# Direct Luminosity Measurements at the LHC – summary

Jaap Panman
CERN, Geneva, Switzerland

March 15, 2011

**Abstract**

A summary of the present status of direct measurements of the luminosity at the LHC is given. Two methods were used, the van der Meer scan method and the beam-gas imaging method, which are briefly explained. Requirements and ideas for improved measurements in 2011 are presented.

## 1 Introduction

Measurements of luminosity on an absolute scale are of general interest for colliding-beam experiments at storage rings. These measurements are needed to determine the absolute cross sections of reaction processes and to quantify the performance of the machine. The required accuracy on the absolute value of the cross section depends on the process of interest and depends on the theoretical precision of the predictions. Arguments for precision targets in the range of 1–2% have been given at this workshop for the production of vector bosons and the elastic production of muon pairs [1, 2, 3].

The present status of direct luminosity measurements have been presented at this workshop by all experiments [4, 5]. The present precision is of the order of 5% using the most recent information on the calibration of the beam intensities [6, 7]. Based on the results of the measurements done in 2010, more knowledge has been gathered on systematic limitations of these measurements. Here, some of these ideas will be presented with the aim to achieve higher precision in forthcoming runs. The optimal solution may be different for each experiment, due to differences in their capabilities. However, an attempt will be made to reconcile the requirements for the different experiments.

In a circular collider the average instantaneous luminosity can be expressed for one pair of colliding bunches as [8, 9]:

$$L = n_1 n_2\, f \sqrt{(\vec{v}_1 - \vec{v}_2)^2 - \frac{(\vec{v}_1 \times \vec{v}_2)^2}{c^2}} \int \rho_1(x,y,z,t)\rho_2(x,y,z,t)\ \mathrm{d}x\,\mathrm{d}y\,\mathrm{d}z\,\mathrm{d}t\ , \qquad (1)$$

where we have introduced the revolution frequency $f$ (11245 Hz), the numbers of protons in the bunches $n_1$ and $n_2$ in both beams, the velocities $\vec{v}_1$ and $\vec{v}_2$, the half crossing-angle $\theta$, and the normalized time and position dependent bunch densities $\rho_j(x,y,z,t)$. The bunch particle densities $\rho_j(x,y,z,t)$ are normalized such that their individual integrals over full space are unity.

For highly relativistic beams colliding with a very small half crossing-angle $\theta$ the Møller factor (the square root factor in the equation) reduces to $2c\cos^2\theta \simeq 2c$. The integral in Eq. 1 is known as the beam overlap integral.

At the LHC a series of experiments were carried out to perform luminosity calibration measurements at each Interaction Point (IP). Two methods were used: the “van der Meer scan” method (VDM) and the “beam-gas imaging” method (BGI).

## 1.1 The "van der Meer scan" method

Van der Meer proposed a beam position scanning method for the ISR which provides a direct measurement of an effective cross section $\sigma$ by measuring the corresponding counting rate as a function of relative offset of the positions of two colliding beams [10]. At the ISR, only vertical displacements where needed owing to the crossing angle between the beams in the horizontal plane and owing to the fact that the beams where not bunched.

For the LHC the beams have to be scanned in both transverse planes [11]. The cross section $\sigma$ can be measured using the equation

$$\sigma = \frac{\int R(\Delta(x), \Delta(y_0))d\Delta(x) \times \int R(\Delta(x_0), \Delta(y))d\Delta(y)}{n_1 n_2 \, f \, R(\Delta(x_0), \Delta(y_0))} \,. \tag{2}$$

$R(\Delta(x)$,$\Delta(y))$ are rates corresponding to the process with cross section $\sigma$. These rates are measured at offsets $\Delta(x)$ and $\Delta(y)$ with respect to the nominal "working point" $(x_0, y_0)$. The scans consist in creating offsets $\Delta(x)$ and $\Delta(y)$ such that practically the full shape of the beams are explored. When integrated over the displacements, the measured rate gives the cross section.

The main assumption is that the density distributions can be factorized. In that case two scans are sufficient to obtain the cross section: one along a constant $y$-displacement $\Delta(y_0)$ and one along a constant $x$-displacement $\Delta(x_0)$. It can be shown that this equation holds in the presence of a non-zero crossing angle $\theta$ [12]. It is also assumed that effects due to bunch evolution during the scans (shape distortions or transverse kicks due to beam-beam effects, emittance growth, bunch current decay), effects due to the transverse bunch distribution tails and effects of the absolute length scale calibration against magnet current trims either are negligible or can be corrected for.

