OBSERVATIONS OF BEAM-BEAM EFFECTS IN THE LHC IN 2011

W. Herr, R. Alemany, X. Buffat, R. Calaga, R. Giachino, G. Papotti, T. Pieloni,
G. Trad (CERN, Geneva, Switzerland), M. Schaumann (RWTH, Aachen)

Abstract

We report on the observations of beam-beam effects during dedicated studies as well as the experience from operation. Where possible, we compare the observations with the expectations.

STUDIES OF HEAD-ON COLLISIONS

The layout of experimental regions in the LHC is shown in Fig.1. The beams travel in separate vacuum chambers

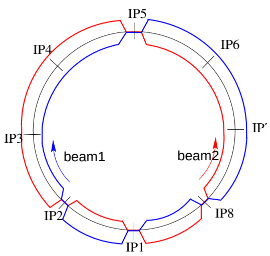

Figure 1: Layout of the experimental collision points in the LHC [1].

and cross in the experimental areas where they share a common beam pipe. In these common regions the beams experience head-on collisions as well as a large number of long range beam-beam encounters [1]. This arrangement together with the bunch filling scheme of the LHC as shown in Fig.2 [1, 2] leads to very different collision pattern for different bunches, often referred to as "PACMAN" bunches. The number of both, head-on as well as

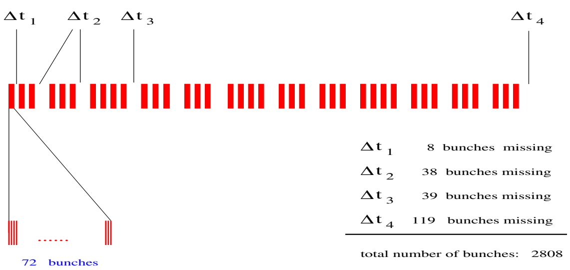

Figure 2: Bunch filling scheme of the nominal LHC.

long range encounters, can be very different for different bunches in the bunch trains and lead to a different integrated beam-beam effect [2]. This was always a worry in the LHC design and the effects have been observed in an early stage of the commissioning. Strategies have been provided to minimize these effect, e.g. different planes for the crossing angles [1, 2].

Head-on beam-beam tune shift

The nominal LHC parameters have been chosen to reach the design luminosity of $1.0 \cdot 10^{34}$ cm^{-2}s^{-1} [1]. The main parameters relevant for beam-beam effects are summarized in Tab.1. At a very early stage of the LHC operation it was tested whether the nominal beam-beam parameters can be achieved. After this has been successfully demonstrated, we have performed a dedicated experiment to test the achievable beam-beam tune shift. To that purpose we have filled the LHC with single bunches per beam, colliding in IP1 and IP5 (see Fig.1). We have used bunch intensities of $\approx 1.9 \cdot 10^{11}$ protons, i.e. well above the nominal and the emittances have been reduced to ≤ 1.20 μm in both planes [3]. It was shown that such bunches can be collided in both interaction points without significant losses or emittance increase [4] and we have demonstrated that a beam-beam tune shift of 0.017 for a single interaction and an integrated tune shift of 0.034 for both collision was possible. These tune shifts have been obtained in the absence of any long range encounters and it should be expected that the operationally possible tune shifts are lower.

Table 1: LHC nominal parameters and achieved during operation and experiments in 2010/2011.

Parameter	**nominal**	**achieved**
Intensity (p/bunch)	$1.15 \cdot 10^{11}$	$2.3 \cdot 10^{11}$
Emittance	3.75 μm	≤ 2.00 μm
β^*	0.55 m	1.5 m
ξ/IP	0.0035	0.0170
Bunch spacing	25 ns	50 ns
Bunches/beam	2808	1380

Effect of number of head-on collisions

Due to the filling pattern in the LHC, different bunches experience different number of head-on as well as long range interactions. Details are given in another contribution [5]. In Fig.3 we show as illustration the losses of bunches with very different (0 - 3) number of head-on collisions. The data was taken during a regular operational fill of 10 hours duration. The correlation between losses and number of head-on collisions is apparent and a more detailed analysis is found in [5]. The transverse emittances during normal operation are larger ($\approx$ 2.5 μm) than in the head-on test. In a second experiment [6] we increased the bunch intensity further to $\approx 2.3 \cdot 10^{11}$ with emittances ≈ 1.80 μm. Although the tuneshift was slightly lower than

