LUMINOSITY MODELING FOR THE LHC

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Abstract

In this paper, a luminosity model based on the three main components responsible for the LHC luminosity degradation (intrabeam scattering, synchrotron radiation and luminosity burn-off), is compared with data from RunII. Based on a Fill-by-Fill analysis and observations, additional sources of luminosity degradation will be discussed. Finally, the model is used for luminosity performance projections for the 2016 LHC parameters.

INTRODUCTION

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

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

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 at 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 2015 RunII data. Finally, luminosity predictions based on the 2016 LHC beam parameters are presented.

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, bunch length, bunch current) were calculated using the "ibs" routine of MADX with synchrotron radiation [5, 6]. The transverse emittance and bunch length evolution was then fully parameterized with respect to initial beam parameters and the time, using simple fit functions. Finally the combined effect in any plane can be calculated through a single parametric function:

$$[\epsilon_x(t), \epsilon_y(t), \sigma_s(t)] = f(En, N_b(t_0), \epsilon_x(t_0), \epsilon_y(t_0), \sigma_s(t_0), t{-}t_0), \tag{2}$$

where $t - t_0$ the time interval for which we need to calculate the effect. The procedure is described in more details in [2].

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:

$$\tau_{nuc} = \frac{N_{b0}}{kL_0\sigma_{tot}}, \tag{3}$$

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 depented as shown in Fig. 1 [7]. At 6.5 TeV $\sigma_{tot} \approx 110\ mb$. The bunch current evolution can then be calculated through $N_b = N_{b0}/(1 + t/\tau_{nuc})$.

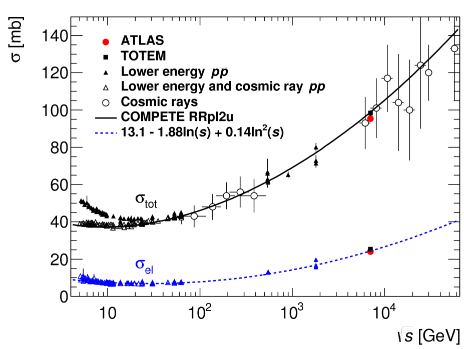

Figure 1: Dependences of total, inelastic and elastic cross-sections on the scattering energy $\sqrt{s}$ [7].

Combining equations 1, 2 and 3 and iterating in small time-steps (such that the current variation in each time-step is relatively small) can give us a self-consistent calculation of the beam parameters, and thus the luminosity evolution in time.

2012 VERSUS 2015 LUMINOSITY EVOLUTION

In 2015 LHC ran at a record beam energy of 6.5 TeV/beam and a relaxed beam configuration with lower bunch intensity, and brightness with respect to 2012 and a relaxed $\beta^* = 80\ cm$, resulting in lower peak luminosity and long luminosity lifetimes with respect to RunI. A comparison between the luminosity evolution of two fills of similar performance from 2012 and 2015 is shown in Fig. 2. It is very interesting to notice that despite the lower peak

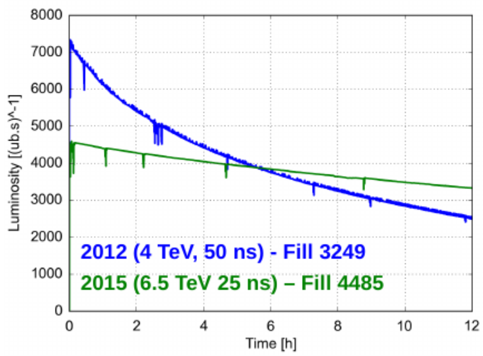

Figure 2: Luminosity evolution of a 50 ns 2012 and 25 ns 2015 fill with similar performance.

luminosity than in 2015, the better lifetime and the larger number of bunches, resulted in very similar integrated luminosities per fill. Table 1 compares the integrated and peak luminosity for two fills of similar performance from 2012 and 2015 along with the corresponding beam parameters.

Table 1: Luminosity performance comparison of two fills of similar performance from 2012 and 2015 respectively.

