CERN-ATS-Note-2010-032 PERF
CERN-TOTEM-Note-2010-001
June 2010

Calibration of the BLM Response at 450 GeV by Beam Scraping with Roman Pots

R.B. Appleby, R. Assmann, M. Deile, J. Kašpar, S. Redaelli

Abstract

This note reports on two calibrations of the conversion factor from the number of protons intercepted by a TOTEM Roman Pot (RP) to the dose measured in a Beam Loss Monitor (BLM) downstream of the RP station. The results are compared with a FLUKA simulation.

1 Introduction

The TOTEM Roman Pots are designed to detect elastically or diffractively scattered protons from Interaction Point 5 [1]. For this purpose, they will approach the beam centre to distances as small as $15\,\sigma$. If – either by a malfunctioning RP position control system or by an accidental beam excursion – a pot enters too deep into the beam, there is a risk of damaging

- the pot by energy deposition at the impact spot,
- or downstream machine elements hit by scattering debris.

To protect the pots and the machine from such accidents, each RP station is followed by a series of BLMs a few metres downstream (Table 1 and Figure 1). If the radiation dose received by the BLM exceeds a threshold, the beam is dumped.

The definition of a meaningful BLM threshold requires two ingredients:

1. The damage level, i.e. the maximum allowable number of protons intercepted by a Roman Pot and lost from their design orbit.
2. The conversion factor between the number of protons lost and the dose detected in the BLM.

As preliminary damage levels, the same values as for the tertiary collimators (TCT) have been adopted [2]. This seems a conservative choice, given that the RPs have much less material along the beam path than a collimator, but detailed studies would be desirable.

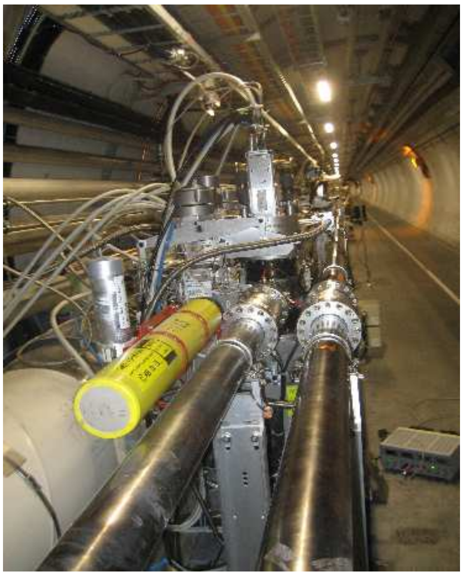

Figure 1: *Photograph of BLMEI.06L5.B2E10_XRP (yellow cylinder) downstream of the station RP-45-220-F (XRPH/V.B6L5.B2).*

Position [m] w.r.t. IP5	RP station TOTEM name	(layout name)	BLM
-228.8900			BLMQI.06L5.B2E22_MQML
-226.7416			BLMQI.06L5.B2E21_MQML_XRP
-225.2220			BLMQI.06L5.B2E10_MQML
-221.0416			BLMEI.06L5.B2E10_XRP
-220.0000	RP-45-220-F-T/B	(XRPV.B6L5.B2)	
-219.5510	RP-45-220-F-H	(XRPH.B6L5.B2)	
-215.0770	RP-45-220-N-H	(XRPH.A6L5.B2)	
-214.6280	RP-45-220-N-T/B	(XRPV.A6L5.B2)	
-164.6000			BLMQI.04L5.B2E10_MQY_XRP
-153.5016			BLMEI.04L5.B2E10_XRP
-151.0100			BLMES.04L5.B2E10_TCLP.4L5.B2
-151.0100			BLMEI.04L5.B2E10_TCLP.4L5.B2
-150.4760	RP-45-147-F-T/B	(XRPV.B4L5.B2)	
-150.0270	RP-45-147-F-H	(XRPH.B4L5.B2)	
-149.3930	RP-45-147-N-H	(XRPH.A4L5.B2)	
-148.9440	RP-45-147-N-T/B	(XRPV.A4L5.B2)	
148.9440	RP-56-147-N-T/B	(XRPV.A4R5.B1)	
149.3930	RP-56-147-N-H	(XRPH.A4R5.B1)	
150.0270	RP-56-147-F-H	(XRPH.B4R5.B1)	
150.4760	RP-56-147-F-T/B	(XRPV.B4R5.B1)	
153.3584			BLMEI.04R5.B1E10_XRP
162.1000			BLMEI.04R5.B1E20_XRP
214.6280	RP-56-220-N-T/B	(XRPV.A6R5.B1)	
215.0770	RP-56-220-N-H	(XRPH.A6R5.B1)	
219.5510	RP-56-220-F-H	(XRPH.B6R5.B1)	
220.0000	RP-56-220-F-T/B	(XRPV.B6R5.B1)	
220.7584			BLMEI.06R5.B1E10_XRP
226.7020			BLMQI.06R5.B1E10_MQML_XRP
229.0900			BLMQI.06R5.B1E20_MQML

