PERFORMANCE OF THE PIXEL LUMINOSITY TELESCOPE FOR LUMINOSITY MEASUREMENT AT CMS DURING RUN2

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The Pixel Luminosity Telescope (PLT) is a dedicated system for luminosity measurement at the CMS experiment using silicon pixel sensors arranged into "telescopes", each consisting of three planes. It was installed in CMS at the beginning of 2015 and has been providing online and offline luminosity measurements throughout Run 2 of the LHC (2015–2018). The online bunch-by-bunch luminosity measurement reads out at the full bunch crossing rate of 40 MHz, using the "fast-or" capability of the pixel readout chip to identify events where a hit is registered in all three sensors in a telescope, corresponding primarily to tracks originating from the interaction point. In addition, the full pixel information is read out at a lower rate, allowing for studies with full track reconstruction. In this talk, we present the results and techniques used during Run 2, including commissioning, luminosity calibration using Van der Meer scans, and measurement and correction of stability and linearity effects using data from emittance scans.

Keywords: LHC, CMS, BRIL, PLT, Luminosity

1. Motivations

The precision measurement of the luminosity delivered to the CMS experiment [1] is crucial to the entire Collaboration. On the one hand, it provides prompt feedback on the LHC performance and operations and the online CMS operations such as measurements of trigger rates. On the other hand, it is used by every physics analysis dealing with cross section and coupling measurements of physics processes and for setting upper limits on the cross section in searches for physics beyond the standard model.

A dedicated group, named "BRIL" (Beam Radiation, Instrumentation, and Luminosity) is responsible in CMS for carrying out the measurement of the luminosity, exploiting several subdetectors, among which the Pixel Luminosity Telescope (PLT) [2], whose design and measurement technique is discussed in these proceedings.

2. The Pixel Luminosity Telescope

The PLT was installed in the CMS detector at the beginning of 2015 for operations during the Run 2 of the LHC (2015–2018). It consists of 48 silicon pixel sensors arranged on 16 "telescopes", 8 on each end of CMS at 1.75 m from the interaction point and $|\eta| \approx 4.2$, nearly parallel to the beam pipe. Each telescope is 7.5 cm long, 5 cm away from the beam pipe, and contains 3 individual sensors.

Figure 1 illustrates eight telescopes of the PLT detector, which correspond to half detector, (left) and the floor PSI46v2 readout chips (right) discussed below.

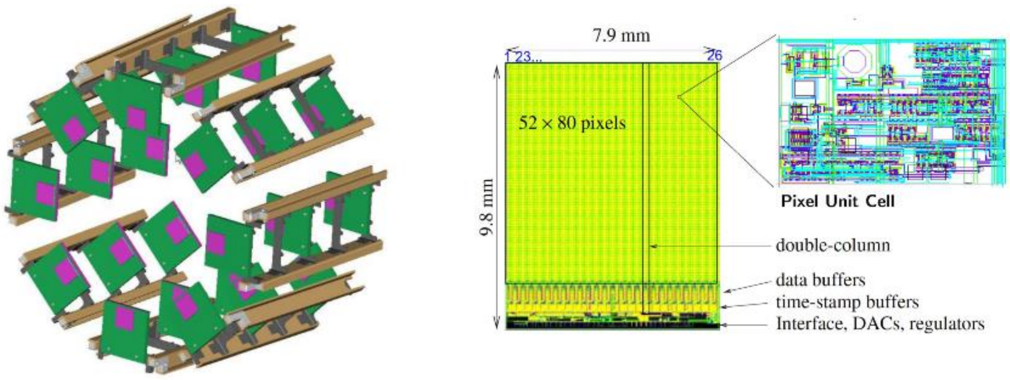

Figure 1. (Left) Picture illustrating eight telescopes of the PLT detector, which correspond to half detector. (Right) Floor plan of the PSI46v2 readout chips

