Luminosity stability analysis of the BCM1F detector

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Abstract

Luminosity is a key quantity in HEP at particle colliders. It is important to measure it with as high a precision as possible, since it is used to compute physics cross-sections. In order to have an accurate value of the luminosity, the stability of the luminometers is constantly monitored and potential sources of inefficiency or non-linearity are studied and corrected. This report presents the steps and some results of an offline analysis of the luminosity stability with focus on the BCM1F detector, one of the luminometers of the BRIL project at the CMS experiment.

Contents

1 Introduction

For my DESY project, I performed a luminosity stability analysis within the Beam Radiation Instrumentation and Luminosity (BRIL) project of the CMS experiment. The main purpose of the analysis was to monitor and study the behavior of one of BRIL's luminometers, the Fast Beam Condition Monitor or BCM1F, during the year 2018. More information about the detector and the BRIL project will be provided in section 3, whereas section 2 is dedicated to luminosity.

During the analysis, I compared the behavior of BCM1F with the behavior of other luminometers and performed cross comparisons between all detectors. Since it turned out that my analysis provided a useful tool to monitor and study all BRIL's detectors, my scripts will be available on GitLab for people working on this project. In sections 4 and 5 the steps of the analysis and some of the results that have been obtained are presented.

In particular, from the analysis described in section 5, an interesting but unwanted behavior of BCM1F pCVD has come to light: the detector loses efficiency at high rate of events but is able to recover during gaps in the filling scheme. This effect could be related to the number of bunches dependency of BCM1F pCVD that is being currently studied at DESY. My analysis could provide some insight into this issue that still has to be understood properly. A possible follow-up is presented in the conclusion.

2 Luminosity

Luminosity is a quantity that gives information about the collision rate at particle accelerators. It depends on the machine parameters and its expression for colliders, such as LHC at CERN, is the following:

$$L = f_{\mathrm{rev}} \frac{N_1 N_2 \, n_{\mathrm{b}}}{A_{\mathrm{eff}}}, \tag{1}$$

where f_{rev} is the revolution frequency, N_1 and N_2 are the numbers of particles per colliding bunches and n_{b} is the number of paired bunches per beam. A_{eff} is the effective overlapping area of the two beams and equals $4\pi\sigma_x\sigma_y$, assuming a Gaussian distribution of the particles in the beam in the two transverse dimensions. Luminosity is expressed in SI units of $\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$, it is often expressed in units of $\mathrm{Hz}/\mu\mathrm{b} = 10^{30}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$.

Luminosity is related to the collision rate by the following equation:

$$R = L \cdot \sigma \tag{2}$$

where R and σ are the rate of events and the cross section of a given physics process, respectively. By integrating this equation over time, one obtains a relation between the number of events and the integrated luminosity:

$$N = \mathscr{L} \cdot \sigma, \qquad \text{where} \qquad \mathscr{L} = \int L \, dt.$$

The integrated luminosity has units of cm^{-2} and is often expressed in terms of the inverse of a non-SI unit, the barn, where $1\,\mathrm{b} = 10^{-24}\,\mathrm{cm}^2$.

Nowadays accelerators for HEP reach very high peak instantaneous luminosities: for the LHC $L \simeq 10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$, while SuperKEKB has a design luminosity of $10^{36}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$; they can deliver to the experiments an integrated luminosity of tens of fb^{-1} per year.

Why is luminosity important?

Luminosity is a very important quantity for HEP at colliders since it is the proportionality constant between the rate of events and the cross section. If the luminosity is known, the experiments at the colliders, such as CMS at LHC, measure the rate of events of a certain physical process and it is possible to obtain the experimental value of the cross section of that given physics process, through equation (2). In this way it is possible to compare the experimental value with a theoretical one and test the predictions of a theory.

In order to obtain the experimental cross section with high accuracy, the luminosity has to be known with very high precision. It is also important to monitor the luminosity during the whole data-taking period, because the instantaneous luminosity will be integrated over this same period. Since luminosity measurement is a very delicate aspect at colliders, the CMS experiment has a dedicated project, BRIL, for this purpose. The BRIL project is presented in the next section.

3 BRIL

The Beam Radiation Instrumentation and Luminosity (BRIL) project is part of the CMS experiment. Among many things, it is dedicated to luminosity measurements and monitoring of the beam conditions. Several detectors within the CMS experiment are part of BRIL and each of them has a different role and is used for a specific purpose. Detectors used to measure luminosity are better known as luminometers and a brief description of them is presented in the following subsection.

As far as the luminosity measurement is concerned, the main target is to obtain an accurate online value of the instantaneous luminosity. In order to achieve this, the BRIL project is also responsible for the offline analysis. This consists in the proper calibration of the BRIL's detectors, which is carried out by studying the sources of inefficiency and non-linearity and correcting them. More details on how the luminosity is measured are offered in section 3.2.

3.1 BRIL's Detectors

In this subsection, the luminometers of the BRIL project are briefly described. Their locations in the CMS experiment are shown in figure 1.

It is worth pointing out that BRIL's detectors have a dedicated readout system and are operated outside the central CMS data acquisition: they are operated continuously during the whole LHC cycle and not only in stable-beams conditions. In this way it is possible to have online values without deadtime effects due to triggering and irrespectively of the state of the CMS readout system.

