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TECHNICAL REPORT

Luminosity determination in $\sqrt{s}$ = 7 TeV proton collisions using the LHCf Front Counter at LHC

The LHCf collaboration

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ABSTRACT: In the Large Hadron Collider forward (LHCf) experiment, the luminosity is determined with the counting rates of detectors called Front Counter. During the LHCf physics operation at $\sqrt{s} = 7$ TeV in 2010, two series of calibration run in the conversion factors from the counting rate to the luminosity were carried out on 26th of April and 9th of May. Using the luminosities determined in the April and May scans with 5 % and 4 % accuracy, the conversion factors were determined with 5.0 % accuracy, providing the luminosity determination at the LHCf experiment with this accuracy.

KEYWORDS: Beam-line instrumentation (beam position and profile monitors; beam-intensity monitors; bunch length monitors); Accelerator Subsystems and Technologies; Scintillators, scintillation and light emission processes (solid, gas and liquid scintillators); Beam Optics

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1 Introduction

1.1 The LHCf experiment

The LHCf experiment [1] is dedicated to measure the particles emitted to forward region of the proton collisions at LHC. The physics goal is to afford the data for the calibration and improvement of the hadronic interaction models.

The LHCf detectors, consisting of imaging calorimeters made of tungsten plates, plastic scintillators and position sensitive sensors, are installed at the ± 140 m from the interaction point (IP). One side is called Arm1 and the other is called Arm2. There are massive zero degree neutral absorbers (Target Neutral Absorber; TAN) in order to protect the outer superconducting beam separation dipoles (D2) from neutral particle debris from the IP. Charged particles from the IP are swept aside by the inner beam separation dipole D1 before reaching the TAN. Inside TAN the beam vacuum chamber makes a Y shaped transition from a single common beam tube facing the IP to two separate beam tubes joining to the arcs of LHC. The Y-chamber has been carefully machined to have a uniform one radiation length projected thickness over a 100 mm $\times$ 100 mm squared on the zero degree crossing angle beam line. In the crotch of this Y-chamber, just behind the 100 mm $\times$ 100 mm square there is an instrumentation slot of 96 mm$^w\times$ 607 mm$^h\times$ 1000 mm^l extending from 67 mm below the beam height to the top of the TAN. The aperture for the LHCf measurements is limited by the width of the slot and by the height of the beam pipe in the D1 dipole projected to the TAN. This unique location covers the rapidity range from 8.4 to infinity.

1.2 Luminosity

The luminosity is an important value to describe the energy spectrum because the number of collisions estimated from the luminosity is necessary to normalize the spectrum. The definition of the luminosity L is given as

$$L = \frac{R_{inel}}{\sigma_{inel}}. \tag{1.1}$$

Here the R_{inel} is the rate of inelastic collisions and σ_{inel} is the inelastic cross section of the proton collisions. In our experiment, the luminosity is determined with the detection rate of a detector as

$$L = C_L R_{det}, \tag{1.2}$$

where R_{det} is the detection rate of a counter and the conversion factor C_L is determined in calibration run where the absolute luminosity can be determined from another way. It should be noted that equation (1.2) is valid only when the luminosity is enough low where the number of multi collisions in a single bunch crossing (pile-up) is small enough to the single collisions. The detector employed for calculating the luminosity is the LHCf sub-detector called the Front Counter (FC).

To estimate the conversion factor, the calibration runs called van der Meer (vdM) scans [2] were carried out on 26th of April and 9th of May in 2010. The vdM scan is the method invented by S. van der Meer in 1968 to find the most effective beam colliding in ISR. By observing the detection rate while displacing one of the two beams on the vertical or horizontal plane, the relationship of the detection rate and the beam displacement would have a Gaussian shape, and the luminosity is given with this deviation (Σ_H and Σ_V) corresponding to the beam width and the beam intensity as

$$L = \frac{n_b f_{rev} I_1 I_2}{2\pi \Sigma_H \Sigma_V}. \tag{1.3}$$

Here the number of bunch is n_b, the revolution frequency is f_{rev}, the beam intensity per bunch is I_1 and I_2 for two beams, respectively. The explanation of FC and the detail of the vdM calibration scans are described in section 1 and 3, respectively. The results of luminosity during the vdM scans and the determination of the conversion factors to be used in the LHCf analysis are reported in section 4.

