# EMITTANCE, INTENSITY AND LUMINOSITY MODELING AND EVOLUTION

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*Abstract*

The LHC luminosity model developed to describe and follow the evolution of the machine luminosity is presented and compared to 2017 data. The model is based on the main mechanisms of luminosity degradation, such as intrabeam scattering, synchrotron radiation, elastic scattering and luminosity burn-off. It was initially introduced for the 2016 run. For the 2017 run, the model estimates are compared with data at the Flat Bottom (450 GeV) and Flat Top (6.5 TeV) energies. The evolution of the emittance and beam lifetime are presented for the entire 2017 run, and the results are compared to the 2016 observations.

## INTRODUCTION

The luminosity, the ratio of the number of events detected in a certain time to the interaction cross-section, is a macroscopic indicator of the global collider performance [1]. The bunch-by-bunch (bbb) variations in the transverse and longitudinal emittances as well as in beam intensity, impact the delivered luminosity. In order to understand the impact of different degradation mechanisms on the luminosity, a bbb model was developed [2]. It is based on the three main mechanisms that determine the luminosity evolution in the LHC: intrabeam scattering (IBS), synchrotron radiation (SR) and luminosity burn-off. It was compared to the data from the 2016 run of the LHC [3].

In this paper, a short description of the model is given. At first, the periods of the 2017 run, corresponding to different beam flavors are discussed. The luminosity imbalance between the experiments of ATLAS and CMS along the year is shown. The extra emittance blow up (on top of IBS, SR and elastic scattering) and extra losses (on top of the expected proton burn off as calculated considering only the inelastic hadron cross-section of 81 mb) are presented for the 2017 data. The luminosity evolution as calculated by the model and as measured by the experiments is given for some fills. Finally, the 2017 cumulated integrated luminosity reveals the impact of the different degradation mechanisms on the delivered luminosity.

## LUMINOSITY MODEL

The bbb luminosity model, that can be applied for both colliding and non-colliding bunches, takes into account intrabeam scattering (IBS), Synchrotron Radiation (SR), proton-proton collisions elastic scattering and burn-off. The IBS, SR and elastic scattering are considered for the emittance growth. The bunch length calculation is based on the IBS and SR effects. The burn-off decay time is considered for the bunch current evolution [1]. Then, the evolution of the beam parameters and the luminosity can be calculated in a self-consistent way by iterating in small time-steps, so that to have a small current variation in each time-step. The luminosity model is described in detail in [2]. Some additional features included in the model during 2017 are the luminosity leveling and the crossing angle anti-leveling.

The infrastructure allows the user to select the model or the data for each specific parameter in a transparent manner. Basically, it is possible to take from the data the evolution of the emittance, the bunch length or the intensity and let the model calculate the remaining beam parameters. In this way, the luminosity estimation can be a result of combining information coming from data and from what is expected from the model. The four different data-model combinations to calculate luminosity are the following:

1. "Pure model"
    - Initial values of bunch intensities, emittances and bunch length taken from the data
    - Model iteration to compute intensity, emittance, bunch length and luminosity evolution
2. "EmpiricalBlowUpBurnOff"
    - Transverse emittance evolution taken from the data
    - Model iteration to compute bunch intensity, bunch length and luminosity evolution
3. "IBSEmpiricalLosses"
    - Intensity evolution taken from the data
    - Model iteration to compute emittance, bunch length and luminosity evolution
4. "EmpiricalBlowUpEmpiricalLosses"
    - Intensity and emittance evolution taken from the data
    - Model iteration to compute luminosity evolution

[1] In the case of the LHC with very small beta functions at the interaction points, only the inelastic part of the proton-proton collisions is expected to contribute to the burn-off losses. The elastic part is causing transverse emittance blow up.

## THE 2017 RUN PERIODS

An automated tool for the LHC performance follow-up (emittance, lifetime, luminosity, etc.) that is based on extracted data from the logging system (CALS) [4] was developed during 2017. The luminosity model is also included and can be applied for each fill. Using this tool, only fills that made it to stable beams are considered for the statistics.

