LUMINOSITY OPTIMIZATION AND CALIBRATION IN THE LHC

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Abstract

We discuss luminosity monitoring, optimization and absolute calibration in the LHC. Interaction rates will be continuously monitored both by detectors on the machine side as well as by the four large LHC experiments. Horizontal and vertical separation scans will be used to optimize luminosity and to measure the beam sizes in the interaction region. An application software has been developed for this purpose. We describe the procedures which have been prepared and discuss expected systematic effects which may limit the accuracy of the measurement.

INTRODUCTION

The event rate $\dot{N}$ of a process of cross section σ and the instantaneous luminosity $\mathcal{L}_0$ are related for head-on collisions of gaussian shaped beams by

$$\mathcal{L}_0 = \frac{N_1 N_2 f \, N_b}{2\pi\sqrt{(\sigma_{1x}^2 + \sigma_{2x}^2)(\sigma_{1y}^2 + \sigma_{2y}^2)}} = \frac{\dot{N}}{\sigma}, \qquad (1)$$

where N_1 and N_2 are the bunch intensities, f the revolution frequency, N_b the number of bunches per beam and $\sigma_{ix,iy}$ the effective transverse beam sizes. The number of bunches and the revolution frequency are accurately known. Bunch intensities are expected to be measured with a precision of roughly 1% [3]. We expect that the accuracy will be mostly limited by the knowledge of the transverse beam dimensions at the interaction region.

SEPARATION SCANS

The separation scans method for luminosity determination was pioneered by Van Der Meer at the ISR [1]. The
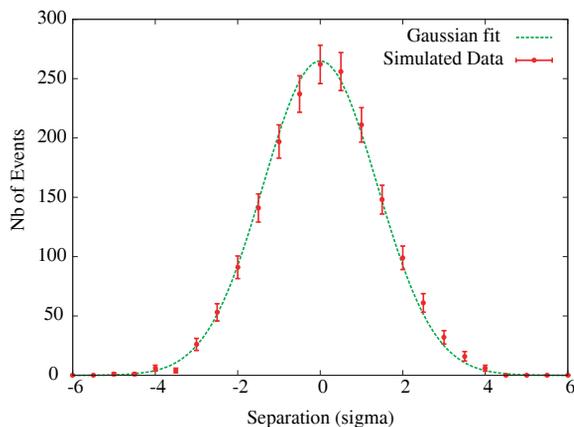
Figure 1: Simulated luminosity scan for two bunches colliding in early run conditions (β^*=11 m, 4×10^{10} p/bunch).

size and shape of the interaction region is measured by recording the relative interaction rates as a function of the transverse beam separation. For gaussian beams, we will have

$$\mathcal{L}(d) = \mathcal{L}_0 \exp\left[\frac{-d^2}{2\sigma_d^2}\right], \qquad (2)$$

where $\sigma_d = \sqrt{\sigma_{1i}^2 + \sigma_{2i}^2}$ and $i = x, y$ for each separation plane, and a fit of the measured interaction rates as function of the separation as illustrated in Fig. 1 will allow to determine the effective beam size as well as the maximum achievable collision rate.

BEAM PARAMETERS AND ABSOLUTE CALIBRATION

The absolute luminosity calibration based on machine parameters is of interest for the early LHC operation before the pp cross-section has been precisely measured at LHC energies [2]. In pp collisions it will be easy to get high counting rates and statistical errors are not expected to be significant. We propose to perform the absolute luminosity calibration at lower intensity and with few bunches without crossing angle as planned in the earlier operation. This should also allow to minimize measurement errors. Table 1 shows the expected range of beam parameters from initial up to nominal operation. We also quote the event rate for a cross section of 10 mb as assumed for the LHC luminosity monitors (BRAN).

