FIRST LUMINOSITY SCANS IN THE LHC

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Abstract

Once circulating beams have been established in the LHC the first step towards collisions is to remove the physical separation used to avoid collisions during injection and ramp. A residual separation can remain after the collapsing of the separation bumps. The so-called Van Der Meer method allows for a minimization of this unwanted separation by transversally scanning one beam through the other. The beam sizes at the IP can also be determined by this method and used to give an absolute measurement of the luminosity. We report on how this measurement was implemented and performed in the LHC to optimize and calibrate luminosity.

INTRODUCTION

The event or collision rate $\dot{N}$ for a given process of cross section σ produced by a machine running with luminosity $\mathcal{L}$ is given by:

$$\dot{N} = \mathcal{L}\sigma \quad (1)$$

The proton-proton cross section is not a priori known at LHC energies, which makes it highly desirable to get the absolute luminosity normalization from machine parameters alone [1]. In the LHC, the beams collide in four interaction regions ATLAS (IP1), ALICE (IP2), CMS (IP5) and LHCb (IP8). All interaction regions are equipped with several monitors, which allow to measure relative collision rates. In this paper we describe how the beams were brought into collision and optimized for the first time in the LHC. We report on the first more extended luminosity scans which were performed to allow for an absolute luminosity calibration.

THE VAN DER MEER SCAN METHOD

The Van Der Meer scan method for luminosity determination was pioneered by S. Van Der Meer at the ISR [2]. The 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, the luminosity as a function of the transverse displacement δu is expressed as:

$$\mathcal{L}(\delta u) = \mathcal{L}_0 \exp\left[-\frac{\delta u^2}{2\sigma_u^2}\right], \quad (2)$$

where

$$\mathcal{L}_0 = \frac{N_1 N_2 \, f \, N_b}{2\pi\sqrt{(\sigma_{1x}^2 + \sigma_{2x}^2)(\sigma_{1y}^2 + \sigma_{2y}^2)}} \quad (3)$$

where $\sigma_u = \sqrt{\sigma_{1u}^2 + \sigma_{2u}^2}$ with $u = x, y$ for each separation plane, N_1 and N_2 are the bunch intensities, N_b the number of colliding bunches and f the revolution frequency. A fit of the measured interaction rates as function of the separation will allow to determine the effective beam size as well as the maximum achievable collision rate. In practice, the scans are performed by moving the beams step-wise across each other in the two transverse planes. The time we allow for data acquisition at each step can be chosen and is typically set to few seconds. For the very first scans at low luminosity with interaction rates of few Hz we allowed for up to a minute to get a sufficient statistical accuracy. The implementation and expected performances in the LHC were presented in [3].

FIRST COLLISIONS IN THE LHC

In the LHC beams were brought into collision at 450 GeV per beam for the first time in the LHC on the 23rd of November 2009. This was done using BPM measurements only to align the beams at the four interaction points. A more detailed description was presented in [4]. The first collisions at 3.5 TeV per beam were established on the 30th of March 2010 based on BPM measurements and beam gas reconstruction from LHCb and CMS.

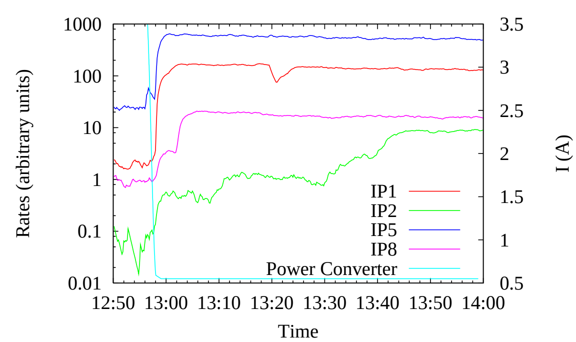

Figure 1: First collisions as seen by the BRANs in all IPs. The power converter data illustrates the moment when the injection separation bumps were ramped down.

Figure 1 illustrates the first collisions at 3.5 TeV as seen by the BRANs in all IPs. The four interaction points were brought into collision at the same time. Additional corrections were necessary in IP8 and IP2 which significantly increased the collision rates. The data shown in this Figure are uncalibrated which explains the difference in rates seen in the various IPs.

LUMINOSITY OPTIMIZATION

The purpose of luminosity optimization scans is to find the optimum position in the horizontal and vertical planes.

A few points around the maximum are sufficient to find the peak.

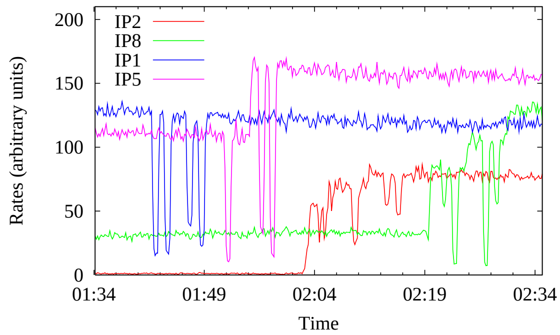

Figure 2: Optimization scans performed for squeezed optics in all IPs.

