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Upgrade of the CMS luminosity instrumentation and the Fast Beam Condition Monitor for HL-LHC

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The high-luminosity upgrade of the LHC (HL-LHC) brings unprecedented requirements for real-time and precision bunch-by-bunch luminosity measurement and beam-induced background monitoring. A key component of the CMS Beam Radiation Instrumentation and Luminosity (BRIL) system is a stand-alone luminometer, the Fast Beam Condition Monitor (FBCM), which is fully independent of the CMS central timing and control distribution, as well as data acquisition services and able to operate at all times with a triggerless readout. In addition, BRIL exploits measurements from the front-end of various CMS subsystems for luminometry. A brief overview of the BRIL Phase-2 strategy, the instrumentation and approaches to achieve 1% offline precision for luminosity measurements is given.

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1. Introduction

With the proposed upgrade of the LHC to the High-Luminosity Large Hadron Collider (HL-LHC), in the ultimate scenario, the average number of the interactions per bunch crossing or "pileup" will increase up to 200 [1], a factor of 7.5 higher than that of the nominal LHC design. The proposed increase will be achieved with various changes to the accelerator system and beam optics. Luminosity leveling is chosen to be the default mode of the operation.

The drastic increase in pileup leads to higher demands for almost every aspect of the instrumentation. The CMS hardware for Phase-2 must be radiation-hard to be able to collect high quality data corresponsing to at least an integrated luminosity of 4000fb^{-1}, and a rate corresponding to the expected instantaneous luminosity of 7.5×10^{34}cm^{-2}s^{-1}. The expected conditions will also bring unprecedented requirements for luminosity and beam-induced background measurements. While making the precise measurements more challenging themselves, the target luminosity uncertainty defined by CMS and Beam Radiation Instrumentation & Luminosity (BRIL) project should be less than 2% for the real-time values and be better than 1% after final calibration. To achieve this ambitious goal, BRIL targets using independent measurements from multiple detectors with orthogonal systematics.

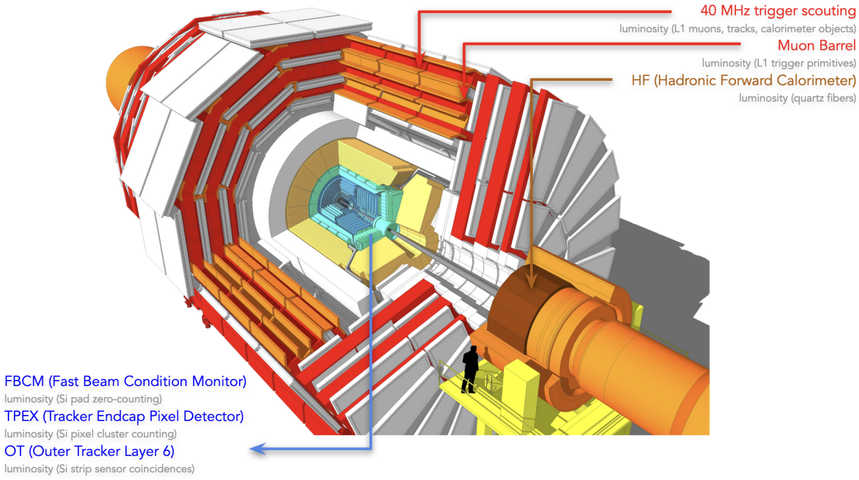

Figure 1: Subsystems for CMS Phase-2 luminosity measurement described in this article.

The BRIL approach is based on the extensive use of data coming from various CMS subsystems for luminosity and beam-induced background measurement [3]. At the heart of the strategy is the Fast Beam Condition Monitor (FBCM), a dedicated Si-pad-based luminometer fully independent from the CMS central trigger and data acquisition services. Complementary to the FBCM, BRIL will also use other CMS systems, including the tracker endcap pixel detector (TEPX), the outer tracker (OT), the muon barrel (MB), the 40 MHz scouting system, and the forward hadron calorimeter (HF) via dedicated data paths. Fig. 1 gives an overview of CMS systems planned for per-bunch luminosity measurement. The underlying strategy and the detailed technical description are summarized in the BRIL Technical Desing Report (TDR) [2]. Here, we provide an overview of the key approaches and subsystems and report on some progress achieved since the TDR.

