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# MONITORING AND MODELLING OF THE LHC EMITTANCE AND LUMINOSITY EVOLUTION IN 2018

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*Abstract*

Operating at 6.5 TeV, the LHC surpassed the expectations and delivered an average of 66 $fb^{-1}$ integrated luminosity to the two high luminosity experiments ATLAS and CMS by the end of 2018. In order to provide a continuous feedback to the machine coordination for further optimizing the performance, an automated tool for monitoring the main beam parameters and machine configurations, has been devised and extensively used. New features like the coupling between the two planes and effects of noise, were added to the numerical model used since 2016 to calculate the machine luminosity. Estimates, based both on simulations and on observed beam parameters, were reported fill-by-fill as well as in overall trends during the year. Highlights of the observations including the observed additional emittance blow up (on top of IBS, SR and elastic scattering) as well as additional losses (on top of the expected proton burn off) are presented for the 2018 data. Finally, cumulated integrated luminosity projections from the model for the entire 2018 data based on different degradation mechanisms are compared also with respect to the achieved luminosity.

## INTRODUCTION

The high brightness 25 ns beams [1] produced with the Batch Compression bunch Merging and Splitting (BCMS) scheme [2, 3] were used for the 2018 run. Aiming to gain some of the luminosity lost during collisions, the crossing angle is gradually reduced (anti-leveling process) [4, 5]. In order to increase the integrated luminosity, the beams are initially squeezed to a $\beta^*$ of 30 cm that is further reduced to 25 cm after some hours in collisions according to the ATS (Achromatic Telescopic Squeeze) [6] optics scheme.

The LHC performance is followed up using an automated tool which is based on extracted data from the logging system CALS [7]. In this paper, the transverse emittance along the LHC energy cycle and the beam losses at collisions are discussed for the 2018 run. The comparison of the measurements to the luminosity model [8, 9] assists in understanding the impact of mechanisms which are beyond the existing model, on the emittance growth and therefore, on the luminosity degradation. Intrabeam Scattering(IBS), Synchrotron Radiation (SR) and elastic scattering are considered for modeling the transverse emittance growth. The bunch length calculation is based on the IBS and SR effects. The luminosity burn-off, causing the bunch current decay due to the collisions, is considered for the intensity evolution. Apart from the luminosity leveling and the crossing angle anti-leveling, in 2018 the transverse emittance coupling [10] was included in the model as an additional feature.

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Table 1: Measured (BSRT) Emittance Along the LHC Cycle

| Emittance [μm] | B1H | B1V | B2H | B2V |
|---|---|---|---|---|
| Injection | 1.4 | 1.3 | 1.4 | 1.4 |
| start of Ramp | 1.6 | 1.5 | 1.6 | 1.5 |
| start of collisions | 2.0 | 1.7 | 1.5 | 1.7 |

## EMITTANCE EVOLUTION

In Table 1, the 2018 measured (by the BSRT: Beam Synchrotron Radiation Telescope [11, 12]) emittances along the LHC energy cycle are given for both Beam 1 (B1) and Beam 2 (B2). The average relative emittance growth of both beams and planes, mainly due to the effects of IBS and e-cloud, during a time of ~33 min spent at injection (from Injection to start of Ramp), is less than 15 %.

Overall the emittances along the cycle are smaller compared to previous years of Run 2 [13]. However, based on the expected growth during the energy Ramp and on observations of previous years, the average 2018 measured emittances at the start of collisions seem to be unrealistically small, specially for the horizontal plane of B2. That is probably due to the 20 % accuracy of the BSRT measurement [14]. This becomes clear in Fig. 1, when comparing the BSRT convoluted (average of two beams) emittances at the start of collisions to the ones of the emittance scans [15] and to the ones extracted by the luminosity of the experiments (ATLAS, CMS). The pink solid lines correspond to BSRT calibration Fills and the dashed ones to Technical Stops (TS). Except for the periods before Fill 6700 and for Fills 7100-7220 having BSRT hardware issues (gray colored areas), for most of the year the BSRT emittances are underestimated. The divergence from the expected emittance values was guiding the BSRT re-calibration.

Based on the results presented in [14] for the calibration Fill 7220, the agreement of emittance scans with the emittances inferred from luminosity is 5-20 % and the emittances from Wire Scanners (WS) [16] are up to 10-15 % lower than the ones extracted from luminosity. Since the BSRT is calibrated with respect to the WS, the discrepancy between the BSRT and the emittances estimated from luminosity is something to be expected. Understanding this difference is important for the validation of the data quality. Based on the results shown in Fig. 1, only Fills for which the convo-

