Beam & Radiation Monitoring for CMS

Alan. J. Bell, CERN, Geneva. On Behalf Of The CMS Beam & Radiation Monitoring Group.

***Abstract*–The Compact Muon Solenoid (CMS) is one of the two large, general purpose experiments situated on the LHC at CERN. Designed to analyze a broad range of momenta and positions of particles created from the √s = 14TeV collisions of protons, CMS requires millions of channels of data coming from a wide variety of detector substances. As with all high energy physics (HEP) experiments knowledge of the beam conditions and luminosity is of vital importance. Accurate monitoring of the beam profile and its temporal behavior helps to protect the experiment by responding to losses in beam control. Additionally, constant monitoring of the radiation inside and around the CMS experiment will aid in predicting the radiation effects of reduced lifetime sustained by the electronic instrumentation within the CMS cavern.**

The Beam Radiation & Monitoring Group of CMS are responsible for the design, installation and future running of seven detectors in CMS which will provide on-line protection and constant radiation monitoring within the CMS experiment. This paper briefly details the basic designs of three of the beam monitoring detectors.

I. INTRODUCTION

CMS is a multipurpose detector designed around a 3.8T solenoid magnet [1]. Calorimeters, pixel tracker and muon chambers are set concentrically around the beam pipe and aim to measure the momenta of all particles produced by the p-p collisions. Many of these detectors can operate safely only when beam conditions are good. The BRM sub-detectors are responsible for the safety of CMS and are pivotal in ensuring delicate systems are shut-down before beam losses can inflict serious damage.

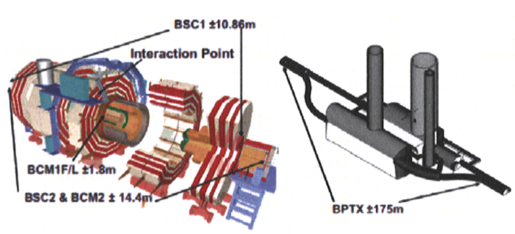

Fig 1. (Left) Exploded view of the CMS detector showing the positions of the BRM sub-detectors. (Right) The CMS cavern and surrounding Long Straight Section in which the BPTX is located ±175m from Interaction Point 5.

Fig 1 shows the positions of the BRM sub-detectors in CMS. The Beam Pickup Timing for the eXperiment (BPTX) electrodes are mounted on the beam pipe in the long straight sections leading in to the CMS cavern. Entering the cavern, the beams then pass by the Beam Conditions Monitor 2 (BCM2), Beam Scintillation Counter (BSC1 & BSC2), Beam Conditions Monitor 1 – Leakage (BSC1L) and Beam Conditions Monitor 1 – Fast (BCM1F).

Protection of any HEP experiment is of vital importance. The purpose built, sensitive electronic detectors throughout CMS are required to operate in a high radiation field environment. However should the instantaneous radiation field greatly increase, many of these systems could be destroyed due to excess currents. It was the task of the CMS BRM group to design and install the safety systems which will predict the loss of beam control and trigger a beam abort if pre-determined thresholds are met, signaling that conditions are deemed unsafe. The abort signal simultaneously causes the LHC kicker magnets to deflect the beams into the beam dump and shuts down all the 'at-risk' detectors. Additionally, extensive monitoring is installed to allow diagnosis of adverse beam conditions.

The BRM system sub-detectors measure every possible aspect of the radiation entering the cavern. The tasks include monitoring of beam timing, intensity and position (BPTX), beam profile and losses (BCM1F, BCM1L, BSC, BCM2), beam halo and minimum bias event triggering (BSC) and ambient radiation dose to the surrounding region (RadMon). The CMS experiment is one point away from the LHC beam dump at point 6 of the LHC. This puts CMS in a relatively dangerous position. The kicker magnets which remove the beam from the LHC and direct it in to the dump, must do so during the 3μs abort gap in the orbit train [2]. Should an asynchronous beam dump occur, the CMS detector could be showered by $\sim 10^{12}$ protons within <0.3μs [3] potentially causing catastrophic damage to the sensitive inner tracker electronics. In such a case, the BRM systems will record data which will be used to give estimates of the radiation flux through many areas of the CMS cavern. This data will in turn give an indication of the detrimental effects (e.g. reduction of lifetime) on the surrounding instrumentation.

