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BUILDING A LUMINOSITY MODEL FOR THE LHC AND HL-LHC *

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Abstract

One key objective of the High Luminosity LHC Upgrade is to determine a set of beam parameters and the hardware configuration that will enable the LHC to reach a peak luminosity of 5×10^{34} cm^{-2} s^{-1} and ultimately 7.5×10^{34} cm^{-2} s^{-1} with leveling, allowing an integrated luminosity of 250-300 fb^{-1} per year. In order to determine the integrated performance, it is important to develop a realistic model of the luminosity evolution during a physics fill. In this paper, different mechanisms affecting luminosity lifetime in the LHC are discussed and a luminosity model is presented. The model is bench-marked with data from LHC Run I.

INTRODUCTION

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

$$\mathcal{L}(t) = \frac{n_b f_{\rm rev} N_1(t) N_2(t)}{2\pi\sigma_x(t)\sigma_y(t)} H\left(\sigma_s(t), \beta^*\right) F_{\rm geom}(\sigma_s(t), \beta^*),$$

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

In 2012, LHC ran at a top energy of 4 TeV and was filled with 50 ns spaced bunches. During collisions different mechanisms arise, causing emittance blow up and/or current losses, leading to luminosity decay in time. In the case of LHC, a simple exponential fit with a constant lifetime over time, cannot describe the luminosity decay. It is thus of paramount importance of identifying and understanding the different complex and interleaved mechanisms leading to luminosity degradation, building finally a model which is essential for optimizing the machine performance and for making accurate predictions for the future of the collider. Such a model can be implemented in an on-line tool for following the luminosity behavior of each LHC fill.

There were several studies concerning the LHC luminosity lifetime [2–8], mainly based on semi-empirical laws through statistical analysis of the LHC run I data. 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. This is clearly shown in Fig. 1, where the bbb integrated luminosity is color-coded with the ratio of the bunch current over transverse emittance (assuming round beams), or initial brightness, at the beginning of collisions for fill 3232. An accurate model should be able thus to represent the contribution of each bunch to luminosity. In this paper, different mechanisms affecting luminosity lifetime in the LHC are discussed and the status of a LHC luminosity model, taking into account the bbb variations, is presented.

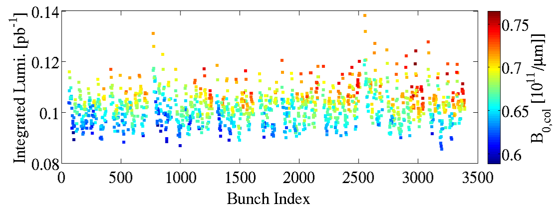

Figure 1: Bunch-by-bunch integrated luminosity for fill3232 from LHC Run I data, color-coded with the initial brightness at collisions.

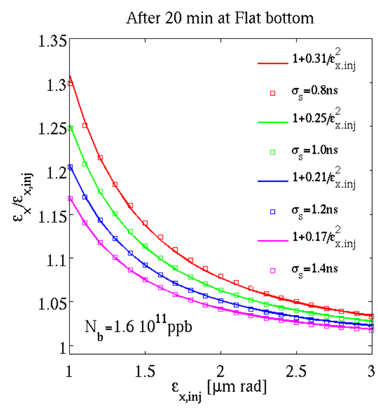

Figure 2: Parameterization of the IBS effect after 20 min at FB with the injected transverse emittance, for different input bunch lengths and for a bunch current of 1.6×10^{11} *ppb*.

EMITTANCE EVOLUTION

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 intra-beam scattering (IBS) effect [9]. During the squeeze and while the beams are brought to collision, the situation becomes more complicated, as during the LHC run I certain bunches were becoming unstable causing emittance blow up and losses [10]. During collisions a combination of effects including burn-off, IBS, beam-beam, noise, etc., cause emittance blow up and current losses [3].

Based on the assumption that IBS is the dominant effect during FB, scaling laws can be derived by using sim-

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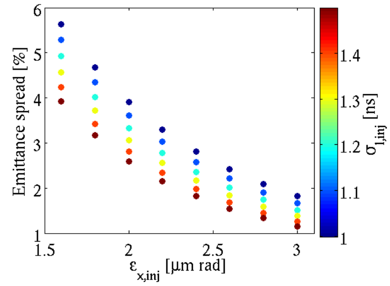

Figure 3: Parameterization of the emittance slope along the LHC train with the injected transverse emittance and bunch length.

ple fit functions. For this, the evolution of different injected beam parameters (transverse emittances, bunch length, bunch current) were calculated using the "ibs" routine [11] of MADX [12] and assuming round beams at injection. Figure 2 shows how the IBS effect after 20 min at FB is parameterized with the injected emittance, for different injected bunch lengths and for one case of bunch current, $N_b = 1.6 \times 10^{11}$ ppb. The simulation data are represented by the squares while the fits by solid lines.

