Fast Beam Conditions Monitoring (BCM1F) for CMS

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Abstract

The CMS Beam Conditions and Radiation Monitoring System (BRM) [1] is composed of different subsystems that perform monitoring of, as well as providing the CMS detector protection from, adverse beam conditions inside and around the CMS experiment.

This paper presents the Fast Beam Conditions Monitoring subsystem (BCM1F), which is designed for fast flux monitoring based on bunch-by-bunch measurements of both beam halo and collision product contributions from the LHC beam. The BCM1F is located inside the CMS pixel detector volume close to the beam-pipe and provides real-time information. The detector uses sCVD (single-crystal Chemical Vapor Deposition) diamond sensors [2] and radiation hard front-end electronics, along with an analog optical readout of the signals.

I. Introduction

The CMS experiment sits in an unprecedentedly high radiation field and much effort has gone into the design and construction of systems with very high radiation tolerance. The LHC is designed to run with 362MJ of stored energy in one beam and with proton intensities in excess of 10^{14} per beam. Even very small fractional losses of this beam can cause serious damage to detector elements.

Whilst the LHC itself has extensive instrumentation designed for machine protection, CMS requirements dictate that CMS must be able to detect beam-related problems as they develop and to assert beam aborts if required. In addition, CMS must be able to log data and perform post-mortem analyses of accidents to understand the accumulated dosage and potential longer term damage to the detector elements. To this end, CMS has implemented within the BRM project, 6 independent and complimentary systems designed to either initiate LHC beam aborts and/or CMS equipment control, or provide fast beam/detector optimisations and diagnostics. Given the nominal LHC collision frequency of 40MHz, the CMS protection mechanisms must be sensitive to very fast changes in beam conditions; the BRM systems have been implemented so to detect changes at the 25ns level, though the initially deployed protection systems will react within times of order 3-40µs.

The BCM1F is one of the faster monitoring systems of the CMS BRM, and is designed to provide real-time fast diagnosis of beam conditions with readout able to resolve the sub-bunch structure.

II. System Overview

The BCM1F uses sensor and electronics that are fast enough to match beam abort scenarios, and small enough to be inserted into areas close to key detector components without adding substantial material or services.

The system is based of four sCVD diamonds, each $5\times5\times0.5mm^3$, positioned on either side of the IP at Z values of ±1.8m close to the beam pipe and the pixel detectors at a radius of 4.5cm (Figure 1).

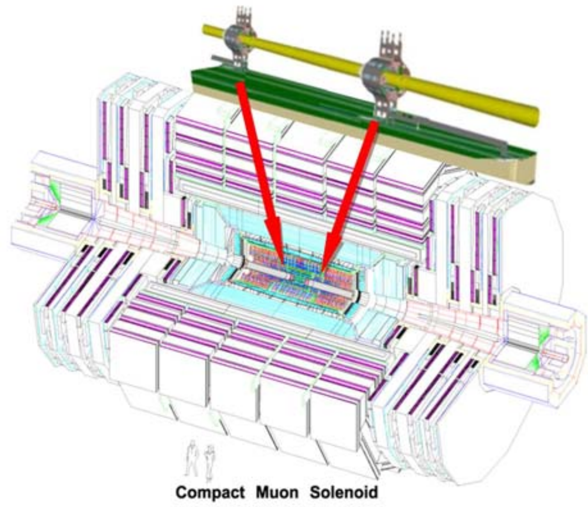

Figure 1: BCM1F locations

The BCM1F diamonds are arranged on the X and Y axes. The purpose of the BCM1F is, as a diagnostic tool, to be able to flag problematic beam conditions resulting in “bursts” of beam loss over very short periods of time. Such beam losses are expected to be one of the critical damage scenarios for the CMS detector systems [3]. The location for the BCM1F is close to the optimal position in terms of timing separation between ingoing and outgoing particles from the IP (i.e. 6,25ns from the IP). The gated rate information from the BCM1F should therefore give a very good handle on the comparative rate of background from beam halo to that from luminosity products.