In order to be useful as beam monitoring devices, the detectors must be radiation hard above and beyond the expected nominal radiation field. The BPTX uses LHC standard button electrodes. The BCM1F, BCM1L and BCM2 detectors use radiation-hard polycrystalline diamonds. The BSC uses PVT scintillation plastic tiles. The RadMon uses RadFET and SRAM devices and also passive TLDs for long-term monitoring [4].

To reduce electronic noise and ground currents, strict CMS grounding rules had to be followed. In the cases of the BSC and BPTX, the signals are transferred to the readout electronics by coaxial cables and so special attention to the grounding scheme of these detectors was required. The

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Alan Bell. University of Geneva, Switzerland & CERN, Geneva Switzerland. Previously at University of Canterbury, Christchurch, New Zealand. (email: alan.bell@cern.ch)

BCM1F and BCM2 use optical fibers between their front-end system and the readout electronics, reducing the risks of ground loops.

During the hugely successful initiatory run of the LHC on September 10, 2008, the BRM sub-detectors were an invaluable source of data, showing that the beams passed through CMS safely and cleanly.

II. The Beam Scintillation Counter

Using Polyvinyl-Toluene (PVT) scintillation tiles [5] , the Beam Scintillation Counter (BSC) covers ~ $1.2m^2$ area at ±10.86m, from the IP ($3.9 < \eta < 4.4$). A further 4 channels are located at ±14.4m for improved time measurement. The tiles connect to four banks of Thorn 9902KA phototubes [6]. Embedded LEDs within the tiles were used for testing and calibration and will be valuable in assessing the radiation damage sustained by individual channels over the 2 to 3 year expected lifetime of the system.

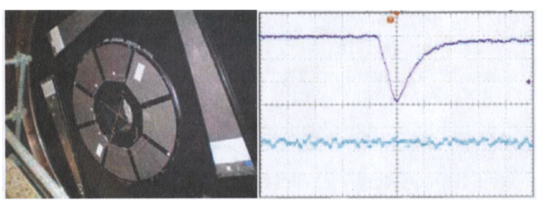

Fig 2. (Left) The scintillation tiles of the Beam Scintillation Counter mounted ±10.86m from the IP. There are a total of 36 channels from the BSC. (Right) An example of the signal seen from the BSC on the LHC start-up day.

Fig 2 shows 16 of the scintillation tiles mounted on the Hadron Forward (HF) calorimeter. An identical arrangement was mounted on to the opposite HF calorimeter and together makes up the 32 channels of the BSC1 sub-detector. Fig 2 also shows the first signal seen from the BSC1 during the LHC start-up on September 10, 2008.

The BSC has a total of 36 independent, MIP sensitive channels and two readout systems [7].

- A NIM based system to provide technical triggers to the CMS Global trigger which are able to detect direction and relative quantity of halo particles and monitor for the occurrence of minimum-bias events. The trigger signals also provide a veto trigger input to the CMS global trigger system. These triggers were active during the LHC runs in 2008.
- A VME based system to record hit rates and timing information with accurate timing data from CAEN Time-to-Digital Converter (TDC), (Model V767 [8]). Pulse height and shape from CAEN Analog-to-Digital Converter (ADC), (Model V1721 [9]) gives evidence on the existence of pilot bunches during the early LHC and CMS commissioning phases. Finally a 1Hz readout of hit rate provided by CAEN VME scalars (Model V560N [10]) gives information of beam quality in the CMS region for detection of beam gas and beam-pipe wall interactions.

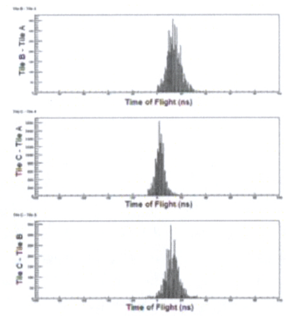

Fig 3. Time of flight (ToF) measurements from the CERN Proton Synchrotron (PS) test beam. Three channels of the BSC were positioned in line with the beam and the ToF measured using CAEN VME modules. The statistical time resolution was approximately 3ns.