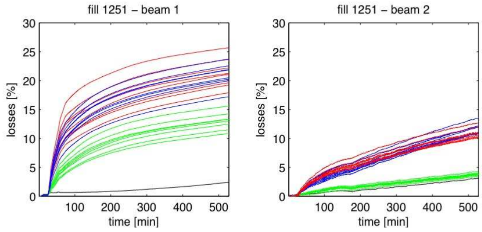

Figure 3: Losses of bunches with different number of head-on collisions [5]. Numerology: blue (3 collisions), red (2 collisions), green (1 collision), black (no collision).

in the previous experiment (0.015), the lifetime was worse. We interpret these results as losses of particles at large amplitudes. This is supported by the observation that the strongest losses occur at the very beginning of a fill (Fig.3).

Can we understand the large head-on beam-beam tune shift ?

The obtained beam-beam parameter is several times larger than the design value and one can discuss the possible reasons. It must be mentioned here that the design value was very conservative and is only 50% of what was obtained in the SPS proton-antiproton collider. The choice of the design parameter was aimed at the nominal peak luminosity using conservative parameters considered safe at the time of the choice.

Nevertheless, the large beam-beam parameter allows to operate with high brightness beams and it is important to identify possible mechanisms that might reduce this brightness. Such limiting factors can be:

- Longitudinal or transverse noise
- Tune modulation and large Q'
- Ripple on power converters

Keeping these effects under control should allow the collision of high brightness beams and to exceed the nominal luminosity substantially. Under the present conditions we do not consider the head-on beam-beam interaction as a limit for the LHC performance.

STUDIES OF LONG RANGE INTERACTIONS

Contrary to the head-on beam-beam effects, the long range beam-beam interactions is expected to play an important role for the LHC performance and the choice of the parameters. To study the effect of long range beam-beam interactions we have performed two dedicated experiments. In the first experiment, the LHC was set up with single trains of 36 bunches per beam, spaced by 50 ns. The bunch intensities were $\approx 1.2\ 10^{11}$ protons and the normalized emittances around 2.5 μm. The trains collided in IP1 and IP5, leading to a maximum of 16 long range encounters per interaction point for nominal bunches. First, the crossing angle (vertical plane) in IP1 was decreased in small steps and the losses of each bunch recorded. The details of this procedure are described in [8].

In the second experiment we injected 3 trains per beam, with 36 bunches per train. The filling scheme was chosen such that some trains have collisions in IP1 and IP5 and other collide only in IP2 or IP8.

Losses due to long-range interactions

From simulations [10] we expected a reduction of the dynamic aperture due to the long-range beam-beam encounters and therefore increased losses when the separation is decreased. To estimate the losses, we have shown in Fig.4

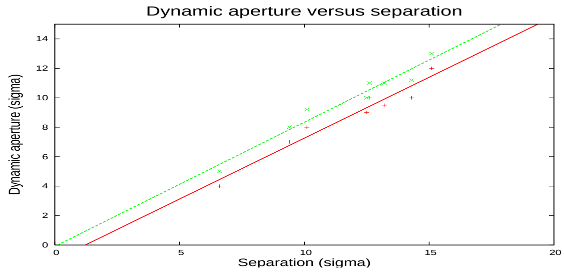

Figure 4: Expected dynamic aperture as function of separation in drift space [10]. Computed for 50 ns and 25 ns separation.

the expected dynamic aperture as a function of the normalized separation [10] for two different bunch spacings (50 ns and 25 ns). From this figure we can determine that visible (i.e. recordable) we can expect for a dynamic aperture around 3 σ and therefore when the separation is reduced to values around 5 σ. For larger separation the dynamic aperture is also decreased but the losses cannot be observed in our experiment.

We have performed two measurements and the results of the first experiment are shown in Fig.5 where the integrated losses for the 36 bunches in beam 1 are shown as a function of time and the relative change of the crossing angle is given in percentage of the nominal (100% $\equiv$ 240 μrad). The nominal value corresponds to a separation of approximately 12 σ at the parasitic encounters.

