LUMINOSITY LIFETIME AT THE LHC IN 2012 PROTON PHYSICS OPERATION

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Abstract

In 2012, the LHC was operated at 4 TeV at top energy with beam parameters that allowed exceeding a peak instantaneous luminosity of 7500 $\mu b^{-1} s^{-1}$ and a total of 23 fb^{-1} integrated luminosity in the ATLAS and CMS experiments. This paper elaborates on the evolution of the LHC luminosity and luminosity lifetime during proton physics fills and through the year 2012. Bunch to bunch differences and the impact of different machine settings are highlighted.

INTRODUCTION

Luminosity is a key factor for the performance of a particle accelerator, linking the event cross-section to the event rate which the experiments can measure. For two colliding bunches of Gaussian and equal shape, the instantaneous luminosity is given by

$$L = \frac{N_1 N_2 f_{rev} \gamma}{4\pi\beta^* \sqrt{\varepsilon_x \varepsilon_y}} S \quad (1)$$

where N_1 (N_2) are the bunch intensities in beam 1 (beam 2), γ is the relativistic factor, β^* the value of the beta function at the interaction point, ε_x (ε_y) the normalized emittances in the horizontal (vertical) planes and S the geometric factor due to the crossing angle. The total instantaneous luminosity is given by summing over all colliding bunch pairs. Given L and $N_{1,2}$, solving Eq. 1 for $\varepsilon_x \varepsilon_y$ allows deriving the emittances assuming round and equal beams, details of the algorithm used can be found in [1]. This is crucial as no device providing reliable measurements of the absolute transverse emittance for physics production beams at flat-top energy was available in 2012.

Due to the intensity losses and the emittance growth while in collisions, the luminosity decays over time. The lifetime, quantified by fitting a single exponential to a certain domain of the luminosity curve, is not constant throughout the physics production part of a fill in the LHC. In 2012, it typically started at ~7 h and got to ~14 h after some hours in collisions. Bunch-to-bunch differences were also observed on the luminosity lifetime.

LHC LUMINOSITY IN 2012

In 2012, the LHC was operated at 4 TeV. Figure 1 shows the evolution of the main beam parameters throughout the year with programmed stops for scheduled maintenance (Technical Stops, TS) and Machine Development (MD) blocks indicated. Also, by the end of July 2012, multiple machine parameters were changed in order to improve the stability, which, along a change of the SPS optics, allowed to inject higher brightness bunches to the LHC. In particular, the following changes were made:

- July 26 (Fill 2880): Increase of the bunch length target for the ramp from 1.2 ns to 1.3 ns to increase the beam stability.
- August 4 (Fill 2911): Increase of the chromaticity to probe the stability region.
- August 7 (Fill 2921): Octupole polarity change.
- August 12 (Fill 2957): New Q20 optics [2] made operational in the SPS allowed to inject higher brightness bunches to the LHC.

While the peak luminosity (Fig. 1a) was increased throughout 2012 thanks to the higher bunch intensity (Fig. 1b), the luminosity lifetime got worse (Fig. 1d). A correlation of the luminosity lifetime to the increased losses and the increased bunch-by-bunch loss differences after the increase of the bunch length target was identified and will be further elaborated on in the next section.

Over the year, the integrated luminosity per fill (Fig. 1e) increased for short fills (less than 3 h in collisions) due to the increased peak luminosity. For long fills (e.g. 10 h in collisions) however, the decreased luminosity lifetime impaired this gain. In total, the LHC delivered an integrated luminosity of more than 23 fb^{-1} to the high-luminosity experiments ATLAS and CMS in 2012.

BUNCH-TO-BUNCH DIFFERENCES

The LHC features a 400 MHz RF system corresponding to a bucket length of 2.5 ns and a harmonic number of $h = 35640$ [3]. For most proton physics production fills in 2012, the LHC was filled with 50 ns spaced bunches. In the SPS, trains of 36 bunches from the PS preinjector complex were combined to form SPS batches of 72 or 144 bunches, which were then injected to the LHC. Figure 2 depicts LHC ring 1 fully filled according to an operational filling scheme of 2012.

Due to the large amount of bunches experiencing different conditions both in the injector chain and the LHC, bunch-to-bunch differences in beam paramerters are expected. In the following, two effects which affected the luminosity on a 10% level in 2012 are highlighted. The impact of other bunch-by-bunch differences observed, e.g. the difference in initial intensities of the first 6 bunches of each 36 bunch PS batch, was significantly lower.