Experiments have shown that the VDM scans of 2010 can already give ≈5% precision.

## 1.2 The beam-gas imaging method

The beam-gas imaging method is based on the detection of interaction vertices of the beam particles with the residual gas in the machine. The position of the beam-gas interactions can be used to measure the beam angles, profiles and relative positions. The transverse shapes of the bunches are then used to calculate the overlap integral. As is also the case for the VDM method the bunch intensities have to be known in addition.

The beam–gas imaging method [13] uses equation (1) directly and neglecting the crossing angle and beam positioning offsets reads:

$$L \approx \frac{n_1 n_2 \, f}{4\pi \sqrt{\left(\sigma_1^{x\,2} + \sigma_2^{x\,2}\right)\left(\sigma_1^{y\,2} + \sigma_2^{y\,2}\right)}} \,, \tag{3}$$

in terms of the Gaussian beam widths $\sigma_{1/2}^{x/y}$.

The reconstruction of beam-gas vertices allows one to obtain an image of the transverse bunch profile along the beam trajectory. The beam overlap-integral is then calculated from the two individual bunch profiles. The simultaneous reconstruction of the luminous region with the vertex detector can also be used to further constrain the beam parameters.

For this method a vertex resolution is needed that is comparable or smaller than the transverse beam sizes. Compared to the VDM method, the disadvantage of a small rate is balanced by the advantages that the method is non-disruptive, the beams do not move and, at least in principle, the method can be applied while taking physics data. The rate can be increased by a limited, controlled increase of the residual vacuum pressure in the vertex detector without danger to the experiment.

It is advantageous to perform the BGI measurement in the same fill as the VDM scans. This would allow a very strict comparison to be performed between the two measurements, and makes it possible to do a large number of cross-checks. Here, emphasis will be given to the van der Meer method.

## 2 Measurements performed

Measurements were carried out at the beam energy of 3.5 TeV ($\sqrt{s} = 7$ TeV) with the BGI method by LHCb [5] and the VDM method at all IPs [4]. The first measurements were performed in April–May 2010 at a $\beta^* = 2$ m, corresponding to an individual beam size of about 45 $\mu$m. Due to the presence of a spectrometer dipole, a net crossing angle of 280 (540) $\mu$rad in the vertical (horizontal) plane was present at IP2 (IP8). No external crossing angle was applied. The VDM scans were done for CMS (IP5) in LHC fills 1058 and 1089 for ATLAS (IP1) in fills 1059 and 1089, for LHCb (IP8) in fill 1059 and for ALICE (IP2) in fill 1090, with either two (1058) or one (1059, 1089, 1090) colliding bunch pair. The bunch population was $\sim 1\,10^{10}$ protons (fills 1058, 1059) or $\sim 2\,10^{10}$ protons (fills 1089, 1090).

A second set of measurements was done in October at the same beam energy with a $\beta^* = 3.5$ m. Scans where performed for ATLAS and CMS in fill 1386, and in fill 1422 for ALICE, ATLAS, and LHCb. In each case at least one scan was performed in both the $x$ and $y$ direction moving both beams symmetrically in opposite direction. ALICE, CMS and LHCb also performed scans where only one beam moved while the other was kept at fixed position. The scans extended up to $\sim 6$ nominal beam $\sigma$ separation between the two beams.

A measurement of the bunch population product $n_1\, n_2$ (see Eq. 1) is essential to obtain a measurement of the luminosity. Two beam current transformers were installed on the vacuum chamber of each circulating beam [14]. For each beam one DC transformer (DCCT) measures the total circulating current and one fast transformer (FBCT) the current observed per 25 ns time slot (i.e. per bunch). The FBCT was cross-checked using the ATLAS BPTX system [15].

The procedure to obtain the number of protons per bunch was defined in Ref. [7]. The DCCT was used to constrain the total intensity while the FBCT defines the intensity ratios per bunch. The "ghost charge", or charge outside the wanted bunches was determined by a combination of counting beam-gas interactions in LHCb and analysis of satellite bunches in ATLAS and CMS. The largest uncertainty is introduced by the current product measured with the DCCT and is 2.7%. This error will improve in 2011.

