First observation of beam-beam interactions in high intensity collisions at the LHC

G. Arduini, W. Herr, J.M. Jowett, E. Laface, M. Meddahi, F. Schmidt
CERN, CH-1211 Geneva 23

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Summary

For the first time bunches were collided in the LHC with close to nominal parameters and so experienced head-on beam-beam effects comparable to those expected with the nominal LHC parameters. Among other things, this provided an opportunity to test the procedure of separating beams at IP2 to reduce the luminosity and pile-up in the ALICE experiment. We report on the observations made during these runs and related tests.

1 Motivation

The purpose of this experiment was to observe the beam behaviour with head-on collisions of bunches with nominal emittance and intensity.

Some observations were done parasitically during two test runs (fills 1068 and 1069) while the four experiments took collision data. Further studies were carried out at the end of the second fill. In particular:

- Test of offset collisions in ALICE
- Exploit available tune space and observe tune spectra under different collision conditions

These observations provide essential input for the strategy for obtaining higher bunch intensity and luminosity in the LHC.
2 Setup and conditions

2.1 Beam energy

The test runs and the experiments were carried out at the injection beam energy, 450 GeV, with unsqueezed values of $\beta^* = 10$ m in all four experiments.

2.2 Filling scheme

The measurements were done with the minimum number of bunches, 2 per beam, arranged to provide 1 colliding pair in each experiment (Table 1).

<table>
<thead>
<tr>
<th>Bucket</th>
<th>beam 1</th>
<th>beam 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>bunch 1</td>
<td>17851</td>
<td>1</td>
</tr>
<tr>
<td>bunch 2</td>
<td>1</td>
<td>8911</td>
</tr>
<tr>
<td>Collisions</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>at IP</td>
<td>1, 2, 5</td>
<td>8</td>
</tr>
<tr>
<td></td>
<td>1, 5</td>
<td>2, 8</td>
</tr>
</tbody>
</table>

Table 1: Collisions of bunches in Beams 1 and 2.

Note that the filling scheme produces different collision sequences for each bunch, simulating, to some extent, effects that we expect later for nominal and other filling schemes [1, 2, 3, 4].

2.3 Beam parameters

The tunes were set to the standard collision values $Q_x \simeq 64.31, Q_y \simeq 59.32$ before collision.

At the beginning of the test runs, the bunch intensities were $N_b \approx 10^{11}$ protons for each of the bunches. By the end of the fill, and for the end-of-fill studies, they had decayed to $N_b \approx 0.7-0.8 \times 10^{11}$.

The (normalised) bunch emittances for Beam 1 were about 3 µm at the beginning. The emittances in the second beam were higher, especially in the vertical plane. By the end of the first fill the vertical emittance of Beam 2 was 7 µm, i.e., about twice the nominal value (see Tab. 2).

3 Test runs

The purpose of the test runs was to deliver $10^6$ events to the experiments and to observe the beam behaviour parasitically.

The bunches were injected with the standard separation bumps on (half-separation of ±2 mm). Then the four bumps were “collapsed” simultaneously to bring the beams into collision. With separation bumps the lifetime was approximately 500-600 hours and dropped...
to 5 hours after the bumps collapsed. A small tune adjustment on Beam 1 ($\Delta Q_h \approx +0.005$) was required to consolidate the lifetime and to stabilize it to $\approx 25h$. The small intensity drop for Beam 1 during this procedure is clearly visible in Figure 1. The emittance increase is moderate for Beam 1.

Figure 2: Beam 2 intensity and sizes at beginning of run. Beam size at position of the monitor.

The equivalent plots are shown in Figure 2 for Beam 2.

No intensity drop was observed when beams were brought into collision; however a slow increase of vertical emittance is visible, confirming previous observations. Since this emittance growth (presumably, the so-called “hump”) is also present for other running conditions, it is not related to the high intensity beam-beam interaction.

The measured emittances at the beginning and end of the two test runs are summarized in Table 2.

This is summarized in Figure 3 using wire scanner data. The first numbers correspond to emittances before the bumps were collapsed. In both fills the beams were kept for about 7 hours.
Table 2: Emittances at beginning and end of the two test runs. Values after the luminosity scans are also given.

