Bunch Current Normalisation Analysis Results

T. Pauly*, CERN, Geneva, Switzerland

Abstract

This paper presents the results of the LHC Bunch Current Normalisation Group, on the absolute normalisation of the bunch populations during LHC fills in April/May 2010 dedicated to Van der Meer scans, as well as an estimation of the systematic uncertainties for Van der Meer scans in October 2010. The analysis methods are discussed, which are based on data from the LHC beam instrumentation and LHC detectors, as well as the estimation of the systematic uncertainties.

INTRODUCTION

During 2010, the LHC performed a series of Van der Meer scans in April, May, and October, for its four experiments ALICE, ATLAS, CMS, and LHCb, in order to obtain an absolute measurement of the luminosity via beam parameters. An important ingredient for this measurement are the bunch population products $N_i^{(1)} \cdot N_i^{(2)}$, where the bunch populations $N_i^{(j)}$ denote the number of protons of bunch i of beam j, where $j = 1, 2$. This note discusses the procedures and results of the measurement of the absolute bunch populations for the series of fills in 2010 dedicated to Van der Meer scans.

The first series of Van der Meer scans took place in April and May 2010, during LHC fills 1058, 1059, 1089, and 1090, with typically 2 or 3 bunches per beam with total beam populations of around 1 to 4×10^{10} protons, colliding head-on without crossing angle. More information is shown in tables 1 and 2. A preliminary analysis provided first beam population results that were used for ICHEP 2010. A more detailed and rigorous analysis followed, which is subject of this paper and described in more detail in [1].

A second series of Van der Meer scans followed in October 2010, in fills 1386 for ATLAS and partially for CMS, and in fill 1422 for LHCb, CMS, and ALICE. A 19-bunch scheme was used with total beam populations of about 1.5×10^{12} protons. The analysis of this data is still in progress; in this paper, we only make an estimate of the expected systematic uncertainties.

* on behalf of the LHC Bunch Current Normalisation Working Group: G. Anders, N. Bacchetta, V. Balagura, C. Barschel, D. Belohrad, D. Berge, H. Burkhardt, S.I. Cooper, M. Ferro-Luzzi, G. Franzoni, C. Gabaldon, M. Gagliardi, J.J. Gras, V. Halyo, B. Heinemann, P. Hopchev, A. Hunt, W. Kozanecki, S. Kwan, M. Ludwig, D. Marlow, P. Odier, S. Pagan Griso, J. Panman, T. Pauly, S. Thoulet, S. White, J.C. Yun , M. Zanetti

ANALYSIS

The analysis of the bunch population normalisation is based on several independent systems: the DC current transformers (DCCT), the fast beam current transformers (FBCT), the ATLAS timing pick-ups (BPTX), and the LHC detectors. The DCCT measure the total current of the circulating beam (bunched and unbunched). A calibration winding allows an absolute calibration via the injection of a known generated current. The FBCT are used for per-bunch measurements of the beam populations; they are only sensitive to bunched beam and measure the current over a threshold of about 5×10^8 protons. The BPTX are electro-static button pick-ups that provide as by-product a per-bunch relative intensity, which is used to cross-check the results from the FBCT. The LHC detectors are used for detailed studies on ghost charge and satellite bunch contributions. In the context of this paper, we define *ghost charge* as the summed charge for all those 25 ns slots which are not visible by the FBCT, i.e. unbunched or below the FBCT threshold. As *satellite bunches*, we denote captured charge in RF buckets with a few tens of nanoseconds around the nominal buckets.

The total beam population N_{tot}^{DCCT} is derived from the DCCT readings S_{DCCT} by applying the DCCT calibration scale factor α and correcting for a non-zero baseline offset N_0^{DCCT}, which is estimated from DCCT data:

$$N_{tot}^{DCCT} = \alpha \cdot S_{DCCT} - N_0^{DCCT} \tag{1}$$

The per-bunch populations for bunch i are then obtained from the FBCT readings S_i^{FBCT} in the following way: the ghost charge contribution N_{ghost}, which is included in N_{tot}^{DCCT} but not in the per-bunch population, is removed from the total bunch population, which is subsequently split in proportion to the per-bunch fractions from the FBCT:

$$N_i^{FBCT} = \left(N_{tot}^{DCCT} - N_{ghost}\right) \cdot \frac{S_i^{FBCT}}{\sum\limits_i S_i^{FBCT}} \tag{2}$$

In the following, we discuss the procedures for determining the DCCT baseline corrections and its uncertainties, the uncertainty of the DCCT scaling factor α, the uncertainty on the per-bunch fractions, and the ghost-charge population. Note, that if not stated otherwise, all systematic uncertainties are taken as uncertainty bands; a quantity with a systematic uncertainty of Δ is conservatively assumed to follow a flat distribution in the interval $[-\Delta, +\Delta]$ around the central value.