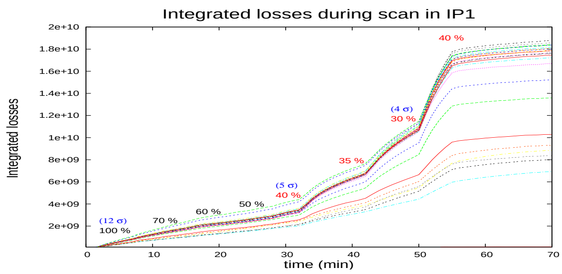

Figure 5: Integrated losses of all bunches as a function of time during scan of beam separation in IP1. Numbers show percentage of full crossing angle.

The losses per bunch observed in the second experiment are shown in Fig.6. The observed behaviour is very similar. In this experiment we have set up several trains with differ-

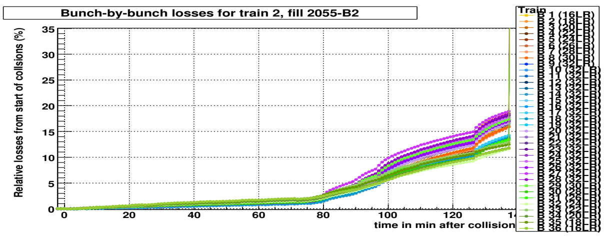

Figure 6: Integrated losses of bunches as a function of time during scan of beam separation in IP1. Bunches colliding in IP1 and IP5. Numbers show percentage of full crossing angle.

ent collision schemes and in Fig.7 we show the losses in the bunches colliding in IP8, but not in IP1 and IP5 where the separation was reduced. As expected, this reduction had no effect on the losses of these bunches (please note change of the scale). In Fig.8 we show the vertical emittances for all

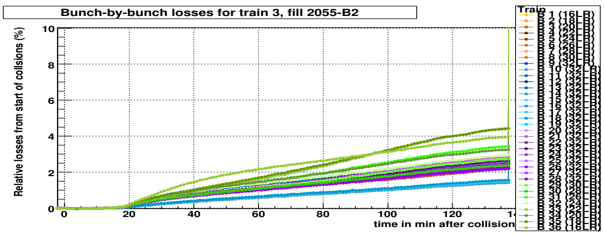

Figure 7: Integrated losses of bunches as a function of time during scan of beam separation in IP1. Bunches without collisions in IP1 and IP5. Numbers show percentage of full crossing angle.

bunches during this second experiment. Such a measurement was not available in the first study. From Figs.5 and 6

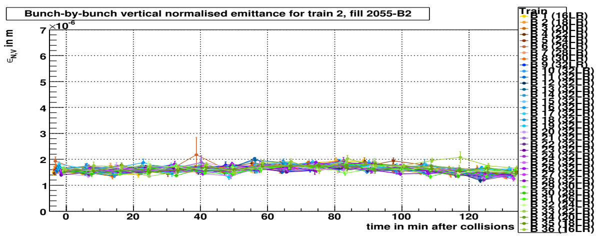

Figure 8: Vertical emittances all bunches as a function of time during scan of beam separation in IP1.

we observe significantly increased losses for some bunches when the separation is reduced to about 40%, i.e. around 5 σ. The emittances are not affected by the reduced separation (Fig.8) and we interpret this as a reduction of the dynamic aperture as expected from the theory and simulations. The emittances, mainly determined by the core of the beam, are not affected in this case.

