WHAT DO WE UNDERSTAND ON THE EMITTANCE GROWTH?

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Abstract

In order to describe and follow the evolution of the LHC luminosity, a model based on the effects of intra-beam scattering, synchrotron radiation, elastic scattering and luminosity burn-off, was developed. These effects are the main mechanisms leading to beam emittance growth and losses. The comparison of different emittance measurements coming from the BSRT (Beam Synchrotron Radiation Telescope) [1, 2], luminosity from experiments (ATLAS and CMS) and emittance scans, is used as a data quality validation test. Concerning the beam emittance growth along the LHC energy cycle, the evolution of the measured emittances are presented for the Run 2 and they are compared to the model results. This comparison is useful for estimating the extra emittance blow up, i.e. on top of what is expected from the effects included in the model, both at Flat Bottom (FB) and at Flat Top (FT) energies (i.e. 450 GeV and 6500 GeV, respectively). The agreement of the model with the data during collisions, assists in understanding the impact of different degradation mechanisms on the delivered luminosity.

INTRODUCTION

Operating at 6.5 TeV, the LHC surpassed the expectations and delivered an average of 66 fb^{-1} integrated luminosity in each of the two high luminosity experiments, ATLAS and CMS, by the end of 2018. The high brightness 25 ns beams [3] produced with the Batch Compression bunch Merging and Splitting (BCMS) scheme [4, 5] were used for the 2018 run. Aiming to gain some of the luminosity lost during collisions [6], the crossing angle is gradually reduced [7]. In order to increase the integrated luminosity, the beams are initially squeezed to a β^* of 30 cm that is further reduced to 25 cm after some hours in collisions according to the ATS (Achromatic Telescopic Squeeze) [8] optics scheme.

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 [9] and used since 2016 to calculate the machine luminosity. 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 is compared to data from the Run 2 of the LHC [10, 11]. In 2018, the transverse emittance coupling between the two planes was added to the luminosity model.

Estimates, based both on observed beam parameters and on model predictions, were reported fill-by-fill as well as in overall trends. In this paper, the measured emittance and the additional emittance blow up (on top of IBS, SR and elastic scattering) are presented for the 2018 data. Moreover, the measured emittances along the LHC energy cycle are given for the BCMS fills of Run 2. Finally, the 2018 cumulated integrated luminosity projections from the model, based on different degradation mechanisms, are compared to the delivered luminosity.

An automated tool which is based on extracted data from the logging system CALS [12] is used for the LHC performance follow-up (emittance, lifetime, luminosity, etc.). In order to provide a continuous feedback to the machine coordination for further optimizing the performance, this tool is extensively used for monitoring the main beam parameters and machine configurations. 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.

LUMINOSITY MODEL

The bbb luminosity model, that is described in detail in [9], takes into account intrabeam scattering (IBS), Synchrotron Radiation (SR), proton-proton collisions elastic scattering and burn-off. It can be applied for both colliding and non-colliding bunches, treating each beam and plane separately. The IBS, SR and elastic scattering are considered for the emittance growth. The bunch length calculation is based on the IBS and SR effects. For the bunch intensity evolution, the luminosity burn-off, causing the bunch current decay due to the collisions, is considered. 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. It is also possible to take the evolution of the emittance, the bunch length or the intensity from measurements and use the model to calculate the evolution of the remaining beam parameters. In this respect, the luminosity estimation can be a result of combining information coming from the model and data, allowing in this way to quantify the contribution of the different luminosity degradation mechanisms.

The comparison of the measurements to the luminosity model [9–11] assists in understanding the impact of mechanisms which are beyond the existing model, on the emittance growth and therefore, on the luminosity degradation. Moreover, since the luminosity model is sensitive to the input beam parameters (emittances, intensities, etc.) used as initial conditions, the agreement between the modeled luminosity and the measured one can be used as a validation of the data quality.

Apart from the luminosity leveling and the crossing angle anti-leveling, in 2018 the transverse emittance coupling [13, 14] was included in the model. Based on the classical formulas for the horizontal and vertical emittances in the presence of linear coupling [1], knowing the coupling coefficient and the tune shift, coupling introduces a factor that results in a smaller horizontal and a larger vertical emittance. Figure 1 shows the emittance evolution for one beam at collisions for an example fill, in the horizontal (left) and vertical (right) plane. The impact of the transverse emittance coupling on the luminosity is presented in Fig. 2, for ATLAS (top) and CMS (bottom).Even if the impact of the transverse emittance coupling on the luminosity calculated by the model is small, it is important to be taken into account in order to get accurate emittance estimations.