2 Front Counter

The FCs are simple and thin detectors composed of plastic scintillators. One of the purpose is to monitor the beam condition by enhancing the detection efficiency rather than the LHCf calorimeters. Two pairs of thin plastic scintillators (40 mm $\times$ 80 mm; the thickness is 2.0 mm for Arm1 and 2.5 mm for Arm2; Saint-Gobain Crystals BC404) are aligned in the vertical and horizontal directions to compose a double layer counter as shown in figure 1. Between the two layers, a copper plate of 0.5 mm thickness is inserted. The scintillators and copper plate are assembled in the aluminum case of 0.5 mm thickness. The total thickness of FCs is 8 mm (0.057 radiation length) and 9 mm (0.061 radiation length) for Arm1 and Arm2, respectively. This detection area is about 5 times larger than the calorimeters. The scintillation photons propagating through the plastic light guides from the scintillators are detected at the HAMAMATSU H3164 PMTs.

FC1 and FC2 are installed in front of the Arm1 and Arm2 LHCf calorimeters behind Y-chamber, respectively. About 90 % of particles $>$ 10 GeV incident to the Y-chamber are gamma-ray at $\sqrt{s} = 7$ TeV proton collisions. These particles are converted to electron and positron pairs and detected at FC. The thresholds for each scintillator channel are set at 0.7 of minimum ionization particle equivalent (MIP) and 0.5 of MIP for Arm 1 and Arm 2, respectively. One MIP is defined as the energy deposit peak in the cosmic ray measurement carried out on ground before installation in the LHC tunnel. The detection condition is that the deposited energy exceed the threshold in

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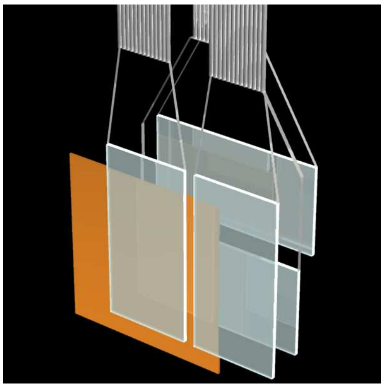

Figure 1. The front counter

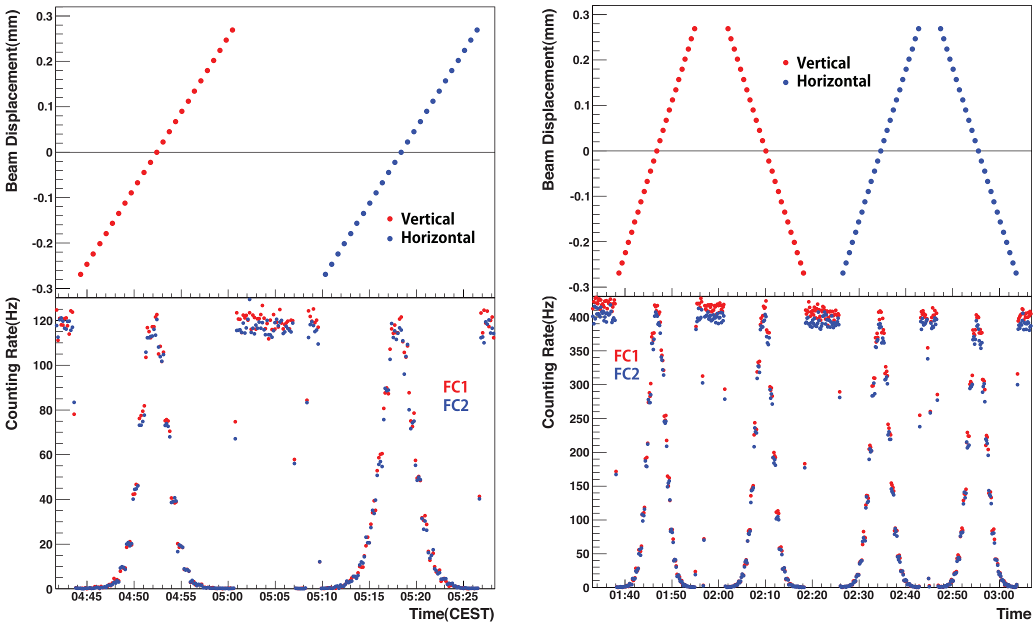

Figure 2. The time history of 26th April vdM and 9th May scan. Top panels show the time history of the beam separation width. Bottom panels show the FC counting rate during the scans. Left and right panels are results of the April and May scans, respectively.

both layers. The acceptance for a single proton-proton collision (ε) is estimated to be ~40% at $\sqrt{s} = 7$ TeV proton-proton collisions by the Monte Carlo simulation.

3 Van der Meer scan at LHC

During the LHCf 7 TeV operation from April to July of 2010, the vdM scans were carried out twice, the first on 26th of April and the second on 9th of May. The left and right panels in figure 2 show the time history of beam separation width and the FC counting rate in the April and May scans, respectively.

