CAN WE PREDICT LUMINOSITY?

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Abstract

In these proceedings, a luminosity model based on the main components (intrabeam scattering, synchrotron radiation, elastic scattering and luminosity burn-off) responsible for the LHC luminosity evolution, is compared with data from the 2016 run of LHC. Based on a bunch-by-bunch and fill-by-fill analysis, the data are compared to the model predictions and possible sources of luminosity degradation are discussed. The impact of the degradation mechanisms on the integrated luminosity is also presented.

INTRODUCTION

The performance of a collider is best described by the luminosity (integrated over time) which, in general, is given by [1]:

$$\mathcal{L}(t) = \frac{n_b f_{rev} N_1(t) N_2(t)}{2\pi\sigma_x(t)\sigma_y(t)} \mathcal{H}\mathcal{F}_g, \quad (1)$$

where n_b the number of colliding bunches, f_{rev} the revolution frequency, $N_{1,2}$ the number of particles per bunch for each beam and $\sigma_{x,y}$ the rms horizontal and vertical beam sizes at the collision point. Due to the crossing angle at collision ϕ and the fact that the beta function varies rapidly around the interaction point (IP), a geometric factor $\mathcal{F}_g(\sigma_s(t),\beta^*)$ and the hourglass effect reduction factor $\mathcal{H}(\sigma_s,\beta^*)$ should be considered, where σ_s and β^* are the rms bunch length and the beta function in the interaction point (IP) collision (assuming round optics) respectively.

Although luminosity is a macroscopic indicator of global collider performance, the observed bunch-by-bunch (bbb) variations in the transverse and longitudinal emittances and in current, impacts its evolution and finally the integrated luminosity per fill. A bbb model was developed based on the three main mechanisms of luminosity degradation in the LHC [2]: intrabeam scattering (IBS), synchrotron radiation (SR) and luminosity burn-off. Here, the model is compared with the LHC beam data from the 2016 run.

MODEL DESCRIPTION

The emittance evolution of the beams in the LHC during the Flat Bottom (FB), the ramp and the first part of the Flat Top (FT) (before the squeeze) is dominated by the intrabeam scattering (IBS) effect [3]. During collisions a combination of effects including burn-off, IBS, beam-beam, noise, etc., cause emittance blow up and/or particle losses [4]. Based on the assumption that IBS and Synchrotron Radiation (SR) are the dominant effects for the emittance evolution during collisions, the evolution of different injected beam parameters (transverse emittances ($\epsilon_{x,y}$), bunch length (σ_l), bunch current (N_b) were calculated using the "ibs" routine of MADX with synchrotron radiation [9, 10]. The transverse emittance and bunch length evolution were then fully parameterized with respect to the initial beam parameters and the time, using multi-parametric fit functions. Finally the combined effect at any plane can be calculated through:

$$\left(\frac{d\epsilon_x}{dt}, \frac{d\epsilon_y}{dt}, \frac{d\sigma_s}{dt}\right)_{IBS+SR} = f(En, N_{b0}, \epsilon_{x0}, \epsilon_{y0}, \sigma_{s0}, dt) \quad (2)$$

where dt the time interval for which the calculation is performed and En the energy. The procedure is described in more details in [2].

The contribution from the proton-proton collisions elastic scattering to the transverse emittance growth [4, 5], is also included, based on:

$$\left(\frac{d\epsilon_{x,y}}{dt}\right)_{elastic} = N_{IP}\beta^*_{x,y}\mathcal{L}\sigma_{el}\left\langle\theta^2_{x,y}\right\rangle/(n_b N_p), \quad (3)$$

where N_{IP} is the number of interaction points, σ_{el} the elastic cross section and $\sqrt{\left\langle\theta^2_{x,y}\right\rangle}$ is the rms proton-proton scattering angle.

