

# Observations of beam-beam effects at the LHC

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## Abstract

This paper introduces a list of observations related to the beam-beam interaction that were collected over the first years of LHC proton physics operation (2010-2012). Beam-beam related effects not only have been extensively observed and recorded, but have also shaped the operation of the LHC for high intensity proton running in a number of ways: construction of the filling scheme, choice of luminosity levelling techniques, instabilities mitigation measures, choice of settings for improving performance (e.g. reduce losses), among others.

## INTRODUCTION

The Large Hadron Collider (LHC) at CERN, Geneva, is a 27 km long circular accelerator [1]. It is based on a superconducting two-in-one magnet design, with dipoles that allow reaching a design energy of 7 TeV per beam. It features 8 straight sections: 4 Interaction Points (IPs) are reserved for accelerator equipment and 4 house particle physics experiments. IP3 and 7 are dedicated to the collimation system, IP4 houses the RF system and most of the beam instrumentation, IP6 is reserved to the beam dump system. IP1 and 5 contain the high luminosity experiments ATLAS and CMS, while IP2 and 8 accommodate the Alice and LHCb experiments together with beam injection (beam 1 through IP2, clockwise; beam 2 through IP8, counter-clockwise).

The luminosity requirements of the four experiments are very different [2]. Two high luminosity experiments and the discovery of a new boson are the reason for the push of high intensity proton physics performance. This is detailed in the next section, where the beam parameters are compared between the Design Report and 2012 operation.

Alice and LHCb have luminosity limitations and thus techniques of luminosity levelling were applied consistently during proton physics production and will be described next. The different luminosity requirements also impact the construction of the filling schemes. Different collision patterns have been used for physics production and during 2012 a change was required to overcome recurrent loss of Landau damping.

Beam parameters were pushed much further during single bunch MDs, achieving very high beam-beam tune shifts. Similar conditions were used for high pile-up studies for the experiments [3].

Scans of the crossing angle were done during MDs

to evaluate the effect of long-range interactions in bunch trains, allowing to measure the onset of losses for scaling laws [4]. The description of these studies and of the observation of orbit effects conclude this paper.

## BEAM PARAMETERS, PERFORMANCE

The operation of the LHC has exceeded all expectations in these first years of luminosity production. The year 2010 was mostly a commissioning year, and the instantaneous luminosity target was exceeded by a factor 2, as  $2.1 \cdot 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$  was achieved. The years 2011 and 2012 were dedicated to luminosity production in search for new physics, and  $5.5 \text{ fb}^{-1}$  and  $23.2 \text{ fb}^{-1}$  were collected in each year respectively. Table 1 shows the machine and beam parameters as defined in [1] compared to the ones used in 2012 operation. Despite the beam energy being about half the design value, the achieved peak luminosity was over 75% of the design value of  $10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ . The  $\beta^*$  at the high luminosity experiments in IP1 and 5 reached almost design values thanks to the excellent physical aperture and the use of “tight collimators” [5].

The key ingredient to the the excellent luminosity performance is the fact that the LHC injectors can deliver much brighter beams with a bunch spacing of 50 ns compared to the nominal 25 ns. At 4 TeV beam energy, the pile-up  $\mu$  (number of inelastic collisions per bunch crossing) is at most 30–35, and this is still acceptable for the high luminosity experiments. This contributed to the choice for 2012 operation of 50 ns spaced beams, which have the ad-

Table 1: Parameter comparison between design values [1] and what was achieved in 2012 operation.

Parameter	design	2012
beam injection energy [TeV]	0.45	0.45
beam energy at collisions [TeV]	7	4
number of bunches	2808	1380
bunch spacing [ns]	25	50
$\beta^*$ [m]	0.55	0.6
intensity [ $10^{11}$ ppb]	1.15	1.65
norm. transv. emittance [ $\mu\text{m}$ ]	3.75	2.5
beam size [ $\mu\text{m}$ ]	16	19
peak luminosity [ $10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ ]	1	0.77
stored energy [MJ]	362	145

ditional advantage of being much less affected by electron cloud than 25 ns spaced beams (this allowed sacrificing less beam time to electron-cloud scrubbing as 3 days were needed for 50 ns versus 2 weeks that would have been required for 25 ns). Note also that the smaller emittance of the 50 ns beams allowed squeezing further (for comparison,  $\beta_{25}^* = 80$  cm) and using a smaller crossing angle, directly contributing to the excellent performance.