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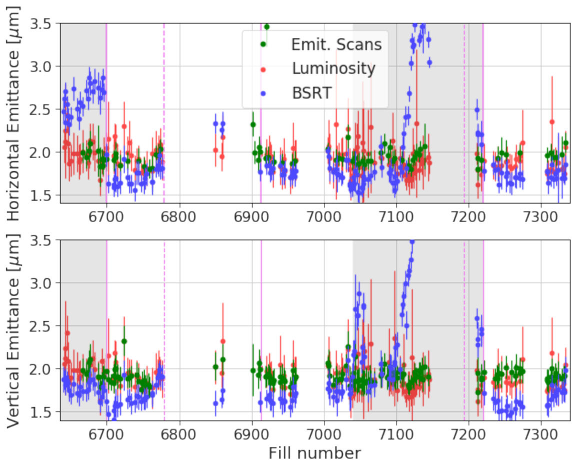


Figure 1: Horizontal (top) and vertical (bottom) convoluted emittances, from Emittance scans, Luminosity and BSRT, at the start of collisions.

luted emittances at start of collisions from luminosity and BSRT differ less than 15 % are considered. In these terms, the average transverse emittances at start of collisions are estimated to be 1.9 µm, corresponding to a 20 % and 25 % blow-up during Ramp in the horizontal and vertical plane, respectively.

### *Extra Emittance Blow-Up*

During Run 2, a transverse emittance growth beyond the model was observed both at Flat Bottom (FB) and at Flat Top (FT) energies, i.e. 450 GeV and 6.5 TeV, respectively [9, 13, 17, 18]. In order to quantify the impact of the mechanisms which lead to the extra emittance growth, the intensity evolution is taken from the data.

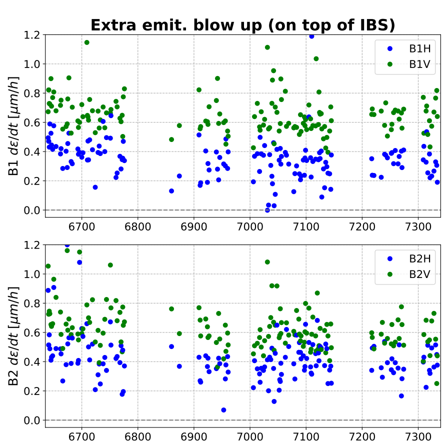


Figure 2: Extra emittance blow-up at FB.

The difference of the measured and model emittances over the total time spend at FB is presented in Fig. 2. Excluding the fills before the first BSRT calibration (Fill 6700), the $d\epsilon/dt$ is practically constant over the year for both beams and planes. In the vertical plane, where no growth is expected because the IBS effect is minor, the blow-up beyond the

Table 2: Measured and Extra Emittance Growth at FB

| Emittance growth [µm/h] | B1H | B1V | B2H | B2V |
|---|---|---|---|---|
| Measured | 0.71 | 0.64 | 0.73 | 0.61 |
| on top of model | 0.34 | 0.64 | 0.41 | 0.61 |
| on top of model&e-cloud | 0.24 | 0.44 | 0.17 | 0.41 |

model is significant. In order to understand the contribution of the e-cloud (which is expected to be one the main effects leading to emittance growth at FB) to this extra growth, the $d\epsilon/dt$ is calculated for the first bunches of the trains which are assumed not to experience e-cloud [13], giving finally the growth that is on top of IBS and e-cloud. The average emittance growths as measured by the BSRT and the ones that are beyond the model are presented in Table 2. The contribution of e-cloud to the emittance growth is 0.1-0.2 µm/h. The ongoing studies to correlate the rest of the extra emittance growth (on top of model & e-cloud) with the estimated growth from noise seem to be promising, explaining half of this extra growth, i.e. 0.1 µm/h and 0.2 µm/h in the horizontal and vertical plane, respectively [13]. The fact that the extra growth in the vertical plane is larger than the one in the horizontal is yet to be understood.

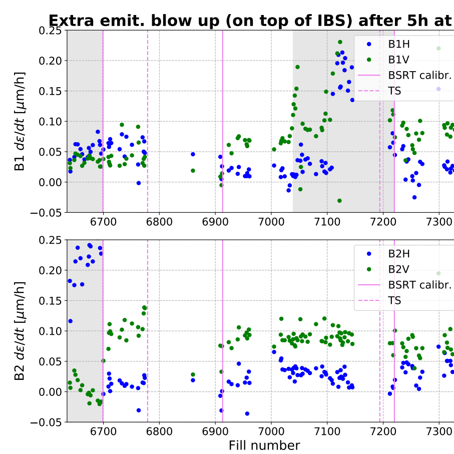


Figure 3: Extra emittance blow-up in collisions. The results in the gray areas are excluded due to BSRT hardware issues.

The difference of the measured and model emittances after 5 h in collisions is shown in Fig. 3. Except for B1 before the first TS, the $d\epsilon/dt$ is in general constant over the year and it is always higher for the vertical plane compared to the horizontal. Excluding the periods for which the BSRT measurements are not reliable (gray colored areas), the average measured and extra emittance growths are summarized in Table 3. In the horizontal plane, only the 50 % of the measured growth is explained by the model. In the verti-

Table 3: Measured and Extra Emittance Growth in Collisions

| Emittance growth [µm/h] | B1H | B1V | B2H | B2V |
|---|---|---|---|---|
| Measured | 0.04 | 0.04 | 0.06 | 0.05 |
| on top of model | 0.02 | 0.07 | 0.03 | 0.09 |

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cal plane the extra growth is larger than the measured one because, with the IBS being a minor effect in this plane, the model predicts damping due to SR, but in reality the observed growth is similar to the one of the horizontal plane. The estimated emittance growth from noise in collisions (noise level in the LHC and of the transverse damper) [19] can probably explain the remaining unknown growth, being around 0.04 μm/h and 0.06 μm/h in the horizontal and vertical plane, respectively [13].

