# LUMINOSITY AND BEAM-BEAM

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*Abstract*

We report on observations on luminosity evolution and beam-beam interaction from the 2011 physics run. Extrapolations for 2012 are attempted and a list of desired studies and machine developments is included.

## INTRODUCTION

The history of the 2011 luminosity production is summarized in the first section of this paper, along with the evolution of the beam parameters and reminders about tune scans and the success of the luminosity levelling technique. One example of a luminosity model simulation is presented next, followed by a comparison between colliding and non-colliding bunches. Highlights of results of beam-beam Machine Developments (MDs) are also introduced, concerning the Head-On (HO) and the Long-Range (LR) component of the beam-beam force. The suggested separation for 2012 operation and a list of desired studies conclude the paper.

## 2011 LUMINOSITY PRODUCTION

The relation between instantaneous luminosity and machine parameters is recalled:

$$L = \frac{f_{rev} n_b I_{b1} I_{b2}}{2\pi\sqrt{(\sigma_{1x}^2+\sigma_{2x}^2)(\sigma_{1y}^2+\sigma_{2y}^2)}} \tag{1}$$

in which $f_{rev}$ is the revolution frequency, $n_b$ is the number of bunches, $I_{b1}$ and $I_{b2}$ are the average bunch intensities in ring 1 and ring 2. The physical transverse beam size $\sigma$ (in x or y plane) is related to the normalized emittance $\epsilon_N$, the optical $\beta$ function at the IP ($\beta^*$) and the relativistic $\gamma$ through $\sigma = \sqrt{\beta^* \epsilon_N/\gamma}$.

An extensive list of instantaneous and integrated luminosity plots can be found in [1], while here only a selection of fills was treated, i.e. from the first 1380 bunches/ring fill (fill nr. 1936) until the end of the proton run (fill nr. 2267). All fills are with 50 ns beams, apart from fill nr. 2186 which is with 25 ns beams. In Fig. 1, the first plot shows the luminosity per colliding pair, highlighting the steady progress throughout the year from 1 to $2.8 \cdot 10^{30}$ Hz/cm$^2$. Fills nr. 2201 and 2252 are the so-called “high pile-up” fills and reached $5.1 \cdot 10^{30}$ Hz/cm$^2$ on very few colliding pairs.

The second plot shows the average intensity per bunch from $1.1 \cdot 10^{11}$ ppb to $1.45 \cdot 10^{11}$ ppb ($2.4 \cdot 10^{11}$ ppb in the high pile-up fills). The specific luminosity is then derived, note in particular the step-up at the change in $\beta^*$ ($\beta^* =$

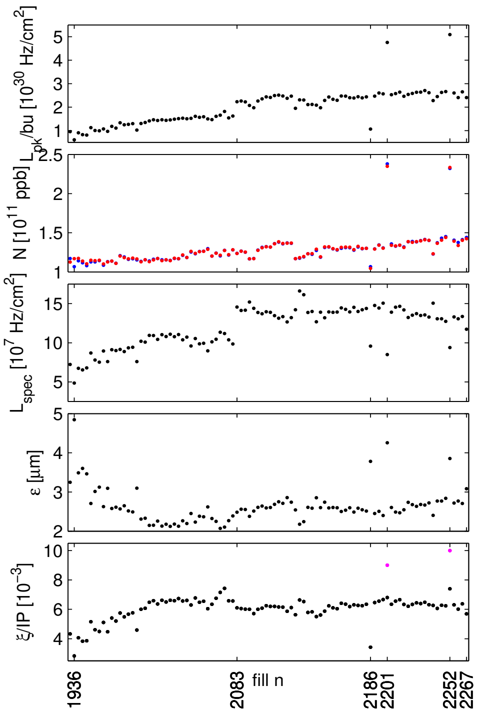


Figure 1: Luminosity per colliding pair (ATLAS), average intensity per bunch (blue for ring 1 and red for ring 2), specific luminosity, normalized emittance and beam-beam parameter for proton fills from nr. 1936 to 2267.

1.5 m before fill nr. 2083 which was the first with $\beta^* =$ 1 m). The emittances are derived in the fourth plot under the assumption of round beams and correct $\beta^*$: the initial values ($\sim$ 3.5 µm) correspond to when transverse blow up was applied at the SPS; later the values increased slowly from 2 µm to 2.7 µm as the intensity increased (according to what can be delivered from the injectors).

