PROCEEDINGS OF SCIENCE

Performance of New and Upgraded Detectors for Luminosity and Beam Condition Measurement at CMS

Jessica Lynn Leonard[*] **on behalf of the CMS Collaboration**
DESY
Platanenallee 6, 15738 Zeuthen, Germany
E-mail: `jessica.lynn.leonard@desy.de`

The beam monitoring and luminosity systems of the CMS experiment are enhanced by several new and upgraded sub-detectors to match the challenges of the LHC operation and physics program at increased energy and higher luminosity. A dedicated pixelated luminosity telescope is installed for a fast and precise luminosity measurement. This detector measures coincidences between several three-layer telescopes of silicon pixel detectors to arrive at luminosity for each colliding LHC bunch pair. An upgraded fast beam conditions monitor measures the particle flux using single crystalline diamond sensors. It is equipped with a dedicated frontend ASIC produced in 130 nm CMOS technology. The excellent time resolution is used to separate collision products from machine induced background, thus serving as online luminosity measurement. A new beam halo monitor at larger radius exploits Cerenkov light from fused silica to provide direction sensitivity and excellent time resolution to separate incoming and outgoing particles. The backend electronics of the beam monitoring systems include dedicated modules with high bandwidth digitizers developed in both VME and microTCA standards for per bunch beam measurements and gain monitoring. All new and upgraded sub-detectors have been taking data from the first day of LHC operation in April 2015 and results on their essential characteristics will be presented.

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[*] Speaker

1. CMS

The Compact Muon Solenoid (CMS) [1] is one of two general-purpose detectors for the Large Hadron Collider at CERN. Detecting the results of proton collisions at center-of-mass energies of up to 14 TeV, its objective is to investigate electroweak symmetry breaking and search for signs of new physics.

2. CMS Beam Radiation Instrumentation and Luminosity

Luminosity is a key parameter of many physics analyses, and as such producing an accurate luminosity measurement is essential. The instrumentation necessary to make such a measurement is in the domain of the Beam Radiation Instrumentation and Luminosity (BRIL) group at CMS. In addition to providing real-time integrated and per-bunch luminosity measurements, the BRIL subdetectors carry out such functions as measuring machine-induced background, ensuring safe operating conditions for the tracker, and protecting CMS from catastrophic beam loss events by activating the beam abort.

The BRIL subsystems are located along the beam pipe, at varying distances from the interaction point horizontally and radially to make complementary measurements. Closest to the interaction point, at a distance of 1.8 m and a small radius of 7 cm, are the Fast Beam Condition Monitor (BCM1F) and the Pixel Luminosity Telescope (PLT), as well as the first location of the beam abort system, BCM1L. The second beam abort system location (BCM2L) is at a distance of 14.4 m from the interaction point. The forward hadronic calorimeter, used for luminosity measurement, is located 11.2 m from the interaction point. Furthest from the interaction point is the Beam Halo Monitor (BHM), at a distance of 20.6 m and a radius from the beam pipe of 1.8 m. The Fast Beam Condition Monitor and the Beam Halo Monitor are located at points at which the bunches of the incoming and outgoing beams are maximally separated in time, making it easier to distinguish machine-induced background from collision products.

The harsher operation conditions foreseen for LHC Run II necessitated upgrades of some BRIL subsystems, as well as the addition of new ones. Diamond sensors that had undergone radiation damage during Run I were replaced in the BCM systems. Higher collision energy and instantaneous luminosity imply higher particle fluxes, so resistance to radiation damage was considered in the upgrades, as well as dynamic range and linearity. In addition, closer bunch spacing (25 ns vs. 50 ns in Run I) makes fast performance desirable. These upgrades and additions will be described more specifically in the following sections, as well as the systems' performances during the initial stages of LHC Run II.