Table 1: Summary of the April-May 2010 LHC luminosity calibration experiments with the Van der Meer method.

Van der Meer scans, April-May 2010							
LHC fill	Approx. start date	time	Approx. stop date	time	IP scanned	Bunch pattern	Approx. bunch population
1058	April 24	11:00	April 24	12:30	IP5	3-bunch	$1.0 \cdot 10^{10} p$
1059	April 26	02:30	April 26	06:00	IP8, IP1	2-bunch	$1.0 \cdot 10^{10} p$
1089	May 8	23:00	May 9	03:30	IP5, IP1	2-bunch	$2.0 \cdot 10^{10} p$
1090	May 10	05:00	May 10	07:00	IP2	2-bunch	$2.0 \cdot 10^{10} p$

Table 2: List of bunch crossings in the four insertion regions for the 3-bunch and 2-bunch patterns. In each line the RF bucket of the encountered Beam2 bunch is given for each IP and for the corresponding bucket of the Beam1 bunch. The numbers in brackets indicate a longitudinally displaced crossing, at 11.23 m (anticlockwise) from the actual IP.

Fill 1058 3-bunch pattern					Fills 1059, 1089 and 1090 2-bunch pattern				
Beam1	Colliding Beam2 RF bucket				Beam1	Colliding Beam2 RF bucket			
RF bucket	IP1	IP2	IP5	IP8	RF bucket	IP1	IP2	IP5	IP8
1	1	8911	1	-	1	1	8911	1	-
8941	(8911)	17851	(8911)	1	17851	-	-	-	8911
17851	17851	-	17851	8911					

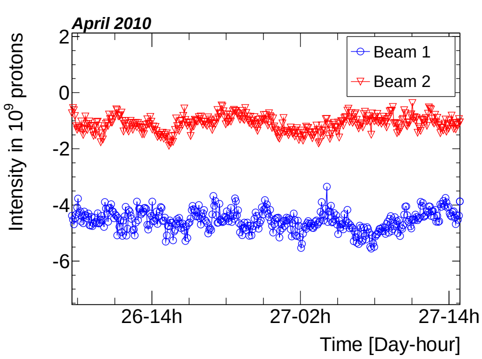

Figure 1: A period without beam (April 26/27, 2010). The DCCT signal is shown versus time for Beam1 (blue circles) and Beam2 (red triangles), with 300 s averaging time.

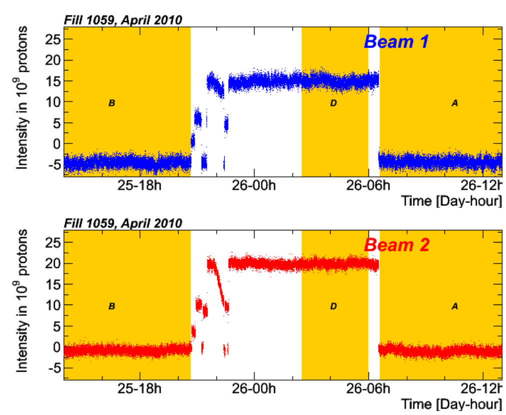

Figure 2: DCCT data for the Van der Meer scan during fill 1059. The periods *before*, *during*, and *after* the scan used to determine the beam populations are indicated by the shaded bands B, D, and A, respectively.

DCCT Baseline Drifts

DCCT baseline drifts have been studied in periods without beam. The white noise of the raw data is about 10^9 protons RMS. It is efficiently suppressed by averaging over time bins of 300 seconds, an appropriate choice large enough to suppress white noise and small compared to the length of a Van der Meer scan. The time-averaged data are shown in Figure 1. Significant baseline drifts are visible. Although their origin is yet unknown, possible causes could be temperature drifts, electromagnetic pick-up in cables and electronics, or mechanical vibrations in the transformer assembly. For a given Van der Meer scan, the DCCT baseline offset N_0^{DCCT} is reconstructed by interpolating between the average baseline offsets determined in a period before and a period after the fill. Figure 2 shows, for fill 1059, the periods before (B), during (D), and after (A) the fill. The DCCT value during these periods is simply the average of the measurements. The systematic uncertainty from the baseline drifts is taken as the maximum of the peak-to-peak variation of the period B and A; numerically $\pm 0.8 \times 10^9$ protons. In the preliminary analysis, a conservative estimate of $\pm 2 \times 10^9$ protons was used.