The linear beam-beam parameter $\xi$ is defined as:

$$\xi = \frac{r_0 I_b}{4\pi\epsilon_N} \tag{2}$$

where $r_0 = 1.54 \cdot 10^{-18}$ m is the classical proton radius. It is shown in the fifth plot as calculated from the emittance (in black) and for the highest value reached for the plane in which the beam size was smallest (in magenta, with beam size from wire scanner measurements).

It is worth mentioning that for both the LHCb and Alice experiments the pile-up $\mu$ (the number of inelastic interactions per crossing) had to be limited: $\mu_{\mathrm{LHCb}} < 2.5$

and $\mu_{\text{Alice}} < 0.05$. To achieve this, the beams were transversely separated and the offset tuned to level the luminosity to the desired value (e.g. $L_{\text{LHCb}} < 3.5 \cdot 10^{32}$ Hz/cm$^2$). The technique was first tested during an MD and then used operationally [2]. Luminosity levelling worked also in the case of the high brightness beams of the high pile-up fill nr. 2252 (with $2.4 \cdot 10^{11}$ ppb and $\epsilon_N \sim 2.7 - 3.5$ µm): the beams were first transversely separated until the luminosity was reduced by a factor ∼40 and the luminosity peak could be recovered once the separation was removed [3].

### *Tune scans*

The tune working point was changed during the year: until fill nr. 1990 the Design Report [4] values of ($Q_x$, $Q_y$) = (0.31, 0.32) was used. For fill nr. 1991, (0.308, 0.318) was used but it resulted in a worse lifetime and losses in collisions. For fill nr. 1992, (0.312, 0.322) was used and kept from then on as it gave a better lifetime at the start of collisions. The intensity lifetime improvement at the start of collisions is very valuable as too high losses could end the fills prematurely.

The intensity lifetimes in the first 5 hours of a few fills before and after the tune change were compared and they were always between 60 and 110 h regardless on the working point. The luminosity lifetimes were also compared for the same fills, and no clear improvement or worsening could be found. These findings are consistent with the tune change affecting mostly the tails of the beam distribution, but not the emittance growth as much.

### *Luminosity analysis*

An analysis similar to what was presented in [5] was performed concerning the luminosity lifetime. For most proton fills of length of at least 10 h, two types of curves were fit to the luminosity decay in a fill: the curve proposed in [6] and alternatively the sum of two exponentials. The time constant in the curve presented in [6] was between 8 and 12 h, the $b$ parameter is $\sim 2/3$. When the sum of two exponentials the two time constants were found to be ≈3 and ≈23 h, highlighting again a fast and slow contribution. For comparison, in fill nr. 1440 (2010) the two time constants were 3 and 29 h. It is worth noting that the scatter in fit parameters was smaller for 2011 than for 2010, which can be traced back to more stable conditions in the 2011 production (e.g. the filling pattern was changed every few fills in 2010).

The proton Burn-Off (BO) per bunch is quantified to $\approx 2.5 \cdot 10^9$ p/h, equivalent to a decay with a time constant of 50 to 60 h. The scattering on residual gas is qualified by a time constant of thousands of hours (see later section on non-colliding bunches).

## LUMINOSITY EVOLUTION MODELLING

A version of the Tevatron luminosity evolution model [7] adapted to bunch-by-bunch studies and with some parameter modifications was applied to the high pile-up physics fill (nr. 2201). The model assumes a aussian shape for the transverse and longitudinal distributions of the beams, and the evolution of the bunch parameters (intensity, transverse emittances and momentum spread) is described through a set of ordinary differential equations taking into account:

- the emittance growth and the particle loss due to scattering at the Interaction Points (IPs) and on residual gas;
- the transverse and longitudinal emittance growth due to IntraBeam Scattering (IBS);
- the increase in longitudinal emittance due to Radio-Frequency (RF) noise;
- the transverse emittance growth due to transverse noise on the betatron sidebands;
- the transverse and longitudinal emittance decrease due to synchrotron radiation damping.

Note that the longitudinal losses are overestimated in the first hours of collisions as, while the initial longitudinal distribution is unknown, it is assumed that the bucket is full from the start and particles are being lost due to diffusion mechanisms (IBS and RF phase noise).

Fill 2201 consisted of colliding one high intensity bunch per ring ($\approx 2.4 \cdot 10^{11}$ ppb with an emittance of $\approx 3.2$ µm) for about 4 h [8].

From the intensity decay, two loss regimes were found for beam 1: after $\approx$ 100 minutes of collisions the losses increased from $\approx 4.1 \cdot 10^9$ p/h to $\approx 6.6 \cdot 10^9$ p/h. This corresponds to a decrease in luminosity BO from $\approx 70\%$ to $\approx 50\%$. For beam 2 the loss rate was constant during the fill ($\approx 6 \cdot 10^9$ p/h and $\approx 53\%$ BO).