For operation after the Long Shutdown of 2013-2014 (LS1), the pile-up  $\mu$  will increase due to the energy increase, and thus 25 ns is the preferred choice (for 50 ns beams,  $\mu_{50} \approx 80 - 120$ ). It is worth pointing out that luminosity levelling techniques might be needed even with 25 ns spaced bunches as  $\mu_{25} \approx 25 - 45$ .

## LUMINOSITY LEVELLING

The Alice and LHCb experiments run with strong pile-up limitations: Alice at  $\mu \approx 0.02$  and LHCb at  $\mu \approx 2.5$ . The limitations come from various factors that range from detector damage to event size limitations, to data taking optimization [2]. In addition to a less aggressive  $\beta^*$  (in 2012,  $\beta^* = 3$  m was used for IP2 and 8), various techniques of luminosity control and levelling were used operationally or tested in special runs at the LHC so far.

The luminosity was levelled operationally at LHCb so that the experiment could run at a constant luminosity of  $4 \cdot 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$ . This was achieved by transversely offsetting the beams at the IP. During the fill, the offset was adjusted in small steps so to modulate the overlap between the two beams to obtain the desired rates [6]. No real limitations to this technique were found, as long as the offset bunch pair had enough tune spread by head-on collisions elsewhere (i.e. in IP1 and 5).

Given that the limitation in Alice is even stronger, the experiment ran for most of 2012 based on collision with so-called “satellite” bunches (“main-satellite” collisions). Satellites bunches have a much lower charge (about a factor 1000 lower than the main bunches), contained in buckets at 25 ns from the main ones (which are at a 50 ns spacing). Note that this technique is not applicable with 25 ns spaced bunches.

During Machine Development (MD) sessions, also techniques of  $\beta^*$  levelling were tested, verifying the feasibility of the orbit control of while squeezing IP1 and 5 in steps until the operational 60 cm [7], [8], [9].

## FILLING SCHEMES & COLLISION PATTERNS

Here we recall a few of the constraints that have to be taken into account in the creation of a filling scheme:

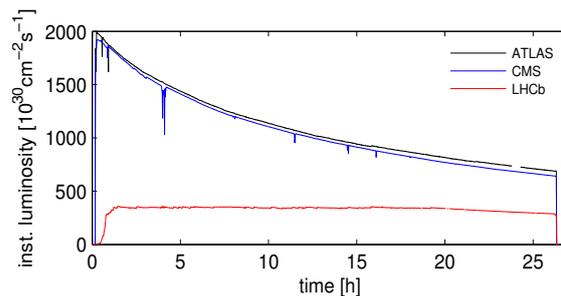


Figure 1: Example of ATLAS, CMS and LHCb instantaneous luminosities during fill 2006 (in 2011). Note that while the luminosities of IP1/5 decrease with time, the luminosity of IP8 is kept constant by reducing the transverse offset and starts decaying only after about 20 hours into production.

- Experiment location: ATLAS, Alice, CMS are located at the IP symmetry point, LHCb is 11.25 m away from it; ATLAS and CMS are diametrically opposed.
- Kicker gaps: injection and extraction kickers require part of the ring not to contain beam (e.g. 925 ns for the LHC injection kicker, 3000 ns for the dump kicker).
- The 400 MHz RF system gives 2.5 ns long buckets and a harmonic number  $h = 35640$ , but 25 ns bunch spacing is the minimum that the experiments' readout can handle (for a maximum of  $\approx 2800$  bunches per ring, taking into account the kicker gaps).
- Bunch spacings that can be created in the LHC injector chain are: 25 ns, 50 ns, 75 ns, 150 ns, or  $>250$  ns.
- The number of PS batch injections into the SPS can be varied dynamically (i.e. 1 to 4 injections).