## BEAM LOSSES

During Run 2, apart from the luminosity burn-off, extra beam losses were observed. In Fig. 4 the average over all physics fills of 2018 beam loss rate normalized to the luminosity and the one standard deviation interval is plotted for both beams [20]. Similar to previous years, fast losses occur during the first couple of hours in stable beams, being more pronounced for B1 than for B2.

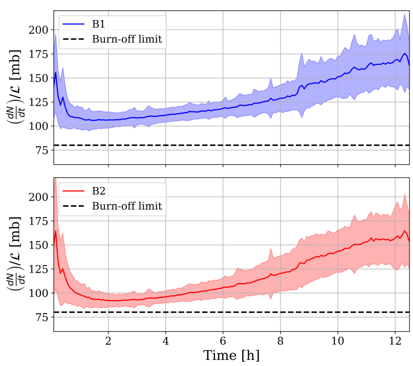


Figure 4: The average over all 2018 Fills of beam loss rate normalized to the luminosity for B1 (blue) and B2 (red) [20].

However, the losses in 2018 do not reach the burn-off limit which is the inelastic cross section of the proton-proton collisions (81 mb), indicated by a black dashed line. These losses have a continuous increase during the crossing angle anti-leveling which is performed to regain some of the luminosity lost during collisions, by increasing the luminosity geometric factor [4,5]. Even though the crossing angle steps induce losses, there is some gain on the integrated luminosity. The studies on losses during the anti-leveling, showed a correlation between the crossing angle variation and the losses due to e-cloud [20, 21].

## LUMINOSITY DEGRADATION SOURCES BEYOND THE MODEL

Fig. 5 shows the luminosity evolution for an example Fill of 2018. The black curve corresponds to the average measured luminosity from the experiments. The luminosity degradation because of the extra losses and of the extra emittance growth is plotted in blue and green, respectively. Combining these two, the calculated (red colored) luminosity is obtained. Considering only the effects included in the existing model results in the "pure model" luminosity

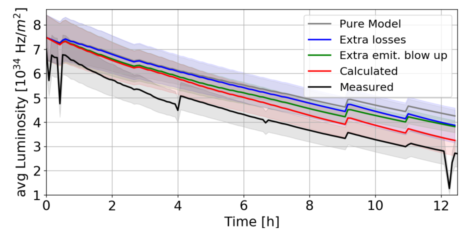


Figure 5: Luminosity evolution for a Fill, as calculated for all model cases and as measured by the experiments (black).

curve (gray colored). Basically, the difference between the gray and the red curve gives the integrated luminosity degradation because of mechanisms that are beyond the model. The disagreement of the initial calculated luminosity from the model with the measured one, can be used as a validation of the data quality (reliability of BSRT measurements). Similarly to the example given for one Fill in Fig. 5, the cumulated integrated luminosity, normalized to the max. value expected from the pure model (gray), is plotted in Fig. 6 for the 2018 Fills having realistic BSRT emittances. The difference between the measured and the calculated curve is explained by the fact that measured emittances were lower by 15 % compared to the ones expected from luminosity. If the BSRT measurements were accurate enough, the red and black curves would overlap. The contribution of the extra losses and the extra emittance blow-up on the luminosity degradation is 5 % and 11 %, respectively.

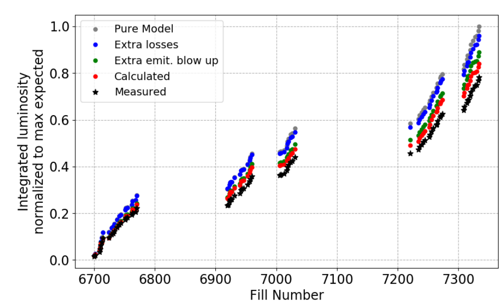


Figure 6: Cumulated integrated luminosity for all model cases and for the measured by the experiments (black), normalized to the max. value expected from pure model (gray).

## SUMMARY AND NEXT STEPS

Overall in 2018, the measured emittances along the energy cycle are smaller compared to previous years. However, the unrealistically small emittances in collisions, due to measurement uncertainties, need to be understood. For both FB and FT energies, the observed extra emittance growth (on top of the model) is similar for both beams, being larger in the vertical compared to the horizontal plane. Additional studies are performed to correlate the unknown extra emittance growth with noise and implement it in the luminosity model. Extra losses have a smaller impact on the luminosity degradation compared to the extra emittance blow up, being more significant in 2018 compared to previous years.

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