OBSERVATION OF BUNCH TO BUNCH DIFFERENCES DUE TO BEAM-BEAM EFFECTS

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Abstract

Due to the bunch filling schemes in the LHC the bunches experience a very different collision schedule and therefore different beam-beam effects. These differences and the effect on the performance have been observed and compared with the expectations. Possible limitations due to these effects are discussed.

FILLING SCHEMES AT THE LHC

The LHC machine houses 4 major experiments: ATLAS, Alice, CMS and LHCb. ATLAS and CMS are the high luminosity experiments, designed for pile-up $\mu \approx 20$ (number of inelastic interactions per crossing). Alice and LHCb are instead designed for much lower luminosities and pile-up: $\mu_{\mathrm{Alice}} < 0.05$ and $\mu_{\mathrm{LHCb}} < 0.5$. These very different constraints impose the need for very different delivered instantaneous luminosities. On one side, the filling schemes are tailored to give a different number of colliding pairs to the experiments, at the same time, techniques of luminosity levelling for the low pile-up experiments are operationally employed. The results concerning levelling by separation are presented separately [1].

ATLAS and CMS are placed in two diametrically opposed Interaction Points (IP), called IP 1 and IP 5. Alice is in IP 2 and LHCb in IP 8. While ATLAS, CMS and Alice are located at the IP symmetry point, the centre of the LHCb experiment is 11.25 m away.

The LHC 400 MHz RF system results in the 2.5 ns bucket structure and a harmonic number h = 35640. Only one out of 10 buckets is filled at most, so that the LHC beam proposed in [2] is characterized by a 25 ns bunch spacing. Assuming the 25 ns structure for the bunches, a 12.5 ns structure derives for the collisions points as the beams circulate in opposite directions and the bunches can meet halfway between two 25 ns positions. The numbering of the buckets is chosen so that bunches sitting in bucket 1 meet in the centre of ATLAS.

Construction of Filling Schemes

The LHC injector chain offers a wide variety of possible beams to fill the LHC. The PSB defines the intensity and the transverse emittance; the PS defines the longitudinal structure; the SPS performs transverse and longitudinal blow up when required and packs together many bunches in a single transfer to the LHC. The spacing between bunches is defined by the injection kickers risetimes for single bunch transfers and by the PS RF cavities when the splittings are used (e.g. [2]). The splittings used so far allow the following bunch spacings: 25 ns, 50 ns, 75 ns, 150 ns. Once the bunch spacing is defined, the number of bunches is also fixed: e.g. for 150 ns 12 bunches and multiples, for 50 ns 6 and multiples, for 75 ns 8 bunches and multiples. The number of PS to SPS transfers can be programmed dynamically, so that it can change from one injection to the next one. The number of PSB to PS transfers is for now not dynamic (an upgrade is foreseen).

The LHC Injection Bucket is defined as the LHC bucket in which the first bunch in the SPS train will be transferred. It is defined dynamically in the filling scheme, provided that it comes at least 925 ns after the last injected bunch (for the injection kicker risetime) and that the abort gap remains empty (for the dump kicker risetime).

A naming convention was established for the filling schemes. The name begins with a description of the bunch spacing (e.g. *50ns* or *Single*); the number of bunches per ring follows (assumed to be equal for the two rings, e.g. *1380b*); the colliding pairs per IP follow in the order: IP1 (equal to IP5), IP2 and IP8. Additionally, *+1small* is sometimes used to indicate that the pilot bunch is not overinjected and more characters are used in the end of the scheme to give further indications (e.g. the maximum number of bunches injected per SPS train, e.g. *144bpi*). An example of filling scheme thoroughly used for physics production in 2011 is *50ns_1380b+1small_1318_39_1296_144bpi*. Most of the filling schemes used for physics production were proposed over time by the LHC Physics Coordinator M. Ferro-Luzzi.

Example: Early Filling Schemes

One of the first filling schemes used for physics production is presented here as an example: *Single_3b_2_2_2*. The initial part of the 2010 LHC operation was spent with schemes for which all the experiments would receive the same number of colliding pairs (pile-up limitations not yet reached for LHCb, Alice running with separated beams to reduce the rates). The filling scheme consisted of 3 bunches per ring: buckets 1, 8941, 17851 for beam 1; buckets 1, 8911, 17851 for beam 2. This filling pattern produces collisions according to Table 1.