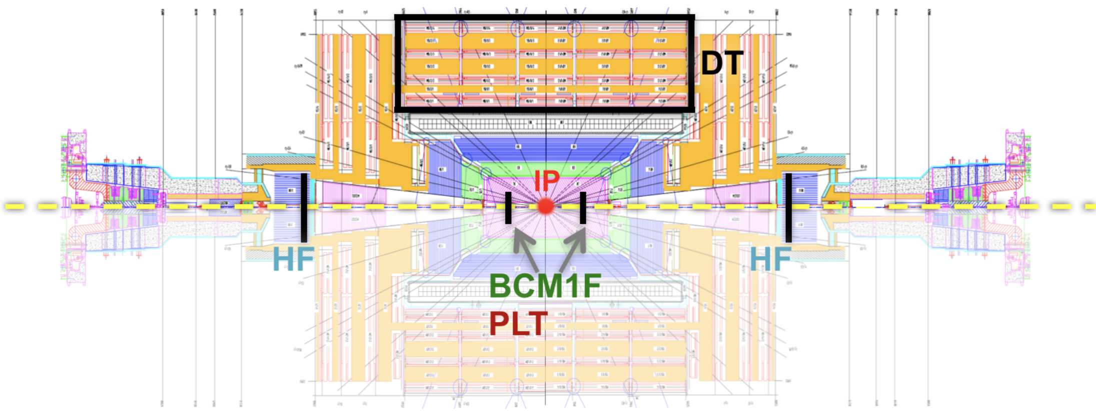


Figure 1: Locations of the BRIL's luminometers within the CMS experiment.

Fast Beam Condition Monitor (BCM1F) The Fast Beam Condition Monitor is located 1.8 m away from the CMS Interaction Point (IP5). It is composed of 24 sensors, each with 2 readout channels, situated at a radius of about 7 cm. Since the upgrade in 2017, it has been composed of three different kinds of sensors: single crystal CVD[1] (sCVD) diamond, polycrystalline CVD (pCVD) diamond and silicon sensors. Both the diamond and the silicon sensors work as solid state ionizing chambers.

All sCVD sensors stopped working during 2017 due to radiation damage. All silicon sensors are now unusable due to high leakage current, but one channel was still working during the beginning of the 2018 data-taking period. pCVD sensors are still working: they are very radiation hard, although less precise than silicon and sCVD sensors.

HF HF is the forward hadron calorimeter of CMS. It is mainly used in physics data acquisition but has a dedicated readout system for luminosity measurement. Two different algorithms are used to analyze data, named HFOC and HFET. The former, HFOC, uses a zero counting algorithm, i.e. it counts all hits without any trigger. The latter is based on energy measurement and at the moment seems to be the best luminometer.

Pixel Luminosity Telescope (PLT) The Pixel Luminosity Telescope is located near BCM1F and is based on silicon pixel sensors. It consists of eight modules and each module is composed of three pads and it counts only the number of simultaneous hits on all the three pads. The readout system in this case is very fast, it works at the same frequency of the collisions, namely 40 MHz.

[1]CVD stands for Chemical Vapor Deposition.

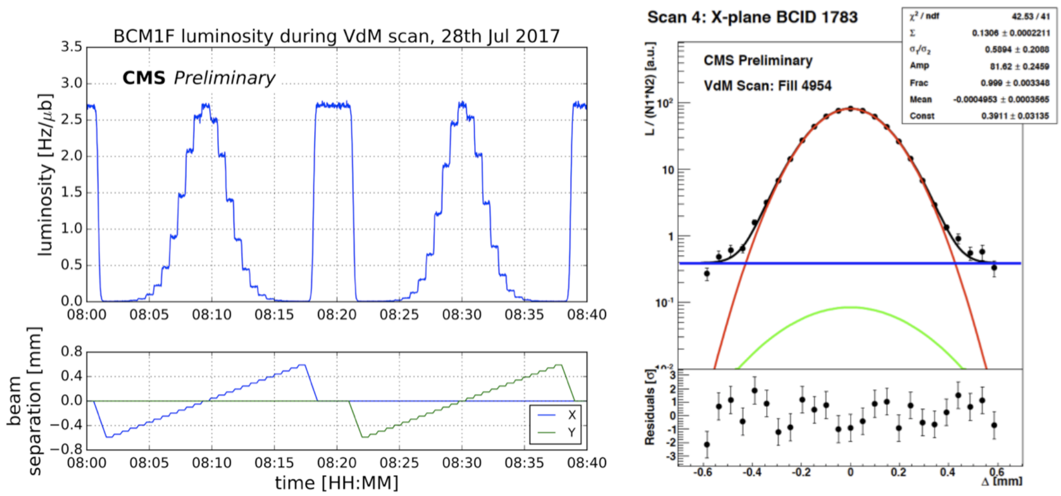
It is also possible to read out single pixels, but in this case the readout system is very slow, working at a frequency of the order of kHz. This data is used to reconstruct particle tracks and estimate the detector hit efficiency.

DT The muon system consists of three sub-systems realized with different kinds of technologies. One of these sub-systems, the Drift Tube, is also used to measure luminosity. It is very precise and highly linear, but, with respect to the other detectors, it suffers from low statistics, due to the relatively low rate of events with muons in the final state. For this reason, it can not be calibrated independently, but is usually used to double-check the linearity and stability of the other luminometers.

3.2 Luminosity measurement

In order to measure luminosity, the detectors need to be calibrated.