Figure 2 shows the optimization of all IPs in series during a squeezed optics physics fill with a luminosity of about $5\,10^{27}\mathrm{cm}^{-2}\mathrm{s}^{-1}$. The luminosity was significantly increased in all IPs except for IP1 where no correction was needed. Each scan consisted of 3 steps of 30 s with a range of $\pm 2\sigma$ for a total duration of a few minutes. The overall duration of the full procedure was 45 minutes. For the time being the limitation on the duration of a scan is the statistical accuracy for each scan step. After each fill the optimum settings are saved and used as the new reference for the next fill. Luminosity optimization using the Van Der Meer scan method is now part of routine operation in the LHC and systematically performed during physics fill.

BEAM SIZE MEASUREMENT

A first attempt of calibrating of the luminosity was performed in ATLAS, CMS and LHCb. This section will describe the method and the first observations from this measurement.

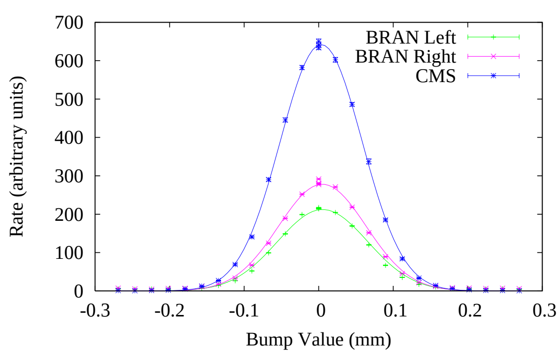

Figure 3: Calibration scan performed in the horizontal plane for IP5.

The transverse displacement of a beam at the IP is generated with a closed orbit bump which also displaces the beam at the tertiary collimators. For the machine protection system to remain efficient the orbit displacement at the collimators has to remain within a certain range. This range was not sufficient to perform calibration scans, it was then decided to move the two beams simultaneously opposite directions which allowed for a scan range of $\pm 6\sigma$. The luminosity formula quoted above assumes perfectly Gaussian beams. During early LHC operation a clear emittance blow-up [5] was seen which could introduce non-Gaussian components to the beam profiles. These non-Gaussian components of the beam still contribute to the overall luminosity and have to be taken into account while computing the overlap integral. The core of the beam, which generally remains Gaussian, is the main contributor to the luminosity. A convenient way to include the tails in the model is to fit the profile with a Gaussian, to model the core, plus another function to fit the tails. The luminosity as function of the separation for an arbitrary beam profile is then:

$$\mathcal{L}(\delta x, \delta y) = \frac{N_1 N_2\, f\, N_b}{A_{\mathrm{eff}}} F(\delta x, \delta y) \tag{4}$$

where A_{eff} is the effective area and is defined as:

$$A_{\mathrm{eff}} = \frac{\int_{-\infty}^{+\infty} F(\delta x, 0) d\delta x \int_{-\infty}^{+\infty} F(0, \delta y) d\delta y}{F(0,0)} \tag{5}$$

$F(\delta x, \delta y)$ is the function describing the overlap profile. For a double Gaussian we have $F(\delta x, \delta y) = F_x(\delta x) F_y(\delta y)$ where

$$F_u(\delta u) = A_{1u} \exp\left[-\frac{\delta u^2}{2\sigma_{1u}^2}\right] + A_{2u} \exp\left[-\frac{\delta u^2}{2\sigma_{2u}^2}\right] \tag{6}$$

This leads to

$$\mathcal{L}_0 = \frac{N_1 N_2\, f\, N_b}{2\pi \sigma_{x\mathrm{eff}} \sigma_{y\mathrm{eff}}} \tag{7}$$

with

$$\sigma_{u\mathrm{eff}} = \frac{A_{1u}\sigma_{1u} + A_{2u}\sigma_{2u}}{A_{1u} + A_{2u}} \tag{8}$$

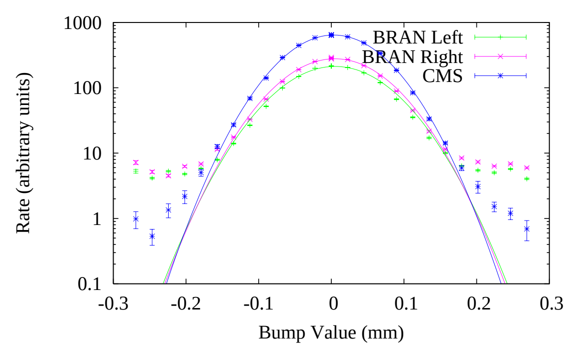

Figure 4: Same horizontal scan in IP5 shown in logarithmic scale with pure Gaussian fits.