Table 1: Single Bunch Luminosity

β^* (m)	σ^* (μm)	N_p p/bunch	$\mathcal{L}$ (cm^{-2}s^{-1})	$\dot{N}$ (Hz)
11	74.36	4×10^{10}	2.59×10^{28}	259
2	31.71	1.15×10^{11}	1.18×10^{30}	11773
0.55	16.63	1.15×10^{11}	3.54×10^{30}	35400

Total rates and luminosities are increased by the number of colliding bunches per beam which is already 43 and 156 in early operation. Even in the early operation, a few seconds will be sufficient to reach a 1% statistical accuracy.

A crossing angle is required for operation with more than 156 bunches to avoid parasitic collisions. The crossing angle reduces the luminosity by a geometric factor

$$F_c = \sqrt{1 + \left(\frac{\theta_c \sigma_z}{2\sigma^*}\right)^2}, \qquad (3)$$

where θ_c the crossing angle, σ_z the bunch length and σ^* the tranverse beam size at the IP. For nominal parameters, the crossing angle will reduce the luminosity by up to 20%

and would result into an additional 2% uncertainty from the knowledge of beam parameters. We propose to perform the luminosity calibration runs with at maximum 156 bunches per beam. The bunch spacing is then sufficiently large, such that no crossing angle is required. The beam-beam effects and the hour glass effect respectively depend on the beam intensity and the ratio $r = \beta^*/\sigma_z$, it is possible to bring those effects to a negligible level by working at low intensity ($\approx 4 \times 10^{10}$ p/bunch) and with a β^* larger than 2 m.

INSTRUMENTATION

We now list the instruments [3] involved and discuss systematic uncertainties.

Beam Position Monitors (BPM)

For the separation scans the only relevant information is the angle and position at the IP which can be determined via a linear interpolation of the measurements made with the BPMs installed next to Q1. They consist of strip lines (BPMSW) at the four IPs with an uncertainty on the zero position of 50 μm and in the case of IP1 and IP5 special button pick ups were installed with an uncertainty of 10 μm. Beam position changes are expected in one plane while scanning the other plane, therefore acquisition will have to be done in both planes for each scan.

Beam Current Transformers (BCT)

The BCTs installed in the LHC will be capable of integrating the charge of each LHC bunch. The presision of these measurements for the nominal LHC beams is expected to be of the order of 1%. An additional uncertainty could come from the longitudinal bunch distribution, unbunched particles or non colliding bunches would be counted in the average beam intensity but would not contribute to the luminosity. A careful bunch by bunch analysis combined with a calibration at the end of the ramp where there is no unbunched components should provide a good understanding of this measurement.

Luminosity Monitors

The LHC is equipped with collision rate monitors at each IP, ionization chamber for IP1 and IP5 and CdTe detector for IP2 and IP8. It is also planned to use the luminosity monitors from the experiments for those special calibration runs which could give better resolution for low intensity. The ZDC (Zero Degree Calorimeter) working in coincidence showed very good performances in terms of signal and background during the scans performed at RHIC.

OPERATIONAL TOOLS

A luminosity scan software as been developed in the framework of the LHC Software Architecture (LSA) [4] to perform these measurements allowing the operator to perform separation or angle scans manually or automatically. Different features are available within the application:

- Monitoring of the relevant devices (BPM, BCT, luminosity monitor, orbit corrector).
- Creation of the separation bumps to be trimmed via LSA or the MADX online model.
- Data exchange with experiments via the Data Interchange Protocol (DIP).
- Online analysis.
- Acquisition of the measurements in a database for offline analysis.
- Default settings for fast optimization.

This application was developed such that all the tools required to perform and analyse a separation or angle scan are available in the same software.

MAGNET PERFORMANCE

The separation at the IP is generated via a four magnet closed orbit bump. The magnets used to steer the beams independently are MCBC and MCBY [3] orbit correctors. It is possible to estimate the length of a full scan by looking a their acceleration and ramping rate. The nominal setting for those magnets were set to 0.67 A/s for the ramping rate and 0.25 A/s^2 for the acceleration. Assuming a scan from -5 σ to 5 σ with 11 acquisition points of 10 s for the 2 m β^* optics each steps would last 17 s for an overall scan length of 3 minutes per plane. The same scan performed for the 11 m β^* optics would last 4 minutes. Hysteresis effects in these magnets during the scan could be a source of uncertainty. In the case of the LHC it was shown that orbit displacements from hysteresis effects in these magnets are, in the worst case, of the order of 0.05 σ [6] which is within the precision of alignement we can get with the Van Der Meer method and can be minimized by always scanning in the same direction.