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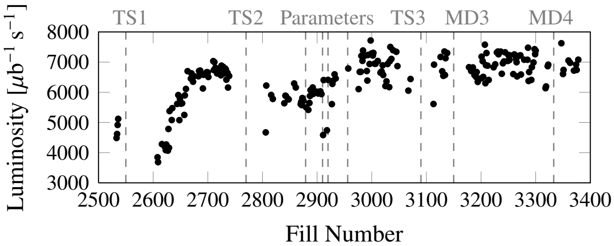
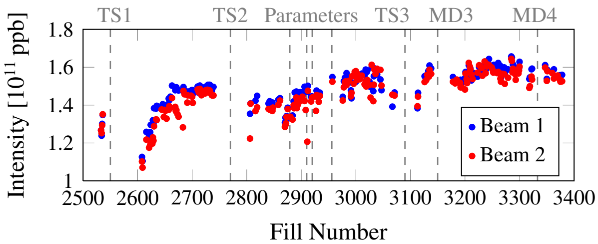
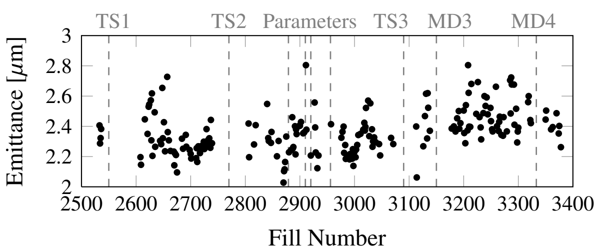


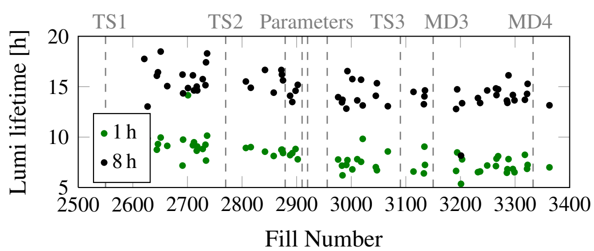
(a) Peak luminosity, ATLAS data



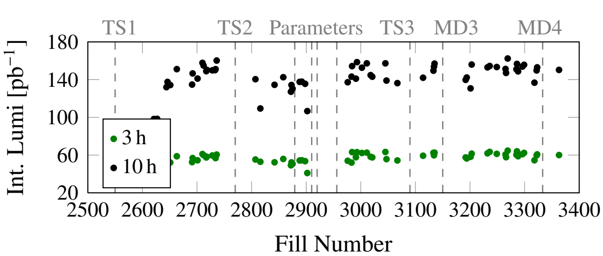
(b) Intensity at the start of collisions



(c) Transverse emittance at the start of collisions, derived from the peak luminosity



(d) Luminosity lifetime after 1 h and 8 h of collisions, based on ATLAS luminosity data



(e) Integrated luminosity in 3 h and 10 h of collisions, based on ATLAS luminosity data

Figure 1: Evolution of main beam parameters throughout 2012. The dashed lines indicate Technical Stops (TS), Machine Development (MD) blocks and changes of settings. For (a), (b) and (c), all fills successfully brought into collisions are taken into account, while (d) and (e) are limited to fills which lasted at least 10 h in collisions.

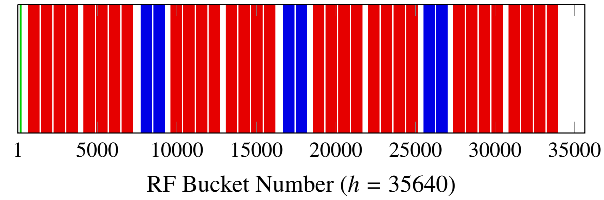


Figure 2: The LHC filling scheme for Beam 1 used in 2012, consisting of 8 batches of 144 bunches (red), 3 batches of 72 bunches (blue) and 6 witness bunches (green). The filling scheme for Beam 2 is identical apart from the position of the witness bunches.

