The CMS Beam Halo Monitor electronics

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ABSTRACT: The CMS Beam Halo Monitor has been successfully installed in the CMS cavern in LHC Long Shutdown 1 for measuring the machine induced background for LHC Run II. The system is based on 40 detector units composed of synthetic quartz Cherenkov radiators coupled to fast photomultiplier tubes (PMTs). The readout electronics chain uses many components developed for the Phase 1 upgrade to the CMS Hadronic Calorimeter electronics, with dedicated firmware and readout adapted to the beam monitoring requirements. The PMT signal is digitized by a charge integrating ASIC (QIE10), providing both the signal rise time, with few nanosecond resolution, and the charge integrated over one bunch crossing. The backend electronics uses microTCA technology and receives data via a high-speed 5 Gbps asynchronous link. It records histograms with sub-bunch crossing timing resolution and is read out via IPbus using the newly designed CMS data acquisition for non-event based data. The data is processed in real time and published to CMS and the LHC, providing online feedback on the beam quality. A dedicated calibration monitoring system has been designed to generate short triggered pulses of light to monitor the efficiency of the system. The electronics has been in operation since the first LHC beams of Run II and has served as the first demonstration of the new QIE10, Microsemi Igloo2 FPGA and high-speed 5 Gbps link with LHC data.

KEYWORDS: Front-end electronics for detector readout; Cherenkov and transition radiation; Beamline instrumentation (beam position and profile monitors; beam-intensity monitors; bunch length monitors)

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1 The Beam Halo Monitor

1.1 Motivation

In the second run of the LHC, the machine will eventually operate at its designed 25 ns bunch spacing, aiming at a luminosity of $2 \times 10^{34}$, twice as much as was foreseen in the initial design. The higher beam intensity implies tighter settings of the collimator systems and an increased susceptibility to electron cloud effects contributing to a higher potential rate of Machine Induced Background (MIB) for the CMS experiment.

The Beam Radiation Instrumentation and Luminosity (BRIL) project has been created in CMS, among other reasons, to build and operate detectors that monitor the beam conditions. These have the dual purpose of protecting the sensitive inner detectors of CMS from beam loss events and detecting when the MIB reaches levels that would interfere with data taking efficiency (see figure 1a). The upgraded BCM1F detector [1] is designed to have sensitivity at a low radius (4.5 cm) where it will be possible to detect beam gas interactions happening in the vicinity of CMS. The Beam Halo Monitor (BHM), located at a higher radius (180 cm) as shown in figure 1b, will be sensitive towards beam gas interactions happening upstream of CMS as well as beam halo interactions with the upstream collimators.

1.2 Detector

The BHM has to be able to detect and correctly identify MIB particles in the context of an intense particle flux, dominated by products of high energy $pp$ collisions. Detection and identification are based on techniques that exploit differences between MIB and other particles, combined into a single instrument:

- The beam halo is composed mostly of muons, while a significant fraction of the $pp$-collision products is composed of neutral particles.
The beam halo and the $pp$-collision products travel in opposite directions.

At several locations along the beampipe, the beam halo and the $pp$-collision products arrive with maximal time separation between each other (12.5 ns).

A Cherenkov based detector can make use of all these characteristics, thanks to the Cherenkov radiation being emitted promptly and in a particular direction with respect to the particle trajectory.

Each BHM detector unit is composed of synthetic quartz cylinders, 100 mm long and 52 mm in diameter, acting as Cherenkov radiators. These are directly coupled to fast, UV-sensitive photomultiplier tubes (PMTs). Particles traveling in the quartz towards the PMT (from right to left in figure 2a) emit Cherenkov light that reaches the photocathode. Particles traveling in the opposite direction also emit light, but this is instead absorbed by a layer of black paint applied to the free face of the quartz. These elements are enclosed in three layers of shielding (figure 2b) to protect the Hamamatsu R2059 PMT from the residual magnetic field of the CMS solenoid and to absorb the large flux of low energy particles present in the cavern. The materials used in the detector have been qualified for the expected radiation dose up to and including the High Luminosity LHC phase (100 krad for 3000 $fb^{-1}$).

The complete detector has twenty units on each end of CMS, mounted around the rotating shielding as shown in figure 1b, and pointed towards the incoming beam. The large analog signal produced by the PMT, which is operated at a gain of $10^7$, is brought to the readout electronics (described in the next section) located in the service cavern via triaxial cables, over a length of about 80 m. The PMT power supply and the calibration system (described in section 3) are also located in the service cavern and connected to each unit with long cables and fibers, respectively. A more complete description of the BHM detector can be found in [2].
2 Readout electronics

The readout chain of this detector uses many components developed for the Phase 1 upgrade to the CMS Hadron Forward (HF) calorimeter electronics [3], with a dedicated firmware and readout adapted to the beam monitoring requirements. These components are split into a fully custom, radiation hard Front-End and a $\mu$TCA-based Back-End, connected by optical links. An overview of the system is shown in figure 3. Minimal modifications are required for use in BHM, such as the capacity to operate during beam ramp (during which the system clock is varying) and the capability to generate and store per-channel occupancy histograms in the readout board. The use in BHM precedes the complete installation of the HF upgrade, and therefore this system makes use of pre-production models of some of the boards.