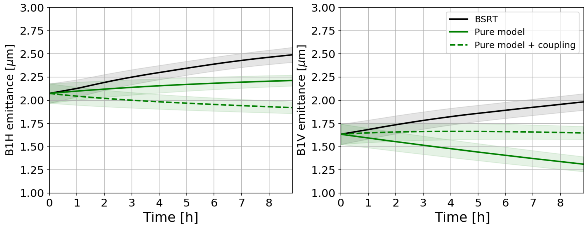

Figure 1: Emittance evolution at collisions for one beam, in the horizontal (left) and vertical (right) plane, as measured by the BSRT (black) and as calculated by the model (green), when including transverse emittance coupling (dashed line).

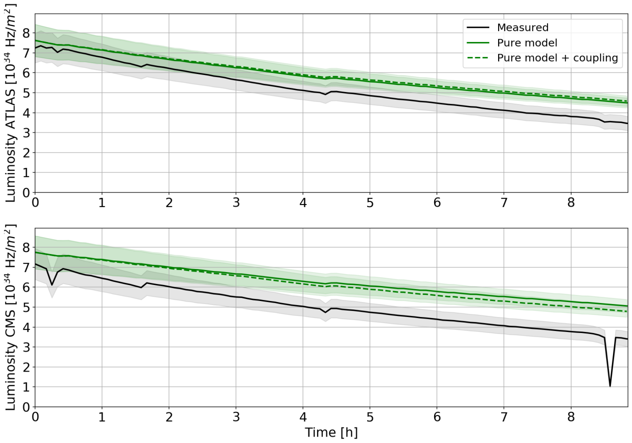

Figure 2: Luminosity evolution (top: ATLAS, bottom: CMS), as measured from experiments and as calculated by the model (green), including also transverse emittance coupling (dashed line).

MEASURED EMITTANCE IN 2018

In Table 1, the 2018 measured (BSRT) 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 spend at injection (from Injection to start of Ramp), is less than 15 %. 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 [2], specially for the horizontal plane of B2.

Table 1: 2018 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

In Fig. 3 the BSRT convoluted (average of two beams for each plane) emittances at the start of collisions are compared to the ones of the emittance scans [16] and to the ones extracted from the luminosity of the LHC experiments (ATLAS and CMS), for the 2018 BCMS fills [3]. The pink solid lines correspond to BSRT calibration fills and the dashed ones to Technical Stops (TS). Except for the periods before

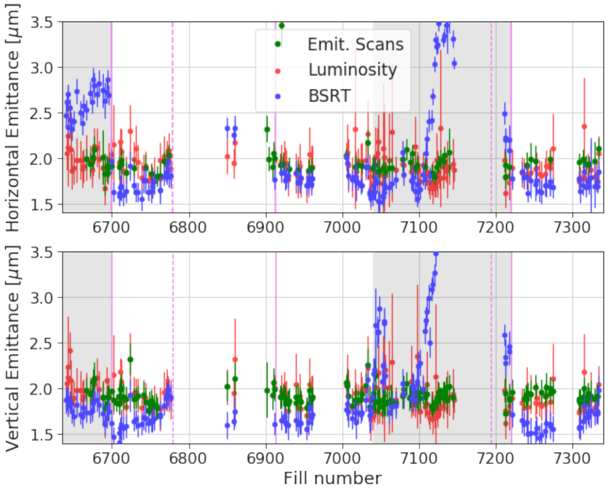

Figure 3: Convoluted (average of the two beams) emittances for the 2018 fills in the horizontal (top) and vertical (bottom) plane, from Emittance scans (green), Luminosity (red) and BSRT (blue).

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[1] The exchange of transverse emittances after the resonance crossing [13] was also studied but had a minor impact and thus, is not considered.

