Performance of the ATLAS Beam Diagnostic Systems

Boštjan Maček on behalf of ATLAS Collaboration
 Jožef Stefan Institute, Ljubljana, Slovenia
 Email: bostjan.macek@ijs.si

Abstract—The beam diagnostic system of the ATLAS detector comprises two diamond sensor based devices. The innovative Beam Conditions Monitor (BCM) is aimed at resolving background from collision particles by sub-ns time-of-flight measurement. The Beam Loss Monitor (BLM) is a clone of the LHC machine BLM system, replacing ionization chambers with diamond sensors. BCM uses $16 \times 1 \times 1 \text{ cm}^2$ 0.5 mm thick polycrystalline chemical vapor deposition (pCVD) diamond sensors arranged in 8 positions at a radius $r \approx 55 \text{ mm}$, $\sim 1.9 \text{ m}$ up- and downstream the interaction point. Time measurements at 2.56 GHz sampling rate are performed to distinguish between collision and shower particles from beam incidents. A FPGA-based readout system performs real-time data analysis and interfaces the results to ATLAS and the LHC beam permit system. The diamond sensors, the detector modules and their readout system are described. Results of performance with LHC beams of increasing energy and intensity including timing separation of collisions from beam related background are presented, and beam abort algorithms discussed. BLM utilizes 12 pCVD diamond sensors close to the beam pipe at $z \approx \pm 3.5 \text{ m}$. The radiation induced currents in the sensors are read by the LHC machine developed readout, averaging the current over various time constants from $40 \mu\text{s}$ to 84 s . Exceeding a preset threshold for any of the readings drops the beam permit and aborts the LHC beam. Both systems provide post-mortem data dump of approximately 1000 LHC turns prior to the anomalous condition, allowing to diagnose its development and to refine the BCM algorithms and BLM thresholds. The systems were employed in various modalities from the first physics LHC run in November 2009, and are adapting their performance to balance between the need to protect the sensitive ATLAS Inner Detector, and yet allow efficient operation of the collider.

I. INTRODUCTION

POTENTIAL abnormal beam conditions could cause substantial damage to the detectors. To that end, the experiments decided to develop their own beam-safety systems in parallel to the one provided by Large Hadronic Collider (LHC). In ATLAS spectrometer this role has been given to the Beam Conditions Monitor (BCM) and Beam Loss Monitor (BLM) systems. Their main purpose is early detection of beam instabilities and, if needed, initiation of the beam abort. Additionally ATLAS BCM provides a relative luminosity measurement, also on a bunch by bunch basis.

II. ATLAS BCM

The ATLAS BCM consists of two sets of four modules - one on each side of the interaction point, at $z_{BCM} = \pm 1.84 \text{ m}$. This symmetrical positioning is shown in figure 1, where also the basic principle of operation is sketched. Utilizing the time

of flight measurement for each of these two stations, and looking at the time difference, one can obtain the position of the particle source. Particles created in bunch crossings at interaction point are detected on both sides at 6.25 ns after the collision. These are called *in-time* hits. In contrast, the particles originating upstream, at $|z| > |z_{BCM}|$, hit the nearest detector station 6.25 ns before the actual bunch crossing (*out-of-time* hits), thus 12.5 ns before they hit the opposite side of BCM. This time difference is almost exactly half of the time interval between the two consecutive LHC bunch crossings. Given sufficient timing resolution, *in-time* hits can be used to monitor collision conditions - luminosity, and the *out-of-time* hits can be a useful selection tool to identify background events. A short description of the system is provided in the following section, for details see [1], [2].

Fig. 1. Principle of operation of Beam Condition Monitor. In case of proton-proton interaction at interaction point (green) secondary particles reach both sides of BCM system simultaneously. In the case of anomalous event such as a proton hitting the collimator (red) one side of BCM system would detect secondary particles before the other. The positioning at $|z_{BCM}| = \pm 1.84 \text{ m}$ defines the time difference between the two sides to be $\sim 12.5 \text{ ns}$.

A. Detector modules

Eight modules are mounted at radius of 55 mm from the beam, and given their distance from the interaction point, this very forward region, thus they reside in a very harsh environment. They are required to be radiation hard since the expected doses are about 0.5 MGy and fluencies of about $10^{15} \text{ particles/cm}^2$ in ten years of ATLAS operation at the nominal LHC luminosity.

To satisfy these requirements pCVD diamond was chosen for the sensor material, for its radiation hardness and fast signal response (rise time $< 1 \text{ ns}$, signal width $\sim 2 \text{ ns}$) allows the measurement on the bunch by bunch basis. Their additional big asset is that they draw negligible leakage currents, eliminating

the need for active cooling, since all power can be dissipated by convection.

