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The CMS Fast Beams Condition Monitor Backend Electronics based on MicroTCA technology

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Abstract

The Fast Beams Condition Monitor (BCM1F), upgraded for LHC Run II, is one sub-system of the Beam Radiation Instrumentation and Luminosity Project of the CMS experiment. It is based on 24 single crystal CVD diamond sensors. Each sensor is metallised with two pads, being read out by a dedicated fast frontend chip produced in 130 nm CMOS technology. Signals for real time monitoring are processed by custom-made back-end electronics to measure separately rates corresponding to LHC collision products, machine induced background and residual activation exploiting different arrival times. The system is built in MicroTCA technology and uses high speed analog-to-digital converters. The data processing module designed for the FPGA allows a distinguishing of collision and machine induced background, both synchronous to the LHC clock, from the residual activation products. In operational modes of high rates, consecutive events, spaced in time by less than 12.5 ns, may partially overlap. Hence, novel signal processing techniques are deployed to resolve overlapping peaks. The high accuracy qualification of the signals is crucial to determine the luminosity and the machine induced background rates for the CMS experiment and the LHC. The architecture of the backend electronics and the signal processing techniques will be presented and its performance thus far using data taken in LHC Run II.

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The CMS Fast Beams Condition Monitor Back-end Electronics based on MicroTCA technology

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Abstract– The Fast Beams Condition Monitor (BCM1F), upgraded for LHC Run II, is used to measure the online luminosity and machine induced background for the CMS experiment. The detector consists of 24 single-crystal CVD diamond sensors that are read out with a custom fast front-end chip fabricated in 130 nm CMOS technology. Since the signals from the sensors are used for real time monitoring of the LHC conditions they are processed by dedicated back-end electronics to measure separately rates corresponding to LHC collision products, machine induced background and residual activation exploiting different arrival times. The system is built in MicroTCA technology and uses high speed analog-to-digital converters. The data processing module designed for the FPGA allows a distinguishing of collision and machine induced background, that are both synchronous to the LHC clock, from the residual activation products, based on arrival time measurements. In operational modes at high rates, consecutive events, spaced in time by less than 12.5 ns, result in signal pileup. Hence, novel signal processing techniques are deployed to resolve overlapping peaks. The high accuracy qualification of the signals is crucial to determine the luminosity and the machine induced background rates for the CMS experiment and the LHC. The architecture of the back-end electronics and the signal processing techniques will be presented and its performance thus far using data taken in LHC Run II.

I. INTRODUCTION

In collider experiments there are two sources of a radiation. The first one are particle collisions. A measure of amount of the particle interaction products is so called luminosity [1]. The second source is Machine Induced Background (MIB) that consist of the particles entering a detector region with the beam. There are several systems [2] in the CMS experiment at CERN measuring the luminosity and MIB at various locations of the experiment. The positions of the detectors were chosen in order to provide the best separation of the particles of a different origin. These systems operate continuously as simple state machines. They are together maintained in a Beam Radiation Instrumentation and Luminosity (BRIL) project. One of the systems is called Fast Beam Conditions Monitor (BCM1F) that is dedicated to measure the beam quality and luminosity in the inner tracker region.

II. STRUCTURE OF THE BCM1F DETECTOR

The front-end modules of the BCM1F detector consist of 24 single crystalline CVD diamond sensors on two parallel planes positioned at the distance of $z = \pm 1.83$ m away from the interaction point (IP), mounted radially at $r = 7.2$ cm from the