Bunch to bunch differences and PACMAN effects

Not all bunches are equally affected. At a smaller separation of 30% all bunches experience significant losses ($\approx$4 σ). Returning to a separation of 40% reduces the losses significantly, suggesting that mainly particles at large amplitudes have been lost during the scan due to a reduced dynamic aperture. Such a behaviour is expected [9, 10]. The different behaviour is interpreted as a "PACMAN" effect and should depend on the number of long range encounters, which varies along the train. This is demonstrated in Fig.9 where we show the integrated losses for the 36 bunches in the train at the end of the experiment. The maximum loss

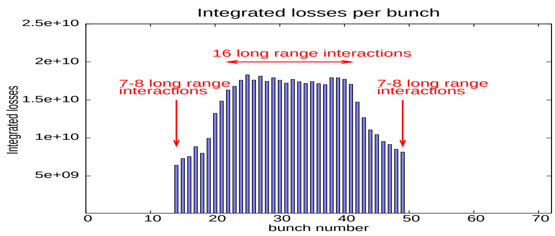

Figure 9: Integrated losses of all bunches along a train of 36 bunches, after reducing the crossing angle in IP1.

is clearly observed for the bunches in the centre of the train with the maximum number of long range interactions (16) and the losses decrease as the number of parasitic encounters decrease. The smallest loss is found for bunches with the minimum number of interactions, i.e. bunches at the beginning and end of the train [1, 2]. It is demonstrated

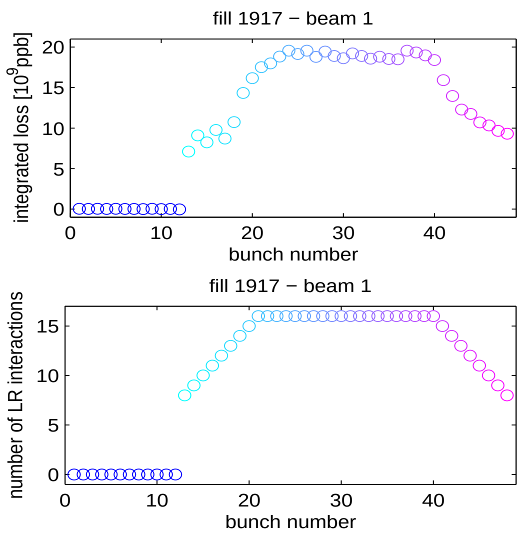

Figure 10: Integrated losses of all bunches along a train of 36 bunches, after reducing the crossing angle in IP1. Second figure shows number of long range encounters for the same bunches.

in Fig.10 where we shows the integrated losses and in the second figure for the same bunches the number of long range encounters. The agreement is rather obvious. This is a very clear demonstration of the expected different behaviour, depending on the number of interactions.

In the second part of the experiment we kept the separation at 40% in IP1 and started to reduce the crossing angle in the collision point IP5, opposite in azimuth to IP1 (Fig.1). Due to this geometry, the same pairs of bunches meet at the interaction points, but the long range separation is in the orthogonal plane. This alternating crossing scheme was designed to compensate first order effects from long range interactions [1]. Fig.11 shows the evolution of the lu-

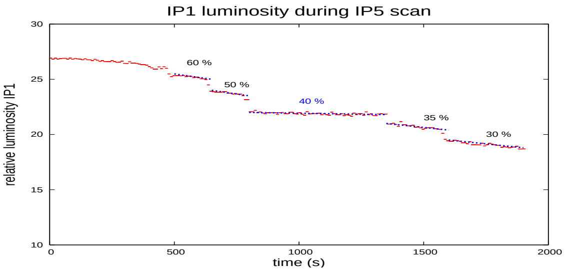

Figure 11: Luminosity in IP1 as a function of time during scan of beam separation in IP5.

minosity in IP1 as we performed the scan in IP5. The numbers indicate again the relative change of separation, this time the horizontal crossing angle in IP5. The luminosity seems to show that the lifetime is best when the separation and crossing angles are equal for the two collision points. It is worse for smaller as well as for larger separation. This is the expected behaviour for a passive compensation due to alternating crossing planes, although further studies are required to conclude.