Polycrystalline diamonds are of $1\text{ cm} \times 1\text{ cm}$ size and $500\text{ }\mu\text{m}$ thickness. They were developed by a collaboration of RD42 [3] and Element Six Ltd. [4], were proven to be radiation hard and to produce fast signals. To achieve high and narrow signal pulses the sensors are operated close to the charge carrier saturation velocity, at bias voltage of $\pm 1000\text{ V}$.

In order to optimize the detector response two such diamonds are connected in parallel with ceramic insert in between. Such a configuration doubles the signal while increasing the noise by only 30%. Bias voltage is applied to outside surfaces of this 'double-decker' configuration, while inner ones are connected to ground and treated as signal lines, leading to the front end electronics within the module. These are two current amplifiers: 500 MHz Agilent MGA-62563 GaAs MMIC and 1 GHz Mini Circuits Gali 52 HBT chips, each providing an amplification of about 20 dB. Module is shown in figure 2. In addition the expected anisotropy of particle direction is exploited with the mounting of modules under 45° with respect to the most probable particle direction (beam line) to gain an additional $\sqrt{2}$ in the signal.

Fig. 2. BCM module without cover, showing the pCVD diamond and the two front-end amplifiers.

B. Read-out

Signals from the modules are routed through 15 m of coaxial cables to region close to ATLAS toroid magnets where much lower levels of radiation are expected (approx. 10 Gy). There signals are digitized. The circuitry hosts a fourth order low-pass filter with 300 MHz bandwidth, NINO chip [5], and laser diodes. The input filter increases the signal to noise ratio and splits the signal in 1 : 20 ration in order to increase dynamical range of the detector. These two signals are than passed to NINO chip, that was originally designed for time of flight measurement of ALICE RPC detector - it features differential input amplifier, discriminator and time over threshold measurement. There is an independent threshold for each of the two signals (from here on named low & high threshold). In the last step, NINO time-over-threshold output signal is converted to an

optical signal, using radiation tolerant laser diodes. Then it gets transmitted over 70 m of optical fibers to the counting room, to be received by photo diodes and converted to PECL electric level signals that are processed by back-end electronics.

For this part the BCM uses two Xilinx ML410 development boards, each hosting one Xilinx Vitrex-4 FPGA chip. Each has 8 dedicated high speed RocketIO input sampling channels. One board is connected to low threshold channels of four horizontal modules ($\pm x$) and high threshold of four vertical modules ($\pm y$), vice-versa for the second board. The sampling is done at 2.56 GHz frequency, thus giving $\sim 400\text{ ps}$ timing resolution. Here data is interpreted as *in-time* or *out-of-time* hits, processed, stored, and further dispatched to different ATLAS and LHC services:

- *LHC Beam/Injection Interlock System*. Two redundant signals are used by the BCM. One of these signals can prohibit injection of proton bunches into LHC and the other can dump the already circulating beam.
- *ATLAS Detector Safety System* is a hardware interlock system, offering ATLAS detector components possibility to react to unwanted situations and protect their hardware. BCM provides four signals; two with severity of warning and two of an error.
- *ATLAS Detector Control System* is a slow detector control system that resides in the software world. Though slower than DSS it provides a valuable control since it enables more sophisticated decision making and greater flexibility.
- *Central Trigger Processor*, as the main ATLAS information filter, receives 6 bits of Level1 trigger information from BCM.
- *ATLAS Triggered DAQ*, accepts a data fragment also from BCM (digitized data) and incorporates it into the event if passed by all levels of trigger. Two arrival times and two time-over-threshold measurements can be recorded in each bunch-crossing for each channel, and in each event, data for 31 bunch-crossings is written.
- *Online Luminosity Calculator*, is one of the two recipients of luminosity data recorded by BCM. The second recipient is the standalone application recording raw luminosity data in the stream dedicated to calibration.

C. Safety system

BCM is a unique safety system in a sense that its logic operates on per-bunch basis. Each bunch interval is searched for the *basic condition* - 3 out of 4 low threshold and 3 out of 4 high threshold channels must register a hit. At low detector occupancies, during the first months of LHC operation, BCM provided active protection. Figure 3 shows the sum of low threshold channel hit rates prior to BCM-triggered beam-abort on 26.3.2010. Additional analysis showed a distinctive background timing signature, indicating an increasing single sided spray of background particles intruding ATLAS.

In order to cope with increasing luminosity hardware changes are under way to increase the effective high/low threshold ratio by an order of magnitude. Additionally, to reduce the sensitivity to single event upsets, two extension algorithms are implemented:

Fig. 3. Signal seen at the LHC dump by ATLAS BCM on March 26, 2010 at 13:41 (Geneva local time). LHC was doing collimator studies at 3.5 TeV. Plot shows development of signal in low threshold channels in about 90ms prior and 10ms after the post mortem event.