beam line. Each 5 mm x 5 mm x 500 μm diamond has a two pad metallization with 25 μm separation. The picture of a BCM1F diamond is presented in Fig. 1. The distance between the sensors and the IP is optimal for the separation of incoming and outgoing particles and corresponds to the time-of-flight of 6.25 ns for relativistic particles. As a sensor, diamond has almost five times wider band gap than silicon [3] and as a consequence it has a lower response to the ionizing particle hit but also it has a very low dark current even in the strongly irradiated areas. For this reason no cooling is required for the diamond detectors. In the BCM1F installation area where space is very limited, this feature becomes advantageous. Another advantage of the diamond sensors is a high response speed due to the high charge carrier mobility in the diamond structure. Hence the diamond sensors can be used for particle arrival time measurement. The metalized diamonds are mounted close to to the front-end electronics (FEE). The front-end ASIC [4] was designed exclusively for the BCM1F and comprises a fast transimpedance preamplifier with active feedback, shaper stage and high-performance output buffer working as single ended-to-differential converter. In response to a charge particle hit, the ASIC generates pulses with a constant peaking time of about 7 ns and full-width-half-maximum (FWHM) of about 9 ns. The structure is linear in a wide range of input charges up to 9 fC in the BCM1F detector that is three times more than a Minimum Ionizing Particle charge. The linearity plot of the ASIC is presented in Fig. 2. The diamonds and the FEE are mounted on complex flex-rigid PCBs Fig. 3. These PCBs are held by a carbon-fiber carriage which is inserted in the pixel service tube. Each of four PCBs has a part dedicated to the analogue signals transmission to the back-end electronics.

Fig. 1 a) Two single crystal CVD diamonds with 10 μm split electrode mask are mounted to the b) dedicated four channel front-end ASIC comprising of a fast transimpedance preamplifier with active feedback, shaper stage, and high-performance output buffer

Fig. 2 Linearity of the front-end fast transimpedance preamplifier. The circuit has a good linearity for the input charges below 6 to 9 fC depending on the bias current. The charge gain varies between 33.1 to 75.9 mV/fC depending on a configuration [4].

Fig. 3 a) Diamond sensors and the front-end electronics are mounted on complex flex-rigid PCBs in two parallel planes perpendicular to the beam line. b) These PCBs are held by a carbon-fiber carriage which is inserted into the pixel service tube.

III. CLASSIFICATION OF THE PARTICLE HITS

The BCM1F system classifies particle hits using its arrival time information. The measurement is done with an LHC Orbit period and 0.8 ns resolution in time. First particles are registered 6.25 ns before the collision. They originate from the MIB. The collisions happen at the Interaction Point (IP) and 6.25 ns later the proton-proton interaction products are registered together with the MIB of the outgoing bunches. Together they constitute a maximum in a timing histogram, but only the collision products are considered as a delivered luminosity. An amount of the MIB particles can be estimated using the value measured before the collision. After the collision, some amount of the residual activation products remain in the detector region and hit the detector randomly in time. This can decrease the accuracy of the luminosity measurement. The future expectations for the LHC are an increasing luminosity up to $10^{34} \text{cm}^{-2} \text{s}^{-1}$ that will increase the BCM1F sensor occupancy to 25%. The increasing number of the activation products can significantly influence on the accuracy of the luminosity measurement. The challenge for the BCM1F is to detect and separate unwanted products from the MIB and collision products.

IV. DETECTOR READOUT AND DATA TRANSMISSION

Most of the particles hitting the sensors have an energy of a Minimum Ionizing Particle (MIP). An example collection of the detector response to the particles of different energies is presented in Fig. 4. Signals from the sensors feed the inputs of the front-end electronics. The output response is transmitted to the back-end electronics [5] using the analog-opto-hybrid modules with 3 lasers installed on each [6], single mode optical fibers and four 12-channel optical receivers [6]. In the time periods when the probability of a particle hit in the detector is very low, the upgraded VME based BCM1F back-end electronics [7] generate triggering pulses that are transmitted to the detector where they trigger the front-end ASIC. The signals feed the second input of the structure that is connected to the same electronics circuit as the detector input. The stimulation corresponds to the MIP particle signal from the sensors. The response is measured by the back-end electronics and used for measuring the gain of the front-end electronics as well as the radiation damage of the detector.

Fig. 4 A collection of single channel detector response to the particles hits of different energies measured by the BMC1F MicroTCA back-end electronics. An amplitude of the Minimum Ionising Particle in the given channel is around 37 ADC counts (72 mV measured at the analog-to-digital converter input). Most of the particle hits locates around this amplitude.

