OVERVIEW AND RELATIVE BUNCH POPULATION MEASUREMENTS

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Abstract

An important aspect of luminosity calibration measurements is the bunch population product normalization. In the case of the LHC, the treatment of this normalization can be split into three subjects: the total current measurement, the corrections from the non-perfect longitudinal distribution and the relative amplitude of the individual bunch populations. In this contribution, an overview of the bunch population normalization is given, as well as a detailed discussion of the measurements of the relative bunch populations in the context of the 2010 and 2011 luminosity calibration measurements performed for each LHC Interaction Point. The various measurement methods of the relative bunch populations are briefly reminded and the impact of their uncertainties on the cross section normalization are summarized.

1 INTRODUCTION

Several luminosity calibration experiments were carried out in 2010 and 2011 at the LHC, with proton collisions (p-p) and with ion collisions (Pb-Pb), to obtain physics cross section normalizations at each Interaction Point (IP). Both the van der Meer (VDM) scan method and the beam-gas imaging (BGI) method were used. The experiments were carried out at the zero-momentum frame energies $\sqrt{s} =$ 7 and 2.76 TeV for p-p and $\sqrt{s} = 7\ Z$ TeV for Pb-Pb. A summary of the most relevant conditions of each set of VDM scans are listed in table 1.

The first measurements showed that one of the dominant uncertainties is introduced through the bunch population product normalization. As a consequence, a detailed bunch population analysis was carried out using data from the LHC Beam Current Transformers (BCTs) and from the LHC detectors (ALICE, ATLAS, CMS and LHCb). An analysis procedure was defined and bunch population uncertainties were quantified. The results of a first analysis for 2010 calibration measurements were documented in two bunch current normalization notes [1, 2] where a detailed description of the procedure used to determine the bunch populations and their associated uncertainties can be found. The precision was limited by the understanding of the BCT data at that stage. Since then, a number of additional tests were carried out which significantly improved the understanding of the bunch current measurements. The purpose of the present contribution and of five more contributions to this workshop [3, 4, 5, 6, 7] is to review the bunch population measurements and their accuracy in the light of these improvements.

As discussed in reference [1], the LHC is equipped with a number of Bunch Current Transformers (BCTs)[1]. Four independent Direct Current Current Transformers (DCCTs), two per ring, are used to measure the total beam current circulating in each LHC ring [7], which we denote $N_{\mathrm{tot},j}$ for beam j. The DCCT is designed to be insensitive to the time structure of the beam. Two Fast Bunch Current Transformers (FBCTs), one per ring, give a measure of the individual bunch charges [8]. The FBCT is designed to produce a signal (one per 25 ns bunch slot) which is proportional to the charge in a slot, by integrating the charge observed inside a fast gate. The IP1 BPTX button pick-up was also used to measure the relative charge in nominally filled slots [3]. Both the FBCT and BPTX devices are "blind" to a slot charge below a given threshold. Such beam charge, if present, will be measured by the DCCT but not by the FBCT/BPTX. This is called the "ghost" charge. It is defined as the total beam population outside the nominally filled 25 ns bunch slots. Other devices , such as the Longitudinal Density Monitor (LDM) [5] or the LHCb detector [4], were also used, when available, to check the relative bunch populations.

The total ghost charge (denoted $N_{\mathrm{ghost},j}$ for beam j) was mainly measured by comparing the beam-gas rates from nominally empty bunch crossings with those of crossings in which only the slot of one beam was filled with a bunch [4]. This technique was pioneered at IP8/LHCb (though efforts are now being made to deploy it at other LHC experiments). Given the nature of the LHCb detector readout electronics, the method was limited to a 25 ns granularity. Furthemore, within the 25 ns of a nominally filled slot the bunch occupies only one of the ten RF bins. Possible "satellite" bunches may populate the other nine RF bins. Such satellite charges were indeed observed and measured in different ways with the LHC detectors (by timing or vertex reconstruction) by monitoring longitudinally displaced collisions. The amount of satellite population is generally small compared to the main bunch population, but nevertheless needs to be quantified to obtain a precise measurement of the bunch population that actually participates in the luminosity signal. At some stage, the LHC LDMs were deployed and commissioned (one per ring) [5]. The LDM allows one to obtain a precise longitudinal distribution of

[1] Throughout this contribution, it is assumed that the measured charge for Pb beams is exactly proportional to the particle population, with 82 as proportionality factor.