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In the April vdM scan, the displacement was performed once for each plane, the first scan in vertical and the second in horizontal. In the May scan, it was twice for each plane, the first two scans in vertical and the rest in horizontal. During these displacements, the FC detection rate was measured for 10 seconds at each beam position. The detection rates were fitted separately for FC1 and FC2 as a function of the beam separation (x) using the following formula,

$$A_1 e^{-\frac{(x-\mu_1)^2}{2\sigma_1^2}} + A_2 e^{-\frac{(x-\mu_2)^2}{2\sigma_2^2}} + ax + b. \tag{3.1}$$

Here A_1, A_2, μ_1, μ_2, σ_1, σ_2, a and b are fit parameters. The background ($ax+b$) is considered as a linear function in equation (3.1). The Σ_H and Σ_V in equation (1.1) are defined by these parameters as

$$\Sigma = \frac{A_1\sigma_1^2 + A_2\sigma_2^2}{A_1 + A_2}, \tag{3.2}$$

and the detection rate of the FCs at the peak is estimated from

$$R_{det,FC} = A_1 + A_2. \tag{3.3}$$

This is valid because practically we obtained $\mu_1 \sim \mu_2$.

Figure 3 and figure 4 show the results of the FC detection rate as a function of the beam separation width together with the best fitting curves. From the residual plots given in the bottom panels, we can conclude the data was reasonably fit with the equation (3.1). The fitting results for the peak detection rate and the beam width (Σ) in the April and May vdM scans are summarized in table 1 and table 2, respectively. Because in the May vdM scan the scan of each plane was performed twice, the results Σ_H, Σ_V and the FC detection rate are averaged over all scans. The summary of these results for the April and May scans is shown in the bottom of table 1 and table 2, respectively.

To estimate the luminosity, the beam intensity is also necessary. The information given by the LHC Bunch Current Working Group [3] during the vdM scans is shown in table 3. These errors are treated as correlated errors between the April and May scans here. While the scan in April and May, the number of colliding bunch at IP1 was one. The parameter n_b and f_{rev} in equation (1.1) are 1 bunch and 11.2 kHz, respectively.

4 Results

As a result of vdM scans, the luminosity of 26th April and 9th May is determined as shown in table 4. It is noted that the main source of the uncertainty comes from the error of the beam intensity determination.

Using the luminosity of $6.0 \times 10^{27}/cm^2s$ and $2.0 \times 10^{28}/cm^2s$ for two scans and an assumption of $\sigma_{inel} = 71.5$ mb, the ratio of the pile-up events to all inelastic collision events can be calculated as 1.8 % and 6.2 %, respectively. When the effect of pile-up is negligible, the conversion factor from the FC detection rate to the luminosity is determined from equation (1.2). To consider the pile-up effect, the correction factors should be applied to the luminosity conversion factors. In the case of

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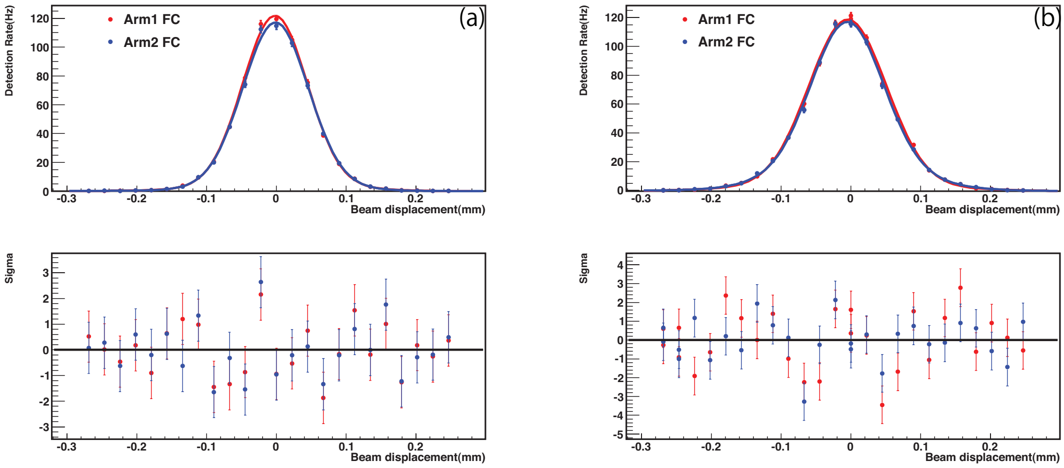

Figure 3. The result of the 26th April vdM scan (a) is the results of the horizontal scan, and (b) is the vertical scan. The upper plots of each figure are the the FC detection rate as a function of the beam displacement. The lower plots shows the residual normalized to the error.