The emittance evolution along the fill can then be estimated, for any time interval for which the bunch current N_b variation is small, using the differential equation:

$$\frac{d\epsilon}{dt} = \left(\frac{d\epsilon}{dt}\right)_{IBS+SR} + \left(\frac{d\epsilon}{dt}\right)_{elastic} \quad (4)$$

The main mechanism of the bunch intensity degradation during collisions is the luminosity burn-off, causing the bunch current decay due to the collisions themselves. The burn-off decay time is given by:

$$\tau_{nuc} = \frac{N_{b0}}{kL_0\sigma_{tot}}, \quad (5)$$

where N_{b0} is the initial bunch intensity, L_0 the initial luminosity, k the number of interaction points and σ_{tot} is the proton-proton total cross section and is energy depended as shown in Fig. 1 [11]. At 6.5 TeV $\sigma_{tot} \approx 110$ *mb*, $\sigma_{el} \approx 30$ *mb* and $\sigma_{inel} \approx 80$ *mb* [11]. 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, while the elastic part is causing transverse emittance blow up described by eq. eq. (3) [6].

The bunch current evolution can then be calculated through:

$$N_b = N_{b0}/(1 + t/\tau_{nuc}). \quad (6)$$

Combining equations eq. (1), eq. (2), eq. (3), eq. (4), eq. (5) and eq. (6) and iterating in small time-steps (such that

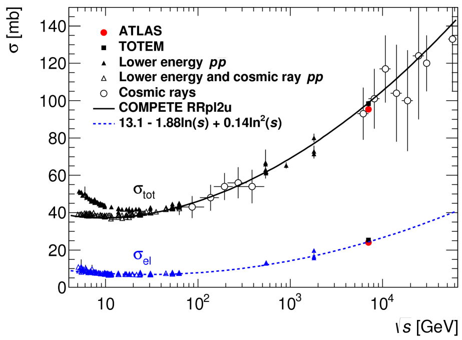

Figure 1: Dependences of total, inelastic and elastic cross-sections on the scattering energy $\sqrt{s}$ [11].

the current variation in each time-step is relatively small) provides a self-consistent calculation of the beam parameters, and thus the luminosity evolution in time. The infrastructure allows the user to select the model or the data for each specific parameter in a transparent manner.

Four different modes are defined and will be used in the next:

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

DATA ANALYSIS

In 2016, the LHC operated with a center of mass energy of 13 TeV and similar beam parameters as in 2015, but with a lower β^* of 40 cm (in 2015 β^*=80 cm), resulting in a significant increase in the integrated luminosity; in 2015 the LHC delivered to CMS an integrated luminosity of 4.2 fb^{-1} while in 2016 42.1 fb^{-1} [7].

For the analysis that follows all the fills of the production period of 2016, after the intensity ramp-up were analyzed.

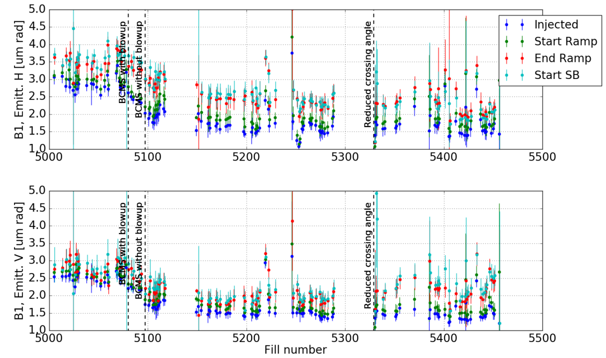

Figure 2: Horizontal (top) and vertical (bottom) emittance evolution from injection to stable beams for all the high intensity fills of 2016.

Those are fills corresponding to the time period from June to October 2016. In order to apply the model, the bunch by bunch transverse emittances, bunch lengths and bunch intensities are required. The bunch by bunch luminosity data are also needed for comparison. For this, the following datasets have been used:

- The bunch-by-bunch intensity sharing is measured by the Fast Beam Current Transformer (FBCT)
- The bunch-by-bunch emittance measurements for both beams and both planes from the synchrotron radiation telescopes (BSRT)
- The bunch-by-bunch bunch lengths as measured by the beam quality monitor (BQM)
- The bunch-by-bunch luminosity data as published from ATLAS and CMS (Massi files)

A more detailed description is presented in [8].