Different number of colliding pairs are provided to the different experiments by shifting the injection buckets appropriately. In Table 2, three examples of filling schemes used in 2012 for physics production are shown. All three schemes are based on 50 ns spaced bunches and main-satellite collisions for Alice (thus zero main-main collisions in IP2). The first scheme was the baseline for 2012 operation, and it aimed at giving the same number of colliding pairs to IP1/5 and 8. Scheme 2 was designed to have all bunches colliding in IP1 and 5, and was obtained by shifting 4 injections in scheme 1. Scheme 3 is a minor modification with respect to scheme 2, designed to include 3 bunches with no collisions in IP1/5 for systematic background studies for ATLAS and CMS.

Table 2: Number of collisions per IP for three filling schemes used in 2012.

Scheme	IP1/5	IP2	IP8
1	1331	0	1320
2	1380	0	1274
3	1377	0	1274

### Loss of Landau damping

The change from scheme 1 to scheme 2 in Table 2 was dictated by the fact that fills were often terminated prematurely due to instabilities. Some bunches in ring 1 were losing intensity very quickly and an interlock kicked in at  $\approx 4 \cdot 10^{10}$  ppb, effectively determining the length of the fill to be much shorter than desirable.

The affected bunches had the peculiarity of colliding only in IP8 (levelled by separation). The lack of Landau damping with respect to the other bunches that collide in IP1/5 was identified to be the reason for the development of the instability [10]. The filling scheme was thus changed to have head-on collisions in IP1/5 for all bunches, so that the head-on beam-beam tune spread would provide the necessary damping.

During in the second part of the 2012 run, selected bunches became frequently unstable at the end of the squeeze, before collisions. The instability was visible on loss measurements and as emittance growth, but it is not fully understood yet at the time of writing and studies are still ongoing [10]. Improvements on beam instrumentation, and in particular for detection of instabilities, are needed [11]: e.g. calibrated bunch-by-bunch emittance measurements, headtail monitors to understand the intrabunch motion, Schottky monitors for bunch-by-bunch tunes and chromaticity, among others. They will help greatly at restart after LS1.

## HIGH HEAD-ON TUNE SHIFT AND HIGH PILE-UP

Single bunches characterized by very high brightness were collided during dedicated MD sessions in 2011 and 2012 [3]. First, in 2011, a possible head-on beam-beam limit was probed with bunches characterized by  $\epsilon \approx 1.3 \mu\text{m}$  and  $N \approx 1.9 \cdot 10^{11}$  ppb [12]. No significant losses nor emittance effects were observed after having performed a tune adjustment to avoid emittance blowup ( $Q_H = Q_V = 0.31$ ). The linear head-on beam-beam parameter  $\xi$  is defined as

$$\xi = \frac{Nr_0}{4\pi\epsilon_n} \quad (1)$$

where  $N$  is the number of protons in the bunch,  $\epsilon_n$  is the normalized emittance and  $r_0 = 1.54 \cdot 10^{-18}$  m is the classical proton radius. During the 2011 experiments at injection energy, at most  $\xi = 0.02/\text{IP}$  and  $\xi = 0.034$  total (for 2 IPs) were achieved, to be compared with the Design Report value of  $\xi = 0.0033/\text{IP}$  for (for 3 head-on IPs, [1]).