Table 1. The fit parameter results of 26th April vdM scan

	Rate(Hz)	Σ_H (μm)	Σ_V (μm)	χ^2/dof
Hrizontal scan				
FC1	121.81 ± 0.10	47.82 ± 0.08	-	18.5/16
FC2	117.09 ± 0.12	48.23 ± 0.10	-	19.5/16
Vertical scan				
FC1	118.65 ± 0.17	-	58.75 ± 0.15	48.9/19
FC2	117.09 ± 0.28	-	56.89 ± 0.26	26.7/19
Summary (average)				
FC 1	121.0 ± 0.1	47.82 ± 0.08	58.75 ± 0.15	-
FC 2	117.1 ± 0.1	48.23 ± 0.10	56.89 ± 0.26	-

ideal measurement without pile-up, the average number of true collisions per one bunch crossing μ_{col} is given as

$$\mu_{col} = \varepsilon \frac{R_{inel}}{f_{rev}}. \tag{4.1}$$

Here, $\varepsilon \sim 0.4$ is the acceptance of FC for a single collision. However, because FC can not identify multi-collisions per bunch, the number of events per crossing counted by FC, μ_{det}, is

$$\mu_{det} = 1 - P(0; \mu_{col}) \tag{4.2}$$

$$= 1 - e^{-\mu_{col}}. \tag{4.3}$$

Here, the $P(n; \mu)$ is the Poissonian probability to have n collisions per one bunch crossing with the mean of μ . Because the conversion factor C_L is defined as equation (1.2), the correction factor

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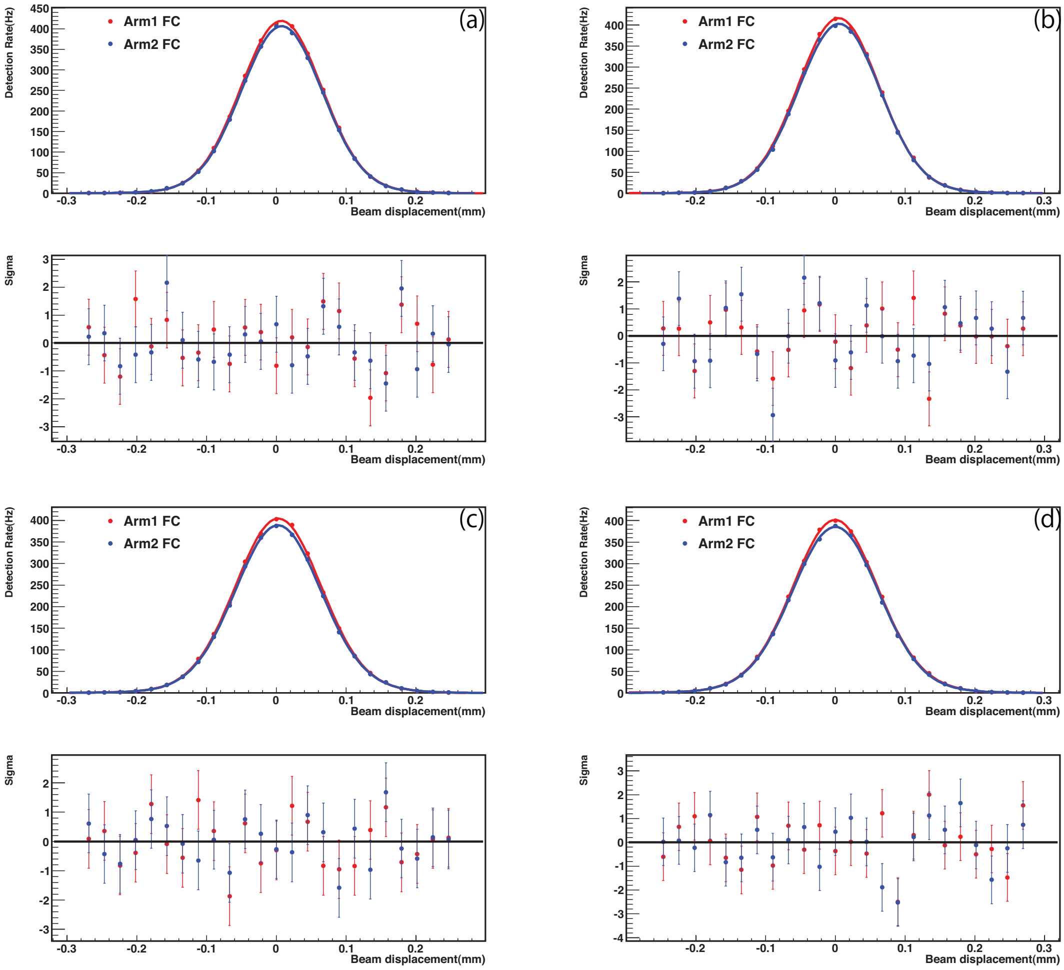

Figure 4. vdM scan 9th May 2010 (a) and (b) are the results of the horizontal scans, and (c) and (d) are the vertical scans. The upper plots of each figure are the the FC detection rate as a function of the beam displacement. The lower plots shows the residual normalized to the error.