Before installation in to the CMS cavern, three channels of the BSC were erected in the PS test beam at CERN. The scintillation tiles were positioned in line with the p-π beam and the time of flight was measured using the CAEN VME Time-to-Digital Converter (TDC). As shown in Fig 3, the TOF measurements were compatible with the expected values with a resolution of ~3ns. This resolution is sufficient for the running of the LHC.

The data from the BSC will be important throughout the commissioning of several sub-detectors of CMS including the Forward Hadron Calorimeter and the Tracker for track based alignment. A radiation hard upgrade of the BSC is currently being designed to cope with the future high luminosity runs of the LHC.

III. The BPTX

The Beam Pick-up Timing for Experiments (BPTX) detector uses two standard LHC beam position monitors each comprising of four electrostatic button electrodes positioned symmetrically around the beam-pipe. The features of the BPTX sub-detector include:

- Fast signal rise-time from the pick-ups ~0.3ns.
- Signal analysis by oscilloscope (LeCroyWR64Xi) running LabView.
- Comparison of timings from opposite beam position monitors gives highly accurate measurements of the Z-vertex and bunch timing relative to the CMS clock [11,12].
- Achieved time resolution of the order of 50ps.
- Signal amplitudes are proportional to beam intensity.
- Combination of Amplitude and Timing information provides accurate bunch pattern monitoring for detecting satellite bunches and beam dump gap contamination.

Fig 4 shows the button electrodes of the BPTX before the installation of the beam pipe and dipole magnets. Readout software for the BPTX was developed using simulated LHC orbit signals generated from a BOBR card [13] and later tested during the SPS test beam where they generated highly accurate measurements of the SPS orbit train, also shown in Fig 4.

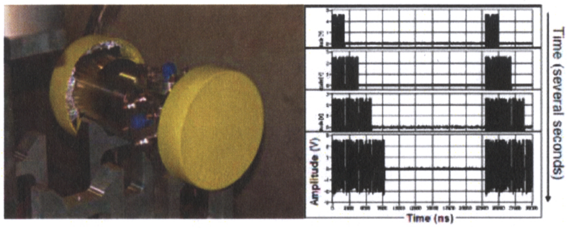

Fig 4. (Left) One set of BPTX electrodes situated on the LHC, ±175m from the CMS IP. The proton beams passing through the center induce a charge into the electrodes giving highly accurate beam timing and position information. (Right) An example of the readout capability of the BPTX. Here, the signal timing and amplitude measurements are used to reconstruct the filling scheme of the SPS test beam.

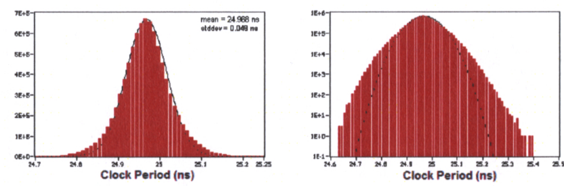

Fig 5. Measurements of LHC bunch clock in SPS test beams with a resolution of 50ps.

The LabView software running on the LeCroy WR64Xi oscilloscope [14] carries out statistical analysis of the beam pickup signals including baseline fluctuation measurements, orbit timing jitter, bunch intensity and bunch length. SPS Clock jitter analysis results are shown in Fig 5.

The BPTX system is the primary reference for triggering on particle beams passing through CMS. It provides a reliable, zero-bias signal with zero dead-time and is used for triggering several subsequent detectors.

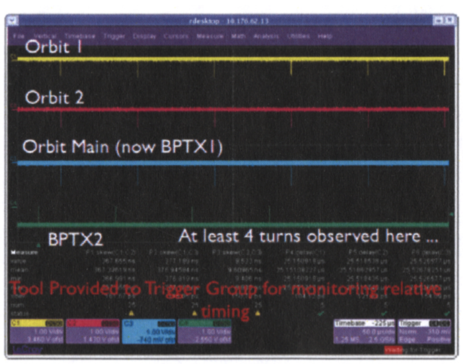

Fig 6. The signal from the BPTX (lowest trace) was important in monitoring the relative timing between the CMS detector and the arrival of the beam. This example shows a single proton bunch passing four times through CMS and around the LHC ring.