2.1 Beam Abort System

The Beam Abort System BCML [2] protects the CMS silicon tracking detectors from catastrophic beam loss events by inducing a beam abort. The BCML units consist of polycrystal CVD diamond sensors. The particle flux incident on the sensors induce a current, and the system initiates a beam abort if the current in at least one channel rises above a predefined threshold, chosen to provide a large safety margin. Diamonds in all the BCML units were replaced in preparation for Run II: only highly-damaged diamonds were replaced in the BCM2L units, all diamonds were replace in the BCM1L units. In addition, the sensors of BCM1L were integrated into the PCB developed for the Fast Beam Condition Monitor (BCM1F) upgrade. Each BCM1L sensor is packaged into a small unit that is affixed perpendicularly to the PCB, and therefore the diamond is aligned parallel with the beam. This serves to increase the amount of charge individual particles generate in the sensor. In Run II the BCML system has already detected multiple beam loss events, although none led to a beam abort.

2.2 Beam Halo Monitor

The Beam Halo Monitor BHM [3] is a newly-developed system for the purpose of measuring machine-induced background at a radius of about 1.8 m. Charged particles travelling with the incoming beam are detected using Cherenkov light produced in a quartz bar, which is read out by a photomultiplier. The directional nature of Cherenkov light makes the system much more sensitive to forward-going particles than to those travelling in the backward direction. There are 20 modules per incoming beam, installed at a distance of 20.6 m down the beam pipe from the interaction point. Currently two readout systems provide hit rates in parallel: VME scalers produce hit rates integrated over the LHC orbit, while a microTCA system in development produces full-orbit hit histograms with 6.25-ns binning.

The directionality of the signal response in BHM was demonstrated early on during LHC “splash” events, during which one beam hits a closed collimator upstream of CMS, sending a shower of particles into the detector. Figure 1 shows the response of two BHM units, one oriented to detect Beam 1 background, and the other oriented for Beam 2, during a Beam 2 splash event. The backwards-facing unit sees a small signal, but the forward-facing unit sees a very large signal, saturating the electronics for tens of nanoseconds. Typical machine-induced background signals are much smaller than the signals in the splash scenario, so the saturation shown here presents no issue for normal operation.

Further tests during circulating beam show that the detected hit rate correlates with the position of the LHC collimators, as shown in Figure 2. The dotted lines represent the collimator position, while the solid lines show the average hit rate per channel for detector units oriented for each beam. As each collimator is closed, the corresponding beam starts scraping the edge of the collimator, producing showers of particles which are then successfully detected in the BHM units.

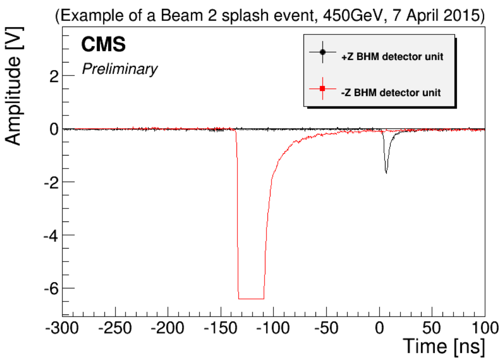

Figure 1: The response of two BHM units, oriented to detect Beams 1 and 2 respectively during a Beam 2 splash event.

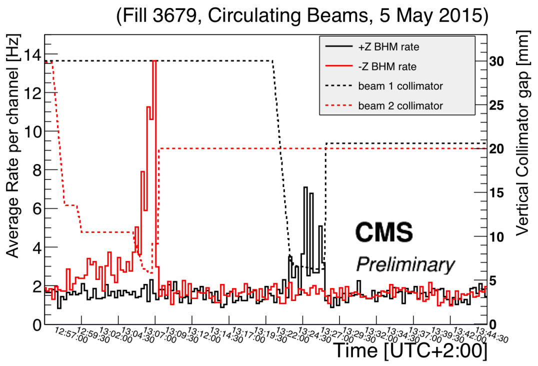

Figure 2: BHM hit rates and collimator positions for Beams 1 and 2. Increased hit rate directly correlates to decreased collimator gap.