Table 1: *Positions of the TOTEM RPs and the relevant BLMs. In the 2009 running period, the RP stations around 150 m were not equipped with detectors. Negative (positive) positions are located in Sector 45 (56).*

The conversion factor from the lost protons to the BLM response is the subject of this note. During the 2009 LHC running period, two calibrations were performed in the context of a beam-based collimator-to-Roman-Pot alignment. The strategy – explained e.g. in [3] – can be briefly summarised as follows.

The collimators are moved to their nominal positions. The first primary collimator jaw is moved to 5.7 σ from the beam centre, where it cuts a sharp edge. Even though the jaw is only scraping one side of the beam, an edge is produced on both sides due to multi-turn betatron oscillations. The beam centre lies therefore exactly in the middle between the two beam edges. Then the opposite jaw of the primary collimator is moved toward the beam until it scrapes the beam's edge. Finally the same procedure is followed with each Roman Pot to be aligned. It is slowly moved towards the beam until the downstream BLM records a spike in the dose rate. At this point, the Roman Pot is known to be at 5.7 σ from the beam centre like the primary collimator.

For the purpose of the BLM calibration, the RP jaws were moved even further into the beam in order to produce losses sufficiently large for a precise dose measurement with the BLM. The number of protons lost in the scraping pots is determined from the beam intensity reduction measured by the fast Beam Current Transformers (BCT [4]).

2 Measurement on 29 November 2009

Figure 2 gives an overview of the test conducted on the 29th November. Both the top and the bottom pot of the unit RP-56-220-N (on beam 1) were moved towards the beam in small steps.

