Results of the LHC DCCT Calibration Studies

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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 note, we discuss the first item in details and in the context of the 2010 and 2011 luminosity calibration measurements performed for each LHC Interaction Point. Effects Internal to the DCCT, the sensitivity to external factors, uncertainty related to the absolute calibration and comparison of two systems are all addressed. The DCCT uncertainty and numerical examples are given.

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.

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 note and of two companion notes [3, 4] 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 (called system A and B), are used to measure the total beam current circulating in each LHC ring. 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. 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. 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) or the LHCb detector, were also used, when available, to check the relative bunch populations.

Furthermore, 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). The LDM allows one to obtain a precise longitudinal distribution of 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.

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 second and third items are discussed in detail in references [3] and [4], respectively. In the present report, we concentrate on the first item, namely the determination of the total beam intensity measurement and its uncertainties. A detailed discussion of the results from which this document is based is provided in reference [5].

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

DCCT UNCERTAINTIES

The analysis of all factors contributing to the DCCT uncertainties are divided in the following three main categories. A schematic overview is given in Fig. 1.

The first section reports on the analysis of effects internal to the DCCT system which may contribute to the total current uncertainty. The second section discusses the sensitivity to external factors and beam conditions, and the third section focuses on uncertainties related to the absolute calibration.

Finally the difference between systems A and B observed throughout 2011 and a summary of the DCCT uncertainties is given in the last section.

Instrumental stability and linearity

Baseline subtraction and noise The baseline correction method and associated uncertainty described in reference [1] has been verified and validated using a period of nine days of continuous noise. An envelope error of $\pm 1 \cdot 10^9$ charges can be assumed provided that the baseline has been corrected manually or that the offset before and after the fill is smaller than $\pm 1 \cdot 10^9$. Additionally a general uncertainty per range has been evaluated by analyzing the offset of each range after every beam dump in physics fills during 2011. This uncertainty has to be used if the baseline has not been corrected or if the range has not been blocked throughout the fill. Additionally, a Fourier analysis of the noise did not reveal any dominating frequency in the available range.

Stability and linearity The long term stability and linearity measurements have been performed with the DC current source placed in the tunnel near the DCCT's. Two measurements per range with a current close to 80% of the range lasting for 12 hours have been used to evaluate the stability of the DCCT signal. The measurements were separated by 3.5 days and are used to evaluate the uncertainty related to the baseline fluctuations. The uncertainty within a fill depends on the signal averaging time and acquisition range. For each range, the observed standard deviation and largest half peak-to-peak deviation of 1 minute and 1 hour average is taken as uncertainty of the baseline stability.

Additionally, 24 hours long term measurement has been performed with a 400 mA current to evaluate possible thermal effects in the front-end electronics. In this case no thermal or daily effect could be observed within 24 hours with a current intensity of 44% of range 1 and the measurement accuracy was limited by the 12-bit ADC.

The DCCT linearity was studied with three measurements performed in the tunnel. A systematic non-linearity of the order of 1 Least Significant Bit (LSB) has been observed for the ranges 1 to 3. The non-linearity measurement is inconclusive for range 4 due to its intrinsic noise level; however, it is expected to be the same as for the other ranges as all ranges are acquired with the same ADC. Therefore an uncertainty of $\pm$ 1 LSB due to the non-linearity of the acquisition has to be assumed.

A control measurement has been performed with an alternate ADC[2] for which a reference response has been measured in the laboratory with the same current source. The DCCT signal from all DCCT's and ranges was acquired in parallel with the default 12-bit acquisition chain and with the NI ADC. The measurement confirmed that the non-linearity originates from the DCCT acquisition chain and not from the current source. The results of the linearity measurement acquired with both ADC's in parallel is shown in Fig. 2 for system B/beam 2 range 1. The DCCT response measured with the NI ADC follows closely its laboratory reference, while as in the previous measurements, the 12-bit ADC shows a positive non-linearity.

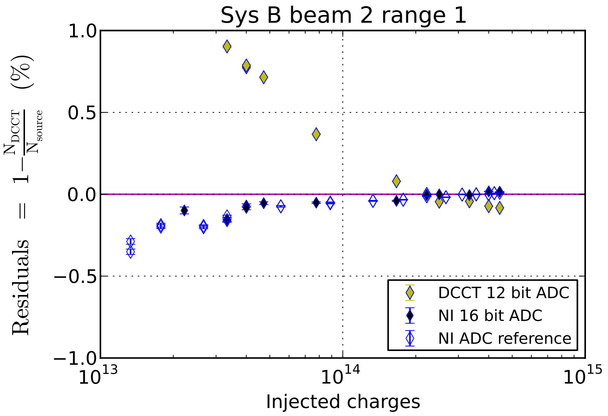

Figure 2: Linearity measurement with the NI ADC acquired in parallel to the DCCT 12-bit ADC. The open dots are the reference response of the NI ADC measured in the laboratory. The filled blue dots are the DCCT response measured with the NI ADC and the filled yellow dots are the DCCT response measured with the 12-bit ADC.

