# LUMINOSITY ANALYSIS

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### *Abstract*

The first year of LHC operation was very successful regarding the peak and integrated luminosity targets, but the luminosity lifetime could probably have been better. For this reason, the luminosity evolution during physics fills is studied and correlated to single beam lifetimes and emittance growth in order to try and understand possible causes of luminosity lifetime decrease, e.g. IBS, beam-beam related phenomena, electron-cloud and possibly the “hump”.

## INTRODUCTION

The instantaneous luminosity can be calculated from the machine parameters according to the well known formula:

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

The revolution frequency $f_{rev}$ and the relativistic $\gamma$ factor that goes into the beam size $\sigma$ are fixed. The $\beta$ function at the interaction point ($\beta^*$, which also contributes to the beam sizes) was 3.5 m in the period of interest for this analysis. The number of bunches $n_b$ changed often, in particular during the month of October when the main aim of the machine commissioning was an intensity ramp up to reach a peak instantaneous luminosity of $10^{32}\text{cm}^{-2}\text{s}^{-1}$, the target for the year. The bunch intensity ($I_{b1}$ and $I_{b2}$) and horizontal and vertical emittance change both from fill to fill and within a fill.

In particular the intensity decrease and the emittance growth (e.g. see [1]) are the main causes for the instantaneous luminosity decay over the fill duration. Examples of causes of intensity loss are luminosity production itself and losses on collimators from tails or due to emittance growth. The emittance increases e.g. due to IntraBeam Scattering (IBS) or scattering on residual gas, due to noise on power converters or RF cavities, due to electron cloud etc. To be noted that also orbit drifts can affect the luminosity by diminishing the overlap region between the two beams, but this effect seems to be negligible at the LHC.

In this paper the analysis is restricted to the period between end of July and end of October 2010, that is proton physics fills from 25 bunches up to bunch trains. The bunch trains consisted mostly of 150 ns spaced bunches (up to 368 bunches per ring), plus one physics fill with 50 ns spaced beams (fill 1459). Only luminosity data gathered from the ATLAS and CMS experiments are used; as the two see collisions from the same pairs of bunches, thus allowing a direct comparison of the results.

## 2010 LUMINOSITY EVOLUTION

The rapid progress of the LHC machine in 2010 is often summarized by plots that show the fill peak luminosity ($L_{pk}$) versus fill number for the high luminosity experiments ATLAS and CMS (e.g. [2], reported here in the first subplot in Figure 1). Fill 1251 marked the beginning of a stable running period (3 weeks in August) with 25 nominal bunches per ring, which finished with a few fills at 48-50 bunches per ring. The steep peak luminosity increase after fill 1364 (the first one with bunch train injections) corresponds to the intensity ramp up period (October), where the number of bunches per ring was increased by about 50 bunches every 3 fills. It is clear how luminosity production with 25 or 50 nominal bunches was rather negligible compared to the last physics fills were 368 bunches per ring produced up to the record $2 \times 10^{32}\text{cm}^{-2}\text{s}^{-1}$ (fill 1440).

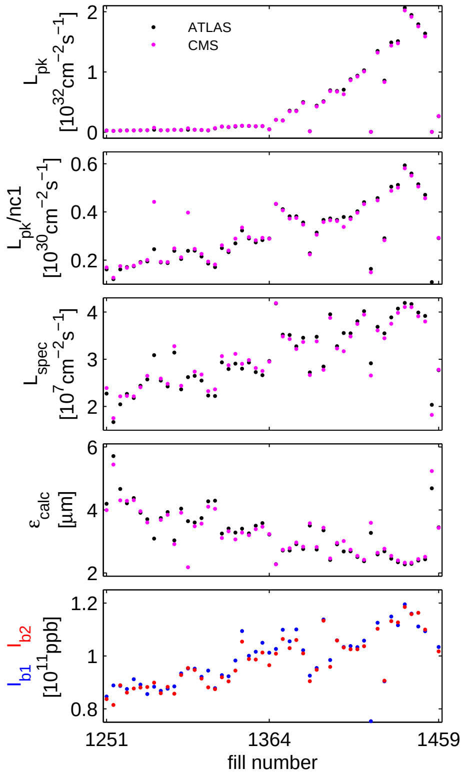

Figure 1: 2010 proton physics fills summaries from fill 1251 to fill 1459.