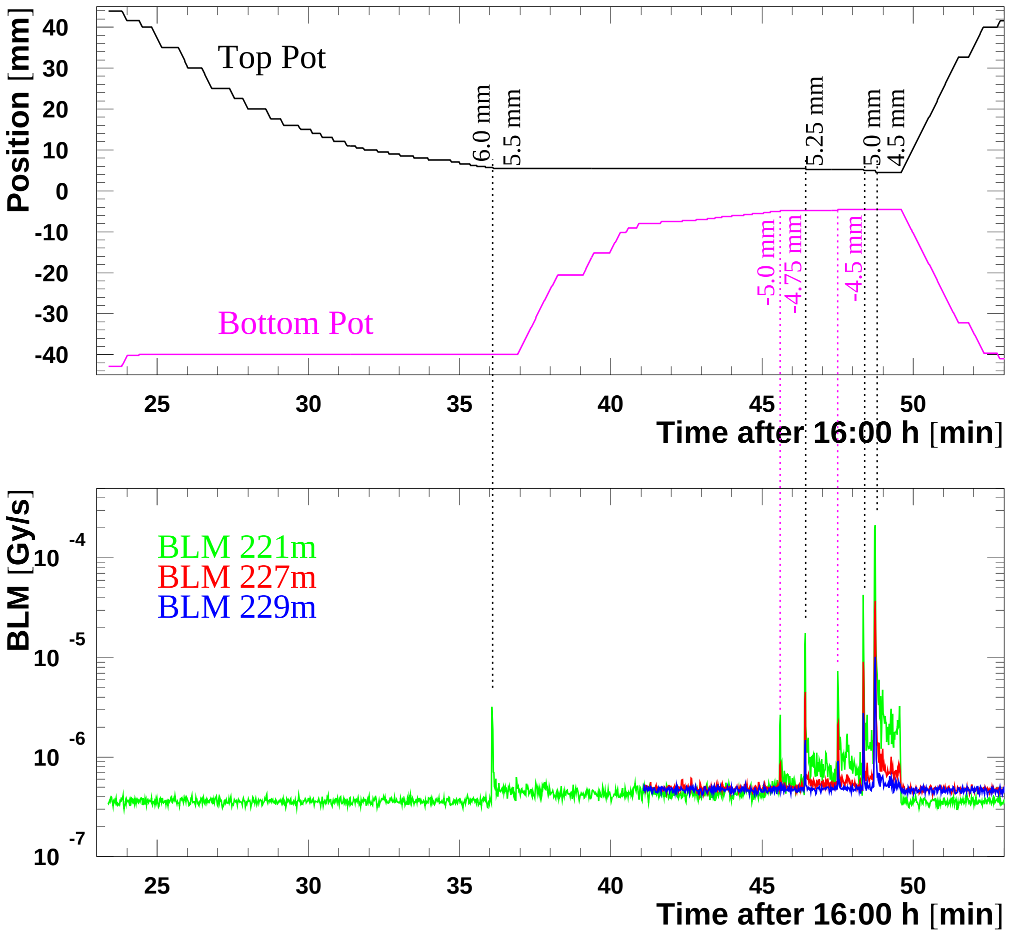

Figure 2: *Overview of the scraping test on 29 November with beam 1. Upper panel: time evolution of the jaw positions of the vertical RP-56-220-N-T/B (XRPV.A6R5.B1) at 215 m. Lower panel: Signals of the 3 nearest BLMs downstream of the RP moved (BLMEI.06R5.B1E10_XRP, BLMQI.06R5.B1E10_MQL_XRP, BLMQI.06R5.B1E20_MQML). At about 16:49:30 h the beam was dumped.*

BLM measurements were performed with the devices BLMEI.06R5.B1, BLMQI.06R5.B1 and BLMQI.06R5.B1, located at 221 m, 227 m and 229 m from the IP, in the region immediately after the RP (see Table 1). The BLMs recorded the first contacts with the beam at distances of +5.5 mm (top pot) and −4.75 mm (bottom pot) from the centre of the beam pipe. From this observation, the vertical beam position can be inferred to be +0.375 mm.