For the VDM method it is important to check the correspondence of the nominal beam displacement and the actual length scale. The check is done by several methods, each essentially moving both beams in the same direction and measuring the position of the luminous region with the vertex detectors.

The overall uncertainty in the VDM method was estimated by the experiments to be of the order of 4–5%. Error sources in addition to the beam intensity uncertainty are the reproducibility, length scale calibration, beam stability (emittance growth) and event counting systematics.

## 3 Requirements for 2011

During VDM scans a number of operational parameters may be chosen to optimize the result of the measurements. These parameters include the LHC filling pattern, individual bunch intensities and emittance, optics parameters such as the $\beta^*$ and crossing angles. We will take the parameters one-by-one and try to find an optimum making use of the 2010 experience.

In some cases a change may need new machine development and qualification procedures, thus only essential parameters should be modified.

### 3.1 LHC filling scheme

The experiments favour to perform the measurements with a limited number of isolated bunches in the machine. The usage of bunch-trains is dis-favoured since it introduces more satellite current (*i.e.* protons outside the intended RF buckets) and aggravates the effects of "afterglow" in the detectors (*i.e.* activity in bunches directly following collisions).

Due to unavoidable differences among the bunches in the machine, the analyses are performed on a bunch-by-bunch basis. When the number of bunches is limited, more statistics *per bunch* can be obtained within the capabilities of the DAQ systems of the experiments. It is also better to create *private* bunch-pairs, *i.e.* pairs colliding in 1 and 5 only, or in 2 and 8 separately. This limits the influence of beam-beam effects.

Taking these considerations into account, ATLAS prefers about 6 colliding bunches and CMS up to 12. ALICE prefers one bunch at a time while for LHCb 12 colliding bunches are optimal. These limitations are not absolute: if more than six bunch pairs collide in ATLAS the surplus bunches can be masked in the DAQ.

Thus, a filling scheme with up to 25 bunches in the machine looks optimal.

### 3.2 Choice of $\mu$

Another important parameter is the number of visible interactions per bunch crossing, $\mu$. The values quoted here are the ones for head-on beams. A too low value would stretch the time spent in VDM scan unnecessarily, while a too high value would create too much pile-up in the detectors.

ATLAS, CMS and LHCb favour $\mu \approx 1$ or a bit higher (up to $\approx 2$). This optimizes the rate while keeping the pile-up under control. ALICE favours a lower value $\mu \approx 0.1$ or a bit higher (up to $\mu \approx 0.5$ can be tolerated).

The optimization of the rate per crossing pair sets constraints on combination of $\epsilon$, $\beta^*$, and bunch intensities. These different "knobs" act differently on other parameters, so that a reasonable optimum set must be defined.

### 3.3 Choice of $\beta^*$

The value of $\beta^*$ is an optics parameter and therefore constant for all bunches. It can, however, be chosen per interaction point.

One should use preferentially existing optics to reduce time spent in specific MD for the scans. Although, for instance the value used at injection is already available, it may need safety qualification for use in collision. At a fixed emittance and beam intensity, a variation of the $\beta^*$ does not influence beam-beam effects contrary to a variation in emittance.

Some systematic difference between different VDM scans have been observed in 2010. These may be due to effects of hysteresis in the corrector magnets. It is possible that higher values of $\beta^*$ reduce these effects. Thus it is interesting to perform at least some measurements with relatively high values.

ATLAS and CMS prefer a value of $\beta^*$ in the range 3.5–11 m. Depending on the intensity of the colliding bunches 10–11 m may give a too low rate for some of the intensity monitors of ATLAS. ALICE has no specific request for $\beta^*$. Their requirement is to limit the rate, so that they may need to work at about 10 m. LHCb prefers to combine the measurements based on the VDM scan with a BGI measurement within the same fill. In that case the 10 m optics is better to fully profit from the vertex resolution in the beam-gas imaging method. It should be studied whether the beam displacements required for the VDM method can be reached for this value of $\beta^*$.

### 3.4 Choice of $\epsilon$

In 2010 the emittance was increased in the SPS for physics fills. With the aim to increase the luminosity this may no longer be the case in the physics fills of 2011. For the luminosity calibration fills it is probably better to work with an increased emittance as was done in 2010; a too low values enhances beam–beam effects. To avoid additional systematic errors in the BGI method it is optimal to make the emittance of colliding bunch-pairs symmetric between beam1 and beam2.