The second subplot in Figure 1 shows the total peak luminosity divided by the number of bunches (nc1) colliding at the Interaction Point (IP), or “peak luminosity per colliding bunch”: a factor three improvement was reached in the period under study. By folding in the intensity per bunch from the fast Beam Current Transformer (fBCT) system, one can derive the specific luminosity and calculate the emittance at the start of the physics fill (assuming equal and round beams). The specific luminosity ($L_{spec}$) and the calculated emittance ($\epsilon_{calc}$) are shown in the third and fourth subplots, while the average bunch intensity per ring ($I_{b1}$, $I_{b2}$) is shown in the fifth subplot of Figure 1. It becomes then clear how the peak luminosity per bunch was increased by a factor three over a few months. First, the intensity per bunch was slowly increased from $0.8\times10^{11}$ ppb to $1.2\times10^{11}$ ppb. Second, the emittance was slowly decreased from 4-5 $\mu$m (above the 3.5 $\mu$m nominal size, [3]) to just above 2 $\mu$m at the start of physics.

## LUMINOSITY LIFETIME COMPARISONS

The luminosity evolution at the Tevatron was described as a fractional power law [4] according to:

$$L = \frac{L_0}{(1 + t/\tau/b)^b} \tag{2}$$

This description worked well also for a selection of LHC physics fills, and the resulting fit parameters $\tau$ and $b$ are plotted in Figure 2 for most long fills with bunch trains. The calculated fit parameters vary quite across fills: the time constant $\tau$ is generally between 10 and 15 hours, but can be as low as 5 hours or above 20 hours; the parameter $b$ is generally between 0.5 and 0.8, but in a few fills it is above 1. It is rather difficult to trace back the reasons of such differences a posteriori, in particular as the configuration of the machine was often changed, as for example the fill pattern. This situation should improve in 2011 when the main aim will be physics running for luminosity production, leading to stable operations and much reduced periods of machine commissioning. This analysis should then be repeated, recalculating $\tau$ and $b$ for many 2011 physics fills, to verify their reproducibility and understand the causes behind the behaviour.

The emittance growth rates were estimated from the luminous region size published by the experiments. A horizontal lifetime $\tau_\epsilon$ of about 30 hours was derived from simple exponential fits ($e^{-t/\tau_\epsilon}$). The measured lifetime though is lower than the expected IBS lifetime (about 38 hours, see for example [5], or [3] scaled for 3.5 TeV and the smaller emittance). This indicates that possibly other phenomena than IBS should be taken into account in order to explain the horizontal growth. The vertical emittance lifetime varies also quite heavily among fills, dropping sometimes below 20 hours, probably when the “hump” happens to coincide with the tune for a long time, causing emittance blow up (more details later, in the paragraph on fill 1372).

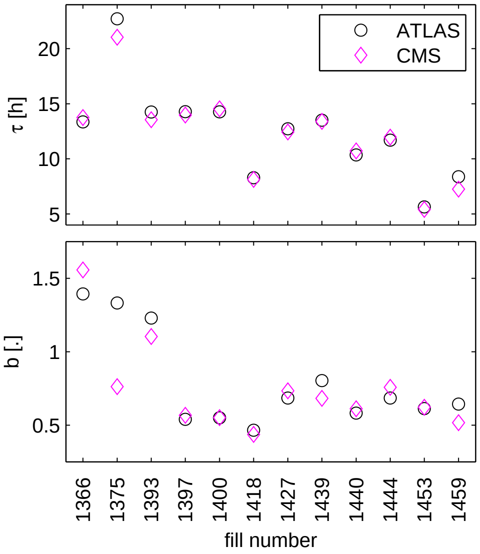

Figure 2: Fit parameters $(\tau, b)$ for different fills, fitting equation (2) to the total luminosity from ATLAS and CMS.

The single beam lifetime was in general excellent (above 100 hours), but it is unfortunately difficult to quantify it precisely. On one side, above a few hundred hours it cannot be measured precisely by the fBCT algorithm used for the displays in the control room [6]. On the other side, squeezed but not colliding beams were never kept for a long enough time to measure such good lifetimes precisely with an offline algorithm.