V. BACK-END ELECTRONICS MEASUREMENTS

The new back-end electronics was developed in order to provide a high performance system that will operate dead time free with a better timing resolution than the upgraded VME based BCM1F back-end electronics. The system is also aimed to resolve the overlapping pulses problem that is caused by the particles hitting the detector with a very small time interval. The BCM1F is operating continuously regardless of the LHC beam presence. The elements used in the system were developed or supported by the CMS community. The system provides the high sampling frequency and enough resources for the signal processing as following.

An amplitude monitor of the gain is developed to histogram the amplitude spectrum of the incoming particles that corresponds to the energy loss distribution of relativistic charged particles traversing the sensors. The histogram

generated is presented in Fig. 5. The amplitude histogram is filled during 2^{14} LHC orbits. This frequency corresponds to the data publication capabilities in CMS for non-event data. The amplitude range is 0 - 500 mV with 8 bit resolution. The maximum of the spectrum indicates the most probable amplitude of the detector response to a MIP particle.

Fig. 5 An example amplitude spectrum of the particles registered by the BCM1F MicroTCA back-end electronics using a simple peak finding algorithm. The measured values correspond to the front-end electronics response to a particle hit. The measurement resolution is 256 bins in a 0-500 mV range. The bins were merged in groups of 3 due to the low statistics collected in the first runs.

A timing histogram represents the distribution of the hits in time that corresponds to the structure of the LHC fill. An example of the timing histogram collected by the Real Histogramming Unit of the VME system is presented in Fig. 6. The time resolution of the histogram is 6.25 ns. That gives 4 bins every 25 ns bunch crossing. The time resolution of the new system is almost 8 times better. The module is being tested, the results are not yet available for public. The new histogram is filled during 2^{14} LHC orbits with a time period of 1 orbit that is 89.1 μ s.

Fig. 6 A Real Time Histogramming Unit (RHU) of the upgraded VME based BCM1F back-end electronics collects the timing histograms with a 0 to 1 LHC orbit range and a 6.25 ns resolution in time. For 25 ns bunch crossings (BX) there are 4 bins/BX. The integration time is 4096 orbits.

The last block provides RAW data collected during 1 orbit of the 2^{14} LHC orbit period. The data is collected without a zero suppression. The 89.1 μ s of samples are stored every 2^{14} LHC orbits. This data is collected in order to provide a reference for the histograms and for the calibration pulse shape analysis.

VI. BACK-END ELECTRONICS ARCHITECTURE

In order to provide the described storage and processing possibilities, the following architecture based on the MicroTCA technology [8] was developed.

The analog signal is transmitted to the back-end electronics where is digitized using 8-bit analog-to-digital converters of FMC125 boards operating at a 1.25 GS/s rate. The FMC125 mezzanines are commercial products developed by the 4DSP company [9] and customized for the project requirements. The modules are synchronized with a LHC clock that is provided to the mezzanines through the front panel. The samples are transmitted through the FMC connectors to the XILINX Virtex-6 FPGAs of the AMC carriers. The CMS GLIB AMC carriers are used. Each board has a high-pin-count FMC connector mounted that is necessary for using 4 channels of the FMC125 mezzanine at a full sampling rate. 12 GLIB boards are mounted in 2 MicroTCA crates. The system control and communication is being operated by NAT MicroTCA Hub modules (MCH) [10]. A communication protocol for the system is IPbus [11], an IP based protocol that is developed by a UK collaboration for controlling CMS trigger and readout. The system is presented in Fig. 7. The system uses 2 MicroTCA crates. The timing information and control commands are received by AMC13XG [12] modules from the Trigger, Control and Distribution System (TCDS) [13] for the CMS. The signals are transmitted through the backplanes to all GLIB modules where they are decoded and used for synchronization with the CMS commands. The processing FPGA uses this information for synchronization and classifying the incoming data.