EMITTANCE EVOLUTION FROM INJECTION TO SABLE BEAMS

Figure 2 shows the average horizontal (top) and vertical (bottom) emittance, for all the production fills of 2016, at different time in the LHC cycle. The emittance at injection is shown in blue, at the beginning of the ramp in green, at the end of the ramp in red and at the beginning of stable beams in cyan. The error-bars correspond to the one standard deviation over all the bunches. Here only the data from beam 1 are shown, however, the situation is very similar for beam 2 as well. At the beginning of the year standard beams were injected in the LHC, with the average injected horizontal/vertical emittance fluctuating around 2.8/2.5μm·rad and arriving at the beginning of stable beams around 3.5/2.9 μm·rad. With the introduction of the BCMS beam production scheme, the emittance was gradually decreased to 1.6/1.5 μm·rad at injection and 2.5/2.0 μm·rad at the beginning of stable beams. It is interesting to notice

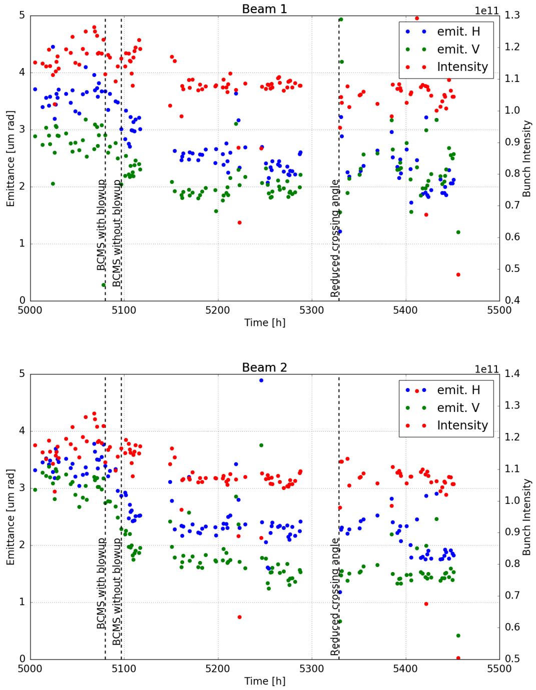

Figure 3: Average bunch intensity (red) and average bunch emittance (H: blue, V:green) for beam 1 (top) and beam 2 (bottom), at the beginning of Stable Beams for the physics fills in 2016.

the large emittance blow up (defined as $\epsilon_{SB}/\epsilon_{inj} - 1$) from injection to stable beams, of the order of 25/16 % in the first part and 55/33 % after the transition to BCMS. This is induced mainly during the Ramp where the intrabeam scattering effect for the range of bunch parameters of 2016 can explain only a small fraction of it; for an injected transverse emittance of 1.5 μm·rad and bunch intensity of 1e11 a horizontal emittance blow up of 13 % from injection to stable beams is expected due to ibs and only 3 % of it is induced during the ramp while no effect is expected in the vertical plane.

The average bunch intensity in the LHC for 2016 was kept in similar levels as in 2015. More specifically, for the first part of the year the average bunch intensity was $N_b \sim 1.2 \times 10^{11}$ while later went down to $N_b \sim 1.1 \times 10^{11}$, with negligible losses along the cycle (from injection to stable beams). Figure 3 shows the evolution of the average bunch intensity (red), horizontal (blue) and vertical (green) emittance values at the beginning of stable beams along the year, for beam1 1 (top) and beam 2 (bottom).

LUMINOSITY IMBALANCE ALONG THE YEAR

Due to the fact that the experiments of ATLAS and CMS have a different crossing plane (vertical for ATLAS and horizontal for CMS) and the horizontal and vertical emittances are not equal during collisions, an imbalance in the luminosity delivered to the two experiments was observed. Aiming