The losses then increase when the beams are put into collisions (e.g. see Figure 4 in the section concerning fill 1459). The intensity lifetime in collisions ($\tau_{b_{1,2}}$) varies between 50 and 120 hours depending on the fill. A parallel sum law relates the intensity lifetime to the lifetimes from all the relevant phenomena, i.e.:

$$\frac{1}{\tau_{b_{1,2}}} = \frac{1}{\tau_{lumi}} + \frac{1}{\tau_{coll}} + \frac{1}{\tau_{gas}} + \ldots \tag{3}$$

The luminosity burnoff can be quantified assuming an average luminosity per collision of $0.4\times10^{32}\text{cm}^{-2}\text{s}^{-1}$ (see Figure 1), 3 collisions per bunch and a cross section of 100 mb, resulting in $1.2 \times 10^5 p/s$ lost or $\tau_{lumi} \cong 230$ hours. The losses on the collimators increase by about two orders of magnitude once the beams are put into collisions, a worst case lifetime was quantified to $\tau_{coll} \cong 120$ hours [7]. The losses due to the presence of residual gas were expected to give about $\tau_{gas} \cong 100$ hours in [3], but were not yet carefully measured at 3.5 TeV. Consequently, a controlled experiment to measure effective growth rates and losses with squeezed but not colliding beams is strongly encouraged in order to have clear indications on single beam parameter evolution.

## BUNCH-BY-BUNCH ANALYSIS

The same functional description in equation (2) can be applied to the single bunch luminosity. The two fit parameters ($\tau$,b) are plotted in Figure 3 for every bunch pair colliding in CMS. The colors are chosen to highlight the head-on collision schedule: red is used for bunches colliding in IP 1 and 5; blue for IP 1, 2 and 5; green for IP 1, 5 and 8; grey for IP 1, 2, 5 and 8. While the "separated" collisions in IP 2 seem to have little impact on lifetime parameters (e.g. no difference between green and grey circles), full head-on collisions in IP 8 modify the luminosity decay sensibly (e.g. red versus green circles).

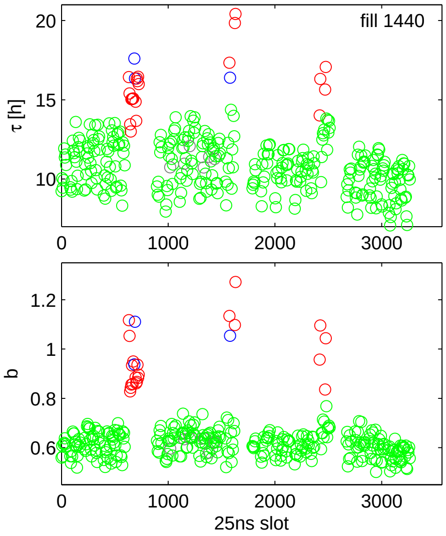

Figure 3: Fit parameters ($\tau, b$) per colliding bunch pair (fill 1440), using equation (2). Color coding to highlight the head-on collision characteristics: grey circles are used for bunch pairs colliding in all IPs; green for IP 1, 5 and 8; blue for IP 1, 5 and 2; red for IP 1 and 5.

The experimental luminosity curves can also be described phenomenologically well by the sum of two exponential functions, even though this description does not reflect the physical processes behind the phenomena. This description divides the behaviour in a fast and a slow component (time constants of about 3 and 30 hours), and it can be seen that while the fast component shows a dependence on the collision pattern, the slow component does not. This is a reminder of how the beam-beam effect is strongest at the beginning of the collision phase, where the beams are the most intense and the emittances are the smallest.

## SPECIAL FILLS

### *Fill 1459: trains with 50 ns spaced bunches*

In 2010 there has been only one physics fill with 50 ns bunch spaced beams (fill 1459), which consisted of 108 bunches per ring, injected in 9 trains of 12 bunches. With 50 ns spaced bunches clear evidence of electron cloud phenomena was observed already at injection energy: pressure rise, emittance growth, bunch shortening, possibly instabilities especially towards the end of SPS batches [8].

Luminosity lifetimes for this fill were particularly bad, mostly due to the high losses observed. Two plots of bunch-by-bunch losses are shown in Figure 4, for beam 1 and beam 2. In order to derive these plots, the intensities measured by the fBCT are analysed from a few minutes before going into collisions until the end of the physics fill. In Figure 4, the initial 75 minutes are shown and the zero of the time axis corresponds to the moment the beams start colliding. The fBCT intensity before collisions is taken as a reference and the intensity lost from then on is plot as loss in per cent, one curve per bunch. The line colors are chosen so to highlight three different families of bunches. In red, bunches which experience sudden losses (limited by the fBCT data being logged in 1 vector per minute). In blue, bunches for which the total losses are important (up to about 30% after one hour from collisions), but develop continuously over time. In green all other bunches.

A more detailed study shows that red bunches were sitting at the end of SPS batches, hinting a possible e-cloud related phenomenon. Blue bunches instead correspond to mid-batch positions, hinting beam-beam related issues. Unfortunately, the lack of statistics for this configuration (only one fill) does not allow to generalize further the conclusions. More information should be available in the 2011 run, when the aim is for running at either 75 ns or 50 ns spaced bunches.