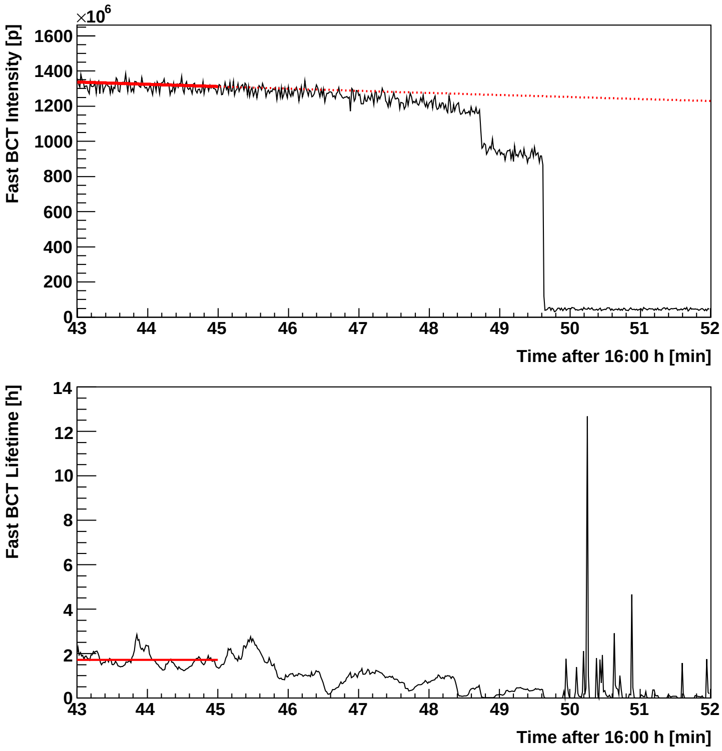

Figure 3: *Data from the fast BCT in the November test: top panel: intensity; bottom panel: lifetime. The red lines represent fits during a stable period between the first contact of the top pot (t =16:36 h, first small spike in Figure 2, bottom) and the moment when the bottom pot touched the beam (t =16:45:36 h). At about 16:49:30 h the beam was dumped.*

The very first spike (t =16:36 h) in the bottom panel of Figure 2, caused by the first beam contact of the top pot, was very small and did not result in any observable intensity drop in the BCT measurement. It is therefore excluded from the analysis. The spikes at t ≥16:45:36 h are very close together in time and are combined in the analysis. The signal from each BLM, with an internal integration time of 0.6 s (running sum RS8), is integrated over the period of the RP move. Each BLM pedestal is separately calculated from the pre-move period and subtracted from the integrand. In addition to the three individual BLM integrals, the sum of all of them was calculated to estimate the total BLM signal during the movement period.

The analysis of the beam current and lifetime data shown in Figure 3 proceeds as follows. In order to separate the losses due to the RP movement from other, unrelated loss mechanisms that were already active before the movements, the current decay was fitted in the few minutes before the move and extrapolated until the end of the move. As a first step, a constant mean lifetime was fitted to the lifetime data before the move (red line in the lower half of Figure 3). Then this lifetime τ is used as a fixed parameter to fit the beam current data with the decay function:

$$I(t) = \frac{I_0}{1 + \frac{t - t_0}{\tau}} \,, \tag{1}$$

where I_0 denotes the beam current at the start time t_0 of the fit. The fitted current is shown as a continuous red line in the upper plot of Figure 3. The extrapolation of the beam

current decay is shown as the red dotted line. It allows an estimation of the unperturbed beam current at a given time if no RP movement had been made. The measured beam current after the movement is averaged over a short time window, and the difference of this current with the extrapolated fitted current gives an estimate of the current change, and hence proton loss, arising from the pot move.
For the RP test on the 29th November considered in this section, the number of protons lost from the beam was calculated to be 3.33×10^8 protons with an uncertainty of 5% from the BCT data [5] plus systematic errors of the same order from the extrapolation.
The integration of the BLMs from 16:45 h to 16:49 h, and subtraction of the pedestals, gives a total summed BLM signal of 0.00143 Gy. This is dominated by the BLM at 221 m, which has an integrated signal of 0.00125 Gy. Hence the total BLM signal per proton lost on the RP is 4.3×10^{-12} Gy. The calibrations of the individual BLMs for two different running sums are listed in Table 2.

3 Measurement on 15 December 2009

Figure 4 gives an overview of the test conducted on the 15th December.

Figure 4: *Overview of the scraping test on 15 December with beam 2. Orange curve: time evolution of the jaw position of RP-45-220-N-T (XRPV.A6L5.B2) at 215 m; green curve: time evolution of the BLM signal at 221 m (BLMEI.06L5.B2E10_XRP). At about 10:17:30 h the beam was lost.*

During this short test only the upper pot RP-45-220-N-T in beam 2 was moved. The BCT current (top) and the lifetime (bottom) can be seen in Figure 6. Just before the test, various collimation changes were made, resulting in a low and bumpy lifetime before the RP movements.
The analysis proceeds in the same way as for the test on the 29th November. The fitted lifetime is rendered by the red line in the lifetime plot, and the resulting fitted current decay can be seen in the top plot, with the dotted red line showing the extrapolation into the RP movement time window. The BLM signals are analysed in the same way, although for the data set with 0.6 s integration time (running sum RS8) only the BLM at 221 m showed a meaningful signal. The difference between the beam current and the fitted current decay gives 2.6×10^8 protons lost from the beam due to the movement of the RP. During the RP movement the BLM was integrated between 10:15:30 h and 10:17:24 h to give a BLM signal of 0.0016 Gy. Therefore the BLM signal per proton lost on the RP is 6.4×10^{-12} Gy. In addition, all BLMs were also analysed for 1.3 s integration time. The summary of all results is given in Table 2.