Period / beams	β^* (m) IP1&5 / 2 / 8	Net angle $\alpha_{\rm net}$ (μrad)	$\sqrt{s}/Z$ (TeV)	LHC fill	Nr of bunches	Colliding in IP1&5 / 2 / 8	scanned IPs	$\langle N\rangle$ ($10^{10}e$)
Apr-May 2010	2 / 2 / 2	0 / 0 / 0	7	1058	3	2 / 2 / 2	5	1.1
				1059	2	1 / 1 / 1	1, 8	1.1
p-p				1089	2	1 / 1 / 1	1, 5	2.0
				1090	2	1 / 1 / 1	2	2.0
Oct 2010	3.5 / 3.5 / 3.5	200 / 500 / 340	7	1386	19	6 / 1 / 12	1, 5	8.0
p-p				1422	16	3 / 1 / 12	2, 5, 8	8.0
Nov 2010 Pb-Pb	3.5 / 3.5 / 3.5	0 / 0 / -	7	1533	121	113 / 114 / 0	1, 2, 5	0.8
Mar 2011	11 / 10 / 10	0 / 710 / 1370	2.76	1653	72 (+4)	64 / 48 / 16	1, 2, 5, 8	9.0
p-p				1658			1	10.5
May 2011 *p-p*	1.5 / 10 / 3	240 / 440 / 1040	7	1783	38 (+1)	14 / 16 / 22	1, 2, 5, 8	8.5
Jun 2011 *p-p*	1.5 / 10 / 3	240 / 440 / 1040	7	1875	1092 (+1)	1042 / 35 / 1008	5	12.0
Oct 2011 *p-p*	90 / 10 / 10	0/ 440 / 540	7	2234	36	4 / 16 / 16	2, 8	9.0
Nov 2011	1 / 1 / 3	240 / 120 / -	7	2335	352	344 / 324 / 0	2	1.0
Pb-Pb				2337			1, 5	1.0

Table 1: VDM luminosity calibration series for the LHC (2010 and 2011). The number of bunches in brackets indicates the number of "pilot" proton bunches in addition to the number of "main" proton bunches. Here, $\langle N\rangle$ is an indicative value of the main bunch charge in units of 10^{10} elementary charges.

the beam charge with a time resolution of about 90 ps. It is now used for constraining both the ghost charge and the satellite populations. Other methods, such as vertex reconstruction and timing correlations, were used in the LHC experiments to constrain the satellite populations (see e.g. [6]).

The bunch population normalization was decomposed in three tasks: (i) determination of the total beam charge, (ii) analysis of the relative bunch populations and (iii) corrections due to the ghost charge and satellite populations.

The first and third items are discussed in detail in references [9] and [10], respectively. In the present contribution, the focus was on the second item, namely the determination of the relative bunch fractions and associated uncertainties. For a much more detailed discussion, we refer the reader to reference [11].

2 FBCT SYSTEMATICS

The scope of the luminosity calibration measurement is primarily to extract a reference cross section σ. For each bunch pair i a cross section result σ_i can be obtained from the Beam1 bunch population $N_{1,i}$, the Beam2 bunch population $N_{2,i}$ and the quantity ξ_i obtained from the luminosity calibration analysis (which is essentially the observed interaction rate per crossing divided by the beam overlap integral):

$$\sigma_i = \frac{\xi_i}{N_{1,i}\,N_{2,i}} = \frac{\xi_i}{P_{1,i}\,P_{2,i}\,N_{\rm main,1}\,N_{\rm main,2}} \qquad (1)$$

Here, $\xi_i = R_i\,A_{\rm eff}/f$ with $A_{\rm eff}$ the effective area measured in the luminosity calibration experiment, f is the revolution frequency, and R_i is the rate of interactions for this bunch pair i corresponding to the above effective area (ξ_i is the rate divided by the specific luminosity at the VDM scan working point). The population fractions $P_{j,i}$ of beam j have been introduced, such that the sum over all the main bunches gives unity. The total population of the main bunches is $N_{{\rm main},j}$. If no bunch-related systematic effects are present, the same cross section result is expected for each bunch pair (within statistical accuracy).

