CMS CR -2022/050

The Compact Muon Solenoid Experiment

Conference Report

Mailing address: CMS CERN, CH-1211 GENEVA 23, Switzerland

26 March 2022

High-precision luminosity instrumentation for the CMS detector at the HL-LHC

Georg Auzinger for the CMS Collaboration

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Presented at *VCI2022 16th Vienna Conference on Instrumentation*

High-precision luminosity instrumentation for the CMS detector at the HL-LHC

Georg Auzinger on Behalf of the CMS Experiment[a]

[a]*European Organisation for Nuclear Research, Esplanade des Particules 1, Geneve, 1211, Switzerland*

Abstract

The high-luminosity upgrade of the LHC (HL-LHC) is foreseen to reach an instantaneous luminosity a factor of five to seven times the nominal LHC design value. This creates the need for new high-precision instrumentation at CMS, using radiation-hard detector technologies. This contribution introduces the instrumentation for bunch-by-bunch online luminosity and beam-induced background measurements in CMS. The Tracker Endcap Pixel Detector (TEPX) will be adapted for precision luminometry by implementing a dedicated trigger type and a real-time data processing system performing clustering on FPGA. The innermost ring of the last TEPX layer (D4R1) will be operated independently from the rest of TEPX, enabling beam monitoring during the LHC ramp and during unqualified beam conditions with a dedicated timing and trigger infrastructure. A new stand-alone luminometer, the Fast Beam Condition Monitor (FBCM), which will be fully independent from the central trigger and data acquisition services and able to operate during all times is also introduced. FBCM is foreseen to utilize silicon-pad sensors with with sub-bunch-crossing time resolution enabling also the measurement of beam induced background. The potential of the exploitation of other CMS subsystems such as the outer tracker, the barrel muon detectors and the 40 MHz L1 trigger scouting system using a common histogramming firmware is also discussed.

Keywords: luminosity, real-time data processing

1. Introduction

The high-luminosity upgrade of the LHC (HL-LHC) is designed to reach instantaneous luminosities that are a factor of 5 to 7 times higher than the nominal LHC design values while at the same time increasing the pile-up parameter – the number of proton-proton interactions per bunch-crossing – to a maximum of 200. This is enabled by various upgrades and changes to the beam optics and making luminosity levelling the default mode of operation.

Combined, these changes will render precision luminosity- and beam-induced background measurements extremely difficult but at the same time increasingly important as luminosity uncertainty is already dominant in key physics channels under study with the CMS experiment. As a consequence, CMS and specifically the Beam Radiation Instrumentation & Luminosity (BRIL) Project have defined a target uncertainty of less than 1% for offline luminosity (including all corrections) and less than 2% for online (real-time) values. In order to achieve this very ambitious goal, a series of redundant, independent and complimentary luminosity measurements with orthogonal systematics is required that allows to disentangle and correct for instrumentation- and beam-specific effects.

For the so-called Phase-2 upgrade, CMS has thus adopted a strategy of combining data from existing or upgraded CMS subsystems for luminosity- and beam-induced background measurements with a dedicated instrument designed for ultimate performance and availability. Figure 1 gives an overview of all CMS systems that are planned to contribute to the luminosity measurement, either via a dedicated data path or by means of performing online histogramming in the respective back-end read-out systems via a dedicated firmware module (section 4). The underlying strategy as well as much more detailed technical descriptions of the various systems are summarised in the BRIL Technical Design Report [1]. The following sections will summarise the features and performance of the new systems.

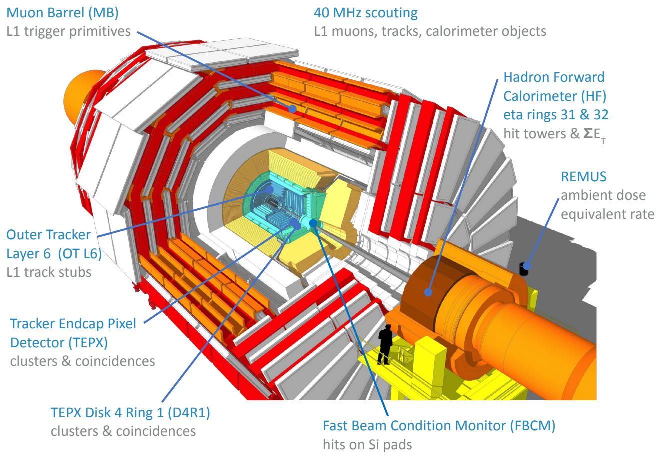

Figure 1: Subsystems for CMS Phase-2 luminosity measurement described in this article.