- *X out of Y algorithm* widens the decision-making time window with demanding at least X bunch intervals to satisfy the basic condition in any interval of Y consecutive bunch intervals.
- *Forgetting Factor algorithm* prefers more recent occurrences of bunch intervals satisfying the basic condition over the older ones. Each bunch interval the current algorithm value is scaled with a factor smaller than one, and if the current bunch interval satisfies the basic condition a constant is added.

D. Luminosity

While the high threshold channels provide the basis for safety functionality, the low threshold channels serve for physics studies. Their MIP sensitivity enables BCM to do luminosity monitoring. Robust method of event counting has been chosen as the basic approach. Additionally, taking advantage of the excellent BCM timing resolution, individual bunch luminosity monitoring is performed. Four measurements are recorded for each bunch interval in the back-end electronics, differing on algorithm for event selection. Three of these are based only on hits detected in the half of bunch interval, where signals from proton-proton collisions are expected, cutting out a significant portion of the background. Fourth event filter does not use sub-bunch timing information, thus including this background, allowing its offline estimation and systematics studies. The event filters are:

- *AND* is a high background suppression algorithm, that requires signals in both $+z$ and $-z$ side of the detector.
- *OR* is a high statistics algorithm, demanding anything detected in the BCM.
- *XOR-C* selects events with detected hits only on $+z$ side of the detector.
- *AND₂₅* requires signals in both $+z$ and $-z$ side of the BCM.

In figure 4 measurements of the normalized rate (sum of all bunches) vs. time for ATLAS run 166924 are shown for the

first three algorithms. Additional algorithm XOR – A (only $-z$ events) is included in the plot, and has been reconstructed from the other three with the unitarity constraint.

Fig. 4. Average number of events per bunch crossing satisfying different algorithm conditions versus time. Event counts are averaged over all colliding bunches. Data are shown for comparison of different algorithm occupancies. For clarity, only the data from horizontal modules are plotted for the run 166924.

The presented results are collected with only half the modules (one back-end readout board) and an independent measurement is done for the other half of modules. As seen in figure 5 consistent results are obtained.

Fig. 5. Average number of events per bunch crossing satisfying the OR algorithm condition versus time. For an event to satisfy the OR condition, it must contain a hit anywhere in BCM detector within second half of the bunch interval. Event counts are averaged over all colliding bunches and scaled to one LHC turn. Data for both RODs (two independent measurements) was extracted from run 166924.

Data is transferred from both readout boards via Ethernet at ~ 1.2 Hz rate and written in a calibration-dedicated stream and send to ATLAS Online Luminosity Calculator. Each data transfer contains info for all event selection algorithms and for all 3564 bunch intervals in the LHC orbit. This enables monitoring of individual bunches and is shown in figure 6.

With the event rates measured one can predict luminosity, taking into account the transfer function shape and appropriate absolute scale calibration. The former is obtained on basis of probability calculation, taking into account the saturation

Fig. 6. Average number of events per LHC turn satisfying the AND algorithm condition. Horizontal axis denotes the sequential number of possible bunch slots, and extends over all 3564 slots covering the entire LHC beam. Bunch train structure of the beam is clearly visible, as well as the relative strength between signals induced by colliding and by unpaired bunches (bunch numbers from 1500-1600). The AND algorithm imposes a stricter selection, which suppresses the afterglow signal visible in OR algorithms. For clarity, only data for horizontal modules are plotted for ATLAS run 166924 (October 16, 2010).

effect, while the latter is measured with the van der Meer scans. Here the two LHC beams are gradually displaced, and the BCM response for the OR algorithm is shown in figure 7. Knowing the bunch proton population and the measured width of the displayed distribution one can calculate luminosity and thus calibrate its absolute scale. The analysis is ongoing.

Fig. 7. BCM data collected during the van der Meer scan on October 10, 2010. The vertical axis quantifies the number of events satisfying the OR algorithm condition normalized to single LHC turn. Only the six colliding bunches are summed into the values shown. Data for both RODs (two independent measurements) are shown as a function of beam separation.

III. ATLAS BLM

The ATLAS Beam Loss Monitor (BLM) is a second system constructed for protection of ATLAS. The detectors themselves are again based on pCVD diamond sensors, 8 mm $\times$ 8 mm in size, and 500 μ m thick. Each diamond is placed in a module box constructed from G10 plates offering electrical shielding and mechanical support (see figure 8). There are 6 modules on each side of the detector, mounted on the Inner Detector End Plate at $z_{BLM} = \pm 3.45$ m and radius of 6.5 cm.

The radiation induced current in each module is read out by BLM-CFC card, which translates this current in a digital signal that is sent through optical link to ATLAS USA 15 counting room. Here BLM TC VME based board is integrating these signals over different time periods ranging from 40 μ s to 84 s. If two of these readings, corresponding to the same side of the detector, exceed threshold, and this happens for both detector sides simultaneously, a beam dump request is issued.

Fig. 8. One of twelve BLM modules before installation. Diamond is inside G10 casing and everything is mounted on a peek holder.

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