B2$ (see Fig. 21): a bunch shortening is observed simultaneously to the intensity loss, corresponding to the first separation step in IP 5 (first separation phase).

For all the other bunches, the bunch length did not bear signs of the losses and the emittance blow-up (horizontal and vertical).

Figure 21: The observed parameters for $b992B2$ (intensity, transverse emittances, bunch length) from the start of the fill until the end of the collisions. The vertical coloured bar delimits the separation steps of every separation phase in both IPs.
4 Summary

For this physics fill, the bunch parameters (intensity, emittances, length) of high pile-up colliding bunches were observed. The intensity losses were analysed and correlations were found with the collision schedule and the evolution of the bunch length. Emittance blow-up was observed in the vertical and horizontal planes and for different bunches, in particular for $b101B1$, $b421B1$, $b992B2$ and $b1061B2$ during the beam separations in IP5. Some effects of the long range interaction were observed for one bunch ($b992B2$) and are still under investigation as well as the different extra bunch losses observed in both beams once the luminosity burn-off losses are excluded.

5 Acknowledgements

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References