Preprint submitted to Nuclear Instruments & Methods, Section A *March 26, 2022*

2. Inner Tracker Luminometry

The so-called Pixel Cluster Counting (PCC) method for measuring luminosity has been used successfully in CMS throughout Run 2 – however, in it's current form, it is an offline method that requires re-processing and analysis of stored data. For the Phase-2 upgrade, BRIL will turn this method into a real-time measurement by using the Tracker Endcap Pixel Detector (TEPX). This part of the CMS Inner Tracker (IT) [2] offers more than 800 million individual pixels distributed over an active area of more than 2 m^2, consisting of four disks of five rings of pixel modules at each end of CMS. The innermost ring of the last disk in z, the so-called Disk 4 Ring 1 (D4R1) lies beyond $\eta = 4$ and thus is not strictly needed for tracking in the range of $0 \leq \eta \leq 4$. It will be operated exclusively by the BRIL Project. Figure 2 shows the layout of one quadrant of the CMS Inner Tracker, with the TEPX disks composed of pixel modules of 2×2 read-out ASICs. D4R1 consists of a total of 20 modules per end of CMS and is shown in red.

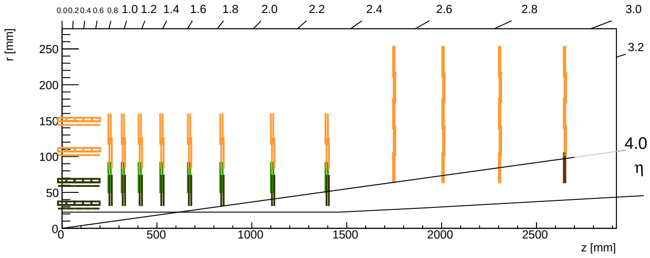

Figure 2: Layout of one quadrant of the CMS Inner Tracker in the $r-z$ plane. The TEPX detector, located at 1700 mm $\leq z \leq$ 2700 mm, consists of four disk of five rings of modules each. The so-called D4R1 under full control of BRIL is shown in red [1].

In order to provide an unbiased, real-time luminosity measurement with parts of the Inner Tracker, a dedicated trigger type is introduced. These so-called luminosity triggers are generated by a dedicated object under full control of BRIL, the so-called BRIL Trigger Board (BTB) and are distributed to the Inner Tracker back-end system via the central Trigger and Clock Distribution System (TCDS2) system [3] along with normal Level-1 triggers. The additional rate budget allocated for these luminosity triggers is 10% of the nominal Phase-2 Level-1 rate of 750 kHz, so 75 kHz. The pixel front end itself is totally agnostic to the trigger type and thus the back end system needs to maintain a record of which bunch crossing was triggered either by the Level-1 system, for luminosity, or both. Once the data corresponding to a trigger is received back from the front end, the back-end will forward the corresponding event fragment either to the data acquisition or to a luminosity processing board via optical link. Figure 3 shows the data flow through the TEPX system.

The luminosity processing boards are based on the same hardware platform as the IT back-end, the so-called Apollo board [4] that offers two Xilinx UltraScale+ FPGAs, a Zynq System-on-Chip as well as high-speed optical links. The board performs real-time geometrical clustering of pixel hits in the event fragments corresponding to a luminosity trigger and the final cluster count is then sent to a dedicated firmware block that will histogram the number of pixel clusters per quarter ring of TEPX as a function of bunch-crossing (BCID) in an LHC orbit, integrated over a period of one second. In simulation, the resulting cluster counts have been found to be highly linear as a function of the pile-up parameter and thus provide an excellent luminosity measurement with a statistical uncertainty of 0.095% per BCID per second [1]. A prototype algorithm has been developed and implemented on the target FPGA family and extensive testing with simulated pixel data has shown a negligible mismatch with respect to the standard CMS High-Level Trigger (HLT) reconstruction algorithm [5]. Resource estimations furthermore indicate that the required number of clustering instances can be placed on the target device with enough resources to spare to improve the algorithm or implement additional features.