Table 3: DCCT total population measurements for all April-May and October 2010 fills with Van der Meer scans. Values marked with $*$ are still under study and not yet finalised.

Fill nr.	LHC ring j	Detailed analysis LHC intensity $N_{\mathrm{tot},j} \cdot 10^{-9}$ baseline-corrected	Preliminary analysis LHC intensity $N_{\mathrm{tot},j} \cdot 10^{-9}$ baseline-corrected
1058	1	32.3 ± 0.8	31.8 ± 2.0
	2	30.3 ± 0.8	28.4 ± 2.0
1059	1	19.2 ± 0.8	18.9 ± 2.0
	2	20.7 ± 0.8	20.6 ± 2.0
1089	1	38.4 ± 0.8	38.1 ± 2.0
	2	43.5 ± 0.8	43.7 ± 2.0
1090	1	37.4 ± 0.8	37.4 ± 2.0
	2	40.6 ± 0.8	40.0 ± 2.0
1386	1	$1737.1 \pm 0.8^{*}$	N/A
	2	$1710.8 \pm 0.8^{*}$	N/A
1422	1	$1195.6 \pm 0.8^{*}$	N/A
	2	$1191.3 \pm 0.8^{*}$	N/A

Correlations between the DCCT baseline drifts of the two beams have been studied using long empty periods in addition to the Van der Meer scan fills, but no correlations have been found. For this reason, the baseline uncertainties of the two beams can be added quadratically.

Scaling Factor Uncertainty

The uncertainty of the absolute scale factor α is dominated by the long-term time stability, which is estimated as $\pm 2\,\%$ from the evolution between calibration periods and Van der Meer scan periods, based on 5 precise calibration points during technical stops. Other possible uncertainties, such as misbehaviour of the DCCT linked to the LHC filling pattern, inaccuracy of the commercial current generator used for calibration, and non-linearities between the working point and the calibration point, have been estimated to be less than $0.1\,\%$ each. It is conservatively assumed that the scale uncertainty is correlated between the two beams in a fill, as well as correlated between two fills.

Per-bunch Uncertainty

In order to study systematic effects of the per-bunch fractions $S_i^{FBCT}/\sum_i S_i^{FBCT}$, cross-checks with measurements from the independent ATLAS BPTX systems have been performed. Figure 3 shows for fill 1295, a fill with a larger spread of bunch intensities, and for each bunch, the proton population measured by the FBCT and the BPTX (uncalibrated). There is a linear correlation between the two systems of better than 1 %, although a non-zero offset is present which is not yet understood. In the presence of this offset, deviations between the two systems of up to 3 % have been observed for the April/May scans, whereas for the October scans the deviations are fill-dependent and are 1.1 % for fill 1386 and 1.7 % for fill 1422. These uncertainties are taken as not correlated between the two beams, thus the quadratic sum is taken for the bunch population product.

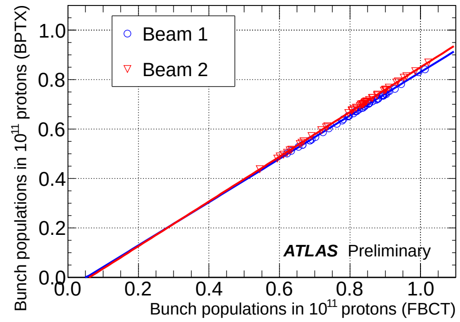

Figure 3: ATLAS BPTX signal versus FBCT signal for LHC fill 1295 (August 2010). Each data point corresponds to a different bunch. The lines are the results of a straight line fit

Ghost Charge and Satellite Bunches

The ghost charge has been estimated using beam gas events recorded by LHCb. Small levels of ghost charge have been identified and corrected for, less than 1 % for the April/May scans and less than 0.5 % for the October scans.

Satellite bunches have been studied by ATLAS and CMS using displayed vertices, as well as timing information from the CMS endcap electromagnetic calorimeters. All methods show consistent results: negligible satellite contributions of less than 2 permil have been identified.