[2] probably due to the 20 % accuracy of the BSRT measurement [15]

[3] Based on emittance scans, the horizontal emittance from ATLAS and the vertical from CMS are considered. A cut on the scan time is set to 30 min since we are interested in emittance values at the start of collisions. Based on the equations for the ATLAS and CMS luminosities, assuming as a bunch length the average value of the two beams, the transverse beam sizes are found and are used to calculate the convoluted emittances inferred from the luminosity. Moreover, in order to have a valid comparison between the different measurements, the time stamps considered for each measurement are very similar.

fill 6700 and for fills 7100-7220 having BSRT hardware issues (gray colored areas), for most of the year the BSRT emittances are underestimated. After the last BSRT calibration performed at fill 7220, the agreement of the BSRT with the other measurements is improved.

The agreement of the emittance scans with the emittances inferred from luminosity is 5–20% and, the emittances from Wire Scanners (WS) [17] are up to 10 – 15% lower than the ones extracted from luminosity, based on the results presented in [15] for a BSRT calibration fill. 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. For the statistics, only fills for which the convoluted 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.

Understanding the discrepancy between different emittance measurements is important since they play a key role for the luminosity estimations as well as, for the validation of the data quality. One of the studies to explain these differences, focuses on fitting accurately the beam distributions [18]. The importance of that was also discussed in [20] for the longitudinal distributions, in order to get a better bunch length estimation. Moreover, the bunch by bunch analysis for various fills during Run 2, underlines the seriousness of fitting accurately the transverse bunch profiles that determine the transverse emittances.

The divergence from the expected emittance values coming from luminosities was guiding the BSRT calibration along the LHC Run 2. Since the BSRT is calibrated with respect to the WS during dedicated low beam intensity fills, such a calibration determines the values of the forthcoming measured emittances. Therefore, it is crucial to develop calibration techniques that take into account the actual shapes of the bunch profiles.

RUN 2 EMITTANCES ALONG THE ENERGY CYCLE

In Fig. 4 the average measured BSRT emittances, for each beam and plane, are given for the Run 2 BCMS fills, along the energy cycle, i.e. injection, start of ramp and start of collisions (Stable Beams). Overall the 2018 emittances along the cycle are smaller compared to previous years of Run 2. Figure 5 shows the relative emittance growth at FB energy (left) and at Ramp (right), for the Run 2 BCMS fills. In general, from Injection to start of Ramp, the emittance growth is about 10 –20 %. At injection energy, apart from the dominant effects of IBS and e-cloud, part of the growth is not understood. Additional studies are performed to correlate the unknown emittance growth with noise and implement it in the luminosity model. During the energy Ramp, this growth is 10 –30 %, being higher for B1 compared to B2. Except for 2016, this growth is higher for the vertical compared to the horizontal plane. The emittance blow-up during the Ramp is only partially understood. The lack of diagnostics to obtain the bunch profiles during the energy Ramp is one of the main issues to be addressed in view of explaining the observed growth and understanding when the blow up is occurring.

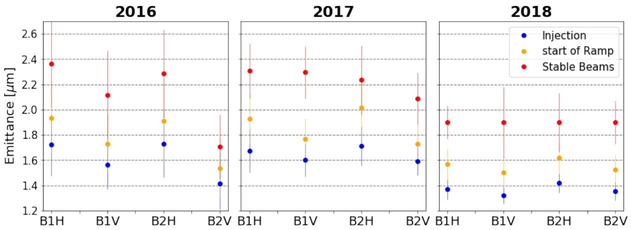

Figure 4: Average emittances (BSRT) along the LHC energy cycle, for the BCMS fills of Run 2.

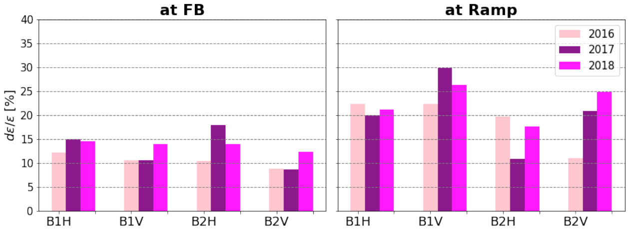

Figure 5: Average relative emittance growth at Flat Bottom (left) and at Ramp (right), for the BCMS fills of Run 2.