The absolute calibration for each detector is obtained through a Van-der-Meer (VdM) scan, which is performed once per year. During the fill dedicated to the VdM scan, LHC operates in dedicated conditions with respect to usual physics fills. During the VdM scan, the two beams are separated and then scanned through one another in discrete steps, in both directions transverse to the beam axis, once at a time, as shown in figure 2a.



(a) (b)

Figure 2: (a) Top: luminosity measured by the BCM1F detector during a VdM scan in the year 2017; bottom: separation of the beams as function of time during a VdM scan. (b) Example of a double-Gaussian fit applied to the detector rates plotted as a function of the beam separation in order to obtain the effective beam size.

The measured rate of events is then plotted as a function of the beam separation for both transverse directions and a double-Gaussian fit is performed in order to extract the effective beam sizes, as shown in figure 2b. The calibration constant is computed using the following relation [1] which combines equations (1) and (2) [2]:

$$\sigma_{\text{vis}} = \frac{2\pi\Sigma_x\Sigma_y\ R_0}{N_1 N_2\ f_{\text{rev}}\ n_{\text{b}}}, \tag{3}$$

where Σ_x and Σ_y are the results of the fit, R_0 is the rate of the events measured by the detector for a zero beam separation (head-on collision) and N_1, N_2, f_{rev} and n_{b} are parameters of the machine. The calibration constant is called σ_{vis}, "sigma visible", and, in few words, corresponds to the effective overlapping area of the two beams as seen by the detector.

Once σ_{vis} is known, each detector measures the rate of events and the luminosity is obtained by $L = R/\sigma_{\text{vis}}$, using the calibration constant relative to the detector. This value of the luminosity is then used to obtain the experimental cross-section for physics processes, as already described in section 2.

In order to have an accurate value of the luminosity, it is important to monitor the stability of the luminometers and to study and correct potential sources of inefficiency or non-linearity.

4 Luminosity stability analysis

For the analysis, data for each fill are available from two different sources: the hdf5 files containing raw data and the luminosity database, accessible through the brilcalc API. In both cases data can be loaded either as raw values or online values. From brilcalc it is also possible to take into account so-called normtags, which contain a calibration obtained after the data-taking (so called "offline" calibration).

The data is loaded in a format with one value of luminosity for each lumisection of the fill and are collected separately for the various detectors.

Once the data is loaded, the ratio of the luminosities of two luminometers is computed and plotted as a function of the luminosity of the reference luminometer. As reference, the luminometer that is considered the most efficient and that displays, at the moment, the most linear response is usually used. BCM1F silicon was considered the best luminometer until it became unusable due to high leakage current; now HFET has taken its place.

The next step is to perform a linear fit on the ratios in order to extract the fit parameters: the slope and the intercept. The former is related to the linearity of the detector's response; the latter gives us information about the relative efficiency of the detector. As an example, the plot in figure 3 has been obtained for one full machine fill. There is evidence that BCM1F silicon is really linear and for this reason it has been used as reference in the ratios. The project is mainly focused on BCM1F pCVD, but this analysis provides also a useful tool to monitor the other detectors' behavior. Indeed, from this plot it is visible that HFET and DT are very linear, whereas PLT and BCM1F pCVD display non-linearities. To be more precise, the online values are already linearity corrected and this figure shows how good the quality of the used linearity correction is.

[2] Equation (3) is obtained from (1) and (2) if $\Sigma^2 = 2\sigma^2$, which is true for head-on collisions and indeed the VdM scan is performed in such operating conditions.

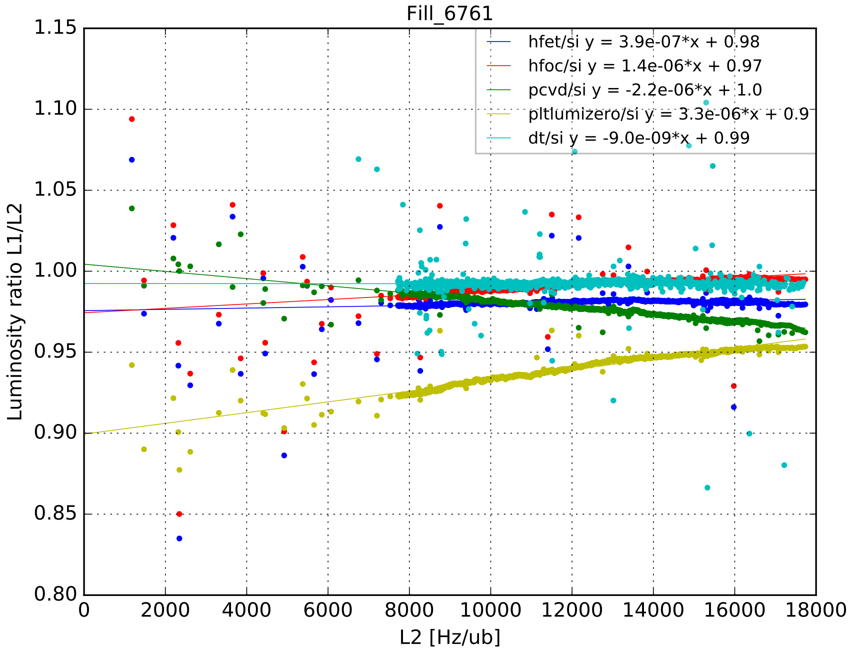


Figure 3: This figure displays luminosity ratios with BCM1F silicon used as reference for a full machine fill. Each point refers to the ratio of rate measurements corrected for visible cross section within one lumisection. The scattered dots are a small subset of points for which the measurements deviate by a few percent, but the ratio at a fixed instantaneous luminosity is generally stable better than permille level. A linear fit has been performed on the ratios to obtain the values of the slope and the intercept, which are related to the linearity and the relative efficiency of the detector, respectively.