The silicon sensors [3] and the PSI46v2 readout chips (ROCs) [4] are the same used in the Phase-0 [5] of the CMS pixel detector. Each sensor is n-in-n type, consists of 80 rows and 52 columns of pixels (or 26 double columns of 160 pixels each), has a size of 150 x 100 μm^2 for a total active area of 8x8 mm^2 and an active thickness of 285 μm. The PSI46v2 ROCs are bump bonded to the sensors and allow two read out modes. The first is the "fast-or" readout, which reads out the signal indicating if any of the pixels in the sensor were hit. The fast-or readout looks for "triple coincidences", where a hit in all three planes in a single telescope is observed, being its rate proportional to the luminosity. This is done at the full bunch crossing rate of 40 MHz, hence rendering the PLT capable of providing online per-bunch luminosity with excellent statistical precision on a short timescale. This feature is unique of the PSI46v2 ROCs and was not used in the main pixel detector. Beside the fast-or readout mode, there is the full pixel data read out, which reads at a lower rate (approximately at 3.3 kHz), which is useful for additional studies.

The three ROCs in a telescope are managed by the token bit manager (TBM) chip, which distributes commands to and coordinates the readout of the individual ROCs. Four telescopes make up a "quadrant" of the PLT, and are controlled by a single port card, which manages the communication and control the signal for that quadrant. The port card is in turn connected to an optical motherboard, which translates the electrical into optical signals transmitted via optical fibers from the CMS experimental cavern to the CMS service cavern where the backend electronics are located. The back-end electronics consist of three parts: the front-end controller (FEC) is responsible for sending commands, as well as clock and trigger signals, to the detector; the pixel front-end driver (FED) reads out and decodes the pixel data, which are then sent over an Slink connection to a dedicated PC; and the fast-or FEDs look for triple coincidences and histogram the results over a "lumi nibble" (4096 orbits), which are then read out over a CAEN VME (VERSA-Module Euro) optical bridge to a dedicated software farm. From there the data are sent to BRILDAQ, a DAQ (Data Acquisition) system dedicated to luminosity and beam measurements. BRILDAQ operates separately from the main CMS DAQ so that it can provide luminosity measurements to the LHC and beam safety measurements even when the CMS DAQ is not running.

3. The luminosity measurement

One possibility to measure the instantaneous luminosity, L, delivered by the LHC could be to consider its expected proportionality to the average rate of triple coincidences, μ, measured in the PLT. However, because of the limited capability of the "fast-or" readout mode, it may happen for multiple particle tracks to be registered as only a single triple coincidence in a telescope. In order to overcome this effect, the actual method used for the luminosity measurement is the so-called "zero-counting" technique. In this method, the number of triple coincidences is assumed to follow a Poisson distribution, with mean value μ, which can be derived from the probability of finding zero triple coincidences, p(0), as $\mu = -\ln[p(0)] = -\ln[1 - p(\neq 0)]$. Here, one just needs to know $p(\neq 0)$, irrespective of the particle track multiplicity that produced the count. The following equation relates μ to L as:

$$\frac{\mathbf{d}\boldsymbol{L}}{\mathbf{d}\boldsymbol{t}} = \mu \frac{\boldsymbol{f}_{\mathbf{orb}}}{\boldsymbol{\sigma}_{\mathbf{vis}}} \qquad (\mathbf{1})$$

where f_{orb} is the LHC orbit frequency of 11246 Hz and σ_{vis} is the "visible cross section", the fraction of the total inelastic cross section which is visible to the PLT. To determine the overall luminosity, μ is measured bunch-by-bunch and telescope-by-telescope; for a single bunch, μ is averaged equally over all telescopes, and then converted to the instantaneous luminosity. The total instantaneous luminosity is then given by the sum over all bunches.