<table>
<thead>
<tr>
<th></th>
<th>$\epsilon_h$ (b1) ($\mu$m)</th>
<th>$\epsilon_v$ (b1) ($\mu$m)</th>
<th>$\epsilon_h$ (b2) ($\mu$m)</th>
<th>$\epsilon_v$ (b2) ($\mu$m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fill 1, begin collisions</td>
<td>2.2</td>
<td>2.4</td>
<td>3.3</td>
<td>3.7</td>
</tr>
<tr>
<td>Fill 1, after lumi scans</td>
<td>2.4</td>
<td>2.7</td>
<td>3.6</td>
<td>4.3</td>
</tr>
<tr>
<td>Fill 1, end collisions</td>
<td>2.9</td>
<td>3.2</td>
<td>4.9</td>
<td>7.4</td>
</tr>
<tr>
<td>Fill 2, begin collisions</td>
<td>2.2</td>
<td>2.4</td>
<td>3.3</td>
<td>3.6</td>
</tr>
<tr>
<td>Fill 2, after lumi scans</td>
<td>2.5</td>
<td>2.8</td>
<td>3.7</td>
<td>4.5</td>
</tr>
<tr>
<td>Fill 2, end collisions</td>
<td>3.5</td>
<td>3.5</td>
<td>4.8</td>
<td>6.3</td>
</tr>
</tbody>
</table>

Figure 3: Emittances for first few hours in the fill. First value before bumps were collapsed.

Assuming that the emittance measurements are correct and using the initial bunch intensity, the beam-beam tune shifts are well above the nominal values, exceeding 0.004 per interaction point.

The conclusions from the test runs are:

- Injection with separation bumps on showed no problems (lifetime), but vertical emittance of Beam 2 was already slightly larger than nominal.
- After collapsing the separation, tune requires adjustment, as expected.
- With nominal intensity and emittances close to nominal the beam lifetime was good and above 10 hours.
- The lifetime of bunch 1 in Beam 1 was lower than all other bunches, most likely caused by the larger number of collisions it experiences. Detailed evaluation is on-going.
4 ALICE separation scan

Once the beam intensities become sufficiently high, it will be necessary to take measures to limit the luminosity in ALICE as compared to ATLAS and CMS. Beyond using higher values of $\beta^*$, it will be necessary to separate the beams at IP2 sufficiently to reduce the luminosity and the event pile-up.

This procedure was tested at the end of the second test fill, no. 1069, on the morning of 3 May 2010. In the plots of this section, the origin of time is taken at 09:30:00 that morning. In most cases, the raw time-series data has been replaced by smooth functions by a process involving moving averages, resampling and interpolation. This takes care of the fact that the time points at which different instruments provide data are not the same and facilitates correlation and derivation of additional quantities. Further details are available at [5].

Maintaining the head-on collisions in ATLAS, CMS and LHCb, the parallel horizontal separation bump was used to re-separate the beams at IP2 to $\pm 2\text{ mm}$. The separation was then scanned from $+2\text{ mm}$ to $-0.5\text{ mm}$, waiting for a few minutes at each point to observe what turned out to be perfectly steady-state behaviour.

The half-separation was reconstructed from the logged strength of one corrector magnet used in the separation bump. This was fitted to the requested bump amplitude, allowing for a calibration factor and an offset (since the same corrector might be used, for example, in an orbit correction) with the result shown in Figure 4.

The variations of the beam intensities during the scan are shown in Figure 5. There was no significant effect on lifetime at any value of the separation.

The beam emittances were measured with the wire scanners on three occasions, before, during and after the separation scan, as shown in Figure 6.

The emittance measurements from the wire-scanners were used to calibrate the much more frequent beam size measurements logged by the synchrotron radiation monitors; the variations fit together well in relative terms as shown Figure 7 although the results are still subject to the same absolute systematic errors as the wire-scans.

With emittances inferred in this way, and the assumption that the optics is ideal ($\beta^* = 10\text{ m}$), we can reconstruct the beam sizes at the IPs (Figure 8).
Figure 4: Half-separation at IP2 during the separation scan, reconstructed from a fit to the variation of a corrector during the fill, allowing for a calibration factor and a small offset from the closed-orbit correction.

Figure 5: Total intensity of Beam 1 and Beam2 during the separation scan.
Figure 6: Linear interpolation of emittances measured by the wire scanner at three times. These values depend on the $\beta$-functions at the wire scanner being correct.
Figure 7: Normalised emittances from synchrotron light monitor (blue, red) for both beams and planes, calibrated using the interpolation of the wire-scanner data (green) at $t = 1380$ s.
Figure 8: Estimated beam sizes at the IPs, $\sigma_{1x}$ (blue), $\sigma_{1y}$ (purple), $\sigma_{2x}$ (red), $\sigma_{2y}$ (orange), assuming the ideal injection optics at the IPs.
4.1 Optics during the measurements

For reference, we provide plots of the optical functions close to the IP in IR2, in the conditions of the experiment, in Figure 9. The dispersion functions generated by the various bumps in the interaction regions are seen to be small.

The corresponding beam envelopes are shown in Figure 10. During the experiment, the beams were brought together through intermediate separations as shown in the right-hand part of Figure 11. From this it can be clearly seen that even small separations of 0–5 beam sizes did not cause any significant beam blowup or reduction in lifetime. Therefore it appears that the range of separations in which useful luminosity reductions for ALICE is accessible.