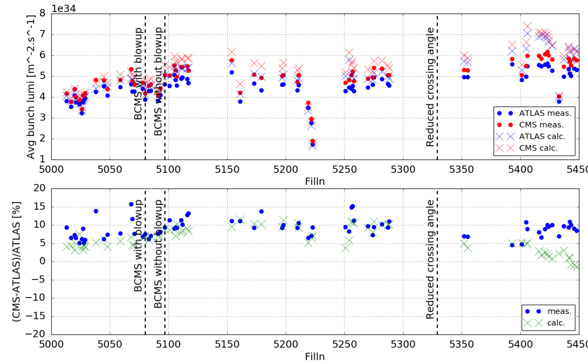

Figure 4: Horizontal (top) and vertical (bottom) emittance evolution from injection to stable beams for all the high intensity fills of 2016.

to understand further this effect, the average peak luminosity for all the fills was calculated through eq. eq. (1) using the measured bunch parameters (transverse emittances, bunch intensity, bunch length) at the beginning of stable beams, for both ATLAS and CMS. This calculated peak luminosity was then compared to the average measured peak luminosity provided by the experiments and the results are shown in the top part of figure 4. The calculated values are shown in crosses while the measured ones in circles. The results for ATLAS are shown in blue while for CMS in red. The bottom plot of fig. 4 shows the luminosity imbalance (defined as $(\mathcal{L}_{CMS} - \mathcal{L}_{ATLAS})/\mathcal{L}_{ATLAS}$) between the two experiments using the same marker convention as in the top one. During the first part of the year, before the transition to BCMS beams, very good agreement between the calculated and measured peak luminosities is observed. After the transition to BCMS, even though the calculated and measured imbalance agrees well, the absolute values start to diverge. In the third part, on the other hand, after the crossing angle reduction, a disagreement is observed both in absolute values and in imbalance. It is important to notice here that a recalibration of the BSRT system was performed before the transition to BCMS and before the crossing angle change. The impact of the calibration factors in these observations is currently under scrutiny.

In order to better understand the observed imbalance between ATLAS and CMS, an experiment was performed where 4 bunches with different pile up density (or brightness) were brought to collision and the crossing angle was gradually reduced to 0 μm·rad, as shown in fig. 5. In the left part of the figure the evolution of the pile-up density of the 4 bunches is presented while in the right the imbalance between ATLAS and CMS. At the beginning of the fill, a 5-8% geometric effect is observed, higher for the higher brightness bunches. At the end of the fill where the crossing angle was reduced to 0, a 5% imbalance is still observed, even though for zero crossing angle theoretically the two experiments should not see any difference. Further investigation is in progress in order to understand this observations.

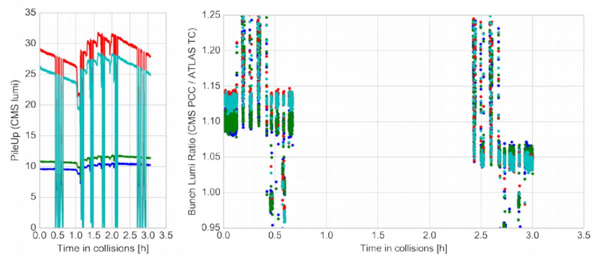

Figure 5: Left: Evolution of the pile-up density of the 4 bunches with different brightness. Right: Luminosity imbalance between ATLAS and CMS. The crossing angles is gradually reduced and at the end the bunches are colliding with zero crossing angle.

LUMINOSITY EVOLUTION

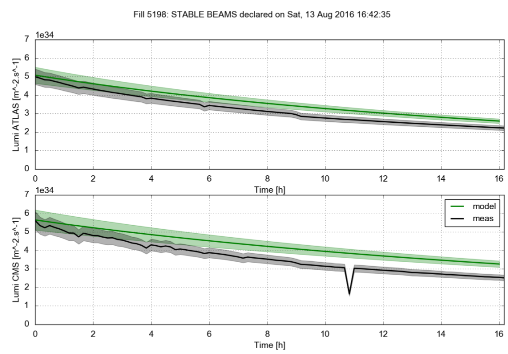

Figure 6: Luminosity evolution comparison between the pure model (green) and measurements (gray).