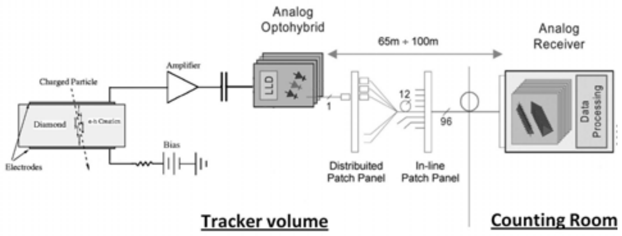

Figure 2: BCM1F readout sketch

The sensor is connected to the JK16 radiation hard amplifier [4], after which the signal is transmitted to the counting room (Figure 2) over an analog optical link built from the CMS tracker optical components [5]. The back end readout produces rate, multiplicity, timing and coincidence information independently of the CMS DAQ. However, there is the possibility to feed information into the event stream via a standard CMS SLINK [6].

A. sCVD Diamond Sensors

A number of outstanding properties like its low leakage current and fast charge collection time, fast signal and low capacitance contributing to high SNR, in addition to their physical dimensions and radiation hardiness, make the CVD diamonds most competitive for the locations close to the interaction region than any other type of detector. The sensor concept and layout is similar to the silicon detectors: two metallization pads, deposited on the opposite surfaces of the crystal, are used to apply the electric field and to collect ionization currents when charged particles pass through. Further, there is no need for any cooling of the diamonds since there is no reverse annealing damage effect as seen in silicon-based detectors.

The majority of actual developments [7,8] are based on polycrystalline CVD samples, but recent improvement in the quality and size of single crystals in conjunction with its superior electrical properties (table 1), determine the choice of the sensor for the CMS detector.

Table 1: pCVD and sCVD diamond electrical properties

PROPERTY	Polycrystalline CVD diamond	Single crystal CVD diamond
Hole mobility (cm^2/Vs)	1,000	3,800
Electron mobility (cm^2/Vs)	1,800	4,500
Carrier lifetime (ns)	~1-10	~2,000
Voltage breakdown (MV/cm)	~0.5	~4
Charge collection distance (µm)	~250 at 1V/um field	Thickness limited

The sensors were manufactured by Element Six (now Diamond Detectors) [9] after a few years of research and development in collaboration with the RD42 [10] project.

B. Front-end Electronics

In addition to the radiation hardness, the detector locations have constrained the front-end layout, readout, monitoring, powering and test facilities.

1) Amplifer:

BCM1F amplifier (JK16) is the FE part of an ASIC [4] developed for readout of silicon strip detectors. The chip is fabricated in a commercial 0.25µm CMOS technology hardened by layout techniques [11].

Each of the 16 channels (Figure 3) comprises a fast transimpedance preamplifier working with an active feedback loop and an amplifier-integrator stage providing 20 ns peaking time.

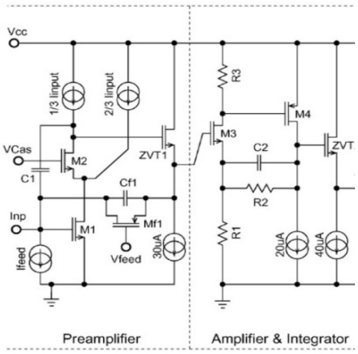

Figure 3: Schematic diagram of one JK16 channel

The circuit has a 4pF input capacitance and a 60mV/fC charge gain. Despite the active feedback loop, excellent noise performance is achieved by proper choice of the feedback current. For a 5pF detector capacitance, measured noise is about 700e^- equivalent noise charge (ENC).

2) Optical Readout:

As mentioned above, the tracker analog optical chain is used to deliver detector signals to the S1 counting room (Figure 2). The JK16 single ended output is AC coupled to the custom-designed laser driver ASIC (LLD) [12], which modulates the edge-emitting laser diode drive current. Single fibers from the pigtailed lasers are connected at the periphery of the CMS Silicon Strip Tracker via single-way connectors to a fan-in, which merges single fibers into a 12-fiber ribbon. There is a second break-point within the CMS detector where the transition to a rugged multi-ribbon cable (8x12-fiber ribbons/cable) is made via 12-channel array connectors. In the