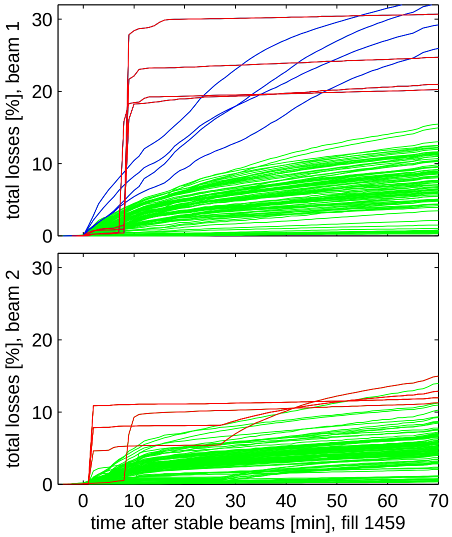

Figure 4: Bunch-by-bunch losses for fill 1459, top plot beam 1, bottom plot beam 2. Color coding: red bunches suffer sudden losses; blue bunches suffer rather big losses which are spread over longer periods of time; all other bunches are plotted in green.

### *Fill 1372: hump on the tune*

The so called "hump" [9] is the manifestation in the tune diagram of an unidentified source of noise, visible in the tune measurement as a higher noise floor in a limited range of frequencies. While the hump is always active, its frequency changes and its effect on the beam (mostly emittance blow up) is visible only when the hump frequency overlaps with the tune. The hump has been observed to be most active on the vertical beam 2 tune.

While looking through luminosity data, one fill (fill 1372) was found to have a particularly "wavy" instantaneous luminosity curve, which was recorded by both ATLAS and CMS and is shown in the first subplot in Figure 5. Looking at the horizontal and vertical emittance derived from luminous region size from the experiments (see Figure 5, second subplot), it seems to be rather evident how the different growth rates in vertical beam size correspond to the different slopes in instantaneous luminosity. Given that the extra emittance growth is observed mostly in the vertical plane, a correlation to the hump activity seemed likely and was later proven by snapshots of the "Hump Buster", an application which shows the tune spectrum as a function of time (e.g. see [9]).

A simple estimation of how much integrated luminosity was lost due to the extra vertical emittance blow up for this fill can be done by recalculating the instantaneous luminosity profile while substituting the vertical emittance with the horizontal emittance, and then integrating over time. The difference in integrated luminosity is around 20%, making the hump rather costly in terms of performance.

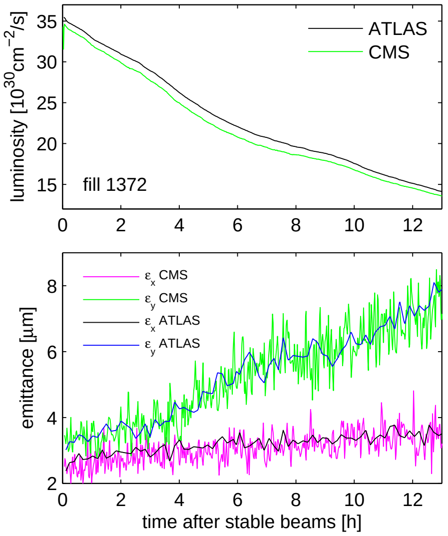

Figure 5: Fill 1372: instantaneous luminosity, top plot, and horizontal and vertical emittance from luminous region, bottom subplot. Changes of slope at about 3, 6 and 9 hours in the luminosity decay correspond to changes of slope in vertical emittance growth.

## CONCLUSIONS AND FUTURE WORK

In this paper a first analysis of the LHC luminosity was set up. The peak luminosity and main beam parameters evolution was looked at for proton physics fills from 25 nominal bunches fills to bunch trains. This showed how the luminosity per bunch was increased by a factor three over time by slowly increasing the bunch intensity and decreasing the emittance. The luminosity lifetime for different fills was characterized with a parametric law (rational of fractional power), highlighting differences between different fills. In order to quantify the impact of different phenomena, dedicated measurements are strongly encouraged, e.g. the evaluation of beam parameters (losses, emittance increase) for squeezed but not colliding beams. A similar analysis was presented for a single fill, looking at bunch-by-bunch differences, confirming that beam-beam related phenomena are stronger in the beginning of the physics period. A couple of fills were looked into a bit more detail, to show the impact of 50 ns bunch spacing and of the hump. All this analysis should be repeated in the future, promptly and on a fill-to-fill basis, so to better correlate observed variations with possible causes.

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