The fit parameters are then plotted as a function of different quantities, such as fill number, peak instantaneous luminosity, integrated delivered luminosity and number of bunches. This is done to see if the detector's response displays any dependency on these quantities and to check the stability over time. Section 4.1 and section 4.2 are dedicated to the comparison between luminometers and normtags, respectively.

4.1 Comparison of luminometers

The comparison between the various luminometers has been performed both with raw and online values. In this report only some results obtained with online values are presented.

In figures 4 and 5 the ratios have been obtained using BCM1F silicon and HFET as reference, respectively. In these figures, each point corresponds to one LHC fill and comes from the fit result of figure 3. In both cases, the plot and the intercept are plotted as a function of the integrated delivered luminosity.

For these plots, only fills of the year 2018 before the first technical stop of the LHC have been used, namely from fill number 6570 to 6778. At the beginning of the year, BCM1F silicon was badly configured and not working: this explains the gap at low integrated luminosity in figure 4 where silicon was used as reference. The gap is not present in figure 5 with HFET as reference, there are just some points missing for silicon.

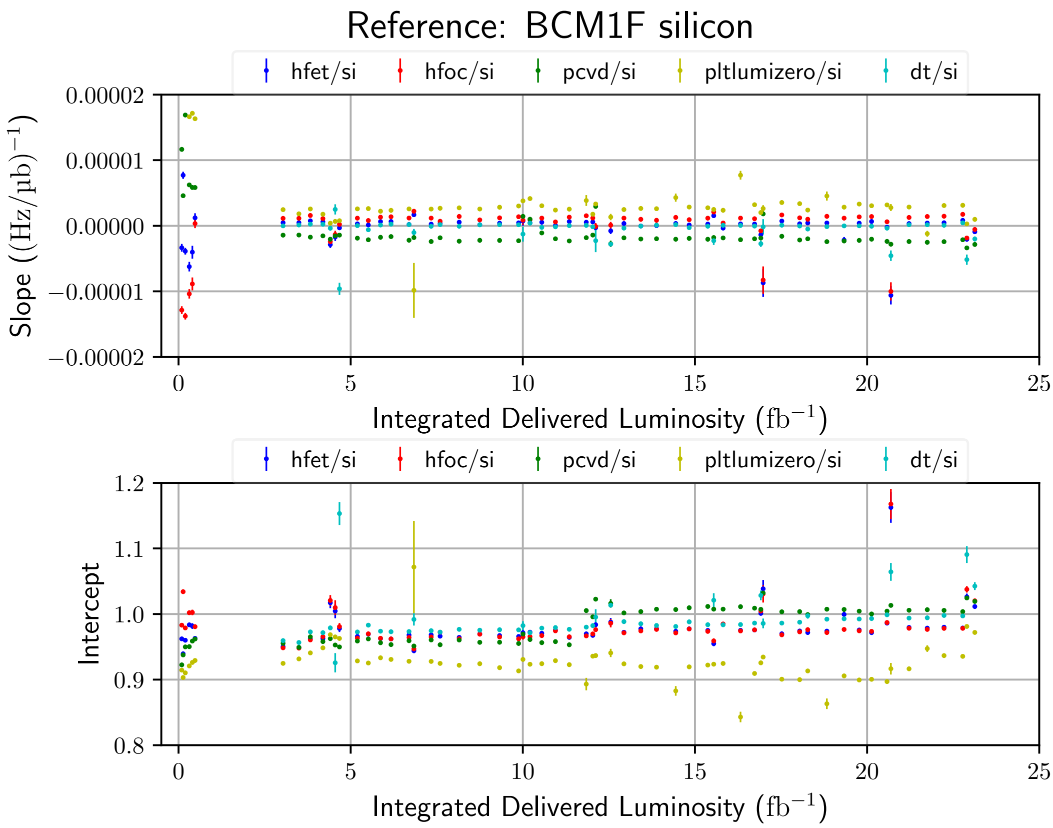


Figure 4: Comparison between BRIL's luminometers using BCM1F silicon as reference. Each point corresponds to one LHC fill and is the result of the linear fit performed on the ratio as shown in figure 3. The gap at low integrated luminosity corresponds to the period when BCM1F silicon was not properly working. At about $12\,\text{fb}^{-1}$ of integrated luminosity, a jump in the intercept of BCM1F pCVD is clearly visible: this increase in the efficiency is the result of an optimization of the read out parameters.

BCM1F pCVD is represented in green in both figures. Looking at the slope, it shows a non-linear behavior if compared to HF and DT. In any case, the non-linearity seems to be relatively constant with time. Looking at the intercept, in both cases a jump in the efficiency at about $12\,\text{fb}^{-1}$ of integrated luminosity is clearly visible. This jump occurs because the read out parameters were optimized resulting in an increased detector efficiency. Apart from this jump and the beginning of the data-taking period, the efficiency looks relatively stable.