Parameter	**2012 (4 TeV)**	**2015 (6.5 TeV)**
Bunch intensity $[10^{11} ppb]$	1.7	1.1
$\epsilon_{x,y}$ $[\mu m \times rad]$	1.6	3
Bunch spacing $[ns]$	50	25
Nb. of bunches	1380	1825
β^* $[cm]$	60	80
Peak lumi. $[(\mu b \times s)^{-1}]$	7200	4500
Integrated lumi. (12h) $[fb^{-1}]$	0.18	0.17

DATA TO MODEL COMPARISON

In LHC RunII, transverse emittance measurements both at Flat Bottom and Flat Top energies and with different means of measurements were available during physics fills:

- Convoluted emittance computation using the luminosity measurements from the experiments. This method assumes equal emittances for both beams and both planes.
- The Beam Synchrotron Radiation Telescope (BSRT) system provides horizontal and vertical beam size data for both beams [8].
- Convoluted horizontal and vertical emittance from OP scans [9]. This method assumes equal emittances per plane for both beams but allows differentiating the horizontal and vertical plane.

The fact that different methods are available, gives the ability to crosscheck and verify the emittance measurements and finally benchmark our model against real data and identify missing components.

In order to compare the data with the model predictions we used as an input to the model the initial transverse emittance given by the BSRT data and the initial bunch current and initial bunch length given by the Beam Quality Monitor (BQM). The luminosity model function was then iterated in time-steps of 20 min in order to calculate the transverse emittance, bunch current and bunch length evolution in time, as described earlier.

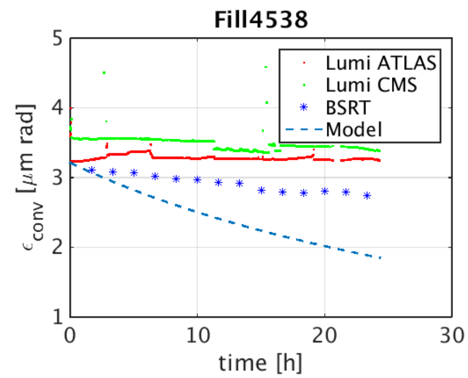

Figure 3: Emittance evolution during collisions, for a typical Fill from 2015, from ATLAS luminosity (red), from CMS (green), from the BSRT data (blue stars) and the model prediction (blue dashed line).

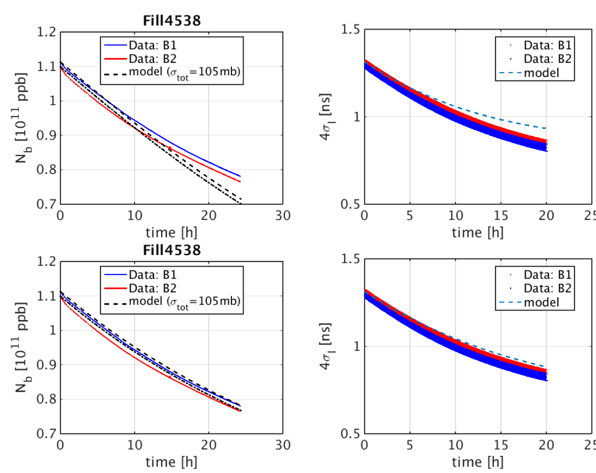

Figure 4: Data to model comparison of the bunch current (left) and bunch length (right) evolution. On top the transverse emittance used is the one predicted by the luminosity model, while on the bottom the transverse emittance used is the one from the data.

A comparison between the averaged (over all colliding bunches) convoluted emittance from ATLAS (red), from CMS (green), from the BSRT data (blue stars) and the model prediction (blue dashed line) is shown in Fig. 3, for one of the longer Fills of 2015. Similar behavior is observed in most of the Physics Fills of this run. A small discrepancy between the different methods of emittance estimation is observed which needs to be understood. What is more remarkable is the large discrepancy between the observed emittance evolution and the one predicted by the model. Overall, even though for this regime of beam parameters the convoluted emittance is expected to shrink, very slow variation of the emittance in time is observed in all the Physics Fills, see also [9]. Large discrepancy is also observed for the other two components of the model, i.e. the bunch current and bunch length as shown in the top plots of Fig. 4, where smoother current decay (left) and more bunch length damping (right) is observed with respect to the model prediction. If, on the other hand, instead of using the transverse emittance evolution prediction from IBS and SR we use the transverse emittance evolution observed from the data and re-iterate the luminosity model function, we see that the agreement between the model and the data for the bunch current (bottom, left) and bunch length (bottom, right) evolution in time becomes much better. This is a strong indication that there is an extra transverse emittance blow up mechanism that needs to be understood and added to the model. This effect causes a reduction in the integrated luminosity for this Fill of the order of 20%. A bunch-by-bunch analysis is currently in progress in order to gain statistics and find correlations that will guide us to identify the effect.