In 2017 different beam flavors were used for the LHC operation; the BCMS (fills 5830-6165), the 8b4e (fills 6167-6263) and the 8b4e BCS (after fill 6266) which correspond to transverse emittances that are respectively around 2.3 µm, 2.6 µm and 1.7 µm. In order to increase the luminosity, the high brightness 25 ns beam [5] produced with the Batch Compression bunch Merging and Splitting (BCMS) scheme [6, 7] was used in the beginning of the run. Later in 2017, the BCMS beam was replaced by the 8b4e beam which consists of trains of eight bunches spaced by 25 nanoseconds and four empty bunch slots. Even if the 8b4e beam pattern gives a lower number of bunches (from 2556 BCMS goes down to 1920 8b4e beams) due to the empty bunch slots, it suppresses the formation of electron clouds [8] compared to the standard beam [2]. Then, the LHC started to exploit the ATS optics [9] by reducing the $\beta^*$ from 40 cm to 30 cm, increasing the virtual luminosity for the experiments. The 8b4e BCS (Batch Compression and Splitting) beam, which is a brighter version of the 8b4e beam, was delivered to the LHC on October in order to push further the luminosity.

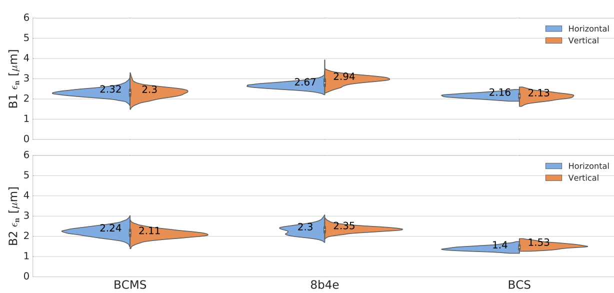


Figure 1: The horizontal (blue) and vertical (orange) emittances at the start of SB versus beam type, for beam 1 (top) and beam 2 (bottom).

Figure 1 shows the horizontal (blue) and vertical (orange) emittances at the start of SB averaged over all the fills of a specific beam type, for beam 1 (top) and beam 2 (bottom). The fills that are used for these statistics are only the ones that correspond to time periods where the BSRT (Beam Synchrotron Radiation Telescope) [10, 11] is well calibrated. More information concerning the measured emittances throughout the nominal LHC cycle can be found in [12].

[2] As a result of the minor electron cloud activity induced, the reduction of the heat load with 8b4e is significant.

## LUMINOSITY IMBALANCE ALONG THE YEAR

Due to the vertical/horizontal crossing scheme in ATLAS and CMS, non-round emittances yield an imbalance in the luminosity delivered to the two experiments, as a result of the geometric reduction function difference. In order to evaluate this effect, the bbb peak luminosity for all the fills was calculated based on the measured bunch parameters (transverse emittances, bunch intensity, bunch length) at the beginning of stable beams, for both experiments. The average peak bunch luminosity per bunch as measured by the experiments (dots) and as calculated based on the beam parameters (crosses) is plotted versus the fill number in Fig. 2 (top) [12]. The periods that correspond to the different beam flavors are color coded, the TS1 and TS2 lines correspond respectively to the first and the second technical stop in 2017. The agreement between the measured and the calculated luminosity is fairly good. The measured (blue dots) and calculated (orange crosses) difference between the CMS and ATLAS luminosity per fill number is presented in Fig. 2 (bottom). ATLAS and CMS measure the same luminosity within 5%. The last period (marked in gray) is not taken into account because the luminosity exceeded the maximum acceptable by the trigger systems of the experiments and levelling by separation was imposed. For most of the 8b4e and BCS fills, the calculated luminosity differs from the measured one and that is because of BSRT calibration issues. Since the measured-calculated difference indicates how accurate are the beam parameters used for the calculated luminosity, these results can be used to validate the data quality.