If it is possible to blow up the emittance for selected bunches in the LHC, interesting studies of systematic effects can be performed.

## 3.5 Choice of bunch intensities

A lower bound on the current in the machine is given by beam instrumentation and the required counting rate in the experiments. Too high values introduce beam–beam effects and pile-up corrections in the experiments. The latter are experiment dependent. The preferred values are approximate and depend on the $\beta^*$ and $\epsilon$ values. ATLAS, CMS and LHCb prefer values in the range $0.8 - 1.0\,10^{11}$, while ALICE prefers lower values. The need for precise orbit measurements constrains these values to be above $0.6\,10^{11}$.

Together with the requested number of bunches, these intensities make offset corrections in the BCTs negligible. The beam intensity measurements put another constraint: it is better to avoid "Range 4" of the DCCT, and with a small number of bunches in the machine the best results can be obtained if the total intensity corresponds to the higher end of "Range 3".

## 3.6 Combination of $\beta^*$, $\epsilon$ and intensities

A combination of the number of bunches, bunch populations, $\beta^*$ and $\epsilon$ values should be chosen to reconcile requests of each of the experiments. The development of new optics for the machine should be avoided.

The filling scheme should be chosen to maximally decouple the different IPs. This is not possible for ATLAS and CMS which share colliding bunch pairs. As ball-park numbers, ATLAS and CMS prefer to use 6–12 colliding pairs, with an intensity of $\approx 0.8\,10^{11}$ and $\beta^* = 3.5$ m. The value of $\epsilon$ should then be chosen to produce a maximum $\mu$ between 1 and 2. ATLAS is also studying the option of using a larger $\beta^*$, such as the value of 10 m used at injection.

ALICE wants to work at lower rates, and to use one colliding pair at the same time. Thus an intensity of $\approx 0.6\,10^{11}$ and a $\beta^* = 10$ m looks optimal with a fairly large emittance.

LHCb wants to combine the VDM and BGI methods in one fill. The optimization of the BGI method requires larger beam widths, so that $\beta^* = 10$ m and fairly large emittances are required. The detector can work optimally with 12 colliding pairs and bunch intensities around $\approx 1.2\,10^{11}$. This provides approximately equal count rates as in the scans of October 2010. To achieve sufficient statistics with the BGI method, a pressure bump should be applied in the vertex detector during these measurements.

A spread of values of the intensities, and possibly $\epsilon$ from bunch to bunch would allow the study of systematic effects to be performed.

## 3.7 Choice of crossing angle

In physics fills with bunch-trains the LHC beams collide with an external crossing angle. This angle is applied in order to avoid parasitic collisions outside the IPs. Since the VDM scans will be performed with small numbers of individual bunches in the machine, in principle no crossing angle is needed. One should keep in mind that ALICE and LHCb have an internal crossing angle due to the field of their dipole spectrometer magnet.

ATLAS and CMS can run without crossing angle. A non-zero crossing angle does not introduce corrections to the VDM method but has to be taken into account for the BGI method.

Other considerations can influence the decision on crossing angles. At zero angle the measurement of satellite interactions allows the experiments to reveal the presence of protons in RF-buckets near the main buckets. However, a new device, the Longitudinal Density Monitor (LDM) which is being commissioned by the BI-group, once operational, can provide the measurement of charges outside the main buckets with high precision.

Therefore there is no compelling reason to have a zero angle in ATLAS and CMS and to profit from existing machine optics settings, the setting for physics fills can be used.

For LHCb the situation is different when the VDM and BGI methods are combined in one fill. LHCb prefers a finite angle ($\approx 0.4$ mrad) to eliminate parasitic collisions which make it impossible to apply the beam-gas method. At the VDM scans in October 2010 satellite collisions were observed at ±75 cm from the IP at large beam displacements. It is better to avoid these collisions during the VDM scan by applying an sufficiently large crossing angle.

## 3.8 Scanning procedures

For the VDM scan several strategies are possible to achieve the required beam displacements. Separations of up to 6 sigma seem optimal. One has to be careful to sweep the magnet currents in one direction during a scan to avoid hysteresis effects. The most straightforward way to achieve this is by starting the two beams positioned at an opposite extreme and then sweep symmetrically in opposite directions. The scan is first done in one coordinate (e.g. $x$) and then in the other orthogonal coordinate. Although the VDM method does not require it, ATLAS preferred to re-centre the scan in the second coordinate on the maximum of the first one.

