

MONITORING AND MODELING OF THE LHC LUMINOSITY EVOLUTION IN 2017

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Abstract

In 2017, the Large Hadron Collider (LHC) restarted operation at 6.5 TeV, after an extended end-of-the-year stop, scheduled to deliver 45 fb^{-1} to the two general-purpose experiments. Continuous monitoring of the key beam parameters and machine configurations that impact the delivered luminosity was introduced, providing fast feedback to operations for further optimization. The numerical model based on simulations and use of selected machine parameters to estimate the machine luminosity was further developed. The luminosity evolution and comparisons to the model predictions is presented in this paper. The impact of the dynamic variation of the crossing angle, which was incorporated into nominal LHC operation, is also discussed.

INTRODUCTION

As in every collider, the estimator of performance is the luminosity delivered to the experiments. The dominant factors in the luminosity estimate are the emittances and the intensities of the colliding bunches. For the 2017 run, LHC incorporated the Achromatic Telescopic Squeeze (ATS) [1] optics scheme, squeezing the beams initially to a β^* of 40 cm and later to 30 cm. A step-wise reduction of the crossing angle [2] was also introduced to regain some of the luminosity lost naturally during collisions. In addition, three bunch schemes were used: the Bunch Compression Merging and Splitting (BCMS, sub-trains of 12 filled slots), 8b4e (8 filled followed by 4 empty slots) and the Bunch Compression and Splitting (BCS), similar to 8b4e bunches, but with lower transverse emittances [3]. These schemes differ in brightness, as well as in their response to electron cloud (e-cloud) effects.

Close monitoring of the beam parameters at a bunch-by-bunch level, exploiting the full instrumentation toolkit of the LHC provides valuable input for machine operation and the means to further optimize performance. In this paper, we present the evolution of the emittance and intensity parameters along the year and their impact on luminosity production. Experimental observations are compared to numerical simulations to identify additional sources of degradation.

EMITTANCE EVOLUTION

The emittance evolution of the LHC beams is dominated by intrabeam scattering (IBS) at the injection energy and during the acceleration stage. During collisions a combination of IBS, Synchrotron Radiation (SR), beam-beam and noise effects cause emittance blow-up. A numerical model

was developed to estimate the evolution of the transverse emittances and the bunch length, based on MAD-X [4, 5] and parametrised using simple fit functions [6, 7].

The injected bunches arrive into the LHC with average (of both beams and planes) emittance of $(1.7 \pm 0.2) \mu\text{m}$ for the BCMS beams, $(1.9 \pm 0.1) \mu\text{m}$ for the 8b4e and $(1.2 \pm 0.1) \mu\text{m}$ for the BCS beams. For all beam flavors the injected emittances follow the brightness of the injectors. Since the injection plateau lasts ~ 40 min, the impact of IBS and e-cloud results in emittance growth. Numerical modelling predicts a growth of $0.3 \mu\text{m h}^{-1}$ in the horizontal plane for the BCMS and 8b4e bunches, while for the brighter BCS beam, a growth of $0.5 \mu\text{m h}^{-1}$ is estimated. No growth is expected in the vertical plane, since coupling is not included in the model. A growth of $(0.6 \pm 0.2) \mu\text{m h}^{-1}$ is observed for the BCMS beams which are affected by the e-cloud effects, and $(0.4 \pm 0.2) \mu\text{m h}^{-1}$ for the other beams, for which e-cloud build-up is significantly reduced. In the vertical plane, a growth of $(0.3 \pm 0.1) \mu\text{m h}^{-1}$ is observed, which is not expected from the model.

During the acceleration of the protons to top energy, emittance measurements are not reliable, due to the light source change of the Beam Synchrotron Radiation Telescope (BSRT), used for the measurement. Based on the values at the start and at the end of the ramp, a large relative blow-up in emittance is observed, with beam-1 growing more than beam-2. Among the different beam flavors, the BCS seems to have the largest blow-up during the ramp for beam-1 (56%), while having the smaller for beam-2 (10%). The horizontal plane of beam-1 seems to suffer the most, while for beam-2 the vertical is more affected. Finally, no blow-up is observed in the special 2.51 TeV fills, where the acceleration process lasted 3 times less than the nominal 6.5 TeV fills and the ramp scheme was updated [8].