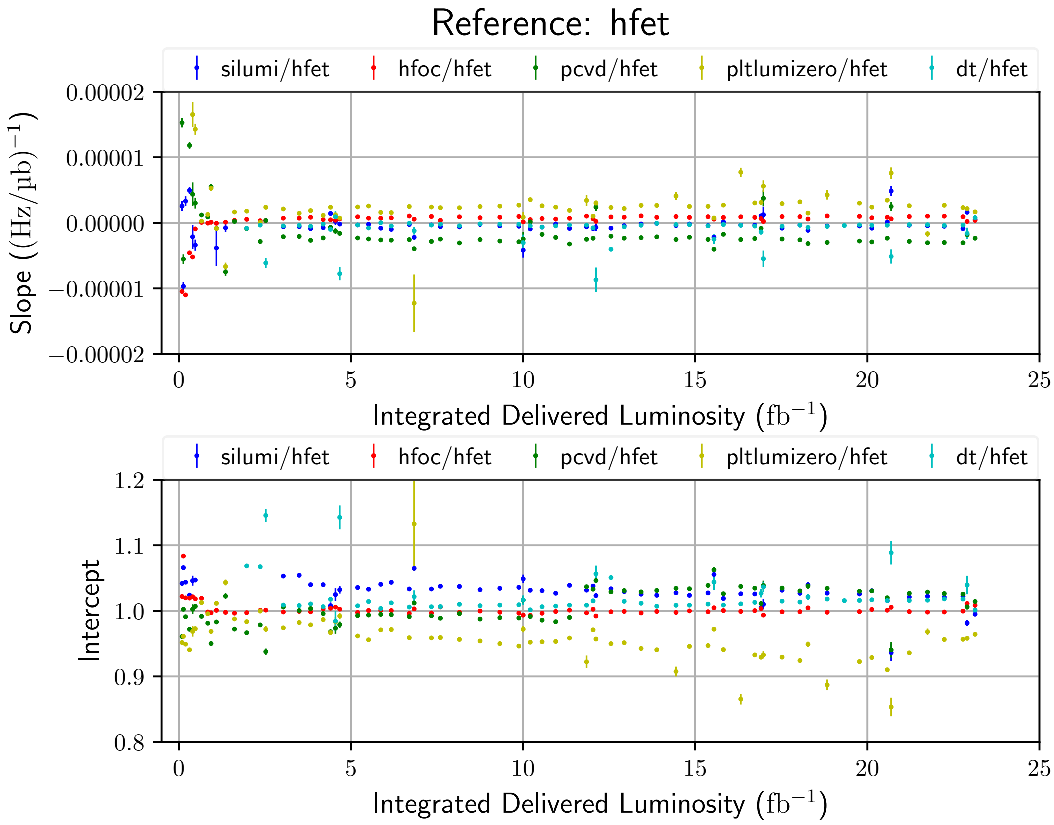


Figure 5: Comparison between BRIL's luminometers using HFET as reference. Each point corresponds to one LHC fill and is the result of the linear fit performed on the ratio as shown in figure 3. At low integrated luminosity, there are missing points for the ratio BCM1F silicon/HFET in the period when BCM1F silicon was not properly working. The jump in the efficiency of BCM1F pCVD at about 12 fb^{-1} is still clearly visible.

4.2 Comparison of normtags

One of the main purposes of the BRIL project is to have a precise online value of the luminosity.

To reach this target, every year an offline analysis is performed to investigate the main sources of inefficiency and non-linearity of the luminometers. In this way, it is possible to correct these inefficiencies and apply the corrections directly to future online measurements.

During this offline process, several calibrations and corrections, also referred to as normtags, are established and applied to the luminosity values. Each version of normtag contains different corrections. The latest version can usually be considered to be the most accurate, until a new normtag is released.

Normtags are available in the luminosity database and can be loaded through brilcalc.

In my analysis I considered three different normtags for BCM1F: two test versions, produced at DESY, and one officially released version.

The first normtag, *bcm1fpcvd18test5*, contains the correction to the number of bunches dependency of BCM1F pCVD. This correction is based on the results of a linearity study that has been carried out at DESY. In this study, BCM1F pCVD has been compared to BCM1F silicon.

The official *bcm1f18v2* normtag is based on the first results of the emittance scan that showed some jumps in the efficiency. The normtag was released taking into account these changes in the efficiency and aiming to correct them. It turned out that these jumps were due to a wrong interpretation of the results of the emittance scan and not due to the detector itself. This normtag includes a correction to the degradation due to radiation damage.

The last normtag, *bcm1fpcvd18test7*, has both corrections of the two previous normtags and includes also a correction to the misinterpreted changes in the efficiency resulted from a first analysis of the emittance scan.