RESULTS

Table 4 lists the uncertainties and their treatment for the preliminary analysis (left) and the detailed analysis (right) for the bunch population product $P_{ij} = N_i^{(1)} \cdot N_j^{(2)}$, where i and j denote the bunch number. In the preliminary analysis, uncertainty bands were converted standard deviation by a factor of $1/\sqrt{3}$. As this corresponds to a confidence level of only 57.7 %, the conversion was changed for the detailed analysis, where the factor of 0.682 gives the preferred 68.2 % confidence level. For the DCCT baseline uncertainty, a conservative single beam uncertainty of $\pm 2 \times 10^9$ was chosen in the preliminary analysis; it was assumed to be fully correlated between the two beams, but uncorrelated between fills. In the more detailed analysis, the uncertainty was reduced to $\pm 0.8 \times 10^9$ and is assumed to be uncorrelated between the two beams and between fills. Note, that the baseline uncertainty is the largest uncertainty for the low-intensity beams used in April and May 2010, while it is negligible for the higher intensity beams used in October 2010.

Table 4: Summary of the treatment of uncertainties for the preliminary and detailed analyses.

Preliminary analysis	Detailed analysis
$\frac{\sigma_{P_{ij}}^{\text{baseline}}}{P_{ij}} = \frac{1}{\sqrt{3}}\left(\frac{\Delta N_{\text{tot},1}}{N_{\text{tot},1}} + \frac{\Delta N_{\text{tot},2}}{N_{\text{tot},2}}\right)$	$\frac{\sigma_{P_{ij}}^{\text{baseline}}}{P_{ij}} = 0.682 \cdot \sqrt{\left(\frac{\Delta N_{\text{tot},1}}{N_{\text{tot},1}}\right)^2 + \left(\frac{\Delta N_{\text{tot},2}}{N_{\text{tot},2}}\right)^2}$
$\frac{\sigma_{P_{ij}}^{\text{scale}}}{P_{ij}} = \frac{2}{\sqrt{3}}\frac{\Delta\alpha}{\alpha} = 2.3\%$	$\frac{\sigma_{P_{ij}}^{\text{scale}}}{P_{ij}} = 0.682 \cdot 2 \cdot \frac{\Delta\alpha}{\alpha} = 2.7\%$
$\frac{\sigma_{P_{ij}}^{\text{FBCT}}}{P_{ij}} = 0$	$\frac{\sigma_{P_{ij}}^{\text{FBCT}}}{P_{ij}} = 0.682 \cdot \sqrt{\left(\frac{\Delta N_{i,1}}{N_{i,1}}\right)^2 + \left(\frac{\Delta N_{j,2}}{N_{j,2}}\right)^2} = 2.9\%$
$\sigma_{P_{ij}} = \sigma_{P_{ij}}^{\text{baseline}} + \sigma_{P_{ij}}^{\text{scale}}$	$\sigma_{P_{ij}} = \sqrt{(\sigma_{P_{ij}}^{\text{baseline}})^2 + (\sigma_{P_{ij}}^{\text{scale}})^2 + (\sigma_{P_{ij}}^{\text{FBCT}})^2}$

Table 5: Summary of the systematic uncertainties for the detailed analysis. The values for the preliminary analysis are shown in parenthesis. The uncertainties marked with * are not yet finalised and under study.

LHC Fill	1058	1059	1089	1090	1386	1422
Baseline drift	2.5 % (7.7 %)	3.9 % (11.7 %)	1.9 % (5.7 %)	2.0 % (6.0 %)	< 0.1 %	< 0.1 %
Scale factor	2.7 % (2.3 %)	2.7 % (2.3 %)	2.7 % (2.3 %)	2.7 % (2.3 %)	2.7 % (2.3 %)	2.7 % (2.3 %)
Per-bunch	2.9 % (0)	2.9 % (0)	2.9 % (0)	2.9 % (0)	1.1 %*	1.7 %*
Combined	4.4 % (10.0 %)	5.5 % (14.0 %)	4.4 % (8.0 %)	4.4 % (8.3 %)	2.9 %*	3.2 %*

The uncertainty on the absolute scale factor is 2 % and assumed to be fully correlated between fills and between the two beams, for both the preliminary analysis and the detailed one.

Per-bunch uncertainties were not considered in the preliminary analysis, while for the detailed analysis, they are taken to be 3 % for the April/May fills and 1.1-1.7 % for the October fills, without correlation between the two beams and between fills.