2.3 Forward Hadronic Calorimeter

The Forward Hadronic Calorimeter HF is a quartz fiber calorimeter. It was the primary online luminometer during Run I, using a zero-counting algorithm on its 864 towers to provide luminosity with 3.7% precision [4].

Several upgrades took place to prepare HF for Run II operation. New photomultipliers were used to address anomalous signals due to particles incident on the PMT window, and to provide multiple-channel readout. In addition, a move was made towards microTCA backend electronics. The HF readout for luminosity provides bunch-by-bunch occupancy and transverse energy sum histograms. The luminosity readout is independent of the general CMS data acquisition and is also decoupled from the trigger data stream.

2.4 Pixel Luminosity Telescope

The Pixel Luminosity Telescope PLT [5] is a dedicated standalone luminosity monitor newly developed and constructed for Run II. It consists of eight 3-plane silicon-pixel telescopes per end, using the standard CMS pixel sensors and frontend electronics. It was designed to provide bunch-by-bunch luminosity with a statistical precision of 1% at 1-Hz readout. It measures luminosity without deadtime by making fast 3-fold coincidences among the telescope planes. It can also read out the full pixel information for purposes such as alignment, systematics, and background studies.

The Pixel Luminosity Telescope was installed and commissioned in early 2015. Functionality was verified in the initial stages of running by the observation of triple-coincidence tracks during collisions. No tracks are seen without collisions, making PLT a zero-noise detector. The active areas of the pixel sensors show uniform track occupancies, as in Figure 3, which shows the occupancies of three pixel sensors in a single telescope. The lower-occupancy areas at the edges of the sensors are due to slight misalignment between the layers of the telescope, which is accounted for by reducing the area of the sensor used for track-finding. In addition, the tracking information is sufficient to make a reconstruction of the beam spot; the reconstruction in the transverse plane is shown in Figure 4 for a single LHC fill.

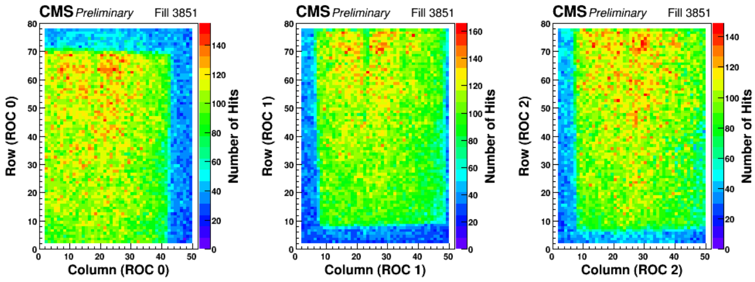

Figure 3: Hit occupancies of three pixel layers of a single PLT telescope. The edge effects are due to slight misalignment between the planes.

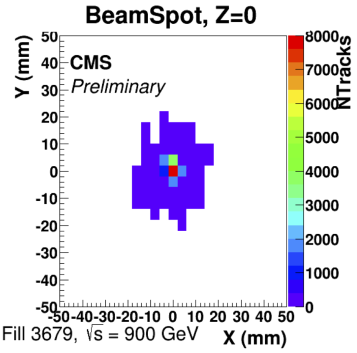

Figure 4: Reconstruction of beam spot in transverse plane using PLT tracks.