4.2 Estimates of beam-beam effects

Assuming the $\beta$-functions are equal in both planes at the interaction points, the horizontal and vertical head-on beam-beam tune-shifts experienced by Beam 2 due to the interaction with Beam 1 can be expressed in terms of the normalised emittances as

$$\xi_{21x} = \frac{N_1 r_p}{2\pi \sqrt{\epsilon_{xn1} \left(\sqrt{\epsilon_{xn1}} + \sqrt{\epsilon_{yn1}}\right)}} \quad \xi_{21y} = \frac{N_1 r_p}{2\pi \sqrt{\epsilon_{yn1} \left(\sqrt{\epsilon_{xn1}} + \sqrt{\epsilon_{yn1}}\right)}},$$

with similar expressions for the effects of Beam 2 on Beam 1. As is well-known, these are independent of energy and $\beta^*$ insofar as the normalised emittances are constant. These four quantities can be estimated as functions of time using the measured emittances plotted in Figure 7 with the result shown in Figure 12.

It is striking that the bunches of Beam 2 were experiencing head-on beam-beam parameters comparable with the value of 0.0037 expected at the full LHC design luminosity of $10^{34}\text{cm}^{-2}\text{s}^{-1}$. 
Figure 9: Optics of Beam 1 (top) and Beam 2 (bottom) around IP2, computed in the conditions of the measurement (injection, unsqueezed optics). Note the horizontal and vertical dispersion functions (amplified by a factor $10^4$) due to the bump configuration (ALICE and LHCb spectrometers and parallel separation in IP2 only).
Figure 10: Computed horizontal and vertical beam envelopes around IP2 in the conditions of the measurement (measured emittances, injection, unsqueezed optics, full separation in IP2 only). During the experiment, the beams were brought together through intermediate separations.
Figure 11: Left: Envelopes of Beam 1 (blue) and Beam 2 (red) \((1, 2)\sigma\) in the transverse plane at IP2 in the conditions at the beginning of the measurement (measured emittances, injection, unsqueezed optics, full separation in IP2 only). The range of the separation scan is shown by the green arrows. Right: Full separation between the two beams at IP2 expressed in units of the four measured beam sizes \((\sigma_{1x} \text{ (blue)}, \sigma_{1y} \text{ (purple)}, \sigma_{2x} \text{ (red)}, \sigma_{2y} \text{ (orange)}\) ) in the course of the separation scan.

\[
\xi_{12 \, x,y}(t), \xi_{21 \, x,y}(t)
\]

Figure 12: Estimated head-on beam-beam tune shift parameter (at IPs other than IP2) for the effect of Beam 2 on Beam 1 and of Beam 1 on Beam 2 \((\xi_{12x} \text{ (blue)}, \xi_{12y} \text{ (purple)}, \xi_{21x} \text{ (red)}, \xi_{21y} \text{ (orange)})\).
5 Tune spectra

In Figs. 13, 14 and 15 we show the observed tune spectra when the collision pattern was changed by re-separating selected interaction points. The peaks move as expected [3], allowing us to estimate the beam-beam tune shift. However, an exact comparison with the theoretical value would require a collision optimization (luminosity scan) since exact head-on collisions are not automatically guaranteed when the bumps are collapsed. Such an optimization was not done for these experiments (but was done for the test runs).

The remaining peak without collisions is the vertical tune signal for Beam 2.

Figure 13: Beam 2 tune spectra for different collision patterns. Left picture corresponds to collisions in all IPs, right picture collisions only in IP1.
Figure 14: Tune spectra for different collision patterns. Red line: collisions in IP1 and IP5, green line: collisions in IP1 only, blue line: no collisions.

Figure 15: Tune spectra for different collision patterns. As in Figure 14, but blue line with collisions in IP8.
6 Summary

The results of our study can be summarised as follows:

- We have successfully collided high intensity bunches in the LHC at 450 GeV.

- At the beginning of the test runs, the head-on beam-beam tune shifts are well above the nominal values.

- A separation scan in IP2 showed no significant side effects on the beam lifetime and emittances with beam-beam tune-shift parameters up to \( \xi \approx 0.0029 \) at the other IPs during the scan. Beam 2 was already somewhat larger than nominal. The scan covered the full range of separations that might be useful as a means to reduce luminosity in IP2. This result is very encouraging for the proposed offset collision scheme. At the level of single bunches, conditions should be, if anything, more favourable at high energy.

- Tune spectra have been analysed and beam-beam tune shifts are visible as expected.

7 Acknowledgement

The help of the OP crews during the test runs and studies was essential for the measurements and the results obtained.
References