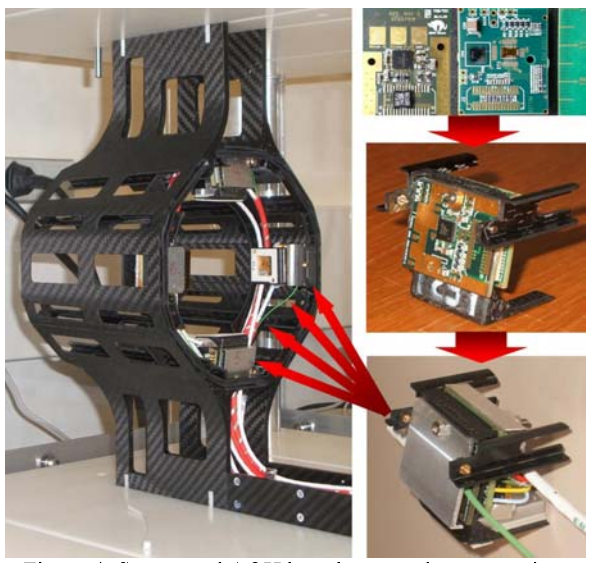
Figure 4: Sensor and AOH boards on carriage mounting

counting room each ribbon connects directly to a 12-channel analog optical receiver NGK.

Due to the frontend envelope limits $25\times29\times15mm^3$, the piggy-back architecture was employed to interconnect, supply and mount the assembly (Figure 4) of the sensor-amplifier and the analog optical hybrid (AOH) on the carriage L-shape. Minor modifications were done to the AOH board to allow opposite mounting orientation of the laser diode imposed by the minimum bending radius of the pigtail fibers. Unlike the Tracker configuration the AOH gains and laser diode bias cannot be programmed via an I^2C interface. Hence, a lot of attention was paid to choose the input polarity and laser bias setting to preserve the dynamic range of the receiver side as well as taking into account heat and radiation impacts on the AOH performance.

C. Patch Panels and Back-end Electronics

Two sets of patch panels were implemented. In the counting room, a 4U chassis houses the PPS1 patch panels which combine and filter high and low voltage, as well as the test pulse facility in one multi-service 8 twisted pair copper cable. On the tracker bulkhead, the PP0 patch panel is used to re-arrange power supplies lines, decouple and regenerate the test-pulse input for each detector.

The CMS tracker 12-channel analog opto-receiver module is used for the BCM1F. Then, signals are fan-out to trigger, time and waveform digitizers.

A general purpose multi-hit TDC with 20-bit resolution and 0.8ns LSB is used to measure the time intervals from different sensors, as well as between ingoing beam particles and outgoing interaction products.

In addition, the BCM1F outputs are sampled at 500MHz by 8-bit resolution flash ADC. The module can be triggered externally or locally if any of digitized inputs exceeds programmable threshold. Upon triggering, the detector data, which is continuously written in a circular memory buffer, freezes the event location for further readout via VME or optical link. Each channel has 2 MSamples memory depth, thus it can capture up to 45 consecutive orbits in continuous sampling mode.

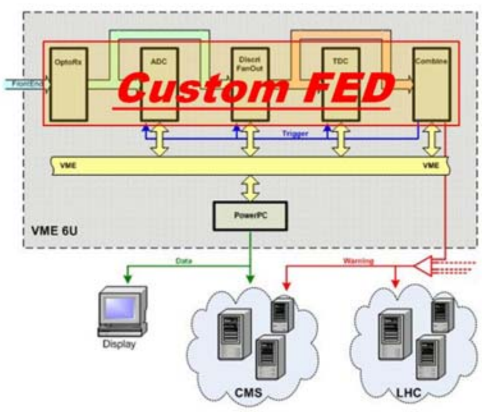

Figure 5: BCM1F backend sketch

A custom Front End Driver (FED) module is under development (Figure 5). The module has 16 acquisition channels delivered via two 12-ways optical receivers and/or 16 differential electrical inputs. The data are digitized at 80MHz by a 10-bit ADC and processed by applying algorithms for pedestal and common mode noise subtraction. The module can generate internal and/or external triggers based on coincidence logic with any of the digitized inputs. The TTC-Rx ASIC provides synchronization with the experiment timing and the data is transmitted to the CMS data acquisition system via the S-LINK64 [6] transmitter mezzanine card at a maximum rate of 400 MB/sec.

III. Detector Test Results

The assembled front-end modules were tested with Sr90 source. Figure 6 shows measured pedestals and pulse height distributions collected at different bias voltages. The pedestal distributions (centred on 0V) are uniform and with good signal to noise separation. At a field of 0.23V/µm field (110V bias for 480µm thickness) the sensor reaches the maximum signal, providing signal-to-noise ratio of 26.