The bunch size measured by the beam synchrotron light monitors (BSRT) were cross-checked using wire scanner measurements at the start and the end of collisions, and precise calibration factors for the BSRT measurements could be derived. A good agreement is found between the measured bunch emittances and length and the simulated evolution (see Fig. 2 for the bunch length). For the intensity decay, the predicted evolution fitted the measurements only for the first 100 minutes of collisions, afterwards higher losses were observed which cannot be predicted by the model. For beam 2, this difference between the measured and simulated trend was observed from the start of collisions.

### *Colliding vs. non-colliding bunches*

An experiment was carried out that helped disentangle the collisions effects from single beam effects and to better understand the contributions of beam scattering on residual gas, IBS and longitudinal diffusion mechanisms caused by the RF phase noise. During two otherwise “normal”

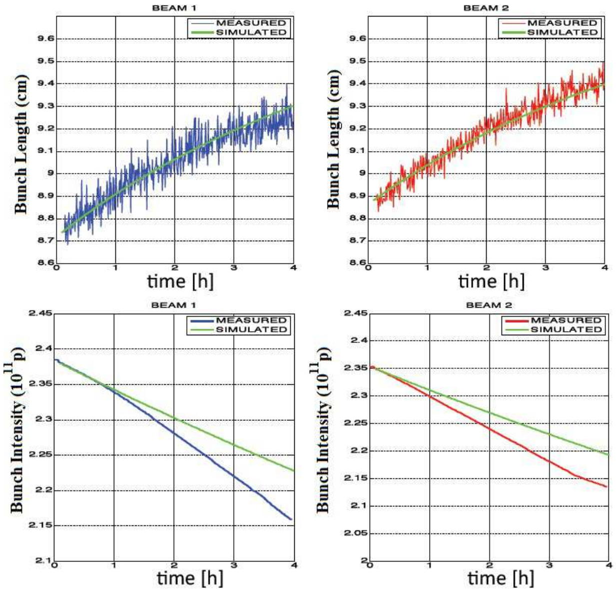


Figure 2: The simulated bunch intensity and length for fill 2201 with the Tevatron luminosity model. The green curves correspond to the simulated evolution of the beam parameters measured and plotted in blue for beam 1 and in red for beam 2.

physics fills (nr. 1855 and 1856), a train of twelve non-colliding bunches per ring was also injected. A comparison between colliding and non-colliding bunch emittance, intensity and length was carried out [9].

A correlation between the number of HO collision and intensity loss was observed in both fills (as already documented in 2010 [10]). Fig. 3 shows the instantaneous bunch losses from the start of collisions. The colour coding highlights how the losses group the bunches in eight "families" according to the IPs where they collide. Higher losses were observed for the bunches experiencing the highest number of collisions while lower losses were observed for the non-colliding bunches.

Two loss regimes were observed for the non-colliding bunches. Losses below $1\%$ were observed for the first $\sim$5 hours for both fills. A lifetime $\tau$ derived from exponential fits ($A \cdot exp(-t/\tau)$) was estimated in the order of thousands of hours [9]. Afterwards, losses are roughly constant until the end of the fill with a rate of $\approx 1.5 \cdot 10^8$ p/h.

The bunch length growth was also divided according to the HO collision schedule and the resulting plot is shown in Fig. 4. The highest growth rate ($\sim$ 8 ps/h) is observed for the non-colliding bunches while for the bunches colliding in four IPs a smaller growth was measured (bunch length clipping due to beam-beam interaction).

### *Simulation of the evolution of the non-colliding bunch parameters*

In the first hours of the fills while the bucket is not yet full, the intensity decay of the non-colliding bunches is

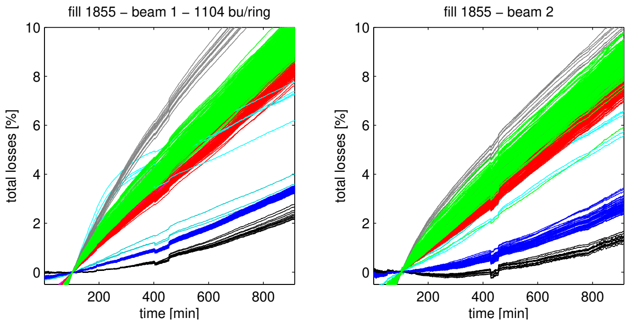


Figure 3: Percentage of the instantaneous bunch losses in collision for fill 1855 (beam 1 on the left, beam 2 on the right) from fast Beam Current Transformer (fBCT) data. Grey for bunches colliding in all IPs, green for IP 1 5 8; red for IP 1 5; cyan for IP 2 8; acquamarine for IP 2, blue for IP 8 and black for non-colliding bunches. The anomaly between 400 and 500 minutes is due to RF trips and fBCT dependence on bunch length.