2. BRIL data acquisition system and histogramming module

Several main factors defined the general data acquisition architecture for luminosity and beam-induced background measurement at CMS. In typical running conditions, the luminosity and background measurements should be provided constantly as a part of CMS feedback to LHC, even outside of stable beams and global CMS runs. Since the LHC orbit is divided evenly to 3564 consecutive bunch-crossings and the typical frequency of luminosity publication is about 1/s, one of the most "natural" ways to aggregate the data is histogramming of the respective observables (e.g., number of pixel clusters, muon trigger objects, or deposited energy in a calorimeter, etc) per bunch crossing integrated over 1 s. That implies that only the relatively small luminosity histograms containing data from events observed up to 40 MHz rate (and even higher for beam-induced background determination that benefits from increased time resolution) need to be read out and processed by a dedicated data acquisition system, BRILDAQ. This system operates independently from the CMS DAQ except for the central Trigger and Clock Distribution System (TCDS2) [4] for most of the detectors. FBCM and D4R1 could operate even without a TCDS2 stream using a special trigger unit called the BRIL Trigger Board (BTB), which will provide a TCDS2-like stream receiving the clock and other LHC signals directly from the machine interface.

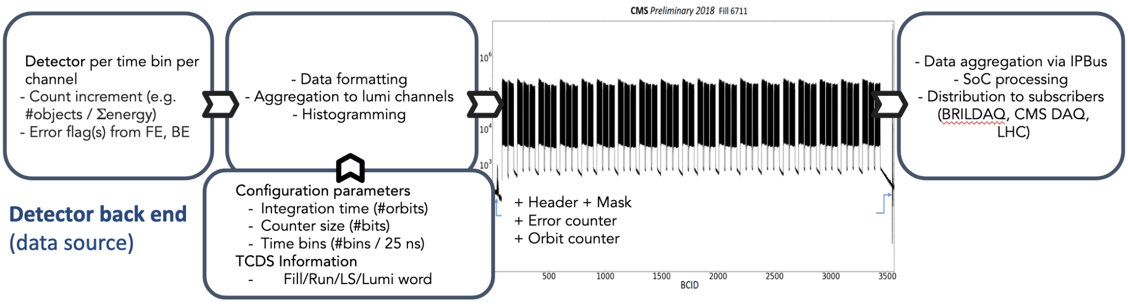

Figure 2: Simplified schematics of the data flow of histogramming module.

In line with the philosophy of maximum commonality, a common histogramming module was developed, which will be integrated to the firmware of the back-end of all subsystems chosen for luminosity measurements. It will be read out via the control network and subsequently injected into the BRILDAQ infrastructure. This approach is very similar to the system implemented for the HF luminosity in Phase 1 [5], proven to provide stable and reliable measurements in various running conditions. Depending on the system, the module may have two acquisition modes: synchronous and asynchronous. In the synchronous mode (which will be used by FBCM, OT, and MB), the data for a given bunch-crossing is expected to arrive from the front-end with a fix latency every clock cycle and could be synchronized with the reference clock. On the contrary, the data may arrive in packages in the asynchronous implementation (TEPX and 40 MHz scouting). Therefore, in the latter case an extra recursive step is required to assign every measurement to the correct bunch-crossing. The generic design of the module remains unchanged across different subsystems; however, it includes extra data preprocessing modules and filters before assigning a count to the histogram. The histograms will be acquired from a Field Programmable Gate Array (FPGA) using the IPbus protocol [6]. For most of the systems the control software infrastructure will run directly on Advanced Telecommunications Computing Architecture (ATCA) hardware based on Xilinx UltraScale or UltraScale+ FPGAs with integrated system-on-chips (SoC) processors.

3. Fast Beam Condition Monitor

FBCM, designed by BRIL, is one of the key systems in the Phase-2 instrumentation portfolio, and is foreseen to be a primary online luminosity and beam-induced background monitor with sub-bunch-crossing time resolution. FBCM is designed to be fully independent from the CMS central TCDS (timing and control distribution system) and DAQ (data acquisition) services and able to operate at all times with a triggerless readout. With this approach, the detector will be able to operate even in special operation modes, e.g., during machine development, when large parts of the CMS detector might be off to protect sensitive hardware from unstable beam conditions.