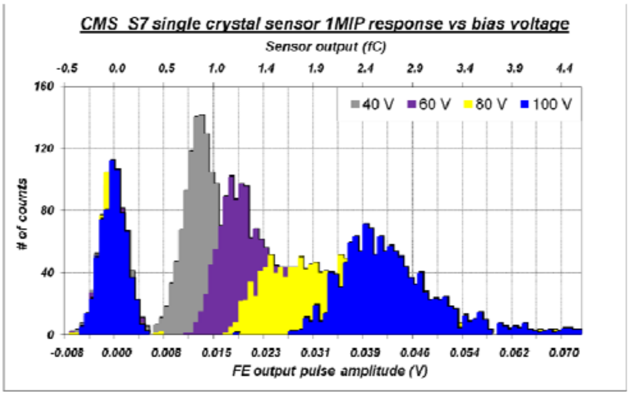

Figure 6: BCM1F module pedestals and pulse height distributions

Figure 7 presents the observed leakage current, the mean and most probable values of the collected charge per MIP as a function of bias voltage. On this plot, the leakage current is dominated by the test setup and passive components on the front-end board.

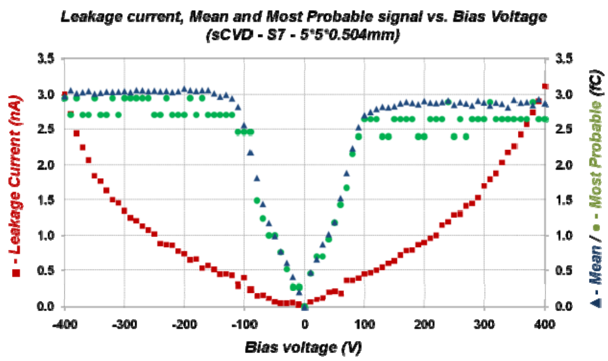

Figure 7: sCVD-S7 MIP response versus bias voltage

IV. Radiation Tolerance Studies

The radiation hardness of single crystal sensors has been evaluated at PSI-Villigen facility and CERN in 2007. Two sCVD (S1 and S2) were exposed to a 60MeV proton beam with an integrated fluence of about 3×10^{14} p/cm^2. The crystal dimensions and radiation doses are listed in Table 2.

Table 2: sCVD dimension and fluence

Sensor sCVD	Thickness	Size	Radiation dose @60MeV	MIP equiv. radiation dose
S1	480μm	4×4 mm^2	3×10^{14} p/cm^2	17.5×10^{14}MIP/cm^2
S2	488μm	4×4 mm^2	3×10^{14} p/cm^2	17.5×10^{14}MIP/cm^2
S7	465μm	5×5 mm^2	none	none

The irradiated samples performance was measured and compared with similar non-irradiated sCVD crystal and the test results are presented in Figure 8. Important signal losses, as well as, some decrease in noise were observed. The 1MIP response has decreased by roughly 80% and signal to noise efficiency degraded from 26 to 7 at a much higher electric field in the crystal.

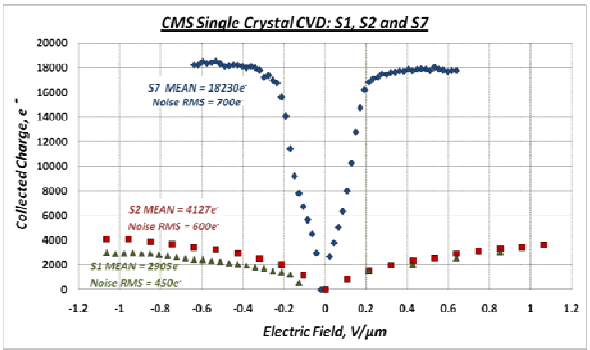

Figure 8: Irradiated and non-irradiated samples MIP response

Previous studies of the CVD diamond radiation hardness [13,14] have been done at 24GeV and 26MeV proton beams. The results presented here tend to support the hypothesis of enhanced damage to particle of low energies.