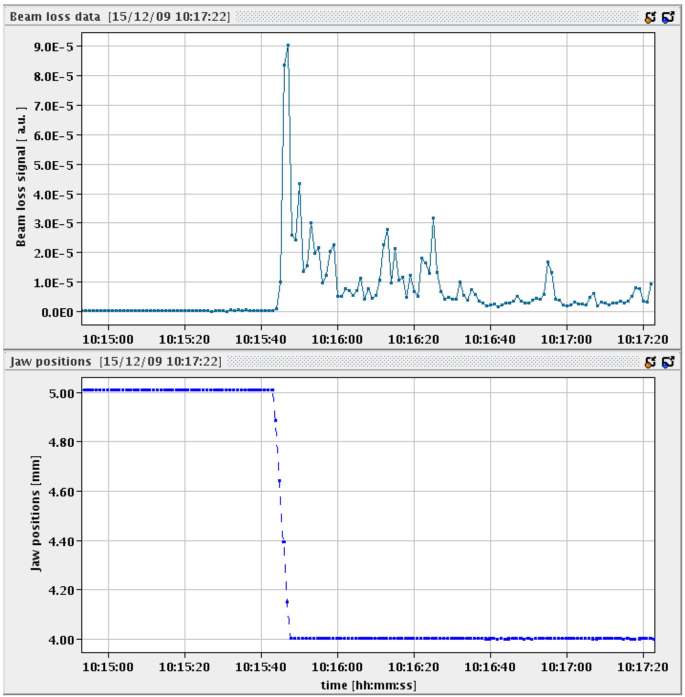

Figure 5: *Zoom of Figure 4 on the time range when the pot scraped the beam. Top panel: BLM signal, bottom panel: RP position.*

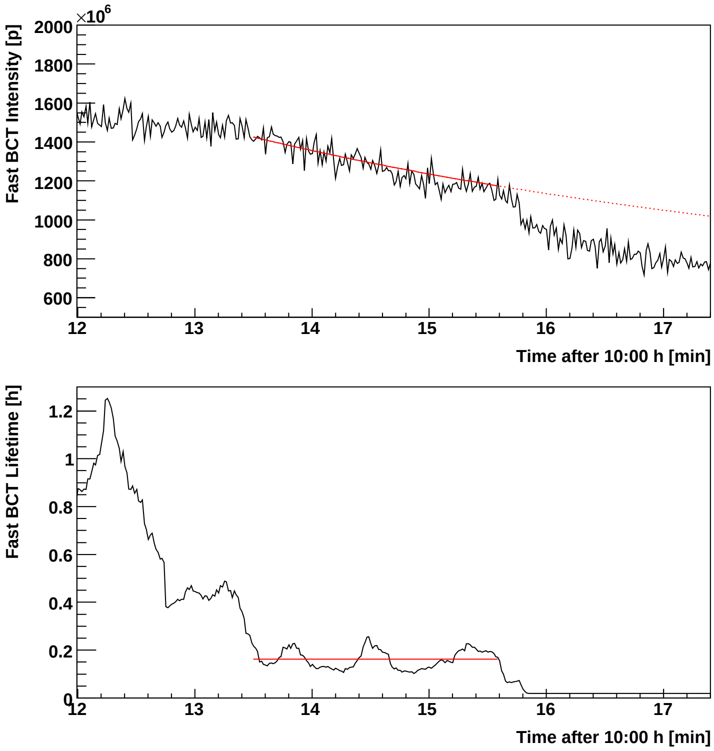

Figure 6: *Data from the fast BCT in the December test: top panel: intensity; bottom panel: lifetime. The red lines represent fits during a stable period between collimator operations (t <10:13:30 h) and the moment when the RP touched the beam (10:15:45 h).*