FBCM uses a modular design with two half-disks of twelve modules at each end of CMS, with 4 service modules placed close to the half-disk outer edge at a radius of reduced radiation fluence (Fig. 3). FBCM utilizes 48 custom front-end ASICs to amplify the signals from 288 CO_2-cooled silicon-pad sensors with a few nanoseconds timing resolution that allows the measurement of the beam-induced background. The electronics system design adapts several components from the CMS Tracker for power, control and read-out functionalities integrated into the service board. The dedicated FBCM ASIC contains 6 channels with ENC (equivalent noise charge) below 1000 e^- and adjustable shaping time to optimize the noise with regard to the sensor leakage current. Each channel outputs a single binary high-speed asynchronous signal carrying the Time-of-Arrival and Time-over-Threshold information. The chip output signal is digitized at a rate of up to 1.28 GHz and then transmitted via a radiation-hard gigabit transceiver and an optical link to the back-end electronics. The luminosity measurement will be based on the zero-counting algorithm [3] (inferring the probability of having zero hits from a Poisson distribution).

The first prototype of the ASIC arrived to CERN after the conference in September 2023 and is undergoing an irradiation and testing campaign. The final choice of the Si-sensors will be made after a test beam scheduled for spring 2024.

4. Tracker Luminosity

In Phase-1, pixel cluster counting (PCC) was proven to be one of the main sources of luminosity determination; however, it was only available offline. One of the most challenging tasks of Phase-2 BRIL upgrade is to provide real-time measurements from the Tracker Endcap Pixel Detector (TEPX) and Outer Tracker (OT) (Fig. 4, left).

TEPX will provide more than 800 million individual pixels over more than 2 m^2 of silicon, with an expected statistical uncertainty of just 0.095% per BCID per second [2]. The innermost ring of the last disk, so-called Disk 4 Ring 1 (D4R1), is beyond the pseudorapidity of 4 and will not be used for tracking. Instead, D4R1 will be operated by the BRIL project.

To provide real-time luminosity measurement with TEPX, dedicated triggers will be required. A dedicated unit BTB will supply the luminosity triggers and distribute via TCDS2 on top of the nominal Phase-2 Level-1 rate of 750 kHz. The rate of dedicated luminosity triggers considering the expected link occupancy is about 75 kHz (or 10% of the full trigger rate). The pixel hits will

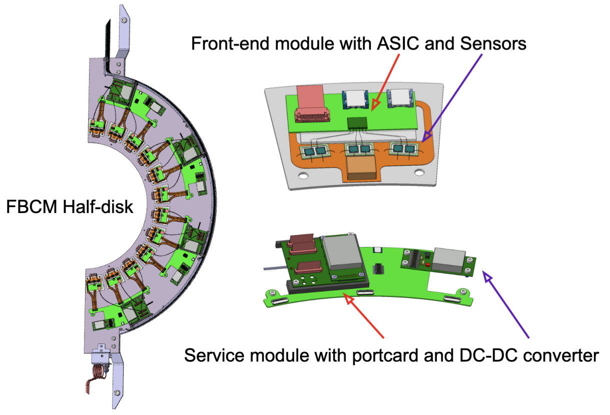

Figure 3: Technical drawing of an FBCM half-disk, a front-end and a service module. Each front-end module is equipped with six CO_2-cooled silicon-pad and one custom read-out ASIC. Each service module consists of one DC-DC converter and an Inner Tracker portcard with an i2c interface.

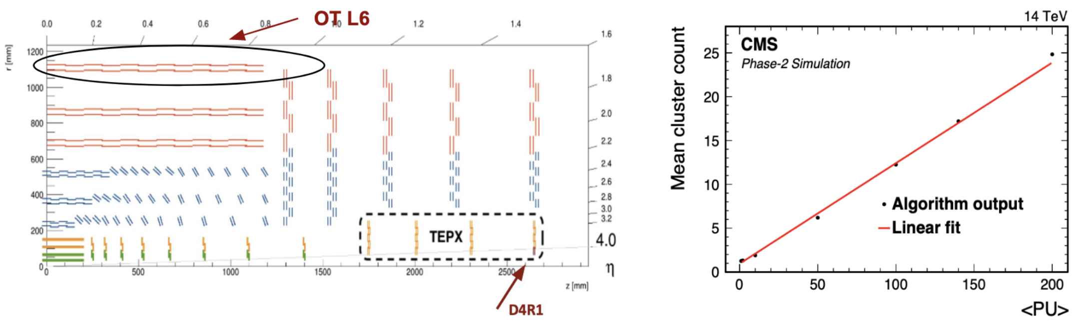

Figure 4: Left: Layout of a CMS tracker quadrant in the r - z plane. The TEPX detector, located at 1700 mm $\leq |z| \leq$ 2700 mm, consists of four disks of five rings of modules each. OT layer 6 will be used for synchronous histogramming of track stubs at a full 40 MHz rate. Right: Mean per-event cluster count at different pileup conditions for D4R1 of TEPX.

be clustered online in FPGA and sent to a histogramming unit on the "lumiblade" (implemented in an ATCA board called Apollo [7]). The clustering algorithm was tested on the target FPGA family using simulated data and compared to the standard CMS High-Level Trigger (HLT) reconstruction algorithm up to a pileup of 200 (Fig. 4, right).