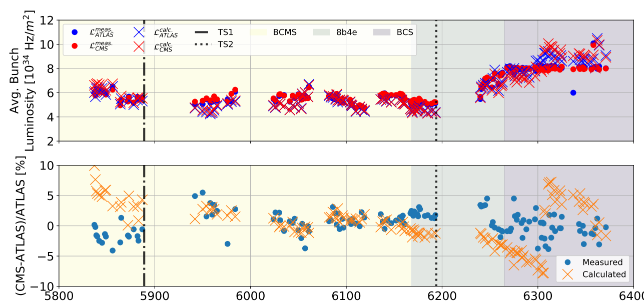


Figure 2: Average peak luminosity per bunch as measured by the experiments (dots) and calculated by the beam parameters (crosses) per fill number (top). Measured (blue dots) and calculated (orange crosses) difference between the CMS and ATLAS luminosity per fill number (bottom).

## EXTRA EMITTANCE BLOW UP

Since 2016, analysis is on going to understand the possible mechanisms that induce the observed extra transverse emittance blow up, that is mainly observed during the ramp. The extra emittance blow up along the year can be found by comparing for each fill the measured emittance growth to the expected one from the model, following the intensity evolution from the data. Fig. 3 shows the measured-model emittance difference per hour, for B1 (top) and B2 (bottom), at 5 h in SB. The blue and green dots correspond to the horizontal and vertical planes, respectively. Excluding the fills before BSRT recalibrations, the $d\epsilon/dt$ is practically constant over the year, including leveling fills (i.e. almost all BCS fills). Also, this ratio remains almost the same

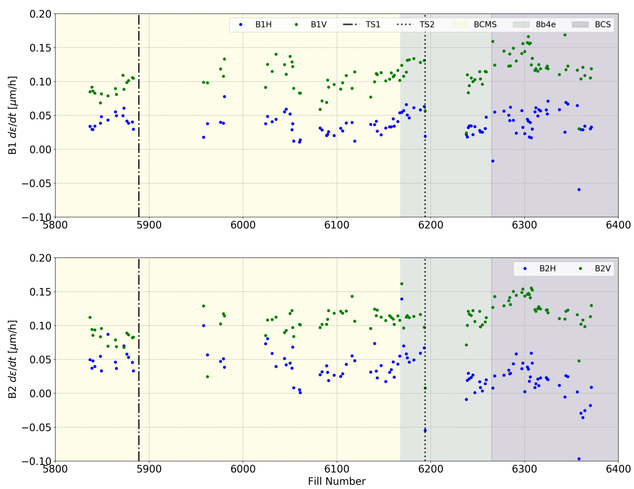


Figure 3: The measured-model emittance difference per hour at 5 h in SB, for B1 (top) and B2 (bottom), for the horizontal (blue dots) and vertical (green dots) plane.

when staying for more than 2 h at SB. For both beams, the measured-model emittance difference is less than 0.05 µm/h for the horizontal and ~0.1 µm/h for the vertical plane. The exact values of the $d\epsilon/dt$ for the different beam flavors and for both beams and planes can be found in Table 1. For the 2016 fills, this difference was for both planes around 0.05 µm/h [3]. As in 2016, the observed extra emittance growth is independent of the bunch brightness.

Table 1: IBS growths of the transverse emittances and energy spread during 1 h at FB energy (450 GeV).

| **Beam Flavors** | **B1 d$\epsilon$/dt** [µm/h] (horiz., vert.) | **B2 d$\epsilon$/dt** [µm/h] (horiz., vert.) |
|---|---|---|
| BCMS | (0.03, 0.10) | (0.03, 0.12) |
| 8b4e | (0.04, 0.11) | (0.04, 0.12) |
| 8b4e BCS | (0.03, 0.11) | (0.01, 0.11) |

## EXTRA LOSSES

For the 2017 physics fills, apart from the luminosity burn-off losses, extra beam losses were observed. In order to understand the size of this effect, the average over all the physics fills beam loss rate normalized to the luminosity, denoted as effective cross-section, is shown in Fig. 4, for beam 1 (top) and beam 2 (bottom). For both beams, fast