α_{cor} is

$$\alpha_{cor} = \frac{\mu_{col}}{\mu_{det}} \tag{4.4}$$

$$= \frac{\mu_{cor}}{1 - e^{-\mu_{col}}} \tag{4.5}$$

After applying the correction factors α_{cor} of 1.008 and 1.026 for the April and May scans, respectively, the conversion factors C_L are calculated and summarized in table 5. From this table, the conversion factors obtained from the two scans are consistent with 0.002 % and 2.7 % difference for Arm1 and Arm2, respectively, and within the uncertainty. The average of the conversion factor for two scans are also shown in table 5. Because in equation (1.2) the dominant uncertainty comes from the error of C_L of 5.0 %, the uncertainty in the LHCf luminosity determination is 5.0 % [4].

Table 2. The fit parameter results of 9th May vdM scan

	Rate(Hz)	Σ_H (μm)	Σ_V (μm)	χ^2/dof
Hrizontal scan 1				
FC1	419.11 $\pm$ 1.36	59.37 $\pm$ 0.08	-	12.0/16
FC2	406.24 $\pm$ 2.87	59.33 $\pm$ 0.08	-	12.2/16
Hrizontal scan 2				
FC1	416.60 $\pm$ 1.00	59.29 $\pm$ 0.25	-	10.6/16
FC2	402.80 $\pm$ 5.21	59.77 $\pm$ 0.12	-	18.2/16
Vertical scan 1				
FC1	404.46 $\pm$ 0.45	-	63.43 $\pm$ 0.14	9.5/16
FC2	388.80 $\pm$ 3.65	-	62.85 $\pm$ 0.14	7.5/16
Vertical scan 2				
FC1	401.55 $\pm$ 0.59	-	62.52 $\pm$ 0.21	14.0/16
FC2	385.64 $\pm$ 0.91	-	63.33 $\pm$ 0.16	13.5/16
Summary (average)				
FC 1	417.5 $\pm$ 0.8	59.36 $\pm$ 0.08	63.15 $\pm$ 0.12	
FC 2	405.4 $\pm$ 2.5	59.47 $\pm$ 0.07	63.06 $\pm$ 0.11	

Table 3. The beam intensity during vdM scans (10^9 protons)

	26th April	9th May
beam 1	8.98 $\pm$ 0.34	18.99 $\pm$ 0.54
beam 2	10.35 $\pm$ 0.37	22.18 $\pm$ 0.61

Table 4. The results of luminosity during vdM scans ($10^{27}/cm^2s$)

	26th April	5th May
FC 1	5.90 $\pm$ 0.36	20.0 $\pm$ 0.88
FC 2	6.04 $\pm$ 0.34	20.0 $\pm$ 0.88

Table 5. The results of conversion factors ($10^{25}/cm^2$)

	26th April	5th May	Average
FC 1	4.92 $\pm$ 0.30	4.91 $\pm$ 0.21	4.92 $\pm$ 0.26
FC 2	5.20 $\pm$ 0.29	5.06 $\pm$ 0.23	5.13 $\pm$ 0.26

5 Summary

In the LHCf experiment, the luminosity is determined by the FC counting rate and the calibrated conversion factors. FC is the simple scintillation sub-detector of LHCf. To calibrate the conversion factor, two vdM scans were carried out during the LHCf 7 TeV physics runs. In these calibration, the luminosity was determined as $6 \times 10^{27}/cm^2s$ and $20 \times 10^{27}/cm^2s$ for the April and May scans, respectively. The pile-up ratios during these luminosity are 1.9 % for the April scan and 6.2 % for

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the May scan. After these effects were corrected, the conversion factors from FC counting rate to the luminosity are estimated as $(4.92\pm0.26)\times10^{25}\ /cm^2$ for the Arm1 FC and $(5.13\pm0.26)\times10^{25}\ /cm^2$ for the Arm2 FC. The 5.0% uncertainty of the conversion factors directly determine the uncertainty in the luminosity determination in the LHCf experiment at the 7 TeV proton collisions.

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