Bunch-by-Bunch Loss Pattern

For long fills, a very reproducible pattern of integrated intensity losses was observed for Beam 1 in both 2011 [4] and 2012 [5], while such a pattern was always negligible, if present at all, for Beam 2. The integrated losses of bunches in Beam 1 after several hours of collisions heavily depend on the length of the proceeding gaps without beam, as depicted in Fig. 3. In particular, the first ~30 bunches of each SPS batch in Beam 1 lose up to 10% less intensity compared to later bunches of the same batch, and the first ~60 bunches of the first SPS batch after the large LHC dump kicker gap lose less than the same bunches in later batches (lower blue line in Fig. 3). The impact of the SPS injection kicker gap between the PS trains of 36 bunches is also visible. The pattern remains visible at the same level on the residual losses when removing the luminosity burn-off component.

The reason for this loss pattern is still unknown, in particular, no correlation to beam-beam long-range encounters is observed. However, after the increase of the target bunch length target for the ramp from 1.2 ns to 1.3 ns (fill 2880), an increase in losses of bunches coming later in SPS batches was observed. The losses of the first bunch of each SPS batch remained at the same level despite of the bunch length increase. This hints that the loss structure is a result of longitudinal losses.

Figure 3: Integrated losses of Beam 1 for fill 3363 after 11 h in collisions, grouped by SPS batches of 144 bunches each.

The impact of the intensity loss pattern of Beam 1 was observed on the bunch-by-bunch luminosity lifetime calculated from ATLAS luminosity data after several hours in collisions. Also, the increase of average losses after the bunch length increase lead to a lower average luminosity lifetime. Comparing fills before and after, the decrease in luminosity lifetime was ~1.5 h in the long term, corresponding to ~7% less integrated luminosity for a fill lasting 11 h in collisions (assuming the same initial luminosity).

End-of-Squeeze Instabilities

In the second half of 2012, after Technical Stop 3 (TS3 in Fig. 1), instabilities of the yet non-colliding beams were frequently observed at the end of the betatron squeeze [1, 5]. These instabilities, while generally neither causing significant intensity losses nor beam dumps, lead to an increase of the transverse emittances of affected bunches from ~2.4 μm to ~3 μm. This created two "families" of bunches distinguished by their transverse emittance at the start of collisions. While in collisions, bunches of the 3 μm family developed a shorter bunch length and higher intensity losses, possibly due to a limitation in off-momentum dynamic aperture. These instabilities are subject to current accelerator physics studies [6].

The main impact on luminosity is emittance-driven. Fills with up to 70% of all bunches in the 3 μm family were observed in late 2012, corresponding to a loss of up to 10% of both peak and integrated luminosity for particular fills. The impact is visible in Fig. 1c as an increase of both the average and the fill-to-fill spread of the transverse emittance at the start of collisions after TS3. As the transverse emittance depicted in Fig. 1c is averaged over all bunches, the increase observed represents the fraction of bunches in the 3 μm emittance family.

CONCLUSIONS

In terms of integrated luminosity, the LHC showed an outstanding performance for the 2012 run, exceeding the initial target by delivering more than 23 fb^{-1} to the high luminosity experiments. However, while the peak luminosity was gradually increased throughout the year, the decreased luminosity lifetime turned out to limit the integrated luminosity reach. In particular, later offline analysis showed that an increase in bunch length in June 2012 affected the integrated luminosity on a ~7% level due to the decreased luminosity lifetime.

Furthermore, bunch instabilities at the end of the squeeze were frequently observed in the second half of 2012 an lead to an increased transverse emittance of the affected bunches. The increase in emittance decreased both the peak and the integrated luminosity of particular fills by up to 10%.

FUTURE WORK

A major part of the future project is to develop a luminosiy model for a better understanding of the evolution of the beam parameters and the luminosity over the course of a fill. The model will likely be based on the well-established Tevatron luminosity model [7], which has already been successfully applied to the LHC previously [8, 9]. This model uses a set of coupled ordinary differential equations to simulate the evolution of main beam parameters for both beams, in particular the intensity, the momentum spread and the transverse emittances. Therefore, the lack of reliable and calibrated measurements of the transverse emittance for physics fills in 2012 makes it difficult to adapt the model to the operational machine parameters of 2012, since there is no way to directly verify the simulation results.

Simulations run on a preliminary set of model parameters match the observed luminosity evolution reasonably well and indicate that the off-momentum acceptance of the machine in collisions was significantly lower in 2012 compared to 2011 operation, leading to a shorter asymptotic bunch length and increased longitudinal losses. If confirmed, these results could explain the increased losses observed after the increase of the bunch length target in mid-2012.

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