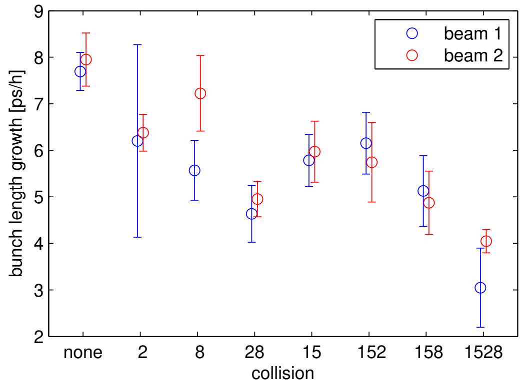


Figure 4: Mean bunch length growth rate per colliding "family".

driven by scattering on residual gas particles. To compare the measured intensity evolution with the simulation output derived from the predicted gas composition, the longitudinal losses were switched off in this simulation and good agreement was found for the initial part of the fill when the bucket is not yet full. For the same fill, the bunch length and transverse emittances predicted by the model fitted smoothly the measured parameters [9].

## RESULTS FROM BEAM-BEAM MDS

### *Head-on interaction*

Dedicated experiments were performed during MD sessions to probe possible limitations deriving from the HO component of the beam-beam force. High brightness single bunches were collided at injection energy and at flat top energy (physics settings). Up to intensities of $2.4 \cdot 10^{11}$ ppb in 2-2.5 μm transverse emittance were put in collision at injection energy [11, 12]. This resulted in a maximum beam-

beam parameter $\xi = 0.017$ per IP, or 0.034 total for two IPs (for comparison, the Design Report value is $\xi = 0.0035$/IP [4]). Only some reduction in intensity lifetime was observed, possibly due to the bigger emittance at injection than flat top energy, so it was suggested to repeat the experiment in physics conditions. This resulted in the first high pile-up fill (nr. 2201), extremely successful as $\mu > 30$ was achieved (for comparison, the Design Report value is 20 for ATLAS and CMS). No sensible limit from the HO component of the beam-beam force has been found yet, and collisions with up to $2.4{\cdot}10^{11}$ ppb could be established with emittances smaller than nominal.

### *Long-range interaction*

Dedicated MDs were performed to observe possible limitations due to the many LR encounters that the bunches experience while circulating in the common vacuum chambers. Fills were brought into collisions with 36-bunch 50 ns trains (bunch trains of minimum length allowing the full complement of LR encounters, i.e. up to 16 LR encounters per IP per 50 ns bunch). The crossing angles at IP1 and IP5 were then reduced in steps (separately and simultaneously in two different sessions, [12, 13]) to reduce the separation until non-negligible losses or lifetime reduction were observed. In Fig. 5, the bunch-by-bunch losses as a function of time are shown while the IP1 crossing angle is reduced in steps [12]. In blue, almost no losses are observed for bunches that do not collide. From cyan to magenta, the losses for each of the 36 bunches that collide in IP1 are shown. The corresponding separation is indicated as percent of the operational crossing angle ($100\% = 240\,\mu\mathrm{rad}$) and as number of $\sigma$. The losses worsen noticeably when the separation is around 4 to 5 $\sigma$. These are due to a reduction in dynamic aperture, as there was no effect on the emittance (verified through BSRT measurements) and the losses recovered when the wider separation is restored. It was also observed that there is a clear dependence of the losses on the bunch position in the batch (PACMAN effect), in particular bunches with more LR encounter experienced higher losses.

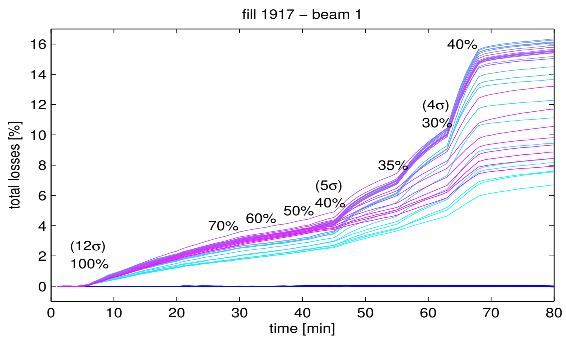


Figure 5: Bunch losses versus time for beam 1; blue curves for non colliding bunches, cyan to magenta for the 36 bunches in the 50 ns spaced bunch train.