The normalizations of the bunch populations of beam j

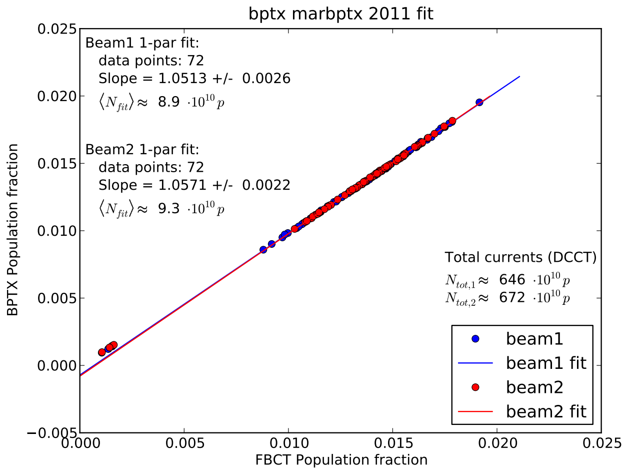

Figure 1: BPTX vs FBCT bunch populations during fill 1653 (just before the Mar 2011 VDM scans). Both device data sets have been normalized such that the sum of the main bunch populations is unity. The lines are the result of a 1-parameter fit excluding the pilot bunches. The fit parameter uncertainty was obtained by forcing $\chi^2/ndf = 1$.

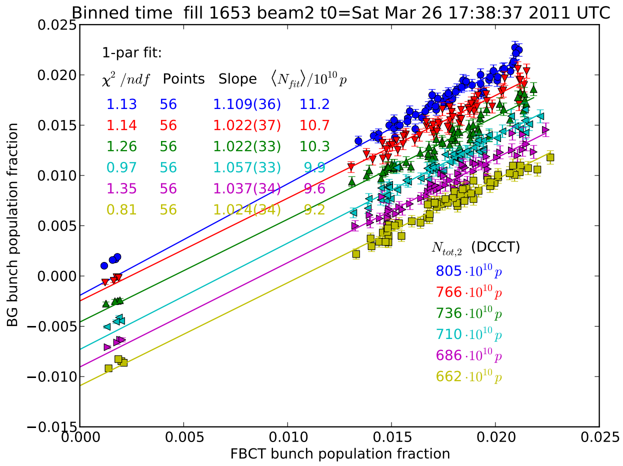

Figure 2: Beam2 population fractions from beam-gas rates versus FBCT bunch populations averaged over subsequent 3 hours bins in fill 1653 (Mar 2011), one color per time bin. For clarity, the data have been shifted down by a fixed amount after each time bin; the y scale is exact only for the first time bin (blue circles). See text for a detailed explanation.

($j = 1$ or 2) is as follows:

$$
\begin{aligned}
N_{\mathrm{main},j} &= \sum_{i \in \mathcal{M}} N_{j,i} = N_{\mathrm{tot},j} - N_{\mathrm{ghost},j} - N_{\mathrm{pilots},j} \\
N_{\mathrm{pilots},j} &= \sum_{i \in \mathcal{P}} N_{j,i} \\
P_{j,i} &= \frac{N_{j,i}}{N_{\mathrm{main},j}} \quad \text{with} \quad \sum_{i \in \mathcal{M}} P_{j,i} = 1 \,.
\end{aligned} \tag{2}
$$

The $P_{j,i}$ are the measured population fractions. $\mathcal{M}$ is the set of main bunches, $\mathcal{P}$ the set of pilot bunches (if present). For details see reference [11].