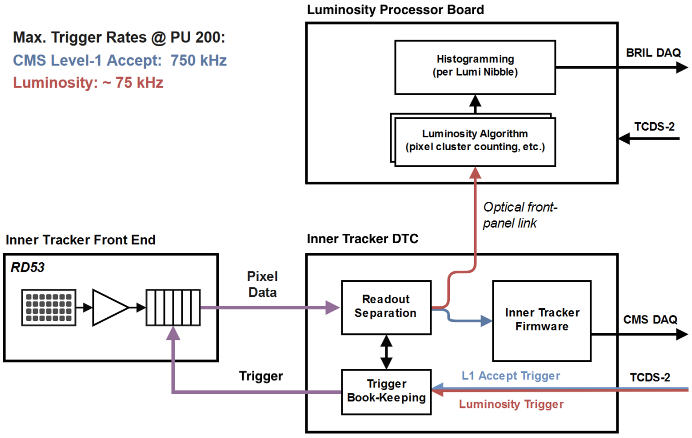

Figure 3: Data flow in the TEPX system. Level-1- and luminosity triggers are distributed by the central TCDS2 system to the TEPX back end where a record of the trigger type is kept. Once an event fragment from the front end is received back, it is forwarded either to the central data acquisition or to a dedicated luminosity processing system via optical links.

In order to fully exploit the benefits of operating D4R1 of TEPX exclusively for luminosity, several further modifications to the system architecture need to be introduced. Contrary to the rest of TEPX that will only be on during qualified beams, BRIL aims to operate D4R1 at all times deemed safe for the detector. However, this requires to clock the system directly on the LHC beam clock rather than the CMS clock as these might not be phase-locked outside of stable beams, in particular during the energy ramp. In order to enable this, the BTB mentioned above has to be introduced as additional node in the D4R1 clock distribution tree. It receives the LHC bunch clock on a dedicated input and performs the tasks of generating a dedicated local TCDS2 control stream in the LHC clock domain but including central synchronisation commands that only the D4R1 front end sees. The transcoding of these synchronisation commands is required so that D4R1 data can be associated with other CMS data at all times [1]. Also, since D4R1 is not used for tracking, the full read-out bandwidth can be devoted to luminosity data - thus a second set of independent luminosity triggers has to be provided for D4R1 by the BTB at a maximum rate of 1 MHz at pileup 200 and possibly up to 4 MHz in low pile-up conditions. Despite the small surface area of D4R1, the high trigger rate yields a statistical uncertainty of 0.1% per BCID per second at a pileup of 200.

3. Fast Beam Condition Monitor

Another key system in the BRIL Phase-2 instrumentation portfolio is a dedicated luminometer designed for the sole purpose of measuring bunch-by-bunch precision luminosity and beam-induced background with sub-bunch-crossing time resolution. This so-called Fast Beam Conditions Monitor (FBCM) is an evolution of the current BCM1F detector [6] operated by BRIL during Run 2 and rebuilt with an improved design for Run 3. FBCM will use up to 336 silicon-pad sensors read-out by 48 asynchronous front-end ASICs with a fast time response (12.5 ns full-width half maximum) and a built-in discriminator. The resulting output is a semi-digital pulse (with well defined logic levels) starting at time-of-arrival (ToA) of a particle and lasting for time-over-threshold (ToT). These signals are then transmitted via low-mass galvanic cables to remote service electronics at the highest possible radius of the mechanical support disk where they are digitized at a rate of up-to 1.28 GHz and transmitted to the back-end via digital optical data links. Similar to the IT, FBCM will be placed in a region of CMS where the radiation environment is at the limit for optoelectronic components as well as for DC-DC converters to survive the full lifespan of the detector, thus the split of the front-end system and the placement of the service electronics at a higher radius.

Since the system is fully asynchronous and not triggered, ToA can be measured with a time resolution of 780 ps which allows to histogram sensor hits with several bins per bunch-crossing and thus enables distinction of beam-induced background from collision products [1]. The measured ToT value can not only be used to monitor the system performance for radiation effects and subsequent signal degradation but also to identify double hits on pads and correct for these in the luminosity calculation.

Compared to other CMS subsystems, the proposed FBCM detector is small but requires active cooling to ensure longevity of the silicon sensors. It is thus located inside the IT volume – where cooling and a dry atmosphere is available – behind the last disk of TEPX. FBCM is designed to entirely use spare IT services [1], specifically two multiservice cables and a 24 fiber bundle per quarter of the system. Figure 4 shows a schematic drawing of a quarter of the FBCM system in the proposed location.