This ability was vital during the LHC runs in 2008 as it allowed all CMS sub-detectors to be 'timed-in' with the CMS clock quickly. This task was achieved within the first few bunches passing through IP 5. Fig 6 shows the BPTX signals produced by a single proton bunch traveling around the LHC four times. By providing this signal as an input to the CMS Global Trigger, where timing comparisons were made with all other CMS sub-detectors, the relative timing between these sub-detectors and the arrival of the proton bunches was found and compensated for.

IV. The BCM2

The BCM2 system is the continuation of the LHC Beam Luminosity Monitor (BLM) system though the CMS cavern [15]. 12 pCVD diamonds per end are arranged around the beam-pipe as concentric rings in two radii. The inner radius of 5cm leaves the diamonds unshielded from interaction point (IP), therefore sensitive to IP products. The outer radius of 29cm is shielded from the IP and is therefore more sensitive to incoming background. The leakage current through the diamonds is related to particle flux. By integrating the leakage current through each diamond, the evolution of beam halo and minimum bias events can be seen. Integration is done over 40μs, unsynchronized to the CMS clock. Typical base leakage currents are of the order of 10pA. Nominal leakage currents during LHC full luminosity are approximately 100nA, based on simulation studies. In the case of accident scenarios when beam control is lost, the expected currents could rise to >10μA. These small currents are DC coupled to CERN designed BLM tunnel cards and readout using LHC BLM software.

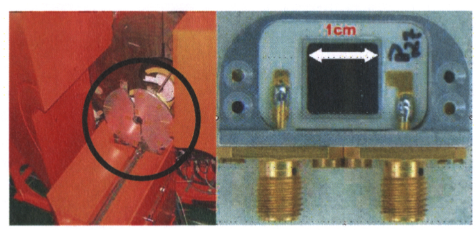

Fig 7. (Left) 12 pCVD diamonds per end are housed within the aluminum structures of the BCM2. (Right) An example of one of the pCVD diamonds of the BCM2. Thickness = 500μm. Area = 1cm^2. Bias voltage = 200V.

The BCM2 comprises of two pairs of half wheels which encompass the beam pipe. The pCVD diamonds are mounted within these wheels. Fig 7 shows one pair of the BCM2 wheels after installation. Also shown is an example of the pCVD diamond in the aluminum housing with its high voltage and signal output connectors.

The BCM2 provides a fast diagnostic tool for monitoring of beam halo and collision products [16]; will provide vital information on beam quality at higher luminosities beyond the current BSC detector capability (≥5 kHz MIP Equivalent) and is designed to last the nominal lifetime of the LHC.

V. Conclusions

The BRM systems in CMS provide a wide and varied range of monitors designed for the protection of the CMS experiment, the measurement of short-term and long-term radiation flux into CMS and post-mortem analysis of possible radiation damage to the detector. Protection is achieved by the signaling of a beam abort derived from the BCM1F and BCM1L sub-detectors [17]. Further monitoring of the radiation flux through CMS and around the CMS cavern provides detailed and accurate information on beam halo particle rates, minimum-bias event rates and ambient radiation background.

The design philosophy of the BRM sub-detectors were such that each detector has a certain level of redundancy, thus allowing one to be compared with another. This aided in the early commissioning of the sub-detectors and produces data on the beam dynamics with a greater certainty. By employing a fast and accurate beam monitoring system in the BPTX, all other BRM sub-detectors, and indeed, all CMS sub-detectors were able to be 'timed-in' quickly and efficiently.

The BRM sub-systems continuously record data, initially to disk and later to a permanent tape storage system which, in the event of a beam abort can be used to perform post-mortem analysis.

All sub-detectors were installed on time and ran successfully during the initiatory running of the LHC.

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