V. Installation and First LHC Beam Hits

The BCM1F assemblies were successfully installed at the beginning of August 2008 (Figure 9), and all 8 modules were

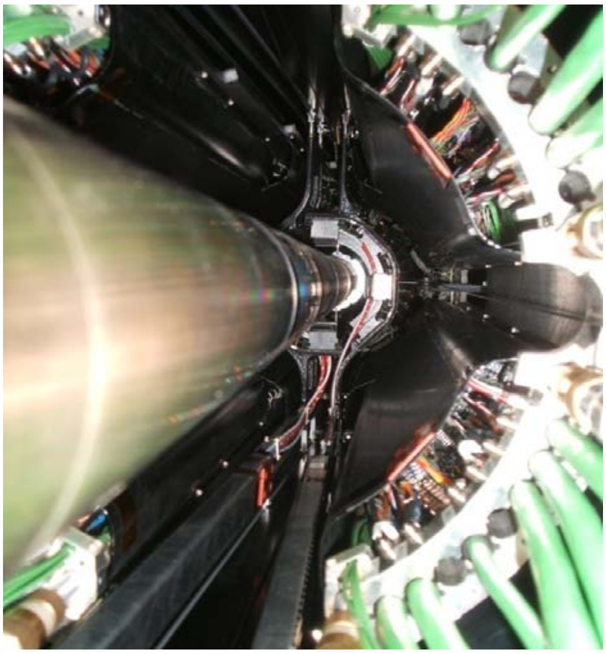
Figure 9: View of the installed BCM1F carriage in the pixel volume surrounded by the pixel services

fully tested and characterised prior to installation in CMS and were fully functional after installation.

Several hundred hits were collected from the very first particles which have been circulated in the CERN LHC on September 10, 2008.

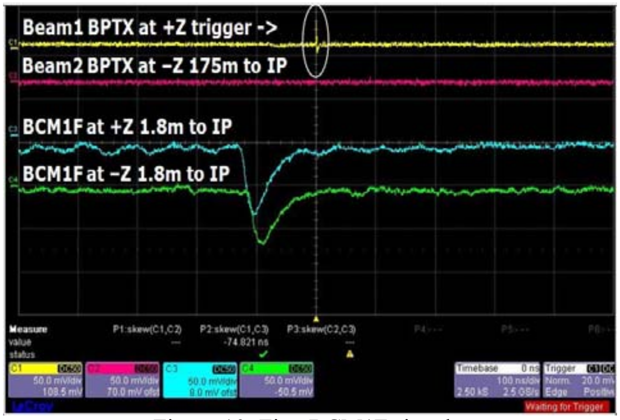

Figure 10: First BCM1F signals

The oscilloscope screenshot (Figure 10) shows the analog sum of 4 BCM1F outputs from either side of the IP, where the trigger was from the beam pickup electrode installed 175m upstream of the IP. The sensor output amplitude corresponds to a 1 MIP response and the time difference between the pulses is consistent with the particle time of flight from left to right side detectors.

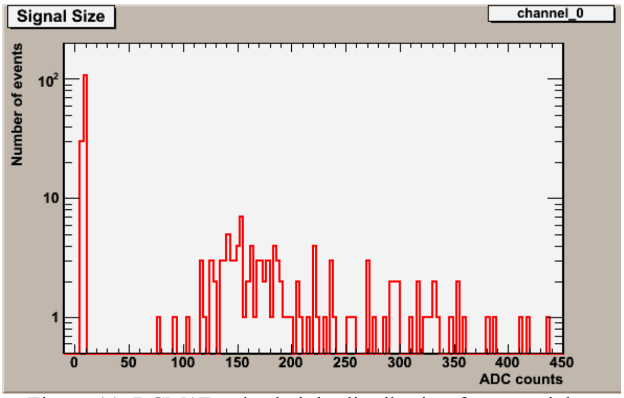

Figure 11: BCM1F pulse height distribution from particles generated by LHC beam losses

Figure 11 shows the signal height distribution from one of the BCM1F sensors. One can mention very good signal-noise separation in spite of low hit number, as well as the rough distribution shape.

VI. Conclusion

A general overview of the sCVD diamond based fast beam condition monitor was presented. All parts of the system were successfully installed in their final positions and exhaustively tested through implemented facilities. The detectors and associated readout chain demonstrated excellent performance in real working conditions at CMS during very first days of the LHC operation.

VII. REFERENCES

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