EXTRA EMITTANCE BLOW UP

During Run 2, a transverse emittance growth beyond the model was observed both at injection and at collision energies [10, 11], i.e. 450 GeV and 6.5 TeV. The extra emittance blow up along the year can be found by comparing for each fill the measured emittance growth with the expected one from the model, following the intensity evolution from the data. As mentioned earlier, since 2018 the transverse emittance coupling is taken into account for the luminosity model estimations. At FB, this results in a minor change of the emittance growth expected from the model ($\pm 10^{-3} \mu m/h$). At collisions, the vertical emittances of the model with coupling agree better with the measured ones and also, the estimation of the modeled luminosity is slightly improved.

At injection energy

The difference of the measured and model emittances over the total time spend at FB is presented in Fig. 6. Excluding some fills, such as the ones before the first BSRT calibration (fill 6700), the $d\epsilon/dt$ is practically constant over the year for both beams and planes, being larger in the vertical compared to the horizontal plane. In the vertical plane, where no growth is expected because the IBS effect is minor, the blow-up beyond the model is significant.

This extra emittance growth that is beyond the model is different along the batches and the trains of each beam and

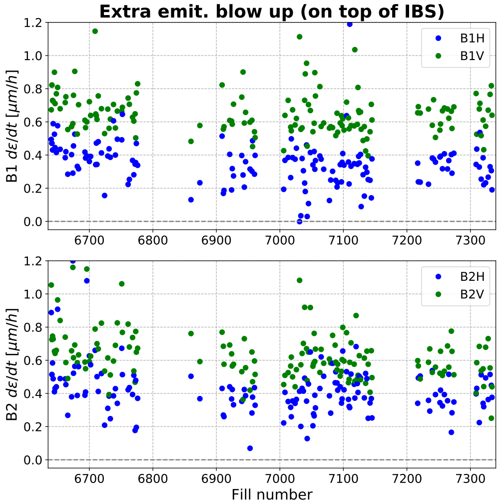

Figure 6: Average Measured-Model emittance difference over time at FB of all bunches, for B1 (top) and B2 (bottom), for all 2018 fills.

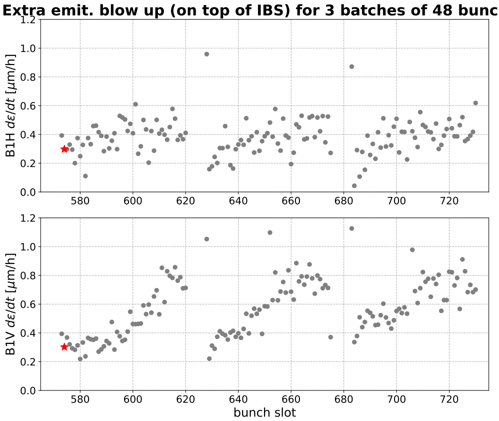

Figure 7: Measured-Model emittance difference over time at FB, for a train of 3 batches of 48 bunches, for B1 horizontal (top) and vertical (bottom). The red star corresponds to the 2^{nd} bunch of the first batch of a train which is assumed not to experience e-cloud.

plane. It is well known that the bunches that are located at the end of a batch or of a train, for the BCMS beams, have a larger blow up due to e-cloud effect which is one the main effects leading to emittance growth at FB. In order to understand the contribution of the e-cloud 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, giving finally the growth that is on top of IBS and e-cloud. Specifically, the 2^{nd} bunch of some trains [4] is considered, as can be seen in Fig. 7 where the extra emittance growth at FB is plotted for one train of B1 horizontal (top) and vertical (bottom). Figure 8 presents the difference of the measured and model emittances of the 2^{nd} bunches in the trains over the time spend at FB, averaged for the horizontal (blue points) and vertical (green points) plane, for B1 (top) and B2 (bottom), for all the 2018 fills. 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 remaining extra emittance growth (on top of model & e-cloud) with the estimated growth from noise seem to be promising. The fact that the extra growth in the vertical plane is larger than the one in the horizontal is yet to be understood. The RF voltage reduction steps from 6 to 4 MV along the year (with 4 MV ever since fill 7092) seem to have no impact on the transverse emittances, as was expected, based on the relation of the bunch length with the transverse emittances in terms of IBS growth.