Comparison of the FBCT data with data from other devices (BPTX, LDM, LHCb beam-gas rates) demonstrated that the FBCTs provide useful and precise measurements of the bunch population fractions. An example is shown in figure 1 which displays the BPTX bunch populations versus the FBCT bunch populations during fill 1653 (just before the Mar 2011 VDM scans). Figure 2 shows the Beam2 population fractions from LHCb beam-gas rates versus FBCT bunch populations averaged over subsequent 3 hours bins in fill 1653 (Mar 2011). Only the unpaired main bunches are shown and have been used in the 1-parameter fit. The populations used in the fit were normalized to unity (both the beam-gas and FBCT data). The lines are the results of the fit. The χ^2/ndf and slope parameter are shown in teh figure for each time bin with uncertainties in brackets. The agreement between the FBCT population fractions and the BPTX or beam-gas data is excellent, considering the fact that the three measurement methods are completely different and performed at distant locations in the rings. One notes however that the fit lines exhibit a small offset at the origin, which might be due to a slight non-linearity of the FBCT. Indeed, a closer look revealed also that the FBCTs might suffer from minor imperfections. For instance, a dependence of the device response on the bunch length and on the beam positions at the device (horizontal and vertical) was observed. The bunch length sensitivity was found to be at the level of 0.3-0.5% for a 0.1 ns change (at about nominal bunch intensity). The position sensitivity was found to be (in the worst plane and ring combination) at most 1% for a 1 mm movement for $\sim 8 \cdot 10^{10} p$ per bunch. Both effects result in a few permil effect during typical VDM scans. See reference [11] for details. An example plot is shown in figure 3 which displays the FBCT signals as a function of horizontal Beam1 displacement in the FBCT. This study was carried out during a machine development period (fill 1910). The bunch length dependence was already reduced in the summer of 2011 by insertion of a 70 MHz filter.

The cross section can be obtained from a 1-parameter least-square minimization of the luminosity calibration data ξ_i. However, in several cases, when fitting the data with this single parameter, the resulting chi-square values per degree of freedom χ^2/ndf were found sizably larger than 1, indicating that systematic uncertainties are affecting the measurements. These may be associated (or not!) with the bunch charge measurement.

A bunch-by-bunch analysis of the VDM cross section results was performed (for each IP and each scan). The data were fitted with one parameter (the cross section), with three parameters (adding one parameter per FBCT for a possible offset or slope) and with five parameters (adding one more parameter per FBCT to take into account a local

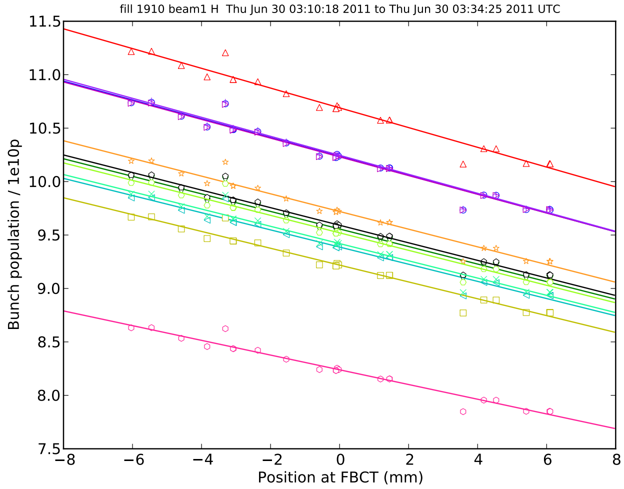

Figure 3: FBCT signals as a function of beam displacement (position). Each of the twelve monitored bunches is assigned a different symbol and color. (shown here for Beam1 and for a horizontal bump in fill 1910). The data of each bunch are fitted with an affine function.

curvature of the response). From this analysis, it resulted that the χ^2/ndf values for the Mar 2011 data were considerably improved with the 3-parameter fits (and slightly more with the 5-parameter fits), while practically no improvement was obtained for the May 2011 scans. Differences in the extracted fit parameters describing the FBCT (or BPTX) devices were found from experiment to experiment, which can be explained by the fact that different bunch pairs (or different fills) were used.

Despite the differences among the slope parameters obtained from the fit results, the cross sections extracted from the 3-parameter fits (and 5-parameter fits) changed by less 0.3% when compared to the 1-parameter fit results. Given the diversity of the results, the goodness-of-fit, etc., between the various scan series, no general prescription can be given on the treatment of these uncertainties. It may be that part of (or even the largest part of) these systematic uncertainties do not originate from the relative population measurements. Other effects, within each experiment, may be the cause of the data spread. Beam-beam effects could be one cause [12].