Given the success of the studies at injection, bunches with similar parameters were put into collisions according to the operational cycle so that the experiments could use such beams to study their own pile-up limitations [2], [3]. The pile-up is  $\mu \approx 19$  in the Design Report [1], but a pile-up of  $\mu_{max} \approx 31$  was achieved in 2011 [13] and  $\mu_{max} \approx 70$  in 2012 [14]. The very high value achieved in 2012 was reached thanks to the very bright single bunches that could be produced thanks to the use of the Q20 optics in the SPS ( $N = 3 \cdot 10^{11}$  ppb and  $\epsilon = 2.2 \mu\text{m}$ , [15]), and is well beyond what the experiments can handle for efficient data taking. Even higher values would have been achieved had the beams not suffered from instabilities during the acceleration ramp and the betatron squeeze (despite the increase in chromaticity and longitudinal size). Only one beam could be brought cleanly into collisions in the time scheduled for the study.

### Coherent modes

Coherent beam-beam modes,  $\sigma$  and  $\pi$ , could be measured during the 2011 experiments with single bunches [16].

It is also worth recalling that in 2010 a tune split had been used to cure instabilities, possibly from coherent modes, with single bunch intensities of  $\approx 0.9 \cdot 10^{11}$  ppb ( $\Delta Q_1 = -0.0025$ ;  $\Delta Q_2 = +0.0025$ ). The tune split was later removed [17] when more bunches were colliding and after observing that the lifetime of one beam was significantly worse than that of the other beam (worse lifetime for the beam with reduced tune).

## SCANS OF CROSSING ANGLE

In successive MD sessions [4], the machine settings were changed starting from the nominal configuration by reducing the crossing angle in steps until losses or lifetime reduction were observed. This allowed recording the separation that corresponded to the onset of beam losses. Bunch-by-bunch differences depending on the number of LR interactions were highlighted (PACMAN effects), with a higher number of LR interactions leading to higher integrated losses, starting at a larger separation. These experiments were repeated for different  $\beta^*$  and bunch intensities; the different machine settings and beam parameters in each experiment are shown in Table 3. The results were used to confirm simulations [18] and predict the required separa-

Table 3: Machine settings and beam parameters for crossing angle scans ( $\alpha$  is the half crossing angle;  $\epsilon$  is the transverse emittance;  $\Delta t$  is the bunch spacing; E is the beam energy).

$\beta^*$ [m]	$\alpha$ [ $\mu\text{rad}$ ]	intensity [ $10^{11}$ ppb]	$\epsilon$ [ $\mu\text{m}$ ]	$\Delta t$ [ns]	E [TeV]
1.5	120	1.2	2-2.5	50	3.5
0.6	145	1.6	2-2.5	50	4
0.6	145	1.2	2-2.5	50	4
1	145	1.0	3.1	25	4

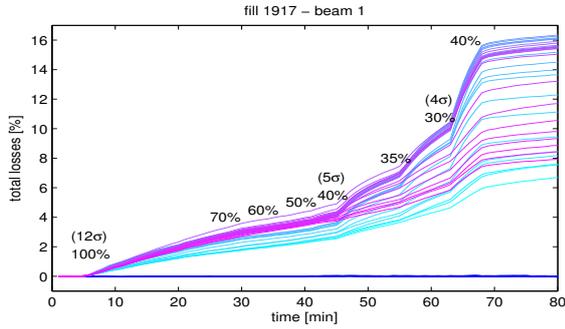


Figure 2: Bunch losses versus time for beam 1; blue curves for non colliding bunches, cyan to magenta for the 36 bunches in the 50 ns spaced bunch train. The separation is indicated in the plot as percentage of the initial crossing angle, or in number of  $\sigma$ .

tion for different scenarios possibly used in future operation. It is proven that it is a dynamic aperture effect, as no effects of the scans were observed on the emittance evolution, and as the losses recovered if a sufficient crossing angle was restored.