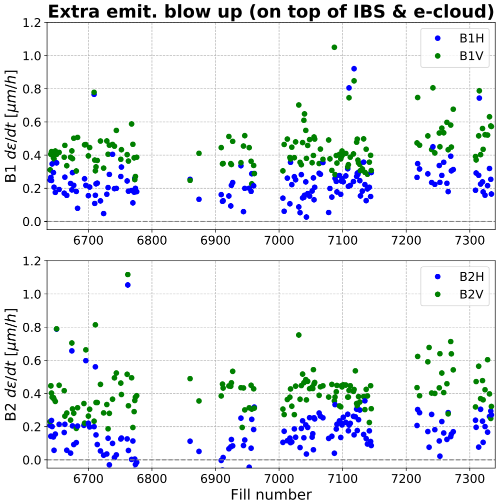

Figure 8: Average Measured-Model emittance difference over time at FB for the 2^{nd} bunch in each train, for B1 (top) and B2 (bottom), for all 2018 fills.

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

At collision energy

Figure 9 shows the measured-model emittance difference per hour, for B1 (top) and B2 (bottom), after some hours at collisions. The blue and green dots correspond to the horizontal and vertical planes, respectively. 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. Taking into account only 2018 fills for which the convoluted emittances at start of collisions from Luminosity and BSRT differ less than 15 % and

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[4] The trains considered are from the 3^{d} up to 12^{th} one in order to exclude bunches that stayed for short time (less than 5 min) at injection energy.

excluding the periods for which the BSRT measurements are not reliable (gray colored areas in Fig. 9), 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 vertical 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 [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.

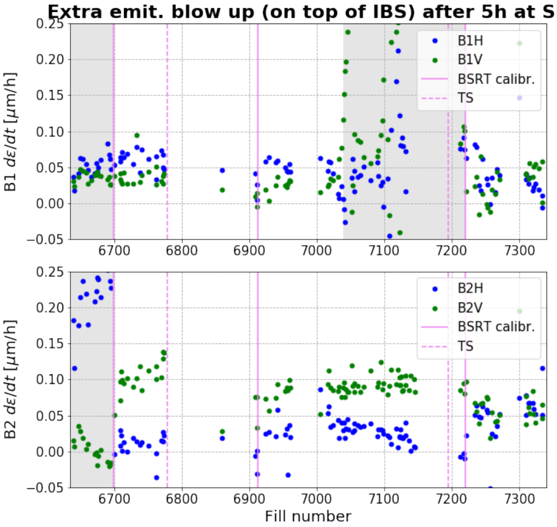

Figure 9: Average Measured-Model emittance difference over time at collisions, for B1 (top) and B2 (bottom).

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

At collision energy, a definition of bunch classes based on the position of bunches in the batches and trains, was used to identify patterns and trends concerning the bbb emittance growth. These studies showed that the extra emittance growth is practically the same for all the bunches independently of their position in a batch or a train, indicating that there is probably no correlation of the extra growth with e-cloud at collision energy.

In 2017, the extra emittance growth ratio remains practically constant during collisions and for both beams, it was less than 0.05 µm/h for the horizontal and ~0.1 µm/h for the vertical plane. The exact $d\epsilon/dt$ values for all the 2017 beam flavors and for both beams and planes can be found in [10]. For the 2016 fills, this difference was for both planes around 0.05 µm/h [11]. Furthermore, during the whole Run 2, the observed extra emittance growth at collisions seems to be independent of the bunch brightness.

LUMINOSITY DEGRADATION SOURCES BEYOND THE MODEL

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, the model was applied for all the production fills of Run 2 in order to quantify the extra transverse emittance blow up and the extra intensity losses that were observed during collisions.

Figure 10 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 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. Due to the fact that the model is sensitive to the initial beam parameters, for this example fill, the model luminosity is not calculated correctly because the emittances used as input are based on measurements which do not agree with the emittances inferred from the measured luminosity or emittance scans (as discussed in Fig. 3). 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 emittance measurements).

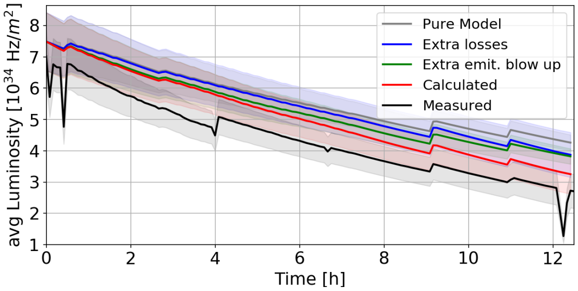

Figure 10: Luminosity evolution for a 2018 fill, as calculated from the pure model (grey), for the case of having extra losses (blue), for the case of having extra emittance blow up (green) and for the calculated (including extra losses & extra emittance blow up) one (red). The black curve corresponds to the average measured luminosity from the experiments.