Another straightforward strategy is to keep one beam at fixed position and move the other beam across. Aperture considerations can limit the maximum excursion in this case. A system of co-moving TCTs may be needed to achieve sufficient beam separation.

A third method was used consisting in starting with the two beams at opposite extreme positions, keeping one beam fixed while moving the other until the beams hit approximately head-on, and then continue by moving the first beam and keeping the second beam fixed.

Differences observed in the final results obtained with these methods have been used as a measure of systematic errors, although the causes are not precisely known. It is therefore important to explore these differences further. Thus one should plan for at least two VDM scans per IP using different scanning strategies. In addition, to understand hysteresis effects, beam movements and measurements which would be expected to maximize these should be envisaged.

It is important to have fully automated procedures. This reduces the time spent and allows the experiments to follow the measurements on-line. For flexibility of the operations it may be needed to make these “file-driven”, i.e. going through a list of pre-defined settings. As an example, the ATLAS length scale calibration had to be performed “by hand”, and required a few hours of beam time.

## 3.9 Supporting measurement procedures

A number of supporting measurements are needed to complete the VDM scans.

### 3.9.1 Study of x–y coupling

The VDM scan is performed by a “crossed” scan in two coordinates. The basic underlying assumption is the factorization of the bunch shapes in these two coordinates. There are some indications (population of the luminous region) that this assumption does not hold perfectly. Thus a dedicated set of measurements to check the $x$–$y$ coupling will be needed. One idea is to perform scans in the $x+y$ and $x-y$ coordinates, but this may be time-consuming and may not be trivial to set up.

### 3.9.2 Study of length scale

The evaluation of the integral in Eq. (2) needs the knowledge of the length scale. The uncertainty introduced in the present measurements is of the order of 1%.

ATLAS used a method whereby the position of each beam was calibrated separately against the vertex detector by measuring the centre of the luminous region scanning each time the other beam across to find the head-on situation. This procedure turned out to be quite lengthy, although some time reduction can be achieved by automation.

LHCb and CMS used a method whereby first the two beams were separated by $\sqrt{2}\,\sigma$ and then both moved in the same direction by the same nominal amount. By measuring at the same time the position of the luminous region and the rate, both the average and differential movements can be controlled. This method can be applied in a much shorter period, but is a bit more difficult to interpret.

It may be possible to combine the two methods into a kind of “leap-frog” movement where each position of beam1 is measured against three positions of beam2 and vice-versa by moving the beams in turn in only one direction. One would measure rate and position for each setting.

Some discussions are still needed to decide on the optimal procedure.

Longitudinal scans have beean performed in 2010. They may have to be repeated to understand geometrical effects.

### 3.9.3 Hysteresis

There are some indications that hysteresis effects limit the precisions of the VDM scans. A definitive test has not yet been devised, and good ideas are needed to get more knowledge.

One possibility is to perform scans in inverted directions. Other short tests can be designed e.g. by separating the beams by moving one at a separation of 1.5 $\sigma$ and back while measuring the rate at each point.

## 3.10 Beam instrumentation

The experiments rely on the excellent performance of the beam instrumentation.

The knowledge of the absolute scale of the beam intensity is essential. Thus one needs the best possible performance of the DCCTs, and calibration strategies optimized for the fills where the VDM/BGI measurements are done.

The bunch-by-bunch populations have been measured using the FBCTs. These remain important for this measurement. A new measurement system, the longitudinal density monitor (LDM) is being commissioned which has the potential to also provide the relative intensities of the bunches. This monitor is expected to make a significant improvement in the uncertainty due to ghost charge.

The measurement of ghost charge outside the wanted buckets has been provided by the experiments. However, the data from the LDM look very promising to provide this measurement with high precision.

Other supporting measurements are helpful: wire-scans and emittance measurements using synchrotron light monitors. The synchrotron light monitors provide valuable information on the emittance growth of the beam. The wire scans provide rough cross-checks but do not enter directly into the measurements.

## 3.11 Combination of VDM and beam-gas imaging method

Important systematics checks can be made by performing the VDM and BGI in the same fill at the same IP, such as at LHCb. The beam intensity systematics drop out so checks of absolute scale of the two methods can be more precise. Beam shape measurements can be compared. The VDM scan can be used to determine a precise beam centring and determine the ratio of the sizes of the two beams. These constraints can reduce the systematic errors in the BGI method.