Finally, to know $\frac{\mathrm{d}L}{\mathrm{d}t}$, σ_{vis} is derived from an independent measurement using the Van der Meer (VdM) scan method [6]. This technique exploits the relationship between L and the beam parameters, being, for the case where there is no crossing angle (head-on colliding beams):

$$\frac{\mathbf{d}\boldsymbol{L}}{\mathbf{d}\boldsymbol{t}} = \frac{\boldsymbol{N}_{\mathbf{1}}\boldsymbol{N}_{\mathbf{2}}\boldsymbol{f}_{\mathbf{orb}}}{\mathbf{2}\boldsymbol{\pi}\boldsymbol{\Sigma}_{\mathbf{x}}\boldsymbol{\Sigma}_{\mathbf{y}}} \qquad (\mathbf{2})$$

where N_1 and N_2 are the LHC beam intensities and Σ_{x} and Σ_{y} are the effective beam widths. The independent measurement, the VdM scan, is performed by varying the beam separation between -6σ and +6σ in steps of 0.5σ, first in the x plane and then in the y plane, and measuring the resulting rate as a function of separation. The rate curve is then fit with a double- (2016, 2017) or single- (2018) Gaussian function, and the background either modeled with a constant term (2016), or subtracted (2017, 2018), to extract Σ_{x} and Σ_{y}.

4. Corrections and systematic effects

The method described in Section 3 assumes ideal and stable detector conditions, while during the data-taking period detector effects may introduce different dependencies on the calibration constants that need to be corrected in order to obtain an accurate luminosity measurement. One of the main corrections concerns about the "accidentals", which corresponds to those cases in which triple coincidences are observed not to be caused by a track originating from the interaction point. This can happen with a track from another source (e.g., a "beam halo" particle passing through the PLT) or due to a random combination of hits not originating from a single track (e.g., from cosmic rays, radioactive decay of activated material, or secondary material interactions in the detector). Since the fast-or data do not include position information, these cannot be identified in the fast-or data, and the full pixel data information is used to estimate the rate at which they occur. This is done by reconstructing tracks from a "pure" sample of events where each plane in the telescope has exactly one hit. Then, the distributions of the track slopes and residuals on each plane are computed and used as a reference. A candidate track is considered to be "accidental" if any of the slopes or residuals is more than 5σ away from the mean of the reference distribution. Figure 2 (left) shows the measured accidental rate in 2016 as a function of the instantaneous luminosity over the course of several fills.

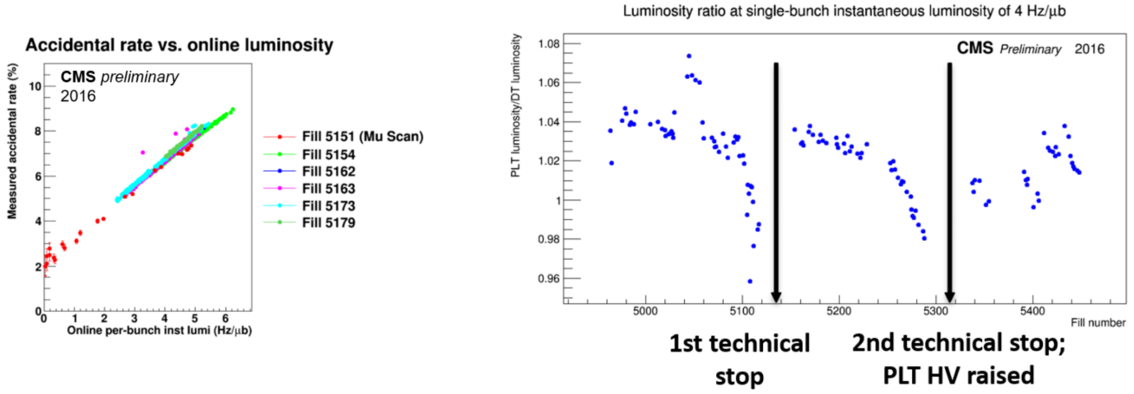

Figure 2. (Left) Accidental rate as a function of instantaneous luminosity for a set of fills. (Right) Ratio of PLT to drift tubes (DT) luminosity over the course of 2016