2.5 Fast Beam Condition Monitor

The Fast Beam Condition Monitor BCM1F consists of 5mm x 5mm single-crystal CVD diamond sensors, with a thickness of 500 microns. During Run I it was used to measure the machine-induced background at low radius to ensure safe operation of the silicon tracking detectors [6]. During Run II it will also function as a luminometer, providing bunch-by-bunch measurements of both beam background flux and collision products. The upgrade to the system included increasing the number of sensors from 8 to 24 and doubling the number of metallization pads per sensor for a total of 48 channels. In addition, a new fast frontend ASIC [7] using 130-nm technology improves performance with a fast rise time and recovery, especially after large signals, as shown in Figure 5. A new data acquisition system has been developed, the Realtime Histogramming Unit (RHU) [8] which provides deadtimeless full-orbit histograms with a binning of 6.25 ns (4 bins per bunch crossing). This allows hits associated with incoming beam to be separated from those arriving with outgoing beam 12.5 ns later. A microTCA-based fast ADC system is in development to use peak-finding/deconvolution algorithms for even better timing resolution. A VME-based ADC system is currently used for monitoring of efficiency and signal characteristics. Figure 6 shows a typical signal amplitude spectrum with the MIP peak clearly visible, as well as a smaller 2-MIP peak.

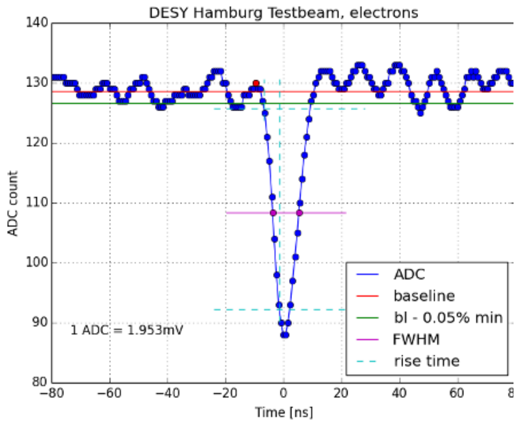

Figure 5: Example of a diamond signal in a test beam, illustrating short rise time of frontend electronics.

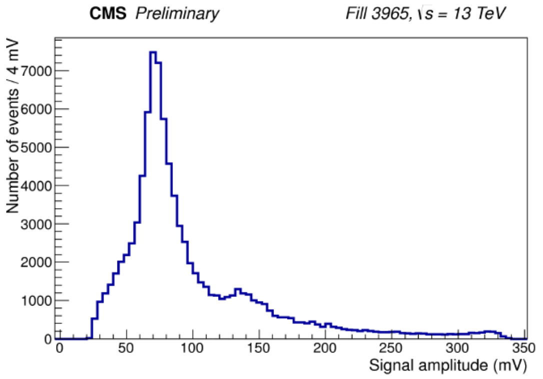

Figure 6: Typical BCM1F signal amplitude spectrum showing MIP peak and 2-MIP peak.

2.6 Integrated BCM/PLT Carriage

A large part of the upgrade campaign centered on a custom, connector-free, semi-rigid integrated PCB to host the wiring of the BCM1L, BCM1F, and PLT detectors. Two distinct designs were needed, "left"-type and "right"-type, to accommodate asymmetries in the detector design. Each PCB fit on a standard 1m x 1m form, but folded out to extend the length of the carbon fiber carriage arm. Figure 7 illustrates the shape and placement of the carriage, PCB, and hosted components, including digital and analog optohybrids and optical connectors.