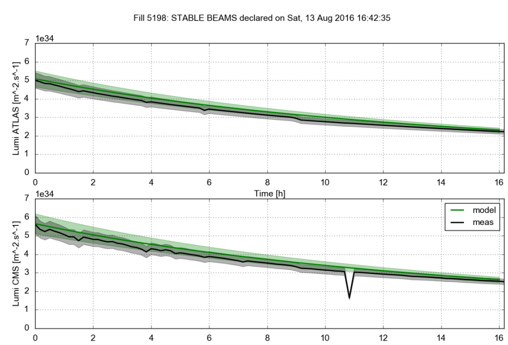

Figure 7: Luminosity evolution comparison between the model using the empirical emittance evolution (“Empirical-BlowUpBurnOff”) (green) and measurements (gray).

In order to validate the luminosity model and identify possible sources of luminosity degradation in 2016, the model was applied bunch-by-bunch to all the production fills of 2016, under different assumptions as described in section “Model description”. Figure 6 (top) shows the comparison of the average luminosity evolution as measured by the experiments (gray) and computed by the “pure” model (green), of a typical fill of 2016 (fill 5198). The predicted luminosity evolution using the “pure” model is overestimated with respect to the measurement. The same observation is valid for the luminosity evolution of all the fills of the year and consequently for the evolution of the bunch-by-bunch transverse emittances, bunch length and bunch intensity as well. Instead, if we use the empirical emittance evolution from the BSRT data, and reiterate the model in order to compute the prediction of the bunch length, bunch intensity and luminosity evolution, the agreement becomes much better, as shown in fig. 7. Eventually, using both the empirical emittance and bunch intensity evolution, the luminosity evolution is very well reproduced. For the example fill, already by using only the empirical emittance blow up the luminosity evolution is very well predicted, showing that the main source of the luminosity degradation for this particular case is an extra emittance blow up mechanism. However, for other fills not only extra emittance blow up but also extra losses were observed. In this respect, a statistical approach was adopted in order to understand the behavior of the luminosity evolution and degradation mechanisms over the year.

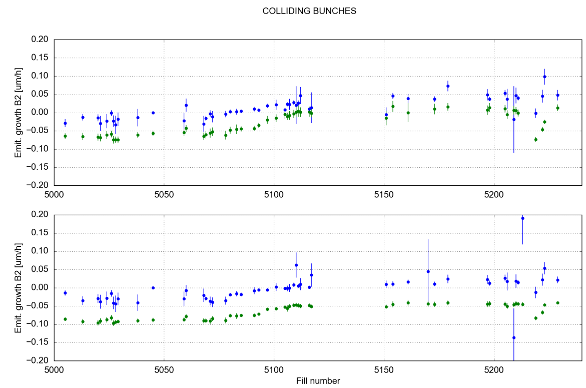

Figure 8: Average emittance growth per fill as predicted by the model (green) and measured (blue) both in the horizontal (top) and vertical (bottom) planes.

EXTRA EMITTANCE BLOW UP

In order to understand the behavior of the extra emittance blow up along the year, the average expected emittance growth per fill from the model was compared to the measured one and the results are shown in fig. 8. The model prediction is shown in green while the BSRT measurements are shown in blue. The results for both horizontal (top) and vertical (bottom) planes are shown. The error-bars indicate the one standard deviation over all the bunches per fill. It is interesting to notice a constant difference between the model prediction and the measurements, which seem to be independent on the bunch brightness. Both planes show an extra emittance blow up of around $0.05\mu m/h$, with respect to the model. Analysis is in progress to understand further the mechanism that induces this extra emittance blow up.

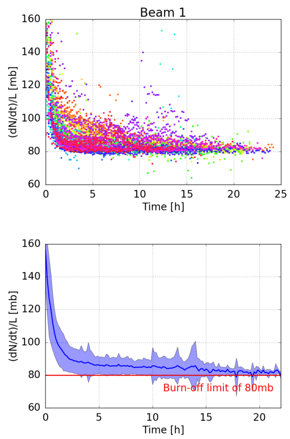

Figure 9: Top: Instantaneous beam loss rate normalized to the luminosity for all the physics fills of 2016. Each color represents a different fill. Bottom: The average and the one standard deviation interval over all the fills.