Another correction is needed when the PLT efficiency is lower than the expected performance. This situation is monitored by continuously comparing PLT rates with respect to other CMS luminosity detectors. As an example, Figure 2 (right) shows the ratio of PLT to drift tubes (DT) luminosity during two periods of 2016 when PLT experienced efficiency loss. This efficiency loss is due to the radiation damage and can be mitigated by increasing the high voltage (as done during 2016 and 2017) or by adjusting the thresholds used in the PLT readout chips to determine hit pixels (as done in 2018). In both cases, the luminosity measurement requires proper corrections for the affected periods.

In 2016, we measured the efficiency in the PLT by looking for events with two hits in two planes consistent with a track passing through the third plane, and then measuring the fraction of events in which the third hit was actually found in the third plane.

After 2016, to account for radiation damage and overall detector changes in efficiency and linearity, we relied on fast luminosity scans with a small beam separation ("emittance scans") performed at the beginning and end of a fill. The emittance scans are conducted similarly to a VdM scan, but in normal physics conditions and over a shorter time. By considering the ratio of the emittance scan over the VdM σ_{vis}, one can infer the efficiency performance of a detector. At the same time, since the emittance scans at the beginning and end of fills are conducted at significantly different single-bunch instantaneous luminosities (SBIL) and individual bunches within a single fill can also exhibit substantially different SBIL, they can also be used to measure the linearity response of a detector. For PLT, efficiency and linearity corrections are applied channel by channel individually, considering only those channels that were operational during the data-taking period. Figure 3 compares the PLT per-channel luminosity as a function of time, showing the total (i.e., over all bunches) instantaneous luminosity as measured by the PLT detector (left) and after applying dedicated weights that are derived from emittance scans to account for detector efficiency and linearity (right). As we can see, the relative difference between the highest and lowest luminosity with respect to the lowest luminosity measured by the PLT channels amounts approximately to 20% before corrections and improves up to 5% after the corrections are applied.

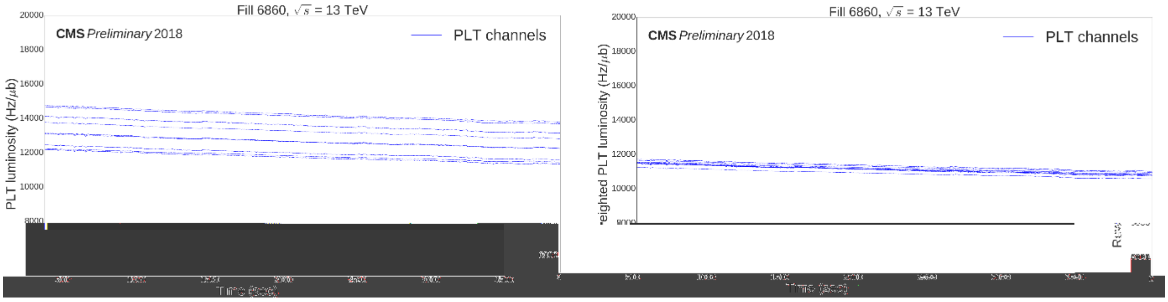

Figure 3. (Left) Pixel Luminosity Telescope (PLT) per-channel luminosity values as a function of time, showing the total (i.e., over all bunches) instantaneous luminosity as measured by the PLT detector. (Right) After applying dedicated weights that are derived from emittance scans to account for detector efficiency and linearity (Right)

5. Summary

In these proceedings we have summarized the performance of the Pixel Luminosity Telescope (PLT) detector in the precision measurement of the luminosity delivered to the CMS experiment. The PLT has been successfully operating during the whole Run 2 (2015–2018), providing online and offline luminosity measurements with high uptime and precision. In order to achieve these high-quality results, detector-related issues and systematics effects in the luminosity measurements have been properly taken into account and corrected in dedicated analyses.

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