After a short period at top energy, which does not contribute to the emittance evolution, the collision process starts. Figure 1 shows the average transverse emittances of beam-1 and beam-2, for the two planes, at the start of collisions for all production fills of the run. Four different measurement methods are shown. The measurement using the BSRT, is compared to emittance scans [9] performed during operation. The observations are complemented with emittance measurements extracted by the luminosity and luminous region provided by the two high luminosity experiments (ATLAS, CMS). This is possible since their crossing planes are rotated by 90° , to passively compensate the tune shift due to the long range beam-beam interactions, and therefore have different luminosity geometric factors. For most of the year, the different methods agree well within the un-

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certainties of each measurement. However, there are clear periods where the BSRT measurements are diverging. This behavior calls for a re-calibration of the instrument, making the monitoring of the emittance evolution crucial for good quality data taking. In terms of absolute numbers, at the start of collisions the two beams appear to be round with BCMS bunches having $(2.3 \pm 0.2) \mu\text{m}$ horizontal emittances for both beams, with a small asymmetry on the vertical plane at $(2.3 \pm 0.3) \mu\text{m}$ and $(2.1 \pm 0.2) \mu\text{m}$ for the two beams. The 8b4e bunches have $(2.7 \pm 0.2) \mu\text{m}$ and $(2.3 \pm 0.2) \mu\text{m}$ in the horizontal plane and $(2.9 \pm 0.2) \mu\text{m}$ and $(2.4 \pm 0.2) \mu\text{m}$ in the vertical, for beam-1 and beam-2 respectively. Finally, the BCS bunches have smaller emittances, as expected, but a discrepancy of $\sim 0.5 \mu\text{m}$ is observed between the two beams, with average values $(2.2 \pm 0.1) \mu\text{m}$ and $(1.4 \pm 0.1) \mu\text{m}$ for the horizontal and $(2.1 \pm 0.2) \mu\text{m}$ and $(1.5 \pm 0.1) \mu\text{m}$ for the vertical plane. In this last period the beams appear to be non-round.

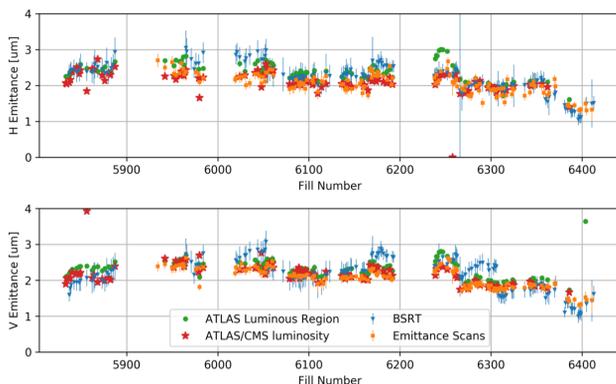


Figure 1: Emittances estimated using different instrumentation techniques at the start of collisions.

Finally, during the collision process, the evolution of the emittances is affected mainly by IBS and SR. Comparing observations and simulations in Figure 2 at the 5 h mark, an additional emittance growth of $<0.05 \mu\text{m h}^{-1}$ is observed in the horizontal plane and $\sim 0.1 \mu\text{m h}^{-1}$ in the vertical plane of both beams. No correlation of the extra growth to brightness was found. The extra vertical growth is larger by a factor 2 compared to the previous run [10].

INTENSITY EVOLUTION AND BEAM LOSSES

The intensity evolution of the two LHC beams, apart from the natural decay is affected by the losses of large amplitude particles, both in the transverse and the longitudinal planes, which are cleaned by the collimation system. Defining as "effective" cross-section the intensity loss rate normalized to the average delivered luminosity, these additional losses can be quantified. If luminosity burn-off would be the only source of beam losses, this estimator should be equal to the proton inelastic cross-section of 81 mb. The effect of elastic and diffractive scattering on the beam, does not lead to significant losses. Figure 3 shows the effective cross-section