As the bunches injected earlier stay longer at FB, the parametrization has to be time dependent. This leads to a generic fit function:

$$\frac{\epsilon_x}{\epsilon_{x,0}} = 1 + \frac{C_0(N_b, \sigma_{s,0}, t)}{\epsilon_{x,0}^2} \quad , \tag{1}$$

depending on the injected emittance $\epsilon_{x,0}$ and bunch length $\sigma_{s,0}$. The constant C_0 is itself a power function of the intensity, the injected bunch length and the time spent at FB:

$$C_0(N_b, \sigma_{s,0}, t) = \alpha_0(\sigma_{s,0}, t) N_b^{\alpha_1(\sigma_{s,0}, t)} \tag{2}$$

The same type of fit function is valid for the case of the ramp, assuming constant bunch length, but also for the first part of FT, before collisions. In these three parts of the LHC cycle, it is assumed that no current losses occur. The IBS effect in the vertical plane is very small in all parts of the cycle. This method can be implemented in an online tool, providing very fast estimates for the specific peak luminosity of each bunch colliding pair, given the injected beam/bunch parameters and the time spent at each part of the cycle.

An alternative approach followed which can be easily implemented in an on-line tool, is through multi-dimensional grids of IBS growth rates corresponding to a large range of transverse emittances, bunch currents and bunch lengths. Fast estimations of the emittance evolution during the fill can be obtained by interpolating through the grids, taking into account any unexpected changes of the beam behaviour.

Due to the different times the bunches stay at FB, bunches injected first will have a larger emittance at the beginning of collisions, due to IBS, than the ones injected later. This leads to a slope in the emittance evolution along the LHC bunch train. Based on the above parameterization, the slope can be calculated for different injected emittances and bunch lengths and the results are shown in Fig. 3. It becomes clear the weak sensitivity of the slope to the initial bunch length after capture for a constant RF voltage. This result is in agreement with what was observed experimentally, where the batch-by-batch controlled longitudinal emittance blow up did not help to improve significantly the specific luminosity slope along the LHC train [13].

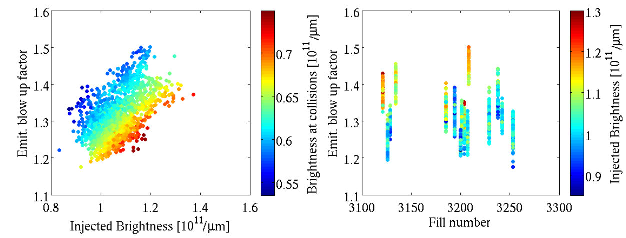

Figure 4: Parameterization of the unknown emittance blow up factor with the injected bunch brightness and the bunch brightness at collisions (left) and with the fill number and the injected brightness (right).

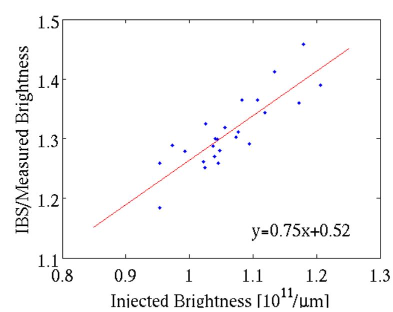

Figure 5: Parameterization of the unknown emittance blow up factor with the mean injected bunch brightness.

Previous studies indicated that, during the squeeze, an instability, which is not yet fully understood, causes an emittance blow-up [10]. In order to add this component to the model, fills with emittance measurements at injection (wire scan data for only the first 144 bunches are available) were studied, with the unstable bunches removed. For this study, the combined data from all those fills were used. Based on the IBS model described earlier, the expected emittance at collisions was calculated for each measured emittance, bunch length and bunch current at injection. It is important to note that the emittance at collisions is the convoluted emittance obtained from the luminosity measurements at the experiments, assuming equal emittances for both beams and both planes. The ratio of the measured emittance at collision and the expected emittance from the IBS model is defined here as the unknown emittance blow-up factor. The dependence of this factor on the injected brightness and the brightness at collisions is presented in Fig. 4 (left). A linear dependence on the injected brightness is observed, with a spread which can be explained by the different behaviour of the machine for different fills, as shown in the right plot of

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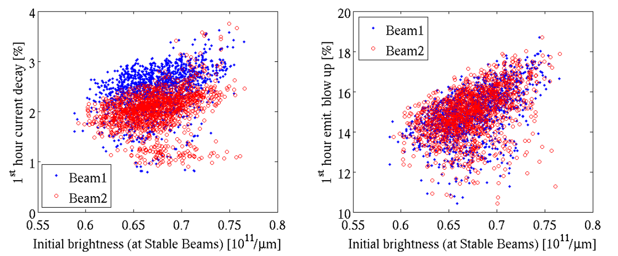

Figure 6: Bunch current decay (left) and emittance blow up (right) for Beam 1 (blue) and Beam 2 (red) after 1 hour at collisions, as a function of the brightness at the begining of collisions.