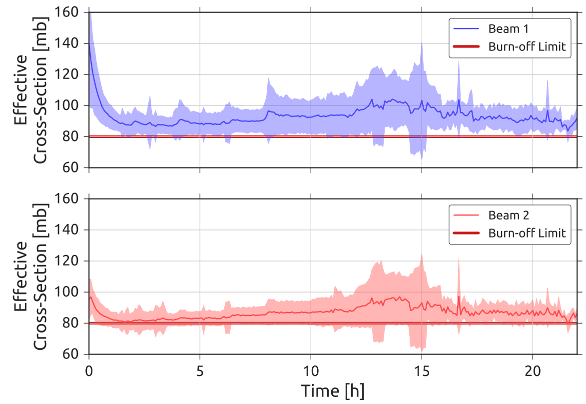


Figure 4: The average over all physics fills of 2017 beam loss rate normalized to the luminosity and the one standard deviation interval, for beam 1 (blue) and beam 2 (red).

losses occur during the first couple of hours in stable beams, while later the losses become burn-off dominated, since they approach the value for the inelastic cross section of the proton-proton collisions that is 81 mb (red solid line). Similarly to the 2016 results, the effect is more pronounced for beam 1 than for beam 2. As compared to the 2016 losses [3], in 2017, the losses reach the burn off limit earlier, having a decay that is 30 % faster. The crossing angle steps (at around 2h, 4h and 8h) induce losses that significantly affect the lifetime. This underlines the importance of performing a smooth crossing angle variation [13].

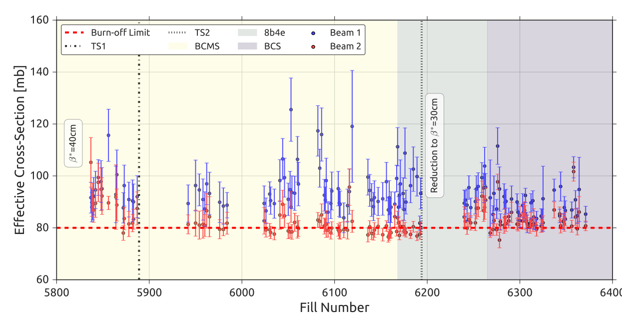


Figure 5: Effective cross section at 1 h in SB along the year, for beam 1 (blue) and beam 2 (red).

The average normalized losses at 1 h in SB for all the fills along the year are presented in Fig. 5, for beam 1 (blue) and beam 2 (red). The red dashed line corresponds to the burn-off limit (81 mb). In agreement with the results shown in Fig. 4, B1 losses are in general higher than the B2 losses. The behavior of the losses is not affected by the reduction of $\beta^*$ after the TS2. Also, it was observed that the LHCb dipole spectrometer magnet did not affect the level of losses. It is interesting to notice that after the emittance reduction the 8b4e BCS beams delivered, the more relaxed settings resulted in smaller losses for both beams, as was predicted by the dynamic aperture (DA) estimations [14]. Therefore, the DA simulations can be used as a guide for tune optimization and loss reduction for different filling schemes, crossing angles, $\beta^*$, etc.

## LUMINOSITY EVOLUTION

In order to understand the possible sources of luminosity degradation, the model was applied to all the production fills of 2017. In Figure 6, the luminosity evolution during a fill as measured by the experiments (gray) is compared to estimates of the pure model (top) and by the "EmpiricalBlowUpEmpiricalLosses" (following the intensity and emittances from data) model (bottom). Practically, Fig. 6 (top) shows how smaller is the integrated luminosity due to the extra emittance blow up and extra losses. For this fill example the empirical model follows very well the measured luminosity, but this is not always the case. Figure 7 shows

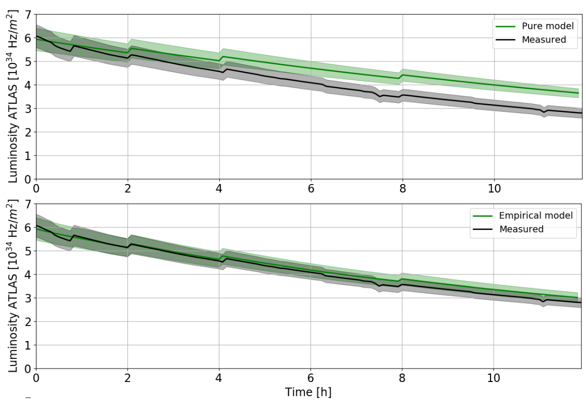


Figure 6: Top: Luminosity evolution comparison between the pure model (green) and measurements (gray). Bottom: Luminosity evolution comparison between the "EmpiricalBlowUpEmpiricalLosses" model (green) and measurements (gray).