As an example, Fig. 2 shows the losses in the case of beam 1 for the first scan in Table 3, when the crossing angle in IP1 was reduced from 120  $\mu\text{rad}$ , or 100%, to a minimum

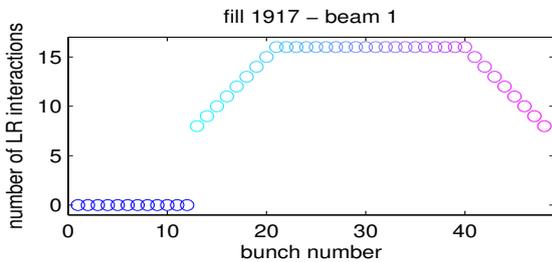


Figure 3: Number of LR encounters per bunch: in blue the 12 non colliding bunches, in cyan fading to magenta the 36 50 ns spaced bunches.

of 40% (corresponding to 4  $\sigma$  beam separation, [19]). It can be seen that the onset of strong losses is between 4 and 5  $\sigma$  separation depending on the number of LR interactions experienced by the bunch (shown in Fig. 3).

The scans proved as evidence for the alternate crossing scheme effectiveness, as when scanning IP5 after IP1 the lifetime seemed best when the separation and the crossing angles were equal for the two IPs (we recall that the crossing plane is vertical in IP1 and horizontal in IP5 to compensate for first order LR effects). A dependence on the number of head-on collisions was shown also.

A scan was performed also for 25 ns spaced beams, i.e. with twice the number of LR interactions, as a bigger separation was expected to be needed and the information will be useful to decide the settings for future operation. An asymmetry between beam 1 and beam 2 was observed but is not fully understood yet (it is possibly related to electron cloud effects).

## ORBIT EFFECTS

A predicted behaviour of PACMAN bunches is the fact that they have different orbits due to LR collisions, and a fully self-consistent treatment was developed to compute the different orbits [20]. The LHC orbit measurement cannot resolve these effects, but the ATLAS vertex centroid measurement [21], [22] was used to qualitatively verify the agreement ([19], [23], [24]).

### Missing LR deflection

The beam dump of a single beam in collisions leads to a transient effect due to missing LR deflections, resulting in a single-turn trajectory perturbation of the other beam. An end-of-fill test was performed with 72 25 ns spaced bunches ( $\approx 1.1 \cdot 10^{11}$  ppb,  $\approx 65 \mu\text{rad}$  half crossing angle, [25]). The horizontal perturbation of the beam 1 orbit in the arc is  $\approx 230 \text{ mm} = 0.6 \sigma_{nom}$  (with  $\sigma_{nom} = 3.5 \mu\text{m}$ ). This leads to beam losses above BLM dump thresholds with physics beam. The effect was observed on beam losses throughout 2012.

## CONCLUSIONS

The operation and performance of the LHC are strongly influenced by beam-beam effects, which, already in these first years of physics production, drove the choice of beam parameters, machine settings and filling schemes so to improve performance and mitigate instabilities. A list of observations from routine operation and dedicated studies was presented in this paper to give an overview of the extent to which beam-beam related effects have shaped LHC operation for high intensity proton physics.