Losses due to long range encounter during operation

Significant losses have also been observed during regular operation. For the first attempt to squeeze the optical functions from β^* = 1.5 m to β^* = 1.0 m, the crossing angle was decreased to reduce the required aperture, thus reducing the separation at the encounters. During the ramp, an instability occurred which (probably) increased the emittances of all bunches, reducing further the normalized beam separation. When the optics was changed, very significant beam losses occurred (see Fig.12) for those bunches colliding in interaction points 1 and 5, where the separation was reduced due to smaller β^*. Bunches colliding only in IP 2 and 8 are not affected. This clearly demonstrates the strong effect of long range encounter and the need for sufficient separation.
A more quantitative comparison with the expectations is shown in Fig.13. The dynamic aperture in units of the beam size is shown as a function of the beam separation [10]. From the relative losses in the experimental studies, we have tried to estimate the dynamic aperture, assuming a Gaussian beam profile and tails. This measurement can obviously only give a rough estimate, but is in very good

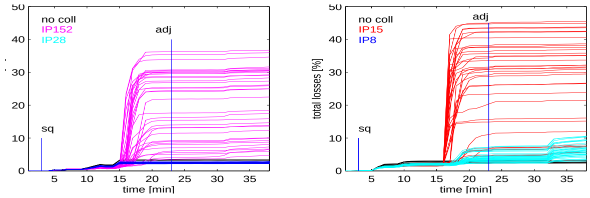

Figure 12: Losses in beam 1 and beam 2 with too small separation.

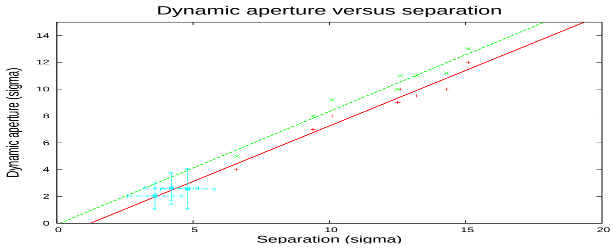

Figure 13: Dynamic aperture versus separation. Comparison with results from experiment.

agreement with the expectations. At larger separation, the losses are too small to get a reasonable estimate. More information can be obtained from an analytical model [11].

Further observations of PACMAN effects

Another predicted behaviour of PACMAN bunches are the different orbits due to the long range interactions. During the second test with reduced long range separation, we have recorded the orbit changes for different separation as shown in Fig.14. The decreased separation, corresponding to stronger dipolar kicks, clearly lead to orbit changes along the corresponding bunch train [12]. The bunches not participating in collisions in IP1 and IP5 are not affected. To study these effects, a fully self-consistent treatment was

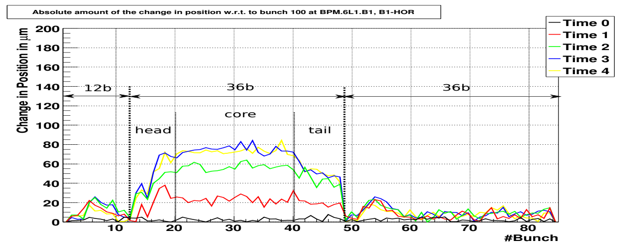

Figure 14: Orbit effect on bunches during long-range separation scan [12].

developed to compute the orbits and tunes for all bunches in the machine under the influence of the strong long range beam-beam interactions [13]. In Fig.15 we show a prediction for the vertical offsets in IP1 [1, 2]. The offsets should vary along the bunch train. Although the orbit measurement in the LHC is not able to resolve these effects, the

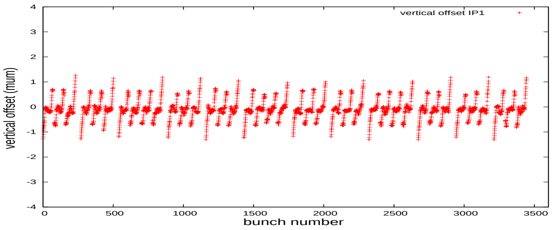

Figure 15: Computed orbit offsets in IP1 along the bunch train [1, 2].

vertex centroid can be measured bunch by bunch in the experiment. The measured orbit in IP1 (ATLAS experiment)

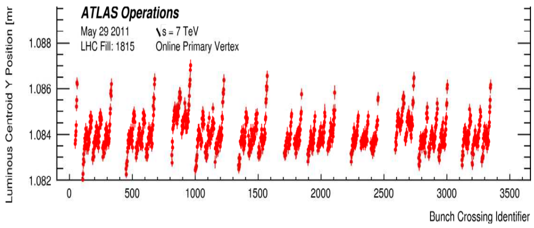

Figure 16: Measured orbit offsets in IP1 along the bunch train [14, 15].

is shown in Fig.16 and at least the qualitative agreement is excellent. This is a further strong indication that the expected PACMAN effects are present and understood and that our computations are reliable.