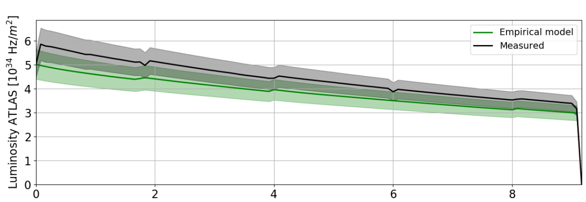


Figure 7: Luminosity evolution comparison between the "EmpiricalBlowUpEmpiricalLosses" (following the intensity and emittances from data) model (green) and measurements (gray).

the luminosity evolution as measured by the experiments (gray) and as computed by the "EmpiricalBlowUpEmpiricalLosses" model (green), for a fill for which the BSRT was not well calibrated. Due to the fact that the model is sensitive to the initial beam parameters, for this example of a fill, the model luminosity is not calculated correctly because of the BSRT calibration issues. In order to understand for which fills the BSRT emittances cannot reproduce the measured luminosity and therefore, where the model-measured discrepancy is expected, the convoluted emittance measurements performed with different methods (i.e. ATLAS Luminous Region, ATLAS/CMS luminosity, BSRT and emittance scans) [12] can be compared. Such comparisons can be used as an additional data quality validation test to discard fills for which the BSRT cannot be trusted.

## IMPACT OF DEGRADATION MECHANISMS ON THE INTEGRATED LUMINOSITY

The accurate predictions the model gives, when using as input valid measured bunch parameters, renders it a very useful tool for understanding the behavior of the luminosity evolution and degradation mechanisms over the year. Considering different data-model combinations which are described earlier in this paper, the model was used for each fill in order to quantify the extra transverse emittance blow up and the extra intensity losses that were observed during collisions. Figure 8 shows the integrated luminosity reduction after 3 h at SB, for ATLAS (top) and CMS (bottom). The integrated luminosity reduction coming from the extra losses and the extra emittance blow up is color coded with blue and green, respectively. Combining both the extra

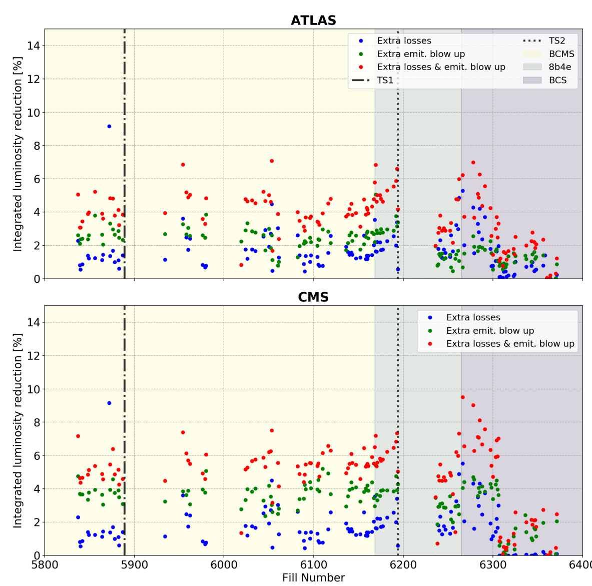


Figure 8: Integrated luminosity reduction after 3 h at SB, for ATLAS (top) and CMS (bottom), due to the extra losses (blue), the extra emittance blow up (green) and for both extra losses and extra emittance blow up (red).

losses and the extra emittance blow up gives the total reduction (red). The contribution of the extra emittance blow-up is in general constant over the year and it is reduced after the TS2, especially for the 8b4e BCS fills after the BSRT calibration (>fill 6307). As was discussed earlier, after the emittance reduction due to the 8b4e BCS beams, the intensity losses were lowered. In agreement with that, the impact of the extra losses on the luminosity degradation is significantly reduced. For the 2017 fills, the integrated luminosity reduction comes mainly from the extra transverse emittance blow up. However, in 2016 the integrated luminosity reduction due to the emittance blow up was rather smooth along the year and the contribution of the extra losses was in many cases larger than the one of the extra emittance blow up [3].