EXTRA LOSSES

As discussed earlier, extra beam losses on top of luminosity burn off losses, were observed for most of the 2016 physics fills. In order to have a better understanding of the effect, the instantaneous loss rate normalized to the luminosity was calculated bunch by bunch for all fills and the average effect over all the bunches per fill is shown in fig. 9. The results for beam 1 are show on the left while the results for beam 2 on the right. In the case of burn off dominated losses, this should reveal the value for the inelastic cross section of the proton-proton collisions (thus $\sim 80mb$). However, this is not the case and a similar trend is observed for all the fills, for both beams; fast losses occur during the first 2-3 h in stable beams, while later the losses become burn-off dominated. The effect is more pronounced for beam 1 than beam 2. In the top plots of fig. 9 each color corresponds to a different fill, while in the bottom one the average effect over all the fills and the one standard deviation interval are shown. The red solid line indicates the inelastic cross section limit of the 80 mb.

Figure 10, shows the average normalized losses over the first hour in stable beams, for all the physics fills. The results for beam 1 are shown in blue while for beam 2 in red. It is very interesting to notice that the losses behavior is very much affected by all the machine changes. The highest losses were observed during the first part of the year while during the middle part, the losses were minimized, and for beam 2 they were very close to the burn-off limit. Systematically for both these periods, beam 1 suffered more from losses than beam 2. After the crossing angle reduction, the losses were again increased, however beam 1 and beam 2 behaved in a much more similar way.

Another very interesting observation is the fact that the losses are minimized when the LHCb was operating in a positive polarity, while they get maximized in the opposite case. Within the same polarity, the losses are larger for larger

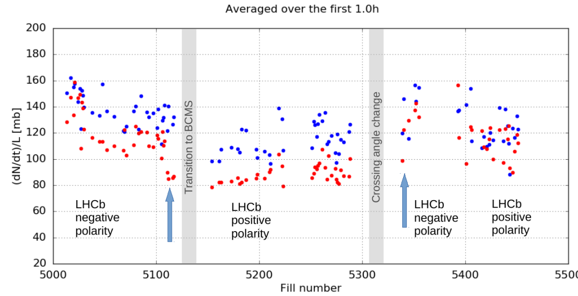

Figure 10: Average normalized losses over the first hour in stable beams for beam 1 (blue) and beam 2 (red).

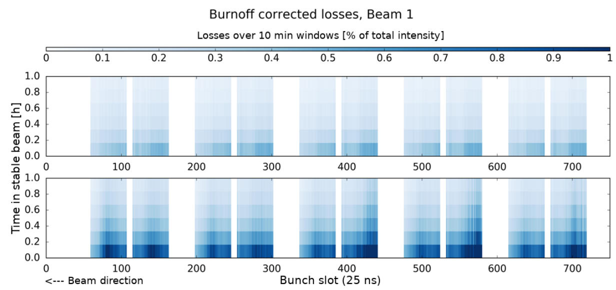

Figure 11: Instantaneous losses over the first hour in stable beams before (top) and after (bottom) the crossing angle reduction.

emittances, which become more pronounced in the first part of the run, with nominal beams and standard emittances (see fig. 3). It should be noted the impact of the tune optimization on the losses behavior. A tune optimization, based on the dynamic aperture studies presented in [13], has a positive impact on the losses behavior. To summarize, the effects and machine conditions that were observed to have an impact on the losses behavior are: the LHCb polarity, the emittance magnitude, the tune and the crossing angle reduction.

The impact of the beam-beam long range effect is also under investigation and some first observations are shown in fig. 11. The colorbar in these plots show the burnoff-corrected losses computed over 10 minutes windows, expressed as percentage of the total intensity for the first hour in SB, before (top) and after (bottom) the crossing angle reduction. The horizontal axis shows the 25 ns bunch slot. Darker color indicates higher losses. In the top plot, with the large crossing angle, the losses are higher at the end of each train, which is a well known signature of the electron cloud effect. On the other hand, after the reduction of the crossing angle, the situation becomes different for many trains where the highest losses are observed in the middle of the trains, which is a signature of the beam-beam long range effect. The effect is more pronounced for beam 1, where the extra losses are higher, as discussed earlier. It is though observed for beam 2 as well. Further investigation is in progress in order to quantify also from simulations the impact of the long-range beam-beam effect on the luminosity lifetime [13].