In order to increase the number of colliding pairs, the scheme was then repeated and shifted by a constant quantity (e.g. 1000 buckets), until 25 bunches per ring (*Multi_25b_16_16_16*, which includes one non colliding bunch per ring). In these conditions the bunches experienced almost only head-on collisions. Long range encounters were experienced only in IP1 and 5 where a crossing angle maintained the beams sufficiently separated.

Table 1: Filling pattern and collision scheme for *Single_3b_2_2_2*, values for beam 1 (B1) and 2 (B2). Filled buckets for the first beam, and colliding bunch at which IP for the second beam.

bucket b1	IP1	IP2	IP5	IP8	total
1	1	8911	1		3
8941		17851		1	2
17851	17851		17851	8911	3
bucket b2	**IP1**	**IP2**	**IP5**	**IP8**	**total**
1	1		1	8941	3
8911		1		17851	2
17851	17851	8941	17851		3

BUNCH-BY-BUNCH LOSSES

Losses from Head-on Collisions

A clear correlation between number of head-on collision and intensity loss was observed throughout 2010 [3]. In particular with the early filling schemes in which the long range encounters were negligible, highest losses were observed for the bunches experiencing the biggest number of collisions (PACMAN effects). An example is shown in Figure 1: the percentage intensity loss since the beginning of the fill is indicated versus time. Each line corresponds to a bunch, and the colour coding reflects the collision schedule. In the example, the bunches colliding only in IP2 and 8 lost about 1-2% of the intensity within the first few hours of collisions, while the bunches colliding also in IP1 and 5 lost 4-5%.

Observations of this kind allowed optimizing the filling scheme when needed: e.g. the *Multi_48b_36_16_36* filling scheme included long-range encounters in IP8 which resulted in extra ≈20% losses after 3 hours of collisions. This scheme was replaced by the *Multi_50b_35_14_35* scheme which was in theory less efficient for luminosity production but did not include these bad encounters resulting in

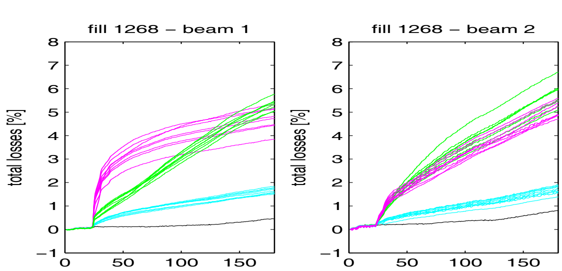

Figure 1: Bunch losses versus time, colour coding to highlight the dependence on the collision schedule: green collisions in IP1, 5 and 8, magenta collisions in IP1, 5 and 2, cyan collisions in IP8 and 2, black non colliding bunch.

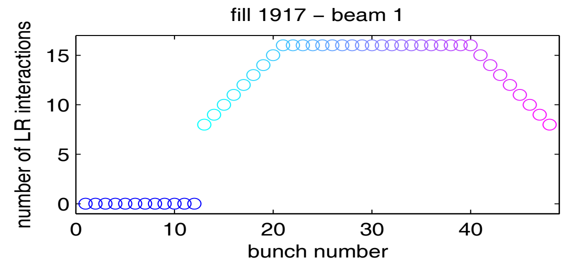

Figure 2: Number of LR encounters per bunch: in blue the 12 non-colliding bunches, in cyan fading to magenta the 36 50 ns spaced bunches.

an overall better performance.

Losses from Long-range Collisions

A controlled experiment was carried out to assess the possible limitations coming from Long Range (LR) encounters [4]. A dedicated fill was brought into collisions with a filling scheme consisting of 12 non colliding bunches and 36 50 ns spaced bunches colliding in IP1 and 5 (*50ns_48b_36_0_0_BBMD1*). The number of LR interactions per bunch is plot in Figure 2: the 12 non colliding bunches have none, the 36 bunch train have from 8 to 16 encounters (PACMAN effects [5]).

The crossing angle was reduced in steps until lifetime reductions or losses were observed. The angle was ramped down in IP1 first, in steps of 10% from the nominal 120° for the half angle. The loss history for beam 1 is plot in Figure 3, the colour coding is consistent with Figure 2. The visible kinks in the curve correspond to the crossing angle changes to 40%, 35% and 30%. It is apparent that the bunches in the middle of the train start suffering earlier than the ones in the perifery. A similar behaviour is observed for beam 2, unfortunately the beam current transformer measurement is noisier.