In order to understand the overall impact of the different degradation mechanisms on the delivered 2017 luminosity, the cumulated integrated luminosity normalized to the maximum value expected from the pure model is presented in Figure 9. That is done for the pure model (black), for the case of the "IBSEmpiricalLosses" (including the extra losses) model (blue) and for the case of the "EmpiricalBlowUpBurnOff" (including the extra emittance blow up) model (green). As was expected from the results presented in Fig. 8, the impact of the extra transverse emittance blow up on the delivered integrated luminosity is significant, while the one of the extra losses is quite small. The calculated (i.e. taking into account the extra losses and extra emittance blow up) integrated luminosity that is plotted in red, shows a loss of 15 % compared to the pure model.

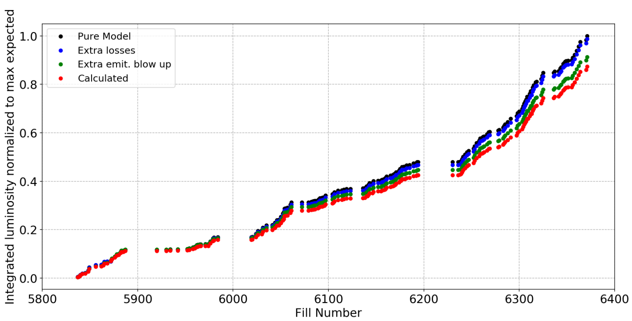


Figure 9: Cumulated integrated luminosity normalized to the maximum value expected from the pure model (black), for the case of including the extra losses (blue), for the case of including the extra emittance blow up (green) and for the calculated (including extra losses & extra emittance blow up) one (red).

## SUMMARY

The LHC luminosity model that was developed to describe and follow the evolution of the machine luminosity is presented and compared to 2017 data. The model that is applied bunch by bunch for all physics fills, is based on the main components responsible for the LHC luminosity evolution (intrabeam scattering, synchrotron radiation, elastic scattering and luminosity burn-off) [2]. During 2017, in the luminosity model some additional features, such as the luminosity leveling and the crossing angle anti-leveling, were included. The fact that the luminosity prediction can be a result of combining measured data and model estimations, renders the model a very useful tool for understanding what are the possible luminosity degradation sources.

For the 2017 LHC operation the different beam flavors used were the BCMS, the 8b4e and the 8b4e BCS. Through the whole 2017 run, the machine performance was followed up with automated tools that are based on extracted data from CALS and modeling. The emittance evolution from injection to stable beams was studied. Apart from the results at stable beams which are presented in this paper, the ones throughout the LHC nominal cycle are discussed in [12].

The comparison between the calculated (based on the bunch characteristics at the start of stable beams) peak luminosity and the one measured by the experiments of ATLAS and CMS was presented. The ATLAS and CMS measure the same luminosity within 5%. The measured-calculated agreement can be used as a data quality check to discard for our statistics fills for which the BSRT emittances cannot be trusted.

An extra transverse emittance blow up (on top of IBS, SR and elastic scattering) was observed in all 2017 fills at SB, as in 2016. In 2017, this extra blow up is less than 0.05 μm/h and around 0.1 μm/h for the horizontal and the vertical plane, respectively. Apart from the extra emittance blow up, extra losses (on top of the expected proton burn off) are present, especially at the first hour in stable beams. As discussed in [15], the change of optics between 2016 and 2017 did not have an impact on the observed extra losses. Similarly to the 2016 results, the extra losses were more pronounced for beam 1 than for beam 2. After the emittance reduction due to the 8b4e BCS beams, the losses for both beams were lowered. The observed intensity losses underline the importance of reviewing the crossing angle anti-leveling, and in particular the evolution of the emittance during leveling.

Due to the fact that the luminosity model is sensitive to initial conditions (i.e. the input bunch parameters), it can accurately follow the measured luminosity only for fills that pass the data quality validation. In order to understand the mechanisms that lead to luminosity degradation, the model was applied to all the production fills of 2017. It was observed that the contribution of the extra emittance blow up to the luminosity degradation is significant, while the impact of the extra losses is small. One of the on-going studies to explain the observed emittance blow up concerns the analysis of the LHC bunch profiles.

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