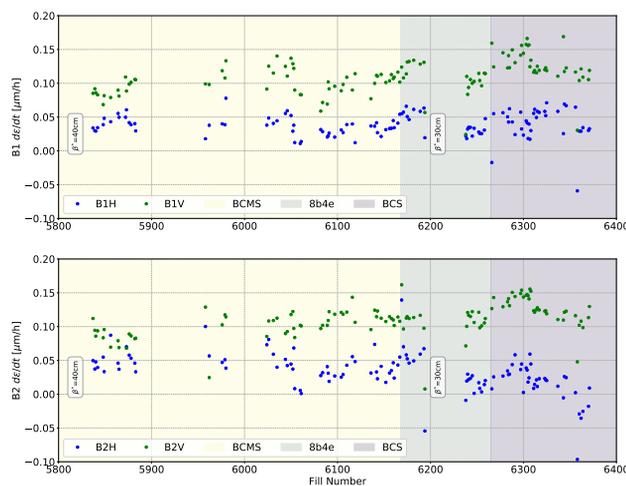


Figure 2: Additional emittance blow-up, on top of the model predictions for the two beams and the two planes.

calculated at 1 h in collisions for the two beams. The error bars correspond to the bunch-by-bunch statistical RMS uncertainty. Clearly, beam-1 has more losses than beam-2. Overall, in 1 h the average effective cross-section of beam-1 is $(92.7 \pm 6.1) \text{ mb}$, while for beam-2 is $(82.8 \pm 3.5) \text{ mb}$. The losses seem almost constant among the different beam flavors and therefore no correlation to brightness is observed. In addition, the LHCb dipole polarity, which changes the total crossing angle of the experiment and therefore changes the impact of the long range beam-beam interactions, seems to have no effect throughout the year, within errors. Finally, the change of the β^* within the run, did not impact the losses. In terms of intensity lifetime, the two beams start colliding with lifetimes of $(19.2 \pm 3.0) \text{ h}$ and $(28.4 \pm 3.0) \text{ h}$, respectively and after 1 h they reach the level of $(26.9 \pm 2.2) \text{ h}$ and $(30.8 \pm 2.1) \text{ h}$. The dynamic variation of the crossing-angle only slightly affects the lifetime of the two beams, if the working point is well controlled [2].

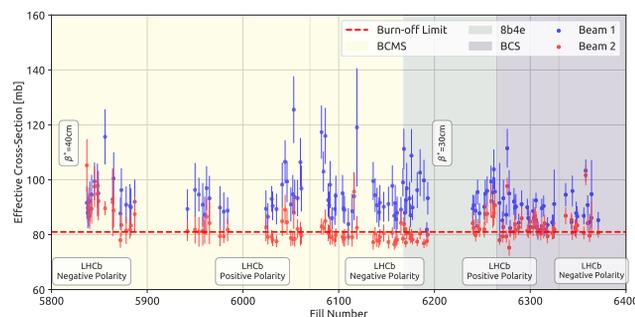


Figure 3: Effective cross-section at 1 hour in collisions as a function of the fill number.

Moreover, as in the previous run, increased losses not related to luminosity production are observed at the start of all fills [10]. These losses decay quickly approaching a constant plateau close to the burn-off limit. Comparing to the past results, in 2017 these losses decay $\sim 30\%$ faster.

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Using the data from the collimation system, a deconvolution of the losses can discriminate between the two transverse planes. In Figure 4, the evolution of total losses is shown for beam-1 for the two planes, including the off-momentum protons. In addition, the percentage of losses related to burn-off are plotted for the two beams. The losses in the first hour are clearly more for beam-1, while a loss of $\sim 10\%$, above burn-off, in total is observed at the end of the fill.