A total of six precise calibrations of the absolute scale factor have been performed in 2011 during the technical stops. The history of the scale factors over nine month is shown in Fig. 3 for system A/beam 1. The scale factors are stable within an envelope of $\pm$ 1 LSB for the ranges 1 to 3 which corresponds to a relative error of $\pm\ 0.06\%$. For range 4 the fluctuations are within $\pm$ 4 LSB which corresponds to a relative error of $\pm\ 0.24\%$ and is compatible with the intrinsic noise level of range 4.

Sensitivity to beam conditions and other external factors

Cross talk between rings To study a possible cross-talk effect between the rings of beam 1 and beam 2, five special machine development (MD) fills have been analyzed in 2010 where only one beam was circulating with a large intensity in the order of 10^{13} protons, while the other ring was empty. No evidence of a cross-talk effect between rings could be observed, the fluctuations stayed within $\pm 0.5 \cdot 10^9$ charges for both system A and system B.

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[2] 16-bit ADC model NI USB-9162 with a connector block NI 9215

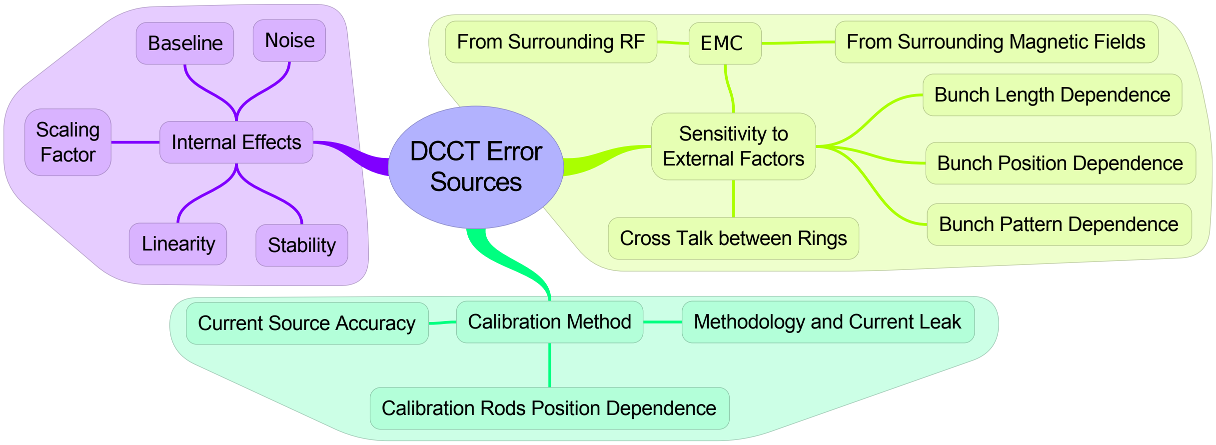

Figure 1: DCCT errors classification.

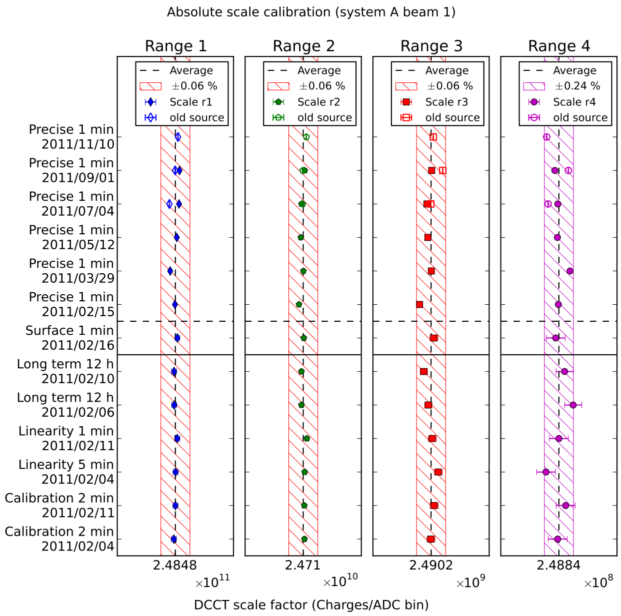

Figure 3: Long term stability of the scaling factor for system A/beam 1. All points below the horizontal dashed line are so called "self" calibrations performed independently from the BI method and software. The points below the continuous horizontal line are calibrations performed with the source in the tunnel instead of on the surface.