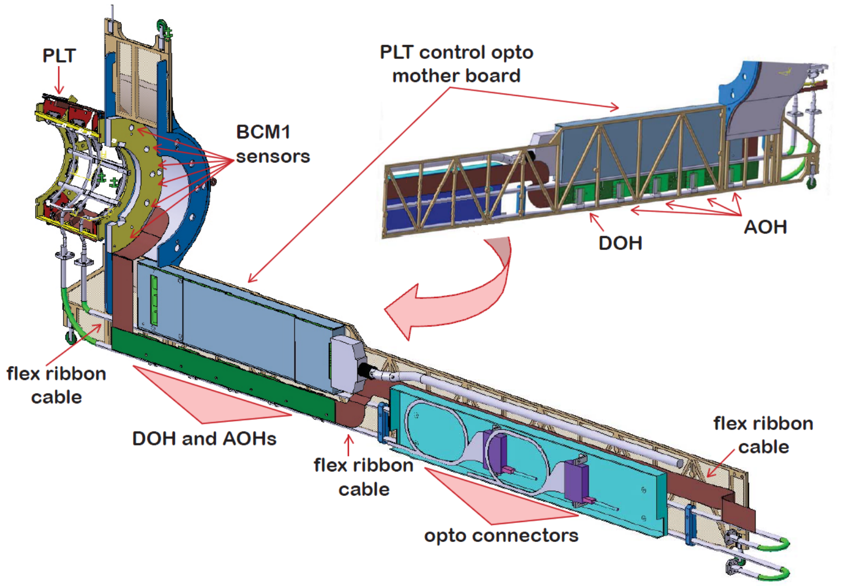

Figure 7: Diagram showing shape and locations of components and custom semi-rigid PCB on carbon fiber carriage.

3. Luminosity Measurement

All three luminometers (HF, PLT, BCM1F) have provided luminosity measurements since the beginning of Run II collisions. All track each other well, as illustrated in Figure 8, and give a per-bunch luminosity measurement, an example of which is shown for a given LHC fill scheme in Figure 9. The data from each luminometer is read out independent of the CMS data acquisition system, and they can therefore provide luminosity information when CMS is not running. At any one time, a single luminometer is chosen to provide the online measurement, although the others are available for backup and cross-check, and data from all three is taken at all times to be used for offline corrections.

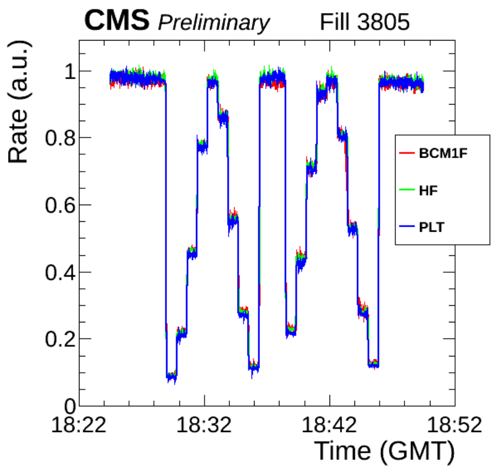

Figure 8: Normalized rate of three luminometers showing good agreement over luminosity range of calibration scan.

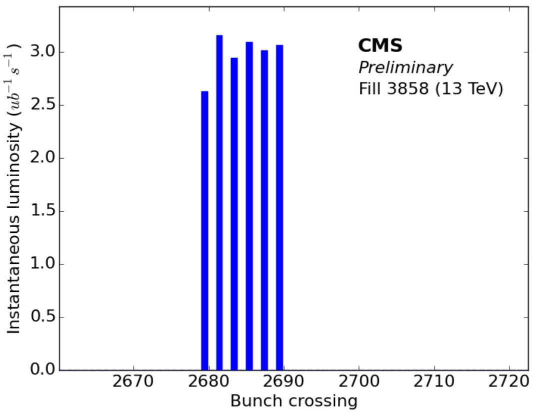

Figure 9: Example of bunch-by-bunch luminosity histogram provided by BCM1F for given LHC fill scheme.

All three luminometers were able to use the very first beam optimization scans for calibration. These scans mimic standard Van der Meer scans [9] for luminosity calibration, and as such they allowed testing of the existing Van der Meer scan analysis workflow as well as provided a preliminary data-driven absolute calibration factor.

4. Conclusion

During the initial stages of LHC Run II, the new and upgraded CMS subsystems for beam monitoring and luminosity have been installed and commissioned and are performing well. The systems include machine-induced background monitoring at high and low radii, as well as multiple luminometers. The background monitors have successfully observed various types of beam loss events. The luminometers have been publishing online luminosity measurements since the start of running, and initial data-driven absolute calibration factors have been derived. These first steps indicate readiness for physics running, and CMS is looking forward to a successful Run II of luminosity and background monitoring.

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