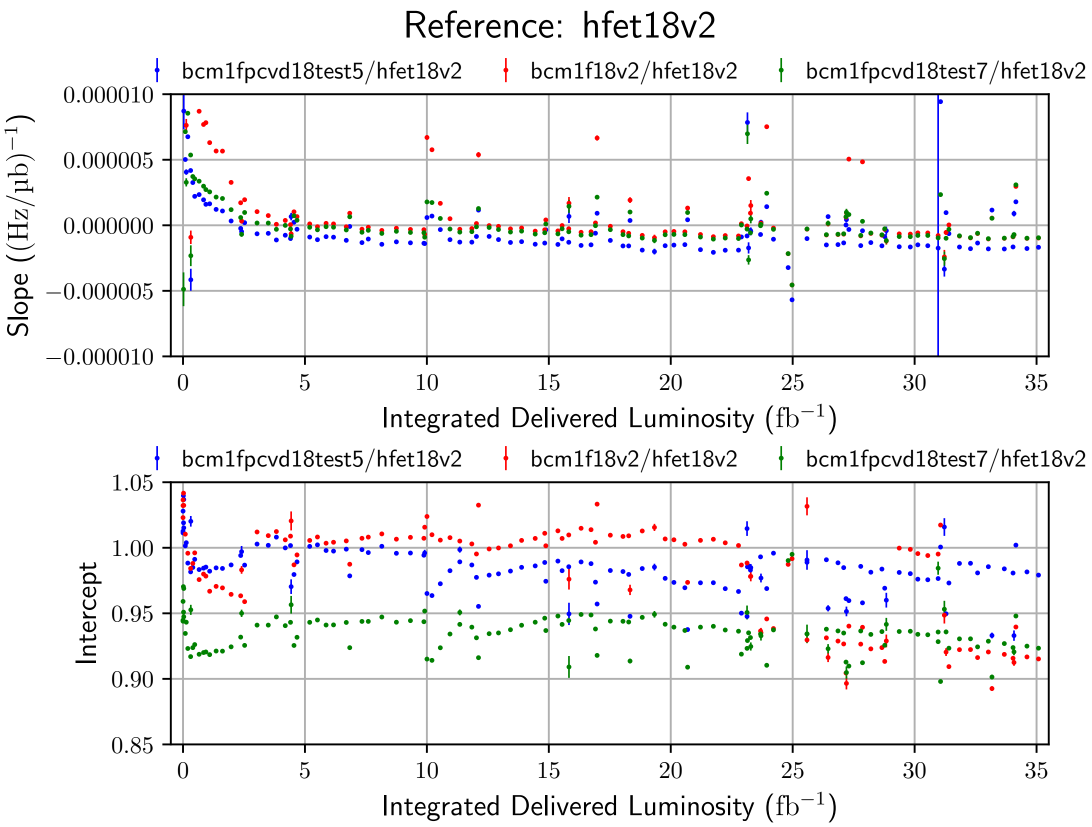


Figure 6: Comparison of three different normtags for the BCM1F detector, using *hfet18v2* normtag as reference. Each point corresponds to one LHC fill and is the result of the linear fit already mentioned.

The parameters of the linear fit which has been performed on the ratios of these normtags to the official v2 normtag for HFET, *hfet18v2*, are plotted in figure 6 as function of the integrated delivered luminosity. For this study fills from 6570 to 7039 of the 2018 data-taking period have been considered.

The slope is displayed in the upper panel of figure 6 and there are red points, corresponding to the official normtag, which are clearly above the others: these correspond to fills with a lower number of bunches. The official normtag has no correction to a number-of-bunches dependency, whereas the other two normatags, *test5* and *test7* for short, do have such a correction. Indeed, the blue and green points for these fills are lower than the red ones.

Looking at the intercept plot at the bottom, *test5*, in blue, a slow degradation is visible, with a recovery of the efficiency at about $23\,\mathrm{fb}^{-1}$ and $32\,\mathrm{fb}^{-1}$ due to annealing in the technical stops. The degradation is due to radiation damage. The other two normtags contain the correction to this effect and indeed they look flatter and more stable in that region.

At high delivered luminosity, the official normtag displays some jumps in the efficiency. As previously stated, these jumps come from the first and inaccurate interpretation of the emittance scan results. A correction to this jumping behavior has been taken into account to produce the new normtag, *test7*, that indeed is relatively stable and flat, although 5 % lower.

At the moment, no new normtag for BCM1F has been released but a new one is available for HFET. Since the new version, *hfet18v3*, is significantly different and more accurate than the previous version 2, it was worth changing the reference in the ratio for *test7*. In figure 7 the results for the ratios of *test7* to both versions of the HFET normtag are displayed. Significant improvements both in the linearity and the efficiency of BCM1F pCVD are clearly visible; indeed the slope and the intercept are more stable and flatter. It means that some of the non-linearity and inefficiency features of the previous analysis were due to an inaccurate understanding of HFET's behavior, and were not due to BCM1F itself.

After this study, *bcm1fpcvd18test7* seems to be a good candidate for a new official normtag for BCM1F, although the efficiency is still more than 5 % lower. This overall difference in the efficiency has to be followed up and understood in order to correct it.

5 Bunch-by-bunch analysis

During a fill, all BRIL's detectors, except for DT, are able to measure luminosity on a bunch-by-bunch basis. Per-bunch data can be loaded both from the hdf5 files and from brilcalc and are obtained in the format of one value of luminosity per lumisection for each bunch crossing[3].

[3]Note that at each bunch crossing there are always the same two bunches colliding, so identifying the bunch crossing or the position of the bunch in the beam is exactly the same thing.