In order to understand the overall impact of the different degradation mechanisms on the delivered luminosity, the cumulated integrated luminosity, normalized to the max. value expected from the pure model (gray), is plotted in Fig. 11 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 16 % 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, with the total calculated (i.e. taking into account the extra losses and extra emittance blow up) degradation being about 16 %.

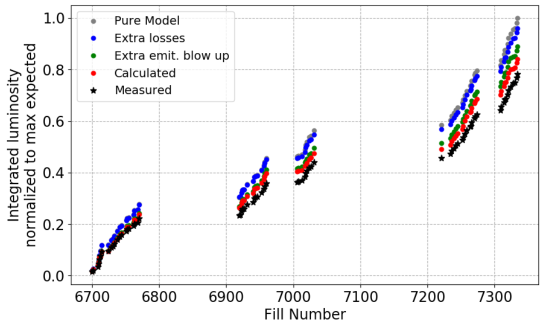

Figure 11: 2018 cumulated integrated luminosity normalized to the maximum value expected from the pure model (grey), for the case of having extra losses (blue), for the case of having extra emittance blow up (green) and for the calculated (including extra losses & extra emittance blow up) one (red). The black curve corresponds to the measured (by the experiments) cumulated integrated luminosity.

In 2017, the impact of the extra transverse emittance blow up on the delivered integrated luminosity is also significant (10 %), while the one of the extra losses is quite small (1 %) and overall, the calculated integrated luminosity was 11 % lower compared to what was expected from the model. 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 [11].

SUMMARY

The LHC performance was followed up with automated tools through the whole Run 2. The emittance evolution from injection to stable beams was studied, giving feedback to machine coordination and guiding BSRT calibration. In 2018, the measured emittances along the energy cycle are smaller compared to previous years. At collision energy, there is a clear discrepancy between different emittance measurements along the 2018 fills, yet to be explained, with the BSRT emittances being in many cases unrealistically small.

The LHC luminosity model that was developed to describe and follow the evolution of the machine luminosity is presented and compared to 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) [9]. Apart from the luminosity leveling and the crossing angle anti-leveling, in 2018 the transverse emittance coupling [13, 14] was included in the model as an additional feature, having a small impact on the luminosity calculated by the model. Furthermore, 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.

The difference of the measured emittance evolution with the one expected from the model shows that there are mechanisms beyond the existing model which result in an emittance growth. One of the main objectives is to understand the discrepancy between different emittance measurements along the year. During the whole LHC cycle there is an unknown emittance growth, which varies with energy. 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. At FB, e-cloud explains 30-50% of the growth that is beyond the model, the remaining unknown extra emittance growth is 0.2 µm/h in the horizontal and 0.4 µm/h in the vertical plane. During the energy Ramp, the measured emittance blow-up that is 10 – 30 %, depending on the year and on the plane (usually more in vertical), is yet to be explained. At FT, the remaining unknown growth is around 0.04 µm/h and 0.06 µm/h in the horizontal and vertical plane, respectively and, it seems that this growth has no correlation with e-cloud or brightness. Some of the on-going studies to explain this growth concerns noise effects, emittance growth due to burn-off, as well as the analysis of the bunch profile shapes. Apart from the extra emittance blow up, extra losses (on top of the expected proton burn off) are observed, especially during the first hour in stable beams [21].

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 for an example fill. 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. In order to understand the mechanisms that lead to luminosity degradation, the model was applied to all the production fills of 2018. The cumulated integrated luminosity for all model cases and for the measured one by the experiments showed that the extra emittance blow up (beyond the mechanisms included in the model) plays an important role in the degradation of the luminosity. Extra losses have a smaller impact, being more predominant in 2018 compared to previous years.

One of the studies that can probably shed light on the observed emittance blow up concerns the analysis of the LHC bunch profiles [18]. The luminosity model was constructed based on the IBS module of MAD-X [22] which assumes Gaussian beam distributions. In order to understand the beam size evolution but also, the remaining discrepancy between the luminosity coming from the model and the measurements, the actual distributions should be known.

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