COHERENT BEAM-BEAM EFFECTS

Due to the strong-strong nature of beam-beam collisions in the LHC, we expect the excitation of coherent beam-beam modes. In very symmetric cases these modes should be observable. In the Fig.17 we show the obtained tune signal without beam-beam interactions. When the beam-beam interaction is switch on, a coherent mode can be observed. In order to study the details and proof its origin, the difference and sum signals between the two beams have been computed and shown in Fig.18. The difference signal

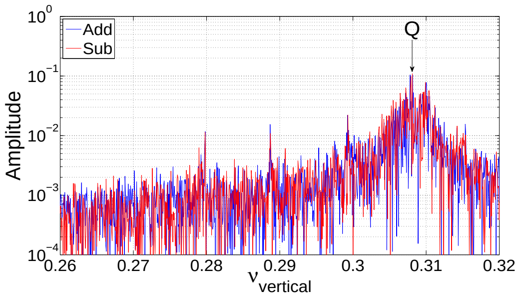

Figure 17: Tune signal without beam-beam effects [7].

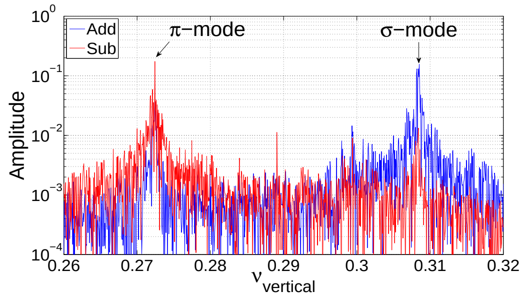

Figure 18: Tune signal with beam-beam effects [7]. The two signals show the difference and sum signals between the two beams.

should only show the π-mode frequency in the spectrum, while the 0-mode should be enhanced in the sum signal. This behaviour is clearly demonstrated in Fig.18 and prove the beam-beam origin of the modes [7].

OPERATION WITH STATIC OFFSETS

Since the LHC experiments have very different requirements, it is necessary to keep the luminosity at a constant and lower level in interaction points IP2 and IP8, while the highest possible luminosities are required in IP1 and IP5. The necessary reduction in IP2 and IP8 cannot be achieved by a larger β^*. As an easy solution it was proposed to collide the beams in these experiments with a small transverse offset between 1 and 4 σ. Although it was thought to be the source of possible problems, this scheme was tested in the machine [16] and found possible. It is now an operational procedure. The time evolution of the luminosities in all interaction points during a regular run are shown in Fig.19. The luminosity is kept constant in IP8 during the whole run without detrimental effects in other interaction points. More details can be found in the contribution to the conference IPAC 2011 [16].

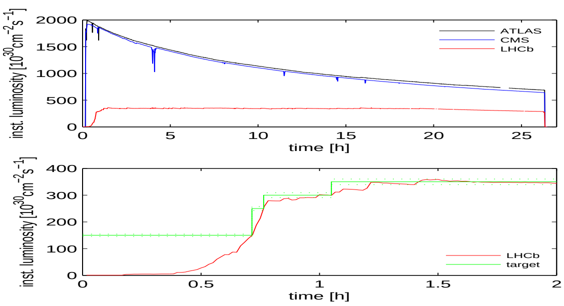

Figure 19: Luminosity levelling in IP8 during regular operation [16].

SUMMARY

We have reported on the first studies of beam-beam effects in the LHC with high intensity, high brightness beams and can summarize the results as:

- Effect of the beam-beam interaction on the beam dynamics clearly established
- LHC allows very large head-on tune shifts above nominal
- Effect of long range interactions on the beam lifetime and losses (dynamic aperture) is clearly visible
- Number of head-on and/or long range interactions important for losses and all predicted PACMAN effects are observed

All observations are in good agreement with the expectations. From this first experience we have confidence that beam-beam effects in the LHC are understood and should allow to reach the target luminosity for the nominal machine at 7 TeV beam energy.

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