All uncertainty contributions were conservatively considered correlated in the preliminary analysis, while in the detailed analysis they are assumed to be uncorrelated.

In table 5 the numeric values of the systematic uncertainties are listed. The values are for the detailed analysis, the values of the preliminary analysis are shown in brackets.

The bunch population results for the April and May 2010 scans are shown in Table 6 for the detailed analysis, as well as the results on the bunch population products; the results of the preliminary analysis are shown in parenthesis.

SUMMARY

In this paper we outlined the detailed bunch current normalisation analysis performed on the Van der Meer scan fills in April, May, and October 2010. For the April and May scans, the central values were updated with respect to the preliminary analysis, and the systematic uncertainties were reduced considerably. The normalisation for the October 2010 Van der Meer scans is still work in progress; its systematic uncertainty is dominated by the absolute scale factor and the relative per-bunch population, while the baseline offset uncertainty is negligible.

REFERENCES

[1] G. Anders *et al.*, "*LHC Bunch Current Normalisation for the April-May 2010 Luminosity Calibration Measurements*," CERN-ATS-Note-2011-004 PERF

Table 6: Summary of results from the detailed analysis for the bunch populations and bunch population products for the April and May 2010 Van der Meer scan fills. Here, the bunches are identified by their nominal RF bucket number b in bracket $N(b)$. The uncertainties are given for 68.2% confidence level. The results given in brackets are those of the preliminary analysis and are standard deviations (57.7% confidence level).

		Fill number			
		1058	1059	1089	1090
Populations $N \cdot 10^{-9}$					
Beam1	$N(1)$	9.56 ± 0.29	8.98 ± 0.34	18.99 ± 0.54	19.91 ± 0.57
		(9.42 ± 0.36)	(8.85 ± 0.55)	(19.01 ± 0.62)	(20.00 ± 0.66)
	$N(8941)$	11.70 ± 0.35	-	-	-
		(11.53 ± 0.44)	-	-	-
	$N(17851)$	11.02 ± 0.33	10.20 ± 0.38	19.08 ± 0.54	17.33 ± 0.50
		(10.85 ± 0.41)	(10.05 ± 0.62)	(19.09 ± 0.62)	(17.40 ± 0.57)
Beam2	$N(1)$	10.19 ± 0.31	10.35 ± 0.37	22.18 ± 0.61	19.54 ± 0.55
		(9.56 ± 0.40)	(10.30 ± 0.59)	(22.34 ± 0.64)	(19.34 ± 0.60)
	$N(8911)$	10.66 ± 0.33	10.35 ± 0.37	21.20 ± 0.59	20.88 ± 0.59
		(10.00 ± 0.42)	(10.30 ± 0.59)	(21.36 ± 0.62)	(20.66 ± 0.64)
	$N(17851)$	9.43 ± 0.29	-	-	-
		(8.85 ± 0.37)	-	-	-
Population products $P_{ij} \cdot 10^{-18} = N_{i,1} \cdot N_{j,2} \cdot 10^{-18}$					
IP1&5	$N(1) \cdot N(1)$	97.5 ± 4.6	92.9 ± 5.2	421.1 ± 18.5	389.0 ± 17.3
		(90.0 ± 9.0)	(91.1 ± 12.8)	(424.6 ± 33.8)	(386.6 ± 32.0)
	$N(17851) \cdot N(17851)$	103.9 ± 4.9	-	-	-
		(96.0 ± 9.6)	-	-	-
IP2	$N(1) \cdot N(8911)$	101.9 ± 4.8	92.9 ± 5.1	402.7 ± 17.7	415.8 ± 18.4
		(94.2 ± 9.4)	(91.1 ± 12.8)	(406.0 ± 32.4)	(413.2 ± 34.2)
	$N(8941) \cdot N(17851)$	110.4 ± 5.2	-	-	-
		(101.9 ± 10.2)	-	-	-
IP8	$N(8941) \cdot N(1)$	119.2 ± 5.6	-	-	-
		(110.1 ± 11.0)	-	-	-
	$N(17851) \cdot N(8911)$	117.5 ± 5.5	105.6 ± 5.9	404.5 ± 17.8	361.9 ± 16.0
		(108.5 ± 10.8)	(103.5 ± 14.5)	(407.9 ± 32.5)	(359.6 ± 29.7)
Relative errors on population products $\sigma_{P_{ij}}/P_{ij}$					
		4.7%	5.6%	4.4%	4.4%
		(10%)	(14%)	(8%)	(8.3%)