2.1 Front-end

The Front-End electronics is based on the Charge Intergator and Encoder, version 10 (QIE10) ASIC, developed at Fermilab [4]. This device includes a multi range charge integrating ADC, with 6 bits of mantissa and 2 for range, as well as a 6 bit TDC with 500 ps resolution. This ASIC is hosted on the Readout Module, shown in figure 4, which features:

1. 24 analog readout channels equipped with QIE10 chips.

2. Two Microsemi IGLOO2 FPGAs. These are responsible for distributing individually phase-adjusted clocks to each QIE, formatting the digitized data into a frame for and serializing it for transmission.

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Figure 3. An overview of the whole readout electronics.
3. Optical data links to the Back-End, implemented with the Versatile Twin Transmitter (VTTx) [5], operated at 5.0 Gbps.

4. A Microsemi ProASIC 3L Bridge FPGA for slow control and monitoring

Instead of the common synchronous technique, where the optical link is driven at a multiple of the system (LHC) clock, the IGLOO2 firmware is programmed to use a slightly faster clock, generated by a free running oscillator, and insert padding words when needed, which are then removed from the data stream at the destination. This has the advantage of simplifying board design by eliminating the need for a radiation tolerant clock cleaner and multiplier.

The Readout Module is housed in a 6U crate with a custom backplane. The backplane signals, which include system clock, reset, slow control (via I2C) and in-system programming of the FPGAs (via JTAG), are driven by a next generation Clock Control and Monitoring (ngCCM) card which acts as the crate controller. This card is in turn completely controlled by a bidirectional optical link with the Front-End electronics.

2.2 Back-end

The Back-End is based on a commercial Micro Telecommunications Computing Architecture (µTCA) crate and MicroTCA Carrier Hub (MCH). Both readout and slow control use a single Gigabit Ethernet link with the IPbus protocol, which is routed to every card by the MCH. Following the standard CMS setup, an AMC13 [6] card is used to decode Trigger, Control and Distribution System (TCDS) commands, distributing the global clock to the other boards.

A CERN GLIB [7] card is configured as next generation Front End Controller (ngFEC) and controls the Front-End ngCCM via a 4.8 Gbps optical link.
Figure 6. Block Diagram of the main functions of the μHTR BHM firmware.

The HCAL μTCA Trigger and Readout Module (μHTR) [8], equipped with two Virtex6 FPGAs and 24 optical link receivers, handles the data links from the Front-End. The firmware loaded on these FPGAs, represented schematically in figure 6, is the most important difference from the baseline HCAL implementation. The Front FPGA receives and decodes the serial data stream, which includes the raw ADC and TDC data for every channel. The ADC value is compared against a programmable threshold; if it exceeds the threshold, the corresponding TDC value is assigned to one of four bins in which a bunch crossing is divided. This information is passed to the Back FPGA, where it is used to produce occupancy histograms.

The occupancy histograms provide a separate count rate per LHC bunch crossing, with a further subdivision for in-time and out-of-time particles. The histograms integrate and are subsequently read out every $2^{14}$ LHC orbits (about 1.5 s), with no dead time thanks to triple buffering of their memory.

Amplitude histograms are also generated in the Front FPGA; they provide charge spectra from the PMTs and are used for monitoring and calibration studies.

2.3 Data acquisition

Both occupancy and amplitude histograms are read out by an application based on the XDAQ framework [9]. This application is not part of the normal CMS event based data acquisition system. Instead, it is part of the BRIL specific data acquisition framework, designed for collecting luminosity and background data. An algorithm processes individual channel data (such as shown in figure 7) to produce a single background rate per beam every LumiSection (about 23 s). Occupancy bins containing MIB counts are summed after correcting for the small pp contribution. The result is then made available to CMS and the LHC.

3 Calibration system

A calibration and monitoring system has been installed in BHM, to evaluate the performance variations in the PMTs and the Cherenkov radiators due to aging and radiation damage. The system uses a light signal produced by UV emitting pulsed LEDs and driven to each detector unit through quartz optical fibers and passive optical splitters, composed of a fiber bundle coupled with a mirror (figure 8).
Figure 7. An example of occupancy histogram showing the bunch trains in an LHC fill. The MIB counts are concentrated in bin 1, while the other bins contain collision products.

Figure 8. An overview of the calibration system.

The light is injected on the front of the quartz bar, and the resulting PMT signal is compared with that of a reference Silicon Photomultiplier (SiPM) that receives the same light signal from the splitter mirror. The LED pulser circuit is housed on a mezzanine card mounted on the QIE Front-End card, while the reference SiPMs are read out by QIE input channels. Each LED feeds ten detector units through one splitter, requiring a total of four sources for the whole system.
Summary

A new Cherenkov-based MIB monitoring system has been installed during LS1. Twenty channels per end, each composed of a Cherenkov radiator coupled to a PMT, are azimuthally distributed around the CMS rotating shielding. The readout electronics, based on a custom Front-End and a uTCA Back-End, measures both signal amplitude and arrival time, discriminating MIB from other particles.

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