4 Comparison with Simulation

The simulation [6] models the region around the 220 m RP structure and the downstream BLMs in the MARS code [7]. Protons with and energy of 7 TeV hit the horizontal pot of the 220 m unit. The BLMs considered in the calculation are located at 221 m and 227 m from the IP, at a distance of 20 cm and 50 cm respectively from the beam pipe in the horizontal plane. The signal is calculated from the response of the BLM to the incident particles of varying energy. The signal in the BLMs per 7 TeV proton incident on the RP is 2.7×10^{-12} Gy for each of the the BLMs at 221 m and 227 m. This can be scaled to a proton energy of 450 GeV by a factor of about 1/4 [8], giving a prediction of 0.7×10^{-12} Gy per incident proton, or 1.4×10^{-12} Gy per incident 450 GeV proton when summed over the both BLMs. To normalise the BLM signal to the number of protons lost from their orbit instead of all incident protons, we have to estimate the fraction of protons that have made a nuclear interaction[1]. The Roman Pot window facing the beam constitutes an Inconel 718 target of $l = 5$ cm length, an inelastic nuclear interaction length $\lambda_I = 16.6$ cm and a total nuclear interaction length $\lambda_T = 10.5$ cm. The interaction length relevant for proton losses is somewhere between λ_I and λ_T, given that not all elastically scattered protons are sufficiently deflected to be lost. Hence the fraction of lost protons will be between $1 - e^{-l/\lambda_I} = 0.26$ and $1 - e^{-l/\lambda_T} = 0.38$, which results in a corrected summed BLM response (at 450 GeV) between 1.4×10^{-12} Gy/p/0.38 $= 3.7 \times 10^{-12}$ Gy/p and 1.4×10^{-12} Gy/p/0.26 $= 5.4 \times 10^{-12}$ Gy/p.

Proton loss	BLM		Dose [Gy]	Sensitivity [10^{-12} Gy / p]
Measurement 29.11.				
3.33×10^8	BLMEI.06R5.B1E10_XRP RS8	(221 m)	1.25×10^{-3}	3.75
3.33×10^8	BLMQI.06R5.B1E10_MQML_XRP RS8	(227 m)	0.14×10^{-3}	0.41
3.33×10^8	BLMQI.06R5.B1E20_MQML RS8	(229 m)	37.0×10^{-6}	0.11
$\mathbf{3.33 \times 10^8}$	**sum RS8**		$\mathbf{1.43 \times 10^{-3}}$	**4.27**
3.33×10^8	BLMEI.06R5.B1E10_XRP RS9	(221 m)	0.74×10^{-3}	2.22
3.33×10^8	BLMQI.06R5.B1E10_MQML_XRP RS9	(227 m)	86×10^{-6}	0.26
3.33×10^8	BLMQI.06R5.B1E20_MQML RS9	(229 m)	23.0×10^{-6}	0.07
$\mathbf{3.33 \times 10^8}$	**sum RS9**		$\mathbf{0.85 \times 10^{-3}}$	**2.55**
Measurement 15.12.				
2.58×10^8	BLMEI.06L5.B2E10_XRP RS8	(221 m)	1.64×10^{-3}	6.36
2.58×10^8	BLMEI.06L5.B2E10_XRP RS9	(221 m)	1.00×10^{-3}	3.88
2.58×10^8	BLMQI.06L5.B2E10_MQML RS9	(225 m)	0.12×10^{-3}	0.47
2.58×10^8	BLMQI.06L5.B2E21_MQML_XRP RS9	(227 m)	0.04×10^{-3}	0.16
2.58×10^8	BLMQI.06L5.B2E22_MQML RS9	(229 m)	0.007×10^{-3}	0.03
$\mathbf{2.58 \times 10^8}$	**sum RS9**		$\mathbf{1.17 \times 10^{-3}}$	**4.54**
Simulation				
$0.26 \div 0.38$	RS8	221 m	0.7×10^{-12}	$1.8 \div 2.7$
$0.26 \div 0.38$	RS8	227 m	0.7×10^{-12}	$1.8 \div 2.7$
$\mathbf{0.26 \div 0.38}$	**sum RS8**		$\mathbf{1.4 \times 10^{-12}}$	$\mathbf{3.7 \div 5.4}$