CALIBRATION SCANS

The LHC will operate with rounds beams, scans in both vertical and horizontal direction should be enough to determine the overlap distribution of the two colliding beams. The calibration scans will be done for the four IPs separately.

Bump Calibration

The knowledge of the length scale of the offest d between the beams is required for absolute luminosity determination. The measurement of the beam position at the IP could be done via the BPMs described above but the experiments can provide us with a much better resolution from the vertex reconstruction. A bump calibration could be performed before the luminosity scan:

- Perform a quick scan to recenter the beams.
- Take measurement during n seconds to get the required precision.
- Move the two beams together to another position.
- Repeat the first two steps again.
- Compute the length scale from the two points.
- Repeat the same procedure in the other plane.

This method was used at SLAC [7] and gave a resolution of $5\,\mu$m or better on the determination of the beam position. This would represent an error of 1-2% on the length scale for a β^* of $2\,$m and would considerably reduce the uncertainty on the effective beam size measurement.

Systematics

Table 2: Expected Uncertainties for Nominal LHC Running Conditions and Conditions Used for Calibration

	Nominal	Calibration
F_c	2%	negligible
Dynamic effects	1%	negligible
Hour glass effect	1%	negligible
Beam current	less than 1%	1%
Hysteresis effects	negligible	negligible
Length scale	1-2%	1-2%
Relative Luminosity	less than 1%	1%

In addition to what is shown in Table 2 we can expect a small uncertainty due to non pp collisions backgrounds. The main extra uncertainty is expected to be associated with our knowledge of the bunch shape and dimensions. Extended non-gaussian tails for example would contribute to the bunch intensities but very little to the collision rates. We are quite confident that a total uncertainty of about 10% in the absolute luminosity calibration could be reached in small number of calibration runs.

OPTIMIZATION

The main goal of optimization is to maximize the integrated lumonisity. It is forseen to use the same method for optimization as for the calibration of the luminosity. However optimization does not require as much precision as calibration, an online study of the averages over the bunches and over a smaller range of separation should be sufficient for optimizing the luminosity. Since the collision rates are the highest at the beginning the integrated luminosity will benefit a lot from every minute saved in the early store. It is therefore necessary to build a fast and automated procedure in order to save as much time as possible, futhermore, it is very desirable to minimize as much as much possible any steering of the beam that could degrade the beam condition during the store.

Early Store

After collapsing the separation bumps and an initial correction using the BPMs the beams will not be perfectly centered. A fast scan over a small range of separation with a small number of acquisition points (-2 σ to +2 σ with 5 acquisition points typically) should be enough to center the beams within $0.1\,\sigma$ [2] in a few minutes which correspond to a relative change of luminosity with respect to the peak of less than 1% (as a reference the expected orbit spread from beam-beam interactions at nominal beam conditions is of the order of $0.3\,\sigma$).

During the Store

The orbit during the store will be affected by various external perturbations such as the ground motion and, without corrections, those perturbations could result in a separation of up to $1\,\sigma$ at the end of the store. A fully automated procedure included in the feeback system was successfully used in RHIC [5] and could be well suited for LHC once we have a good understanding of the machine. In the first month of operation it might be safer to manually perform this optimization using the same procedure as for the early store.

CONCLUSION

We describe plans for luminosity optimization and calibration in the LHC using transverse separation scans. An online application has been developed to control and monitor these scans. It will allow to determine the effective size and shape of the beams in collision and allow to minimize any offsets between the colliding beams. The knowledge of the transverse beam sizes can be used to predict the absolute luminosity. We expect that a systematic uncertainty of about 10 % could be reached in a small number of calibration runs.

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