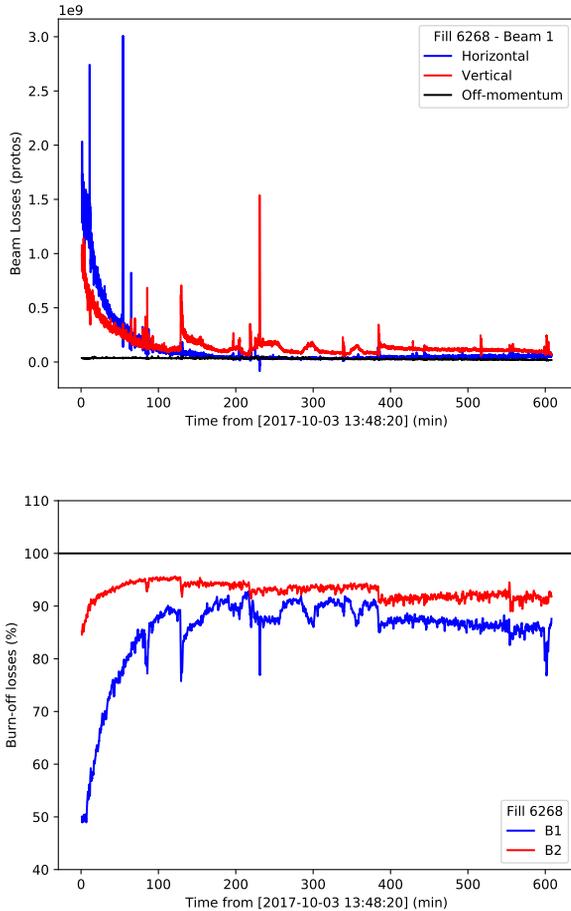


Figure 4: Evolution of the beam-1 losses for a selected fill, deconvolved for the two planes and the off-momentum protons, as seen by the collimation system (top). Time evolution of the percentage burn-off losses for the two beams (bottom).

DELIVERED & LOST LUMINOSITY

The luminosity estimated by the machine parameters is compared to the one measured by the experiments. Figure 5 shows this comparison in terms of the average peak bunch luminosity. A good agreement at the level of 3% is found along the year. Fills where leveling by separation was imposed are not taken into account.

An imbalance can occur if the beams are significantly non-round, due to the configuration of the crossing planes of the two experiments. This imbalance is shown in the bottom plot of Figure 5 and is found to be improved by a factor

2 compared to the previous run, resulting in an average of $<5\%$.

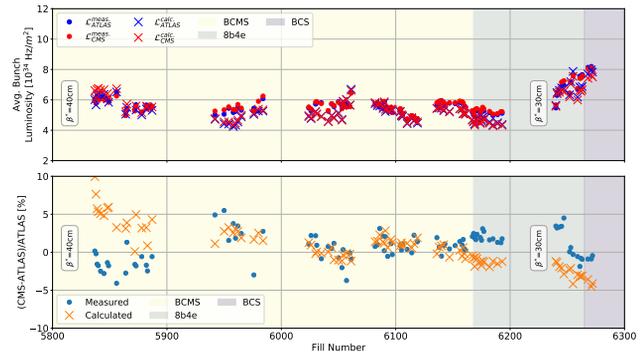


Figure 5: Comparison of the measured and calculated average bunch peak luminosity and the imbalance between the two high luminosity experiments.

To calculate the luminosity loss from the observed intensity losses and emittance blow-up, the measured values are fed into the model. The results are normalized to the pure expectation of the model, which estimates the evolution of the intensity and the emittances, based only on the respective initial conditions. Figure 6 shows the luminosity loss from the two sources. The largest impact on the result is attributed to the extra emittance growth, while the intensity losses have a smaller effect. In total, an integrated luminosity loss of 15%, is estimated from adding all sources.

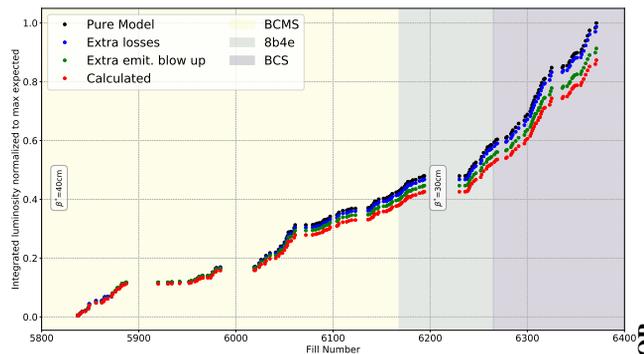


Figure 6: Cumulative integrated luminosity loss normalized to the model expectation for the ATLAS experiment.

CONCLUSION

Despite the operational challenges during the run [11], LHC exceeded the luminosity goal, delivering to ATLAS and CMS $>50 \text{ fb}^{-1}$. The continuous monitoring of the machine parameters was crucial for providing feedback for the machine operation. Additional sources of luminosity degradation were found in terms of emittance blow-up and extra intensity losses. Additional studies are performed to identify the responsible underlying physics mechanisms.

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