Given the current understanding of the systematic effects of the relative population measurement, "fudged" uncertainties were also produced. The fudged values were obtained by increasing the ξ_i uncertainties of each experimental data set with a common factor (one per scan and experiment) such as to obtain $\chi^2/ndf = 1$. From the available data sets, all fudged uncertainties on $\delta\sigma/\sigma$ remained at the level of 0.1 to 0.2%, with the exception of the CMS Nov 2010 results (Pb-Pb) which lies around 0.5%. For the Nov 2010, Mar, May, Oct and Nov 2011 scan series, it is advocated to use fudged cross section uncertainties as uncertainties due to the relative bunch population measurements.

In order to reduce the importance of relative bunch population uncertainties in future luminosity calibration experiments, one should avoid mixing low and high population bunches, due to the possible 'curvature' in the FBCT response, unless one uses accurate means to correct for this effect. In general, all bunch properties (charge, length, position) should be made as homogeneous as possible. The individual bunch properties should be measured (bunch length and bunch positions at FBCT) during luminosity calibration experiments. In the ideal case, all bunches should be colliding at the IP where the calibration is being performed. This is to avoid possible systematic effects due to different behaviour of colliding and unpaired bunches.

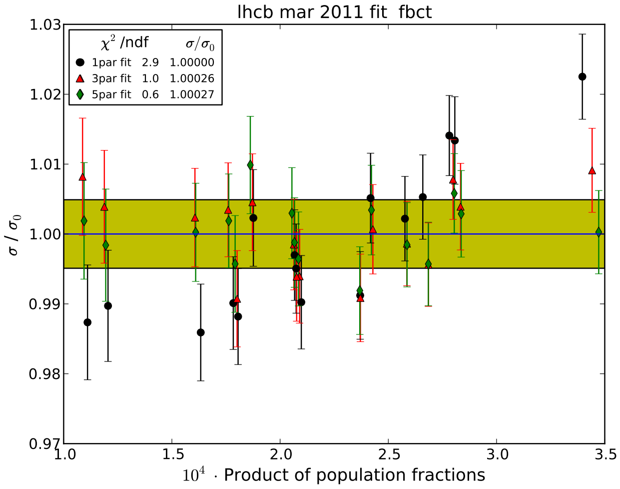

Figure 4: Example result of the bunch-by-bunch cross section analysis (here for LHCB in the Mar 2011 scans, fill 1653). '1-par' = raw data fitted with one parameter (σ_0). '3-par' = affine fit with three parameters (σ_0, β_1 and β_2). '5-par' = quadratic fit with five parameters (σ_0, β_1, β_2, γ_1 and γ_2). The band indicates the range $\pm 3\delta\sigma_0/\sigma_0$.

Several other improvements may be expected for 2012. Beam-gas data from LHCb with enhanced rates (by gas injection) should allow one to measure bunch charges with an accuracy better than 1% per nominal bunch in 1000 s. One more LHC device, the wall-current monitor (WCM), will be commissioned to measure the relative bunch populations. In addition, the IP1 BPTX data nd the LDM data will be pushed to the LHC logging database for widespread use. In order to better understand the FBCT systematic effects, some measurements could be repeated: (a) phase scans for a better understanding of the FBCT efficiency over 25 ns, (b) beam position dependence studies, this time at flat top and with controlled bunch length, (c) bunch length dependence studies, with controlled position per bunch at the FBCT (and calibrated bunch length measurement), possibly using controlled longitudinal blow-up. (d) controlled total current losses at flat top to check the FBCT vs DCCT ratio. Furthermore, work on reducing the FBCT sensitivity to bunch length and position will be continued,

3 DISCUSSION AND SUMMARY

The measurements of the bunch population fractions were critically reviewed in the context of the 2010 and 2011 luminosity calibration experiments. The data from main device, the FBCT, were compared to several different data sets from radically different devices. This comparison indicated that the FBCTs provide a precise measurement of the relative bunch populations, though a careful look also revealed a number of systematic effects which could alter the cross section measurements at the level of a few permil.

These findings were corroborated by a detailed analysis of the bunch-by-bunch cross section data. This analysis indicated that the possible systematic effects of the measurements of the bunch population fraction on the extracted cross section are smaller than 0.5% (see details in reference [11]).

A number of possible improvements or studies for 2012 were mentioned.

4 REFERENCES

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