Bunch position dependence The sensitivity of the DCCT with respect to the bunch position has been tested by moving each beams in the vertical and horizontal planes during a machine development (MD) fill[3]. No correlation with the beam position could be observed in the beam decay.

Interference from magnetic field A possible interference between the LHC magnetic fields present at high energy and the DCCT response has been analyzed for all physics fill in 2011. The DCCT signal was analyzed during the energy ramp down, after a beam dump. No correlation between the LHC energy and the DCCT signal without beam could be observed and the baseline remained always within $\pm\ 5 \cdot 10^9$ charges which is consistent with the previous baseline measurements.

Interference from RF The LHC RF system is composed of 8 single-cell cavities per ring located on each side of the interaction point 4 (IP4), about 200 m away from the DCCT's. During a fill setup, and before the first beam injection, the field from each cavity is ramped up from 0.02 MV/m ($\mathrm{RF_{off}}$) to about 0.75 MV/m ($\mathrm{RF_{on}}$). A possible interference between the RF field variation and the DCCT signal was evaluated by measuring the DCCT offset over 120 seconds before and after the RF field was switched on. Using 86 fills which had a clear RF transition permitted to show that the DCCT's are unaffected by the cavity field of the RF accelerating system located at IP4.

Bunch pattern dependence The DCCT proved to be sensitive to the bunch pattern in 2010 with bunch spacings of 150 ns and 50 ns grouped in bunch trains. The problem has been identified in the laboratory and corrected in the 2011 hardware [6]. The misbehavior was due to saturation effects in the front-end amplifiers. Three measurements have been performed to test the DCCT dependence on the bunch pattern: a measurement with beam debunching during an MD fill, a laboratory measurement to test the sensitivity to an injected RF sine wave and a laboratory measurement simulating high intensity bunch trains.

The DCCT signal was not affected by the bunch length or the filling pattern measured during the beam debunching process; however, the low intensity of the beam limits the significance of the measurement. With the laboratory RF measurement, the DCCT was exposed to an RF sine wave which was swept over a wide frequency range to test if the DCCT is sensitive to a specific harmonic. The DCCT proved to be unaffected by all tested RF frequencies from 1 kHz to 110 MHz and no resonance has been found. In

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[3] Fill 1910 on 30 June 2011.

all measurements the DCCT signal is compatible with the noise of the selected range.

For the laboratory bunch pattern measurement the new front-end cards have been tested in the laboratory with a spare DCCT. The configuration in the laboratory was identical to that in the LHC tunnel including the beam pipe section and high-frequency (HF) bypass. However, the acquisition of the DCCT signal was different and used a portable 16-bit ADC. A computer controlled scope generated a voltage pattern over time with a maximal amplitude of 1 V. The generated pattern, which represents one or more bunch trains simulating an LHC filling pattern, was repeated at a frequency of 11245 Hz and amplified to an equivalent intensity of up to 1200 nominal bunches. While the known problem could be reproduced with the 2010 hardware, the corrected DCCT front-end electronics were stable during all tested patterns. The measurements with the highest intensity were constant within a 0.1% band for all tested patterns; the accuracy was limited by the instrumentation and electronic components.

Calibration Method

The stability of the scaling factor during the year shows that the reproducibility of the calibration method combined with the stability of the scaling factor are limited by the resolution of the ADC only. The following sources of uncertainty related to the calibration itself have been analyzed:

- The precision of the current source used for the calibration
- The position of the calibration rods
- The methodology of the standard BI calibration procedure
- A possible current leak between the surface and the tunnel

Current source accuracy The absolute scale for each transformer is calibrated with a precise DC current source. Two sources are available: the model Yokogawa 7651 was used for the 2010 calibrations and the model Yokogawa GS200 was used for the 2011 calibrations. The most precise laboratory measurement was reached by measuring the voltage drop across a known precise resistance using a soldered 4-wire (Kelvin) setup to eliminate both wiring and contact resistances. The measurement confirmed the accuracy of both current sources within an envelope error of $\pm 0.05\%$. This measurement could not reach the claimed accuracy of the sources of 0.02%, but is used as systematic uncertainty for the calibration of the DCCT's. Furthermore, it has been verified that, for a DC current, the DCCT is not sensitive to the cable position and no error is introduced by the fact that the calibration current is not injected at the center of the DCCT but by 4 rods placed on the side.