Figure 4 shows a scan done in IP5 on a logarithmic scale for which a pure Gauss and a double Gauss fit has been applied. We can clearly see the presence of non-Gaussian tails. This effect was systematically seen in all IPs for both planes. In order to extract the correct beam size from the overlap profile it is important to know the absolute displacement generated with the closed orbit bump. An error on the relative scale of the beam position would directly translate in an uncertainty on the fitted beam size. A measurement of this error was done in IP1 and IP5 by displacing the two beams transversally in the same direction, which results in a displacement of the luminous region, and compare the values given by the magnet settings with the position of the luminous region reconstructed by the experiments.

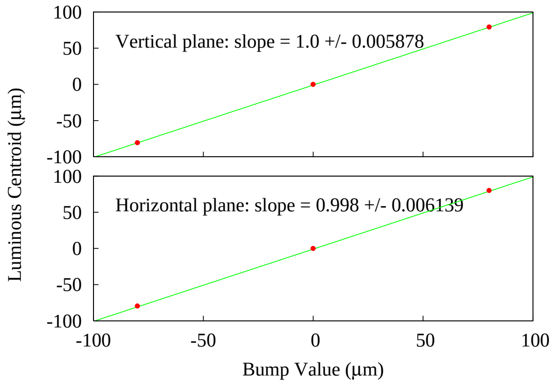

Figure 5: Bump Calibration in IP5.

An excellent agreement was observed between the theoretical value as given by the magnet settings and the measured luminous region centroid given by the experiments. The same measurement in IP1 [6] gave a slope of 0.979 ± 0.009 and 1.011 ± 0.013 in the horizontal and vertical planes respectively.

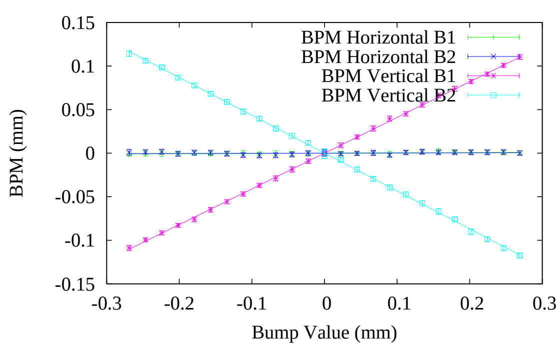

Figure 6: Beam position given by the BPMs as a function of the bump value.

The position of the beams can be measured independently using the BPMs which are situated in Q1 on each side of the IP. No optical element is present between these two BPMs, the position is therefore directly measured with a linear interpolation. The beam position as a function of the bump value has very linear behavior and almost no coupling between planes was observed as illustrated Figure 6. Table 1 summarizes the effective beam sizes derived from the Van Der Meer scans. 1-2% has been added to the statiscal error from the bump calibration. The overall error on the beam sizes ranges from 1% to 4%. The largest error on A_{eff} is of 5% in LHCb but could be improved by adding more scan points (CMS and ATLAS had twice as much).

LUMINOSITY CALIBRATION

Normalizing the luminosity requires an absolute knowledge of the beam intensity which can be obtained from

Table 1: Effective beam size derived from the scans.

	$\sigma_{x\text{eff}}$ (mm)	$\sigma_{y\text{eff}}$ (mm)
IP1	0.0473±1.314E-3	0.0550±1.289E-3
IP5	0.0546±0.567E-3	0.0693±1.526E-3
IP8	0.0466±1.177E-3	0.0517±2.007E-3

FBCTs [5]. For the early LHC operation at low intensity as relevant here, the uncertainty was estimated at 5% per beam for the bunch by bunch measurements. The FBCTs have a resolution of 10 RF buckets, in case of injection mismatch particles can be captured in the buckets following the injected ones but will not participate to the overall luminosity. This effect is expected to be small but needs to be quantified. In case particles are injected in the wrong bucket experiments should be able to monitor off center collisions and measure this effect. On the longer term the longitudinal density monitor [8] should fully determine the longitudinal beam profile. Other effects such as emittance blow-up, hysteresis effects and orbit stability during the scan have to be taken into account and may contribute at the few percent level to the overall uncertainty.

SUMMARY

The Van Der Meer scan method has been successfully used in the LHC to optimize the luminosity. Calibration scans were performed in three of the four experiments and the first results are very encouraging, statistical accuracy on the beam size measurement is not expected to be an issue and the systematics proved to be rather small. For the time being, the overall error on the calibration of the luminosity is dominated by the uncertainty from intensity measurements but special efforts are made to bring it down. Further uncertainties remain to be studied but are expected to be small.

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