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## REFERENCES

- [1] O. S. Brüning, P. Collier, P. Lebrun, S. Myers, R. Ostojic, J. Poole, P. Proudlock, "LHC Design Report", CERN-2004-003-V-1.
- [2] R. Jacobsson, "Needs and requirements from the LHC physics experiments", these proceedings.
- [3] G. Trad, "Beam-beam effects with a high pile-up test in the LHC", these proceedings.
- [4] W. Herr, "Long range beam-beam effects and experience in the LHC", these proceedings.
- [5] R. Bruce, R.W. Assmann, F. Burkart, M. Cauchi, D. Deboy, L. Lari, S. Redaelli, A. Rossi, B. Salvachua, G. Valentino, D. Wollmann, "Collimation settings and performance", LHC Performance Workshop, Chamonix, 6-10 Feb. 2012.
- [6] D. Jacquet and F. Follin "Implementation and experience with luminosity levelling with offset beams", these proceedings.
- [7] X. Buffat, W. Herr, M. Lamont, T. Pieloni, S. Redaelli, J. Wenninger, "Results of  $\beta^*$  luminosity levelling MD", CERN-ATS-Note-2012-071 MD.
- [8] X. Buffat, W. Herr, T. Pieloni, L. Ponce, S. Redaelli, J. Wenninger, "MD on squeeze with colliding beams", CERN-ATS-Note-2013-002 MD.
- [9] B. Muratori, T. Pieloni, "Luminosity levelling techniques: implications for beam-beam interactions", these proceedings.
- [10] X. Buffat, "Consequences of missing collisions, beam stability and Landau damping", these proceedings.
- [11] R. Giachino, "Diagnostics needs for beam-beam studies and optimization", these proceedings.
- [12] R. Alemany, X. Buffat, R. Calaga, K. Cornelis, M. Fitterer, R. Giachino, W. Herr, A. McPherson, R. Miyamoto, G. Papotti, T. Pieloni, S. Redaelli, F. Roncarolo, M. Schaumann, R. Suykerbuyk, G. Trad, S. Paret, "Head-on beam-beam tune shifts with high brightness beams in the LHC", CERN-ATS-Note-2011-029 MD.
- [13] G. Trad, R. Alemany, X. Buffat, R. Calaga, K. Cornelis, G. Crockford, R. Giachino, W. Herr, G. Papotti, M. Pojer, M. Schaumann, "Beam parameters observations during a high pile-up collisions fill", CERN-ATS-Note-2011-105 MD.
- [14] G. Trad, R. Alemany, X. Buffat, R. Calaga, K. Cornelis, W. Herr, D. Jacquet, G. Papotti, M. Schaumann, W. Venturini Delsolaro, "Beam parameters observations during the second high pile-up collisions fill in 2011", CERN-ATS-Note-2012-010 MD.
- [15] Y. Papaphilippou, G. Arduini, T. Argyropoulos, W. Bartmann, H. Bartosik, C. Bracco, T. Bohl, S. Cetour-Cave, K. Cornelis, L. Drosdal, J. Esteban-Muller, B. Goddard, A. Guerrero, W. Hoeffle, V. Kain, G. Rumolo, B. Salvant, E. Shaposhnikova, H. Timko, D. Valuch, G. Vanbavickove, "Operational performance of the LHC proton beams with the SPS low transition energy optics", THPWO080, these proceedings.
- [16] X. Buffat, "Coherent beam-beam modes in the LHC", these proceedings.
- [17] G. Papotti and W. Herr, "Observations of bunch-by-bunch losses in the 2010 LHC proton physics operation", CERN-ATS-Note-2011-073 PERF.
- [18] D. Kaltchev, "Analysis of long range studies in the LHC - comparison with the model", these proceedings.
- [19] M. Albert, R. Alemany, R. Assmann, X. Buffat, R. Calaga, K. Cornelis, M. Fitterer, R. Giachino, W. Herr, R. Miyamoto, L. Normann, G. Papotti, T. Pieloni, L. Ponce, S. Redaelli, M. Schaumann, G. Trad, D. Wollmann, "Head-on beam-beam collisions with high intensities and long range beam-beam studies in the LHC", CERN-ATS-Note-2011-058 MD.
- [20] W. Herr and H. Grote "Self-consistent orbits with beam-beam effects in the LHC", Proc. 2001 Workshop on beam-beam effects, FNAL, 25-27 June 2001.
- [21] W. Kozanecki and J. Cogan, private communication (2011).
- [22] R. Bartoldus, Online determination of the LHC Luminous Region with the ATLAS High Level trigger, TIPP 2011, Int. Conf. on Tech. and Instr. in Particle Physics, Chicago (2011).
- [23] R. Alemany, R. Assmann, X. Buffat, R. Calaga, M. Fitterer, R. Giachino, G.H. Hemelsoet, W. Herr, G. Papotti, T. Pieloni, M. Poyer, M. Schaumann, M ; G. Trad, D. Wollmann, "Observed Orbit Effects during Long Range Beam-Beam Studies", CERN-ATS-Note-2012-021 MD.
- [24] M. Schaumann, "Observed beam-beam induced orbit effects at LHC", these proceedings.
- [25] T. Baer, "Beam-beam effects during the beam dump process", these proceedings.