Methodology and current leak The precise calibration is performed with the help of the DCCT control software and acquisition chain in the back-end electronic rack on the surface. The scaling factor is the ratio of the charges specified by the operator (equivalent to a given calibration current) and the offset corrected average signal over 60 seconds.

A series of independent calibrations[4] has been performed with the current source placed in the tunnel, and one measurement was performed with the source connected to the surface electronics. The raw DCCT signal was saved into files by the DCCT software, but the subsequent data analysis was performed offline. The offset was subtracted using a period before and after the signal as done with the baseline analysis. The scaling factors measured with both methods agree within an envelope of $\pm$ 1 LSB (equivalent to $\pm$ 0.06% at 80% of the range) for the ranges 1 to 3 and within $\pm$ 4 LSB ($\pm$ 0.24%) for range 4 and no difference can be seen between the two methods. Furthermore there is no difference between the calibrations performed with the source in the tunnel or on the surface excluding a possible current leak in the 500 meter cables and switches between the surface and the calibration rods in the tunnel. The measured scaling factors are shown in Fig. 3 for system A/beam 1.

Difference between systems A and B

The bunch pattern-related misbehavior was systematically visible during the 2010 bunch train injections where both systems A and B were behaving differently; however, this behavior was not observed with the corrected hardware in 2011. A systematic study of all injections during 2010 and 2011 permits to assert the stability of the new hardware. Indeed the injections during 2011 are performed not only with high intensities up to $2 \cdot 10^{14}$ charges in total, but also with different train length from 8 to 144 bunches per train. Furthermore, during a fill injection each additional train changes the filling pattern and thus the harmonics seen by the DCCT. Both independent DCCT systems A and B provided a consistent measurement throughout all physics injections in 2011 within the resolution of the 12-bit ADC or within the noise level of range 4. Fig. 4 shows the relative difference between system A and B versus the intensity for all injection steps in 2011. The DCCT accuracy is therefore at best limited by the 12-bit ADC; furthermore, no other uncorrelated systematic error has been revealed with this consistency check. An envelope uncertainty of $\pm$ 1 LSB is taken for the ranges 1 to 3 and of $\pm$ 10 LSB for range 4.

SUMMARY OF UNCERTAINTIES

The DCCT system proved to be stable and consistent throughout all tests documented in reference [5]. No sensitivity to external factor or to the beam conditions could be found. The uncertainty of 0.1% attributed to the laboratory measurement of the bunch pattern dependence is probably limited by the instrumentation and components used in the setup. For the DCCT internal effects, the acquisition chain with the 12-bit ADC is limiting the accuracy of the ranges

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[4] so-called "self" calibrations

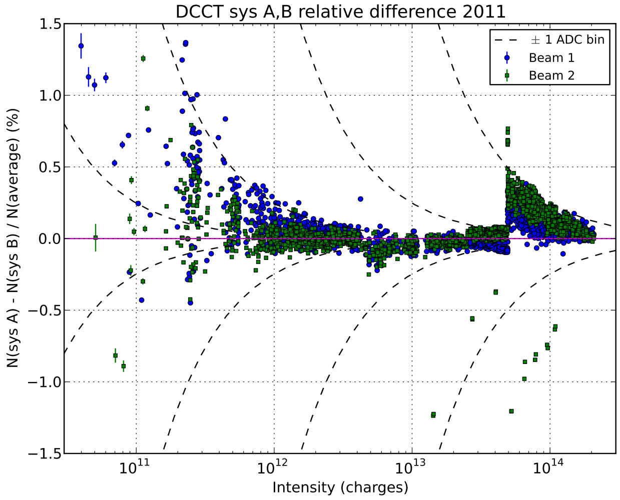

Figure 4: Relative difference between system A and B for 2011 *vs.* beam intensity. Each point is a 60 s average of an injection step. A relative difference caused by 1 LSB difference is indicated by a dashed line.

Table 1: Summary of tested source of uncertainty without measurable effect.

Source of uncertainty
Cross-talk between beams Noise change during dump of other beam
Sensitivity to injected RF sine wave No resonance found between 1 kHz - 110 MHz
Sensitivity to LHC energy No correlation observed with LHC energy
Sensitivity to LHC RF system No correlation observed with LHC RF cavity field
Thermal effect during 24 hours under load No systematic drift of day/night effect
Current leak during calibration from surface No difference between the source on the surface or in the tunnel
Methodology of calibration procedure No difference between “self” calibration and standard BI procedure
Seasonal fluctuations of calibration factors Calibrations stable within expected ADC bit accuracy, verified over 9 month
Off-center position of calibration rods
Bunch position dependence (MD) No dependence found with beam movement during MD
Bunch pattern dependence (MD) No dependence found during beam debunching with RF off

1 to 3, while the noise level is limiting range 4. No error could be found in the calibration method and the accuracy of both sources was tested down to 0.05% in the laboratory. This uncertainty reflects the limits of the laboratory instrumentation and components and is higher than the specifications provided by the manufacturer.