The additional GLIB modules are allocated to another BRIL system, the BPTX detector. The BPTX uses two standard LHC beam position monitors (BPM) each comprising of four electrostatic button electrodes positioned symmetrically around the beam-pipe. Comparison of timings from opposite beam position monitors gives the highly accurate measurements of the longitudinal interaction point and bunch timing relative to the CMS clock. The FMC mezzanines are configured in a 1-channel working mode with the maximum of 5 Gs/s of the sampling rate.

The last important element of the system is the readout monitoring. For this purpose the GLIB board is used with a custom FMC mezzanine EDA-02707-V1 mounted. The mezzanine hosts eight SFP optical modules operating at up to 800Mbit/s each. The module provides signals for control and configuration of the Linear Laser Drivers (LLD) of the AOHs and DOH being the part of the front-end. The lasers operate in a high radiation field, so the parameters will change with

accumulated radiation dose and the bias and gain corrections will be needed.

Fig. 7 The MicroTCA BCM1F back-end electronics register the signals from 48 channels of the detector synchronically to the LHC clock and using LHC orbit clock as a trigger. There are 12 AMC (CMS GLIB) carriers installed in 2 MicroTCA crates used by the BCM1F readout. Additional GLIB board is used for the front-end electronics control and 2 others for the other BRIL system usage.

VII. PULSE DETECTION AND MEASUREMENT

The majority of the signals registered in the system are the single pulses. In the first step of the processing they need to be detected and noise peaks must be rejected. Data from the ADCs is transmitted to the FPGA in pairs of 8 bit samples with half of the sampling frequency $f_s/2$. The deserializing block parallelize the data into groups of eight samples. The processing module receives the groups and store it into a FIFO-like buffer of 24 positions. With a frequency of $f_s/8$ the new group of eight samples comes into the buffer and the oldest group leave it. The baseline level is measured and the dynamic threshold over the baseline level is set. The samples are masked. The samples over the threshold level are given the mask value of 1 and the samples below the threshold the mask value of 0 as presented in Fig. 8. The logic conditions are checked. If the pulse arrives, the first samples over the threshold are visible in the buffer 0 position, than they are shifted to the older positions. For the BCM1F generated pulse AND condition of the group 0 is true, OR condition of group 1 is true and OR condition of group 2 is always false. An example is presented in Table I. The oldest samples are in the group 2. All the samples are below the threshold. Both logical conditions are false. There is no pulse in this group. In the group 1 some samples are below the threshold, but some of them exceed the threshold and get the mask value 1. The AND condition is still false, but the OR condition is true. That indicates that we may have registered a pulse. Samples in the youngest group 0 contains only positive samples so the mask is all ones. The AND and OR conditions are true. This indicates that the signal registered is a pulse of a proper length. This

operation is performed in parallel so that the result is available 3 clock cycles after the pulse reach the processing block.

Fig. 8 Mask setting for the pulse. The threshold is set dynamically over the baseline level. Samples below the threshold are masked in order to check the logical conditions for a digitized signal.

TABLE I. LOGICAL CONDITIONS FOR THE SAMPLED PULSE

	MASK	AND	OR	COMMENT
GROUP 2	0000 0000	0	0	NO SAMPLES > VTH
GROUP 1	0011 1111	0	1	SOME SAMPLES > VTH
GROUP 0	1111 1111	1	1	ALL SAMPLES > VTH

The front-end ASIC generates the pulses of the same peaking time independent of amplitude. For a proper dynamic threshold setting, the rising edge of the pulse consist of the equal number of samples for the amplitudes in the linear range of the front-end electronics operation. An example of the MIP and 2 MIP pulses sampled with 1.25 GS/s frequency is presented in Fig. 9. The processing block performs the peaking time measurement. The accuracy of this measurement depends on the local baseline measurement and the threshold setting. Each detector channel must be characterized separately. The amplitude and shape of the 1 MIP pulse depends on the diamonds characteristics, front-end electronics routing as well as the laser characteristics. A mean value from several calibration pulses for each channel is counted and updated on-line then used as a model signal.