Fig. 4 and the uncertainty in the emittances for both beams and planes at collision.

Repeating the same exercise using mean values instead of the bbb parameters, a linear scaling for the unknown emittance blow-up factor can be derived, as shown in Fig. 5. Although the estimation suffers from the lack of bbb emittance measurements during the LHC cycle, it indicates clearly the brightness dependent behavior of the emittance blow-up during the cycle up to collisions and establishes a crude scaling law for the LHC Run I data. Using this linear fit and the values of emittance at collisions an extrapolation can be done for the emittance at injection, in the case that emittance measurements at injection are missing. This fit function can also serve as a filter for the unstable bunches, as they follow a completely different behavior than the one expected by the function, within a spread. Applying the IBS model with the extrapolated injected emittance values, the measured current and the measured bunch length at injection, the emittance slope at collisions was verified to be the IBS expected slope for many fills.

During collisions (i.e. at Stable Beams as called in the LHC), the emittance evolution is not driven only by IBS. In fact, there is an additional emittance blow-up of around 25 – 30% after 8 h at Stable Beams. The elastic scattering effects at the IPs provides an additional although small contribution to this emittance increase [3]. The effect of other diffusion mechanisms on the emittance evolution during collisions, like the Beam-Beam effect, electron-cloud, non-linearities, noise, etc. are under investigation in order to fully assess these observations.

CURRENT DECAY

An unavoidable current decay mechanism at collisions is the luminosity burn-off, with a lifetime depending on the instantaneous luminosity and the proton-proton total cross section. However, in the case of LHC, other losses at collimators are dominant for the characterization of the current lifetime [3, 14]. The beam lifetime reduction due to the beam-beam effect is discussed in [15].

One common observation from all LHC fills, is the fast current decay in the first hour of collisions. These losses but also the emittance blow up after 1 hour at collisions, have a clear dependence on the bunch brightness at the begining of collisions, as shown in Fig. 6. In order to understand if those fast losses are also associated with the long-range beam-beam effect, and disentangle them from other brightness dependent effects, an observable was defined from the product of the brightness of each bunch with the mean brightness of the long-range encounters seen by the bunch. Figure 7 (left) shows the crude linear dependence of this observable with the current decay after 1 h of collisions, for fill 3232 of LHC Run I data. It is noticeable that the slope of the linear fit is changing with the number of long-range encounters. Figure 7 (right) shows the dependence of the slope on the number of LR encounters for 4 different fills: 2710, 3229, 3261, 3232. A clear trend of slope increase with the number of long range encounters is observed. For fill 2710, where the brightness is lower, weak correlation is observed. An intuitive interpretation of this observation is that while coming to and during collisions, a brightness dependent mechanism blows up the core of the beam creating tails, which then leads to losses due to the long-range interaction of the bunches. Although, as mentioned, the trend is clear, it is difficult at this point to obtain an accurate expalanation and a scaling of this observable with the number of long-range encounters, due to the variation of the conditions of each bunch (orbit, tunes, collisions in other IPs, etc.). Work is in progress in order to include statistics for more fills but also bench-mark the observations with simulations, in order to provide a scaling law to be added to the luminosity model.

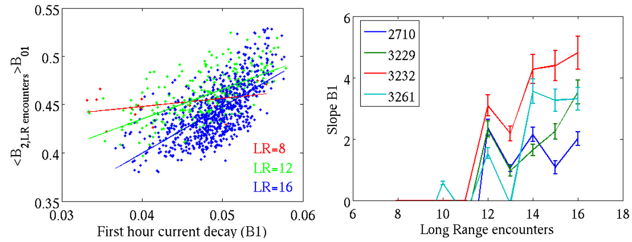

Figure 7: Left: Correlations between the long-range beam-beam observable with the first hour current decay and the number of long range encounters for fill 3232. Right: Dependence of the linear fit slope on the number of LR encounters.

SUMMARY AND OUTLOOK

A status report on the development of a LHC luminosity model is presented. A non-exhaustive list of different mechanisms affecting the luminosity lifetime has been addressed. Emphasis is given to the need of a model that takes into account the bunch-by-bunch variations of the beam parameters (bunch current, transverse and longitudinal emittances). The LHC Run 1 data were used to benchmark each component of the model. Building a model which includes the basic contributions to the luminosity lifetime can provide confidence in making safe predictions for the future run of LHC and for the HL-LHC parameters.

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