A snapshot of the losses at time 70 minutes is shown in Figure 4, highlighting the fact that the bunches experienced an integrated loss roughly proportional to the number of long range encounters. This is interpreted as reduction of the dynamic aperture due to the LR beam-beam interaction [6]. If it is a dynamic aperture effect, no change is ex-

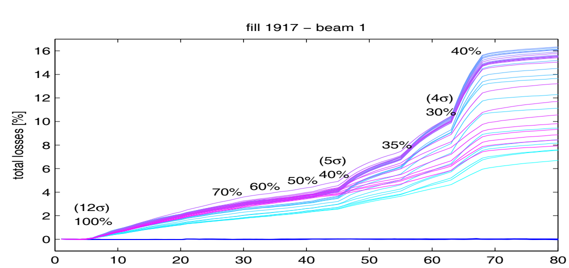

Figure 3: Bunch losses versus time for the beam 1, colour coding as in Figure 2.

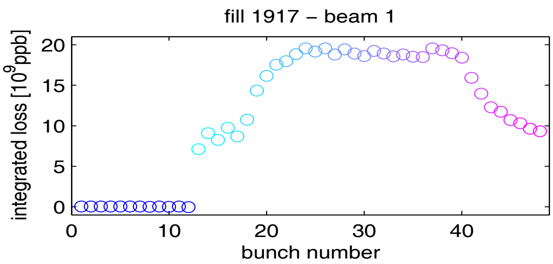

Figure 4: Beam 1 bunch losses at time 70 minutes, colour coding as in Figure 2.

pected in the emittance, and changes in the emittance were not observed (in synchrotron light measurements and specific luminosity). Due to the alternating crossing used at the LHC IP1 and IP5, the tune difference between bunches experiencing a different number of LR interactions is largely suppressed [5]. This explains why the largest losses are experienced by the bunches with the highest number of LR interactions as predicted in [7].

EFFECTS ON LUMINOSITY

The luminosity evolution at the Tevatron was approximately described by a fractional power law [8]:

$$L = \frac{L_0}{(1 + t/\tau/b)^b} \qquad (1)$$

This description worked well also for a selection of 2010 LHC physics fills, and could be applied to single bunch luminosity evolution within the same fill [9]. The resulting fit parameters τ and b are plotted in Figure 5 for the different bunches in fill 1440. The colour coding highlights the pattern in head on collisions, showing that the evolution in influenced by the collision pattern. In particular, collisions in IP2 seem to have little influence on the luminosity evolution (green and grey bunches have similar behaviour, red and blue also). In fact, at the time, IP2 was taking data with separated beams to reduce the pile up. This functional description highlights how the beam-beam effects are strongest in the beginning of the fill, when the emittance is smallest and the intensity is highest.

CONCLUSIONS

The different luminosity and pile up requirements of the LHC experiments demand for flexible filling schemes. To allow tailoring the number of colliding pairs to each experiment's needs, the full flexibility of the CERN accelerator chain is used. Examples of filling schemes are presented and it is highlighted how the number of head on and long range collisions are different from bunch to bunch. The effects on losses and luminosity are presented. For early filling schemes in which head on collisions were dominant, losses were observed to be higher for bunches with a higher

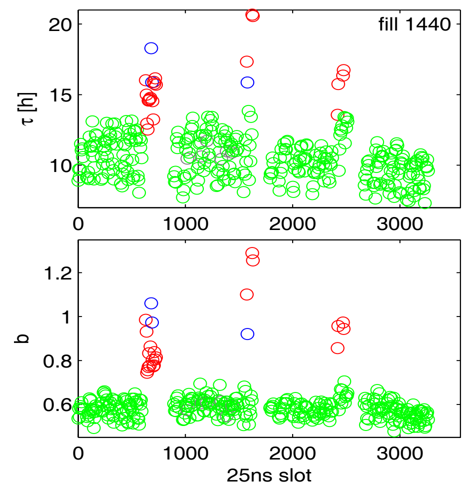

Figure 5: Luminosity evolution dependence on collision schedule: grey for bunch pairs colliding in all IPs; green for collisions in IP1, 5, 8; blue for IP1, 5, 2; red for IP 1, 5.

number of collisions. For a dedicated long range experiment, the effect of the reduction of the dynamic aperture is observed as increased losses for the bunches experiencing a higher number of long range encounters.

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