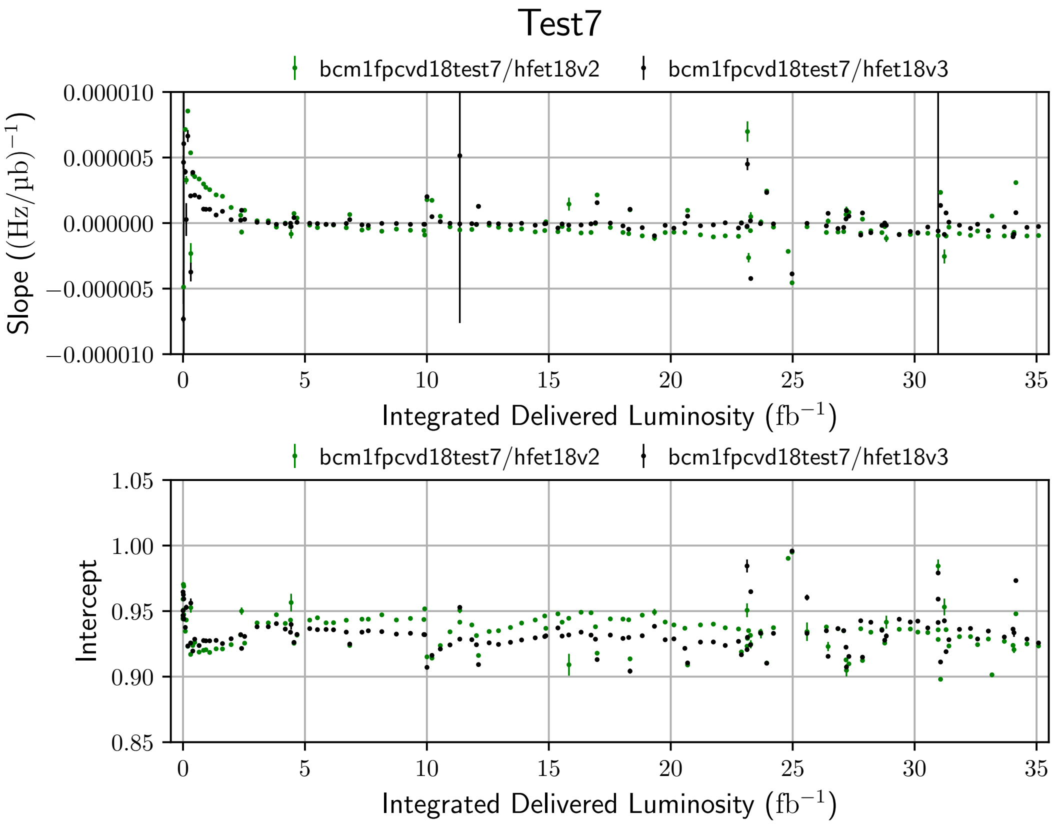
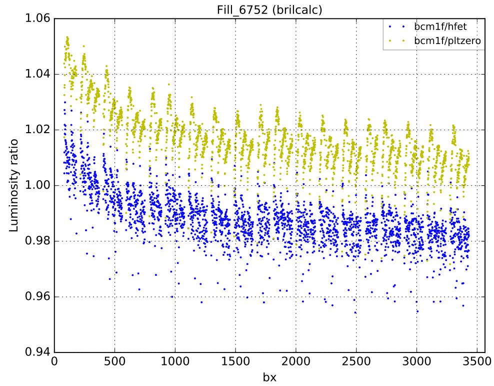


Figure 7: Each point corresponds to one LHC fill and is the result of the linear fit already mentioned. Significant improvements both in the linearity and the efficiency for *test7* are visible after applying a new normtag to HFET.

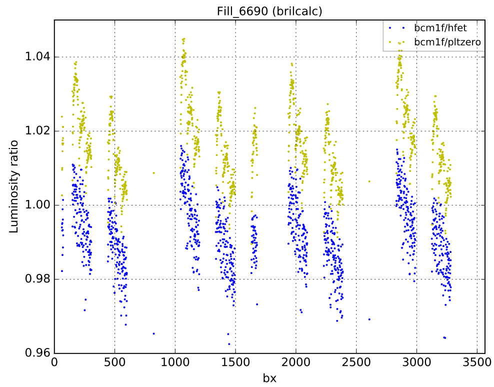
To proceed with the analysis, all rate measurements from one fill for each bunch crossing are summed up to obtain one luminosity value per bx; this is performed for each luminometer considered and for each fill separately. The next step is to compute the ratio between different detectors and plot it as function of the bunch crossing identification number, or bx.

This analysis provides a useful tool to compare the behavior of the various detectors during one LHC turn and to highlight potential bunch train and filling scheme dependencies.

In figure 8 the results for the ratios of BCM1F pCVD over HFET and over PLT are displayed. On the left the results for a full machine fill, i.e. a fill with 2544 colliding bunches, are reported, while on the right for a fill with a lower number of colliding bunches. In this way it is possible to highlight potential differences in the behavior of BCM1F pCVD for different operating conditions.



(a) *Fill 6752, 2544 colliding bunches.*



(b) *Fill 6690, 1214 colliding bunches.*

Figure 8: Ratios of BCM1F pCVD over HFET, in blue, and PLT,in yellow, for (a) a full machine fill, 6752, and (b) a fill with low number of bunches, 6690. The capability of BCM1F pCVD to recover during gaps is clearly visible in both plots. This behavior could be related to the bunches and filling scheme dependency of BCM1F.

In figure 8a a long term drift by about 2.5 % downwards is clearly visible, before the ratio saturates for later bx. This drift is apparently due to a specific BCM1F pCVD behavior: a loss of efficiency at a high rate of events and a subsequent recovery during the abort gap[4]. The ability of pCVD to recover during gaps is even more visible in figure 8b, where the lower number of bunches implies more gaps in the orbit. In addition, the recovery seems to scale with the length of the gap.