The source of uncertainties without any measurable effect are listed in Table 1. The listed effects have been analyzed and the fluctuations are either compatible with the noise level or within one LSB. The summary of the DCCT uncertainties affecting the total intensity are listed in Table 2. All uncertainties are given as an envelope error (100% confidence level). To interpret the listed envelope uncertainties in terms of 68.3% confidence level, the numbers in Table 2 should be multiplied by 0.683.

The following errors should be considered as correlated between fills:

- The current source precision, because the same source is used for all calibrations throughout the year.
- The non-linearity of the 12-bit ADC, because all fills are acquired with the same ADC.
- The bunch pattern dependence, because the laboratory measurement is applied to all DCCT’s and it is not possible to exclude a systematic effect below 0.1%.

The other errors are related to random fluctuations and can be treated as uncorrelated between fills.

REFERENCES

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[3] G. Anders, *et al.* *Study of the Relative LHC Bunch Populations for Luminosity Calibration*. CERN-ATS-Note-2012-028 PERF, (BCNWG Note 3) (2012). URL `http://cdsweb.cern.ch/record/1427726`

[4] A. Alici, *et al.* *Study of the LHC Ghost Charge and Satellite Bunches for Luminosity Calibration*. CERN-ATS-Note-2012-029 PERF, (BCNWG Note 4) (2012). URL `http://cdsweb.cern.ch/record/1427728`

[5] C. Barschel, *et al.* *Results of the LHC DCCT Calibration Studies*. CERN-ATS-Note-2012-026 PERF, (2012). URL `http://cdsweb.cern.ch/record/1425904`

[6] P. Odier, *et al.* *Operational Experience and Improvements of the LHC Beam Current Transformers*. Proceedings of DIPAC11, Hamburg, Germany (2011).

Table 2: Source of uncertainties per beam. All numbers are given as envelope error (100% confidence level). For the baseline correction, the reduced error of $\pm\, 1 \cdot 10^9$ charges can be used if the offset is corrected or smaller than $\pm\, 1 \cdot 10^9\ e$. Otherwise the more generic errors dependent on the range must be used. For the long term stability of the baseline, the indicated errors depend on the signal averaging time. A normalization of the beam intensity using a 1 hour average or more can use the lower errors provided in parenthesis. Low intensity fills acquired with range 4 will benefit from a longer averaging time, while the difference is negligible for the other ranges.

Source of uncertainty	Range	Relative error (%)	Absolute error	Correlated btw. beams
Current source precision		$\pm\ 0.05\%$		yes
accuracy limited by instrumentation				
Baseline correction				
If data is manually baseline corrected			$\pm\ 1 \cdot 10^9\ e$	
If data is not baseline corrected	1		$(\pm\ 6 \cdot 10^{10}\ e)$	
	2		$(\pm\ 7 \cdot 10^9\ e)$	
	3		$(\pm\ 4 \cdot 10^9\ e)$	
	4		$(\pm\ 4 \cdot 10^9\ e)$	
Non-linearity of 12-bit ADC			$\pm$ 1 LSB	yes
non-linearity tue to acquisition chain				
beam 1, 2 and all ranges share same ADC				
Long term stability of baseline				
observed fluctuations within 2×12 hours	1		$\pm\ 1.1 \cdot 10^{11}\ e$	
if signal average ≥ 1 minute	2		$\pm\ 1.0 \cdot 10^{10}\ e$	
	3		$\pm\ 2.4 \cdot 10^9\ e$	
	4		$\pm\ 2.3 \cdot 10^9\ e$	
observed fluctuations within 2×12 hours	1		$(\pm\ 7.3 \cdot 10^9\ e)$	
if signal average ≥ 1 hour	2		$(\pm\ 1.1 \cdot 10^9\ e)$	
	3		$(\pm\ 1.1 \cdot 10^9\ e)$	
	4		$(\pm\ 1.0 \cdot 10^9\ e)$	
Long term stability of calibration factor	1,2,3		$\pm$ 1 LSB	
envelope observed within 9 month	4		$\pm$ 4 LSB	
Bunch pattern dependence (laboratory test)		$\pm 0.1\%$		yes
accuracy limited by instrumentation				
Difference between system A and B	1,2,3		$\pm$ 1 LSB	
observed during all physics injections 2011	4		$\pm$ 10 LSB	
range 4 limited by noise				