The luminosity measurement with FBCM is based on the zero-counting algorithm (inferring the probability of having zero hits from a Poisson distribution) and extensive system optimisations have been performed in simulations, striking an optimal balance between statistical uncertainty and linearity as a function of the pile-up parameter. These simulations also place some pragmatic assumptions on the specifications of the to-be designed front-end ASIC. In the BRIL Technical Design Report a placement radius of the sensor pads at $r = 14.5$ cm was assumed together with a pad area of $A = 2.89$ mm^{2}and a position of $z = 283.5$ cm yielding a statistical uncertainty of 0.18% per BCID per second [1]. Furthermore, the effects of radiation damage on the system performance have been studied for different HL-LHC scenarios (Figure 5) and indicate that the effects on luminosity performance are minor, even at the end of the system's lifespan.

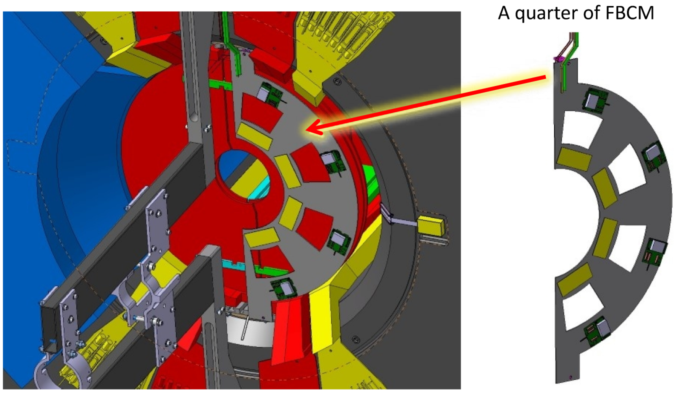

Figure 4: Technical drawing of one FBCM half-disk placed inside the CMS Tracker volume behind the last disk of TEPX. The system is designed to use IT service electronics and spare IT services [1].

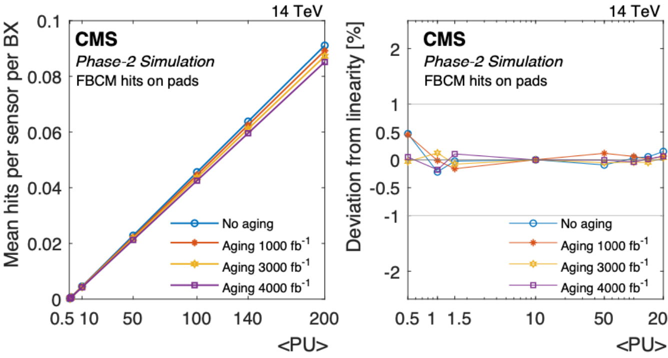

Figure 5: Simulated linearity and deviation from linearity for FBCM corresponding to different aging scenarios. These data assume a placement radius of the sensors of $r = 14.5$ cm and a surface of $A = 2.89$ mm^2 [1].

With the asynchronous read-out system, the sub bunch-crossing time resolution and the fully independent operation, FBCM fills an important role in the BRIL portfolio that can not be performed by any other CMS subsystem. Furthermore it allows BRIL to still provide online luminosity and beam-induced background numbers even in special beam conditions such as during technical stops or during machine development when large parts of the CMS detector are off or when the risk to other systems is deemed too high.

4. Luminometry using other CMS Subsystems

Along with the IT and the FBCM described above, several other CMS subsystems are going to provide data input for the luminosity measurement during the HL-LHC for a maximum number of independently calibrated systems that can be compared in order to separate detector effects from actual changes in luminosity. Specifically, subsystems that provide trigger primitives at the full bunch-crossing rate of 40 MHz lend themselves to this purpose as they allow precision bunch-by-bunch measurements with good statistical performance.

Outer Tracker

The Phase-2 Upgrade of the CMS Outer Tracker [2] is designed to provide trigger primitives for the Level-1 track trigger by correlating hits on two closely spaced silicon sensors (stub, Figure 6) in the front-end electronics at 40 MHz. These stubs are then shipped to the back-end system where they are ordered and forwarded to the Level-1 track finder. By integrating a dedicated and common histogramming firmware block, developed by BRIL and used across all systems contributing to the luminosity measurement into the Outer Tracker back end, these trigger primitives are easily accessible for BRIL. Extensive simulations were performed to estimate the linearity of the stub count rate as a function of the pile-up parameter and it was found that the outermost barrel layer (layer 6) has a very small deviation from linear behaviour. In order to reflect the physical mapping of front-end modules to back-end boards, the 12 modules composing a barrel ladder (equal ϕ) will be grouped in a single histogram. Taking this into account in the simulation, the Outer Tracker stubs yield a statistical uncertainty of 0.029% per BCID per second at a pileup of 200 [1] and thus provide the best statistical precision of any BRIL system, albeit only being available during stable beams.