Fig. 9 A 1MIP and a high amplitude particle response of the detector digitized by the MicroTCA back-end electronics with a sampling period is 08. ns and an 8-bit amplitude resolution.

VIII. OVERLAPPING PULSES

With increasing luminosity, particles can hit the detector with a very small time interval. That can cause producing

overlapping pulses by the front-end electronics. The multiple pulses can be caused both by the collision products and residual activation products. The latter can arrive in a random time, however, majority of them is registered directly after the collision. This can influence the accuracy of the luminosity measurement. For this reason the overlapping pulses have to be resolved and a different method must be provided. An example of the overlapping pulses measured on the output of the test board with a front-end ASIC mounted is presented in Fig. 10. The input was stimulated using two voltage steps corresponding to the sensor response of a MIP particle hits with a time interval of 12.5 ns. The response was measured on the ASIC output and on the output of the optical receiver the same as used in the experiment. Double pulses can be resolved in both cases. 1 MIP height pulses can be considered as distinguishable up to 10 ns of the time interval.

Fig. 10 Two 1MIP hits triggered with a time interval of 12.5 ns were provided to the front-end electronics circuit. The red signal was measured directly on the ASIC output and the blue one on output of the optical receiver.

IX. MULTIPLE PULSES RESOLVING METHOD

The method was simulated using single pulses measured in the experiment. The pulses were extracted from the raw data registered during early CMS runs in 2015. The baseline level was removed and the overlapping pulses were generated. The method was tested using the pulses triggered with a time interval of 12.8 ns and 10.4 ns. It was required to meet several conditions as following: to be implementable in FPGA, applicable for pulses of different amplitudes as well as for multiple overlapping pulses, operate without introducing dead time. It is proved that the system is linear for a wide range of the input charges. Higher charges can occur but are relatively rare and have a very low influence on the accuracy of the luminosity measurement. The front-end electronics response is constant in time for different input charges. The short recovery time allows measuring hits arriving with a time interval of 12.5 ns with a shape of the single pulse preserved for both pulses. These features allows proposing a fast, light method that is presented in Fig. 11 for 12.8 ns time interval and in Fig. 12 for 10.4 ns time interval.

The first waveform presents two overlapping pulses with different time intervals as already mentioned. In a first step the pulse detection is performed. If the signal over threshold is classified as a detector generated pulse, the single pulse

amplitude measurement is performed using the previously described method.

Fig. 11 Two 1 MIP pulses overlapping with a 12.8 ns time interval. In the left-hand side waveform the pulses are plotted in blue, and the fit to the model signal is plotted in red dotted. The horizontal dotted line is the threshold level, and the vertical line indicates the position of the maximum. In the right-hand side waveform the result of removing the first signal is plotted in black.

Fig. 12 Two 1 MIP pulses overlapping with a 10.4 ns time interval. In the left-hand side waveform the pulses are plotted in blue, and the fit to the model signal is plotted in red dotted. The horizontal dotted line is the threshold level, and the vertical line indicates the position of the maximum. In the right-hand side waveform the result of removing the first signal is plotted in black.

As a result the position and amplitude of the first pulse is known even if the pulse is not clearly visible. In the second step, the reference signal is collected from memory. For simulation purpose the polynomial fit to the MIP pulse was used. In the FPGA implementation the model signal is being generated using collection of the configuration pulses. The reference signal amplitude corresponds to the amplitude measured in the previous step. The signal is positioned using the time shift as measured before. In the next step the reference signal is subtracted from the overlapped signal. The result plotted in black is treated as an input to the second instance of the same processing block. If the second pulse appeared it will be detected by the pulse classifying module.

Fig. 13 Two overlapping pulses of 1 MIP and 0.5 MIP amplitudes with a time interval of 12.8 ns

Fig. 14 Three overlapping pulses of amplitudes 1 MIP, 0.7 MIP and 1.3 MIP and the time intervals of 12.8 and 5.6 ns.