OT luminosity will be based on counting trigger primitives for the Level-1 track trigger, the so-called stubs at the full collision rate of 40 MHz. These will be histogrammed in the OT back end. A statistical uncertainty of 0.029‰ per BCID per second yields the best statistical precision of any BRIL system; however, the operation of OT is limited only to stable beams. The histogramming unit with synchronous implementation was tested with OT test bench using the OT-μDTC board [9] (data, trigger and control board using the uTCA platform). The next step is the migration of the firmware to the OT DTC (using the ATCA Serenity board [10]) and continue the validation with the final read out of the OT 2S (strip-on-strip) modules.

5. Luminometry with other CMS subsystems

In addition to the tracker and standalone FBCM, BRIL will rely on the data coming from the front-end modules of various subsystems, which will provide trigger primitives at the full bunch-crossing rate of 40 MHz, histogrammed on a bunch-by-bunch basis. The chosen primitives are expected to be linear with pileup and in most cases statistically powerful enough to allow independent calibration in vdM conditions. Comparing multiple independently calibrated systems, one may reveal hidden systematics, thus differentiating the detector effects from the actual changes in luminosity to achieve the precision goal for HL-LHC.

In Run2, the rates of the barrel muon track stubs were successfully used for cross-detector stability studies. While demonstrating great linearity and stability, the statistics were too low for per-bunch measurement and limited to orbit-integrated data aggregated over extended integration periods of one lumisection ($\tilde{2}$3 s). In Phase-2, BRIL will adopt a new data path to use muon barrel (MB) trigger primitives, which yields significantly higher rates. Along with intensive simulations, a histogramming firmware module was deployed to the back-end of the DT system based on the TM7 board for the first Phase-2 MB slice test [8]. The preliminary results obtained in one of the physics fills in Run3 have proved the validity of the approach, allowing access to per-bunch crossing data and providing sufficient time resolution for the emittance scan (hence calibration of the detector). In the next steps, the complete integration of the MB demonstrator to BRILDAQ is foreseen to study the system's performance over extended data-taking periods. Meanwhile, the implementation of the histogramming module to the final Phase-2 DT back-end electronics are scheduled for 2024.

Another promising system for luminosity measurement is the 40 MHz Scouting System [11], designed to store various L1-trigger outputs at full 40 MHz rate for rare physics searches, L1 commissioning and etc. The BRIL histogramming firmware was integrated to L1 hardware and DAQ, and the first samples of Run-3 data were already recorded. Currently, two trigger primitives are selected for histogramming, namely muons from the Barrel Muon Track Finder and muon candidates identified by the Global Muon Trigger. However, with the generalized and flexible approach, other trigger objects could be considered, e.g., Level-1 track candidates or clusters from the Global Calorimeter trigger as a part of the Phase-2 Upgrade.

Finally, BRIL will continue to use a forward Hadron Calorimeter, proven to be one of the most reliable sources for both online and offline luminosity. The HF uses two methods: HFOC is based on "zero counting", which tracks the fraction of bunch crossings with no energy depositions above a threshold in the HF trigger towers, and the "HF transverse energy" method (HFET), which relies on the measured transverse energy sum. For the Phase-2 Upgrade BRIL will implement the generic histogramming module to the final ATCA back-end of HF once it is available.

6. Conclusions

The BRIL Project, responsible for measuring luminosity in CMS, will exploit multiple CMS detectors with orthogonal systematics for its Phase-2 upgrade. A fully independent detector FBCM will provide luminosity and beam-induced background measurements with sub-bunch crossing time resolution in various running conditions, including special fills dedicated to machine development with unstable beam conditions. Complementary to FBCM, BRIL will utilize dedicated data paths

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for measurements using the tracker and muon systems. This will be achieved by implementating a generic histogramming unit into the back end of the detectors. Along with the forward hadron calorimeter that will get a back end upgrade, these new systems will not only provide excellent statistical uncertainty but combined will allow BRIL to approach the ambitious goal of less than 1% luminosity uncertainty.

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