Table 2: *Summary of all measurements and simulation results. The running sum RS8 stands for 0.6 s integration time per data point, RS9 for 1.3 s.*

A comparison with the data (Table 2) shows that the order of magnitude of the BLM sensitivity is correctly rendered by the simulation, but a fully quantitative prediction is not possible. Why the BLMs at 221 m and 227 m see the same signal in the simulation

[1] Event-by-event information was not stored in the simulation.

despite their different distances from the RP, is not understood. In the data, the responses of the two BLMs differ by an order of magnitude. Hovever, one has to bear in mind the following differences between the simulation model and the real conditions:

- The simulation was performed for 7 TeV proton energy where the shower development will not be the same as at 450 GeV.
- The simulation calculated the response to horizontal pot movements whereas the experiment was made with the vertical pots.
- In the November test, both the top and the bottom pots were moved almost simultaneously and in an alternating sequence, which mixes the BLM responses and makes quantitative evaluations more difficult.

The different measurements agree with each other within a factor 2. The calibration is subject to considerable systematic errors, dominated by the fit and the extrapolation of the beam intensity decay before the RP movements. This can be clearly seen from the unstable BCT lifetime measurements.

5 Conclusion

Two calibrations of the BLM Response at a proton energy of 450 GeV have been performed by scraping each of the two LHC beams with Roman Pots of the 220 m station. The sensitivity of the BLMs positioned 6 m after the pots at 215 m was found to be at the level of a few 10^{-12} Gy per proton lost in the RP.
Further calibrations will have to be done in 2010 at a proton energy of 3.5 TeV. The measurements for the response to individual pot movements (i.e. top, bottom, horizontal) should have a sufficient time separation in order to avoid correlations due to BLM baseline shifts.

References

[1] TOTEM Collaboration, *Technical Design Report*, CERN-LHCC-2004-002; addendum CERN-LHCC-2004-020.
G. Anelli et al. (TOTEM Collaboration), "The TOTEM Experiment at the CERN Large Hadron Collider", 2008 JINST 3 S08007.

[2] A.G. Alonso, T. Boehlen, M. Sapinski, "Initial Settings of Beam Loss Monitors Thresholds on LHC Collimators", EDMS 995569, August 2009.
M. Sapinski: email communication on 30.11.2009.

[3] C. Bracco et al., "Collimators and Beam Cleaning: First Results and Future Plans", Proceedings from the LHC beam commissioning workshop, Evian 2010, https://espace.cern.ch/acc-tec-sector/Evian/Proceedings.aspx .

[4] O.R. Jones et al., "First Results from the LHC Beam Instrumentation Systems", LHC Performance Note 006 (2009).
O.R. Jones, "Performance of and First Experiences with the LHC Beam Diagnostics", Proceedings of DIPAC'09, article MOOA02,
http://dipac09.web.psi.ch/Proceedings/index.htm .
D. Belohrad, M. Ludwig et al., "Commissioning and First Performance of the LHC Beam Current Measurement Systems", Proceedings of IPAC'10, article MOPE059,
http://ipac10fs2.kek.jp/ipac10/MOPE059.PDF .

[5] M. Ludwig, private communication: Due to noise at the very low beam intensities in the tests considered here ($< 2 \times 10^9$ p/bunch), the precision of the fast BCT LOBW channel was around 5%.

[6] R.B. Appleby et al, The proceedings of PAC2009, Vancouver, CA, article TH5RFP031, http://trshare.triumf.ca/~pac09proc/Proceedings .

[7] N.V. Mokhov, "The MARS Code System User's Guide", Fermilab-FN-628, 1995. N.V. Mokhov, "Status of MARS Code", Fermilab-Conf-03/053, 2003. http://www-ap.fnal.gov/MARS/ .

[8] M. Sapinski, private communication.