OPTIMAL FILL TIMES AND LUMINOSITY PROJECTIONS FOR 2016

A set for proposed beam parameters for the beginning of the Run in 2016 are given in Table 2. Assuming that

Table 2: Proposed beam parameters for 2016.

Parameter	**2016** 40 *cm*	**2016** 50 *cm*
Bunch intensity [$10^{11}\, ppb$]	1.2	1.2
ϵ_{xy} [$\mu m - rad$]	3.0	3.0
4σ bunch length [ns]	1.3	1.3
Bunch spacing [ns]	25	25
β^* [cm]	40	50
ϕ[μrad]	410	370
Int. Lumi (20h) [pb/bunch]	0.221	0.205

the emittance evolution will be as in 2015, thus slow variation of the convoluted emittance along the fill, the expected average specific luminosity per bunch is shown in Fig. 5. The projected integrated luminosity for the 40 cm β^* case is 0.221 pb/bunch while for the 50 cm β^* case is 0.205 pb/bunch, over a fill time of 20h.

A fill by fill statistical analysis of the availability of the machine in 2015 [10], showed that the most probable turnaround time of the machine at operating at 25 ns is 6-8 h. Figure 6 shows how the optimal fill time is parameterized with the preparation (or turnaround) time of the machine for the $\beta^* = 40\ cm$ case with the emittance evolving very slowly along the fill, as observed in 2015 (blue), for the $\beta^* = 40\ cm$ based on the IBS+SR+Burn-off model (green) and for the 2015 (dashed, light-blue) case. In all cases we see that the

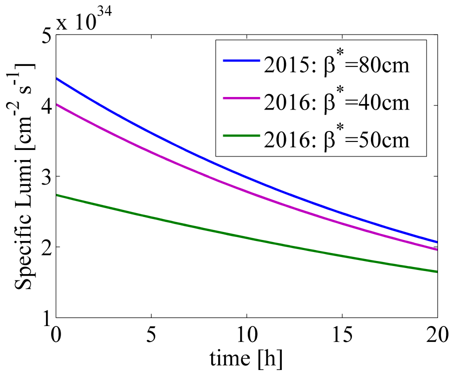

Figure 5: The expected average luminosity per bunch for the proposed 2016 LHC parameters.

optimal fill time increases rapidly with the turnaround time and long fills are favorable. Following the blue line, for a short turnaround time of $t_t = 3\ h$ the optimal fill time is 13 h, while for $t_t = 8\ h$ the optimal fill time increases to 25 h.

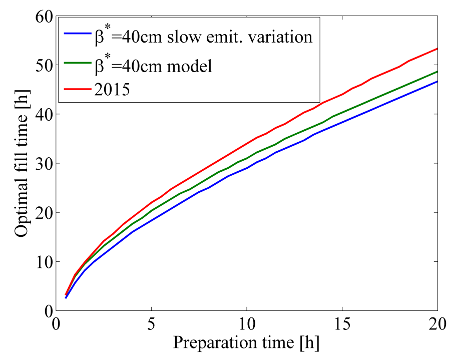

Figure 6: Optimal fill time for the LHC parameterized with the turnaround time of the machine.

SUMMARY AND OUTLOOK

A luminosity model for the LHC, including IBS, SR and Burn-off at Flat Top (4 TeV, 6.5 TeV and 7 TeV) and Flat Bottom energies is available and can be easily applied bunch-by-bunch. The model is based on analytical formulas which assume Gaussian distributions which is not always the case for the LHC (especially in the longitudinal plane). Work is in progress to understand the effect of the beam distribution on the IBS evolution of the bunch characteristics.

In this paper, the model has been compared with data from 2015 RunII of LHC. In all physics fills slow evolution of the convoluted emittance has been observed, while emittance damping was expected. Using the measured emittance, a good prediction for the bunch length and bunch current evolution was found. This is a strong indication that other sources of transverse emittance blow up exist and need to be identified and added to the model. A bunch-by-bunch analysis is in progress, aiming to show correlations that will help understand and identify the underlying cause.

Finally, the model was used to make predictions for the expected integrated luminosity and the optimal fill time, based on the 2016 proposed bunch parameters. As in 2015, long fills will be favorable with the optimal fill time increasing rapidly with the turnaround time of the machine.

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