The BGI method needs a few hours of stable beam conditions. (Assuming that the amount of gas can be increased by passively applying a vacuum bump at the vertex detector.) An optimization of the BGI result requires beam sizes much larger than the resolution of the vertex detector. For LHCb this requirement would favour large values of $\beta^*$ such as 10 m. Such a $\beta^*$ would also be acceptable for the VDM method.

### 3.12 Additional ideas

The question arises whether we can do the scans simultaneously for different experiments. This would bring an obvious gain in time. However, one is not sure that the induced beam movements are sufficiently controlled.

The performance of more frequent VDM scans at end of fills under physics conditions can be investigated. While this is useful for width measurements of the beams it remains to be understood whether competing luminosity measurements can be achieved.

LHCb is planning to run BGI measurements and VDM scans at $\beta^* = 10$ m during TOTEM-CMS/ALPHA runs.

## 4 Summary

A precise measurement of the luminosity have a clear physics justification down to the few % level. For the first year of operation the precision reached is already better than 5% and expectations are that this can be improved significantly. Such a performance was only possible thanks to close collaboration of machine experts and the experiments.

Although the requirements of the experiments are quite diverse, they may still be accommodated by the machine.

## 5 Acknowledgements

I would like to thank the ALICE, ATLAS, CMS and LHCb speakers for their valuable input and for making available their talks ahead of time, the theorists for providing guidance and inspiration, the machine experts for their clear presentation of the capabilities of the LHC and its instrumentation and Massi Ferro-Luzzi for valuable discussions and for recording the comments after this presentation.

## References

[1] *"Motivations and precision targets for luminosity"*, M. Mangano, *Talk presented at this workshop*, (2011).

[2] *"Indirect luminosity measurements: theoretical assessment"*, V. Khoze, *Talk presented at this workshop*, (2011).

[3] *"Indirect luminosity measurement"*, J. Anderson, *Talk presented at this workshop*, (2011).

[4] *"ALICE 2010 luminosity determination"*, K. Oyama, *Talk presented at this workshop*, (2011); *"LHCb 2010 luminosity determination"*, V. Balagura, *Talk presented at this workshop*, (2011); *"CMS 2010 luminosity determination"*, M. Zanetti, *Talk presented at this workshop*, (2011); *"ATLAS 2010 luminosity determination"*, M. Huhtinen, *Talk presented at this workshop*, (2011).

[5] *"LHCb beam-gas imaging results"*, P. Hopchev, *Talk presented at this workshop*, (2011).

[6] *"BCTs and BPTX analysis results"*, T. Pauly, *Talk presented at this workshop*, (2011).

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

[8] C. Møller, K. Danske Vidensk. Selsk. Mat.-Fys. Medd. **23**, 1 (1945).

[9] see e.g. O. Napoly, *Particle Acc.*, **40**, 181 (1993); W. Herr, B. Muratory, "Concept of Luminosity", Proceedings of CERN Accelerator School, 361 (2003).

[10] *"Calibration of the effective beam height in the ISR"*, S. van der Meer, ISR-PO/68-31, 1968 (CERN).

[11] *"Absolute Luminosity from Machine Parameters"*, H. Burkhardt, P. Grafström, LHC-PROJECT- -Report-1019 ; CERN-LHC-PROJECT-Report-1019.

[12] V. Balagura, arXiv:1103.1129 [physics.ins-det], 2011; *"Luminosity measurements in the first LHCb data"*, V. Balagura, in proc. of the 2010 Rencontres de Moriond (QCD), La Thuile, 2010.

[13] *"Proposal for an absolute luminosity determination in colliding beam experiments using vertex detection of beam-gas interactions"*, M. Ferro-Luzzi, Nucl. Instrum. Methods **A 553**, 388 (2005).

[14] *"The 2010 LHC DC BCT measurement system [...]"*, P. Odier, J.-J. Gras, M. Ludwig, S. Thoulet, LHC-Project-Note-432, and *"The 2010 LHC ring Fast BCT measurement system [...]"*, D. Belohrad, J.-J. Gras, M. Ludwig, LHC-Project-Note-433.

[15] *"The ATLAS beam pick-up based timing system"*, C. Ohm, T. Pauly, Nucl. Instrum. Methods **A 623**, 558 (2010).