This method can be successfully used to resolve pulses of different amplitudes as presented in Fig. 13. The blue dotted waveform are 2 overlapping pulses of the amplitudes of 1 MIP and 0.5 MIP with a time interval of 12.8 ns. The black waveform is the signal emerged from the overlapped pulses. For multiple overlapping pulses the module the same processing block can be used sequentially. The number of instantiations depends on how many pulses need to be resolved. In the system the expected probability of registering 2 overlapping during a single bunch crossing pulses is 6% whereas probability of registering 3 overlapping pulses is about 1.5%, so 3 levels of processing are considered. In Fig. 14 three overlapping pulses of the amplitudes 1 MIP, 0.7 MIP and 1.3 MIP are presented. The second pulse appeared after 12.8 ns and third one 5.6 ns after the second pulse. The result of the processing is plotted in black. The method can be implemented in FPGA, however it requires using a proper model of each channel. During the operation characteristics of the channels will change slightly due to the high radiation field. For this reason the models will be adapted on-line. The current implementation is using result of the off-line processing so it needs to be updated.

X. SUMMARY

The increased performance of the LHC with a collision energy of up to 14 TeV, higher luminosity and 25 ns bunch spacing will increase the importance of real-time monitoring at high rates. The beam monitoring systems of the CMS have been upgraded for optimal performance for LHC Run II. The BCM1F system is designed to monitor the flux of particles originating from the proton-proton interactions and machine induced background (MIB).

The previous BCM1F system operated successfully in a high radiation field during Run I and was the basis for the design of a new system. A new front-end consist of 24 single crystalline CVD diamond sensors mounted on two parallel planes positioned at the distance of $z = \pm 1.83$ m away from the interaction point (IP), mounted radially at $r = 7.2$ cm from the beam line. Each 5 mm x 5 mm x 500 μ m diamond has a two pad metallization with 25 μ m pitch that will decrease the hit probability of a single channel. The distance between the sensors and the IP is optimal for the separation of incoming and outgoing particles and corresponds to the time-of-flight of

6.25 ns for relativistic particles. For Run II the instantaneous luminosity is foreseen to increase in excess of 10^{34} cm⁻²s⁻¹, corresponding to the BCM1F sensor occupancy of about 25%.

The sensors are connected to a dedicated front-end chip comprising of a fast transimpedance preamplifier with active feedback, shaper stage and high-performance output buffer. The signals are transmitted to the counting room through the optical path including radiation hard Analog Opto Hybrids and four 12-channels optical receivers. Differences in distance between two sides of the detector to the back-end electronics as well as between the BCM1F and Beam Pick-up Timing for Experiments (BPTX) detectors that are also brought to the back-end electronics are compensated by the fibers length.

The back-end electronics is realized in MicroTCA technology. Analog signals coming from the detectors are digitized with 1.25 GS/s and 5 GS/s sampling rate using custom modified commercial FMC-HPC analog-to-digital converter board. Processing platform is Virtex-6 (Xilinx) of the CMS designed AMC carrier. The acquisition is synchronized with the RF generated 40.08 MHz LHC clock and triggered by the LHC orbit clock. The CMS timing information is provided by the Trigger, Control and Distribution System (TCDS). The TCDS signals are distributed through the backplane using a dedicated timing module.

Data processing is realized in real time on FPGA. Data channels are grouped in pairs for studying systematics relating to charge sharing between two channels for the same diamond. Each FPGA covers processing of 4 channels. The majority of processing power is focused on measuring the arrival time and amplitude of the incoming signals. The data processing module allows for distinguishing of collision and machine induced background, both synchronous to the LHC clock, from the residual activation products. A challenge for the data processing module is the identification of multiple hits of the particles in a single diamond, combined with a short recovery time of the front-end ASIC. The samples are registered with the time resolution of 0.8 ns with jitter of the order ps while the peaking time of the pulse is about 9 ns for given capacitance of the detector and response of the full front-end readout chain. The time and amplitude measurement method combines the fast time counters and mathematical operations using a unique model signal generated using configuration pules for each channel. Results are presented in amplitude and timing histograms.

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