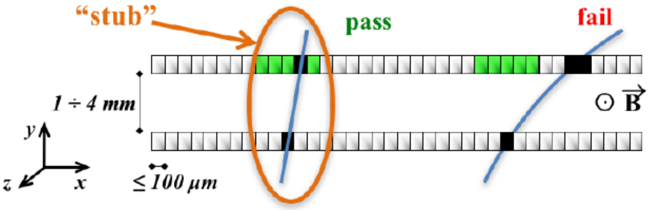

Figure 6: Concept of the Outer Tracker trigger primitives: hits on two closely spaced sensors form a stub if the offset between the two hits is compatible with a track with a transverse momentum of more than 2 GeV.

Muon Barrel Luminosity

During Run 2, the rate of barrel muon track candidates was used to measure orbit-integrated luminosity over extended integration periods and yielded excellent linearity and stability. However, the rate of a per-bunch measurement would be too low for usable statistical precision. In order to improve on this, BRIL has adopted a new data path based on barrel muon trigger primitives that provide higher count rates. Similar to the Outer Tracker, a common histogramming firmware block is deployed in the Phase-2 muon barrel back-end system called On-board Electronics for DT (OBDT) [7] that produces the Level-1 input. The expected statistical precision was derived from linear extrapolation of historic CMS data to high pile-up conditions and is 1.2% per BCID per second for a pileup of 200 [1].

Trigger Scouting

Another systems with interesting prospects for luminosity measurement in Phase-2 is the so-called 40 MHz scouting system [3]. It is designed to directly store either trigger primitives, intermediate products or trigger outputs on a temporary storage at the full 40 MHz rate for rare physics searches that wouldn't otherwise warrant dedicated Level-1 trigger menus or for diagnostic purposes. Having this data available in a single hardware platform (that is used to interface the Level-1 system to storage) rather than the heterogeneous Level-1 trigger system makes it very attractive to integrate the aforementioned common histogramming firmware there and provide luminosity data. Currently muon candidates identified by the Global Muon Trigger as well as intermediate muons from the Barrel Muon Track Finder are foreseen to be histogrammed but many more trigger outputs, like the Level 1 track candidates are possible (Figure 7) and need to be further investigated for the Phase-2 Upgrade.

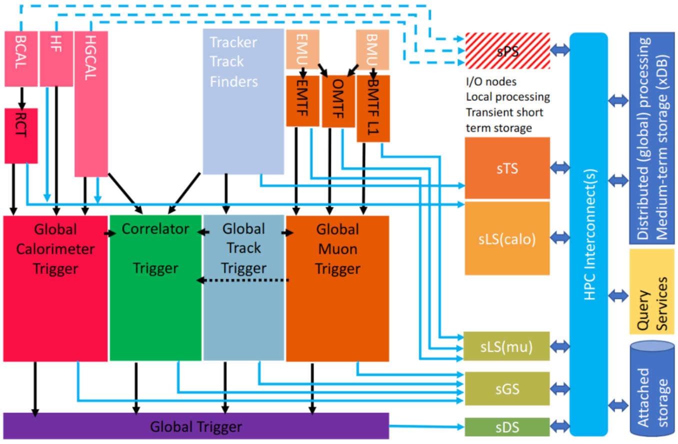

Figure 7: Proposed architecture of the CMS Phase-2 trigger scouting system. Traditional Level-1 trigger data flow is vertical whereas data streams to the scouting interface are indicated in horizontal blue arrows. Outputs from all stages of the CMS Level-1 system are currently foreseen.

5. Summary & Conclusion

For its Phase-2 upgrade, the BRIL Project, responsible for measuring luminosity in CMS, has adopted a multi-pronged strategy of exploiting CMS subsystems with diverse properties and orthogonal systematics for luminosity. In this scheme, BRIL will become a consumer of subsystem data but will also operate a dedicated data processing back end for parts of the Inner Tracker as well as a fully independent, purpose-built luminosity detector, FBCM. Along with the existing and largely unmodified use of the Hadron Forward (HF) calorimeter, these new systems will not only provide excellent statistical uncertainty but together will allow BRIL to approach the ambitious goal of less than 1% luminosity uncertainty.

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