## 2012 PARAMETERS

The strong effect of LR encounters and the need for a minimum separation to guarantee enough dynamic aperture was already discussed in the above (see Fig. 5, [12, 13]). Another example comes from the first $\beta^* = 1$ m set up and is described in [13]. A more quantitative comparison with the expectations is shown in Fig. 6, where the dynamic aperture in units of beam size is shown as a function of beam separation. The calculated dynamic aperture is shown for two bunch spacings (i.e. 25 ns and 50 ns, same bunch intensity for both cases [14]). Due to the larger number of encounters, the dynamic aperture is reduced for the smaller spacing, in agreement with the findings described above. From Fig. 6 one should expect visible losses when the separation is reduced to 4 $\sigma$ or less, for larger separation the losses are too small to be recorded in our experiment.

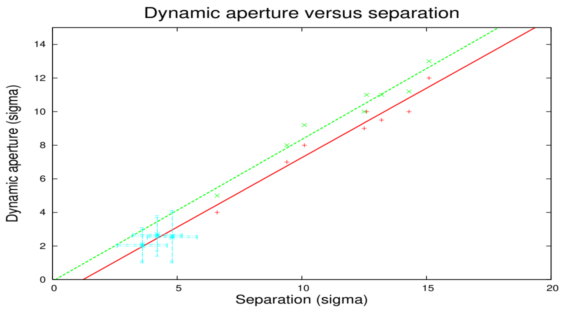


Figure 6: Dynamic aperture in units of beam size shown as a function of beam separation for 25 ns (red) and 50 ns (green). In cyan, estimations of dynamic aperture from MD sessions (see Fig. 5, [12]).

In order to have a dynamic aperture of 8 $\sigma$, it is suggested to aim for 10 $\sigma$ separation for 50 ns beams and 12 $\sigma$ separation for 25 ns beams.

## FUTURE STUDIES

A list of studies to be performed in 2012 was suggested by the beam-beam team. The list includes:

- further studies towards the definition of a HO beam-beam limit, in particular in the presence of unequal emittances and $\beta^*$;
- study the emittance growth caused by transverse noise sources, e.g. using the transverse damper (relevant especially for HL-LHC);
- further study the LR limit, in particular: with 25 ns beams, with 50 ns beams with different $\beta^*$ (1 m and 2 m) and with ultimate intensity (relevant for operation after the first long shutdown);
- continue the studies for the half integer tune working point, which could provide more space for the tune footprint;
- continue the studies on coherent beam-beam modes.

For 2012 it is also suggested to proceed with the exploration of the tune diagram and to perform tune scans; to try and reduce the gain of the transverse damper (until complete off) for studies of emittance growth in collisions for the luminosity model. The non-colliding bunch experiment should be repeated as it is vital for many applications; moreover the fBCT was improved since the previous iteration (new filters were added to reduce the dependence on bunch length), and it is almost transparent to physics production as it only requires two additional injections (it can be ideally scheduled during the intensity ramp up that follows the technical stops, when the machine is not completely filled).

Concerning the luminosity model, work is ongoing. In particular, absolute emittance measurements are required, and a number of other parameters should be known as precisely as possible (e.g. the contribution to the emittance growth of transverse damper and RF noise).

## CONCLUSIONS AND FUTURE WORK

This paper summarizes a number of observations and studies concerning luminosity evolution and beam-beam interactions in 2011 proton operation at the LHC. The time constants for the luminosity lifetime were identified and different growth rates for the emittances measured, also depending on the collision scheme. It was identified that the losses from scattering on residual gas are very small, quantified in lifetimes of thousands of hours. Work is ongoing for a LHC luminosity model, the results from one sample fill were presented showing that the emittance growth rates could be reproduced much better than the intensity loss. It was highlighted that the HO component of the beam-beam force has so far not proven to be limiting, as up to $2.4 \cdot 10^{11}$ ppb could be collided without lifetime or loss problems. It was shown that the losses depend on the number of LR encounters when the separation is not sufficient; the reduction in dynamic aperture can be limited provided that the separation is sufficient (e.g. for 50 ns beams high losses started to appear when the separation dropped below 4 to $5\,\sigma$). The recommended separation for 2012 operation is $10\,\sigma$ for 50 ns beams and $12\,\sigma$ for 25 ns beams.

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