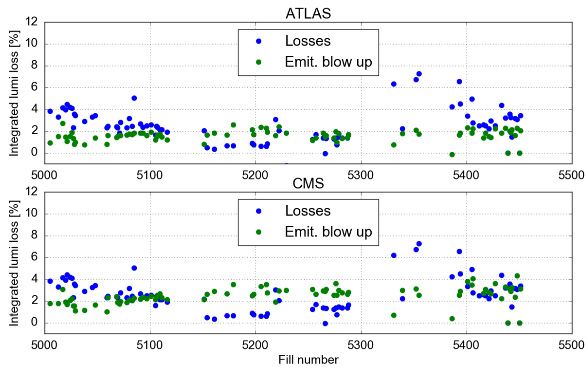

Figure 12: Integrated luminosity loss due to the extra losses (blue) and due to the extra emittance blow up (green) for the physics fills in 2016.

IMPACT OF DEGRADATION MECHANISMS ON THE INTEGRATED LUMINOSITY

The extra emittance blow up and the extra intensity losses that were observed during collisions and discussed in the previous sections cause a luminosity degradation. In order to quantify this effect, the luminosity model was called under different assumptions for each fill and the integrated luminosity for each case was computed after 3 h in stable beams. Three different cases are compared: EmpiricalBlowUpBurnOff (2), IBSEmpiricalLosses (3) and EmpiricalBlowUpLosses (4). Case 4 is the one which represents the real data. The ratio between (4) and (2) reveals the integrated luminosity loss due to the extra emittance blow up while the ratio between (4) and (3) due to the extra losses. The results are presented in fig. 12. It is interesting to notice that the evolution of the integrated luminosity loss due to the emittance blow up (green) is rather smooth along the year. On the other hand, the loss due to the extra losses varies along the year and it follows the machine changes in the same way as the extra (on top of burn-off) intensity losses.

SUMMARY

A luminosity model based on the main components responsible for the LHC luminosity degradation (intrabeam scattering, synchrotron radiation, elastic scattering and luminosity burn-off) was applied to the LHC data from the 2016 run. The model was applied bunch by bunch to all physics fills and under different assumptions. The comparison between the model predictions and the measured evolution of the bunch characteristics (intensity, horizontal and vertical emittances and bunch length) and thus the luminosity led us to some interesting conclusions for the performance of the machine in 2016.

At first, the emittance evolution from injection to stable beams was discussed. An extra emittance blow up, coming mainly during the ramp, was present in all fills. This cannot be explained by the intrabeam scattering effect. Arriving at stable beams a comparison between the peak luminosity as computed from the measured bunch characteristics and as measured by the experiments of ATLAS and CMS was performed. Before the transition to the BCMS beams, very good agreement is observed both in absolute value and in ratio between the two experiments. After the transition to BCMS a divergence start to appear, however the ratio still agrees very well. In the last part of the year, both the absolute values and the ratio disagree. This discrepancy needs further investigation; the impact of the calibration of the BSRT instrument and the calibration of the experiments are under scrutiny.

During collisions, both an extra emittance blow up and extra losses, especially at the first 2-3 h in stable beams are observed. Higher losses were observed for standard beams with larger emittances while the minimum losses were observed for the BCMS beams with small emittances. A clear impact of the LHCb polarity is observed; higher losses are observed when the LHCb operates with negative polarity. The losses were then again increased after the crossing angle reduction. A tune optimization after this, had a clear positive impact on the minimization of the losses. It is also interesting to notice that after the crossing angle reduction, signatures of the long-range beam-beam effect start to be present in the losses patterns.

Finally, the impact of the degradation mechanisms to the integrated luminosity over the first 3 h in stable beams was studied. The impact of the extra emittance blow up is very smooth along the year, while the impact of the extra losses varies, depending on the changes taking place in the machine.

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