This is an expected, yet unwanted, behavior of pCVD. The different behaviors observed with the two filling schemes could be related to the number-of-bunches dependency of the detector that is currently under study at DESY. This dependency still has to be understood properly. A possible next analysis step could be to obtain a parametrization

[4]The abort gap is a $\sim 3\,\mu s$ gap in the filling scheme where there are no bunches, visible at the end of the orbit in figure 8a. The abort gap is needed for the procedure of beam dump.

of the drift and to simulate it through MC simulation in order to obtain a good understanding of the detector's behavior.

By zooming in a bit in figure 8a, additional features come to light (see figure 9).

For example, the blue points, corresponding to the ratio BCM1F pCVD over HFET, are largely scattered, and since this scattering is not visible in the other ratio it is probably an effect of HFET. This behavior is somehow surprising, since HFET is quite stable and one would expect more statistical precision.

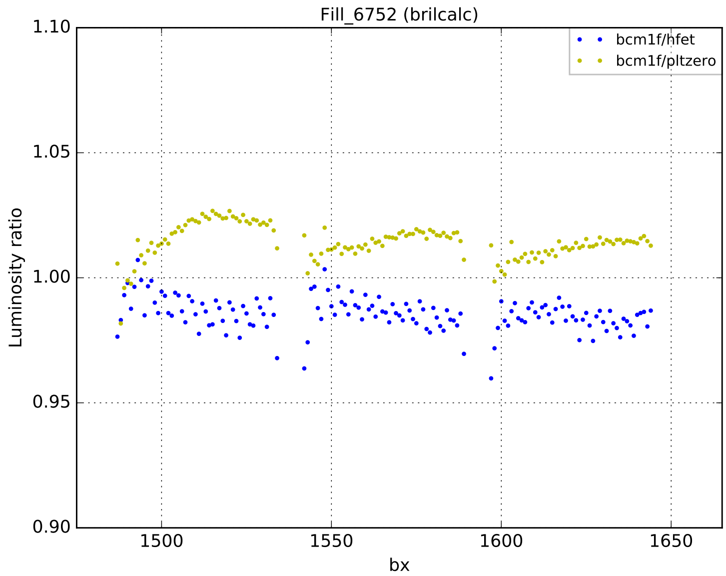


Figure 9: This figure presents a zoom of figure 8a, restricted to the bx range 1475-1665. The zoom has been performed to point out other behaviors, not necessarily due to BCM1F pCVD. The large scattering is probably an effect of HFET, whereas the short drifts upwards are probably due to PLT.

In addition, it emerges that there are some short drifts upwards in the ratio of BCM1F pCVD over PLT. Again, since this effect is not visible in the other ratio, it is probably due to PLT, which is displaying a train-dependent behavior.

It is also possible to compare the start and the end of a fill to check if there is any change in the behavior of the detector. This can be done by selecting for example the first and the last 150 lumisections, which correspond to about the first and the last hour of the fill. An example for a full machine fill is reported in figure 10. From this analysis, it turns out that the long drift downwards is similar at the start and the end of a fill without significant changes.

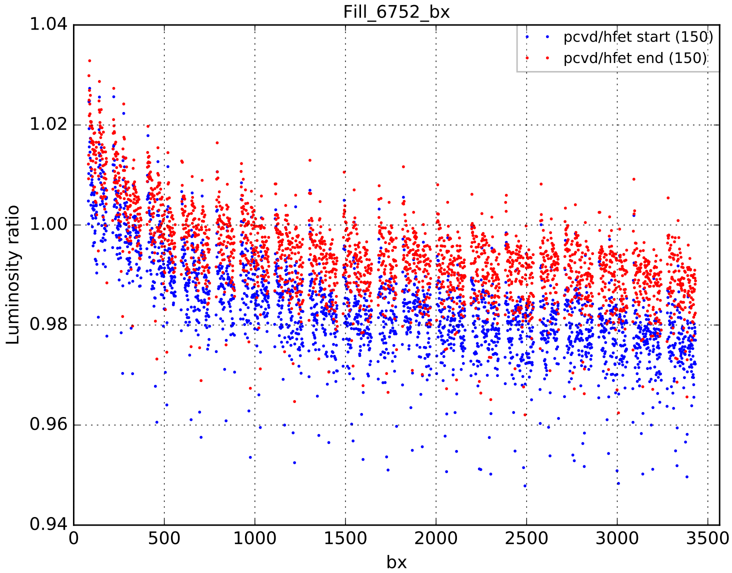


Figure 10: Comparison between the start and the end of a full machine fill: the behavior of the detector does not display significant changes during a fill.

6 Conclusion

In my project I developed a useful tool to analyze offline luminosity values and identify non-linearity behavior and loss of efficiency of the detectors. It is also possible to compare new normtags version, as soon as they are released, with the older ones, to see if any improvement has been effectively introduced and to test our comprehension of the detector's behavior.

The bunch-by-bunch analysis highlighted some behaviors that are still to be properly understood. Some efforts have to be put in this direction, in order to obtain a full comprehension of the detector's response and eventually correct the inefficiencies. A possible way to reach this target would be to obtain a parametrization of the loss of efficiency of BCM1F pCVD during the orbit and perform MC simulation of the efficiency for a given filling scheme.

References

[1] Olena Karacheban. “Luminosity measurement at CMS”. PhD thesis. Fakultät für MINT – Mathematik, Informatik, Physik, Elektro- und Informationstechnik der Brandenburgischen Technischen Universität Cottbus-Senftenberg, 2016.