

The ATLAS Beam Condition Monitor Commissioning

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Abstract

The ATLAS Beam Condition Monitor (BCM) based on radiation hard pCVD diamond sensors and event-by-event measurements of environment close to interaction point ($z=\pm 184$ cm, $r=5.5$ cm) has been installed in the Pixel detector since early 2008 and together with the Pixel detector in the ATLAS cavern since June 2008. The sensors and front end electronics were shown to withstand 50 Mrad and 10^{15} particles/cm² expected in LHC lifetime. Recently the full readout chain, partly made of radiation tolerant electronics, still inside of the ATLAS spectrometer and partly in the electronics room, was completed and the system was operated in time of the first LHC single beams and is ready now for the first collisions which will follow after the LHC repair.

I. INTRODUCTION

Potential detector damage resulting from abnormal beam conditions could damage ATLAS Inner Detector which encouraged the implementation of Beam Condition Monitor (BCM) [1] in ATLAS spectrometer. The aim of ATLAS BCM is to monitor the beam conditions and luminosity very close to the ATLAS interaction point, inside the Inner Detector. It consists of 8 detector modules organized in two sets of four modules on each side of the interaction point. The pCVD diamond sensors of each of the BCM modules are located symmetrically around the interaction point at $z=184$ cm and $r=55$ mm and supported on the ATLAS Pixel carbon fibre structure which also serves for the support of BCM supply and signal cables. Figure 1 shows the mechanical mounting and the inside of one of the modules with the diamond sensors and front end electronics visible.

The modules are required to be radiation hard since they will be installed close to interaction point and close to the beam-pipe in the place where expected radiation will reach doses of about 50 Mrad and fluences of about 10^{15} particles/cm² in 10 years of operation of ATLAS at nominal luminosity. pCVD diamonds were chosen for their radiation hardness and fast signal response which allows to measure the beam conditions on the bunch by bunch basis. They were also shown to draw only tiny

leakage currents allowing for no active cooling which is neither required for the amplifiers that can dissipate the heat by convection to the surrounding Pixel gas volume.

Each BCM module consists of two polycrystalline CVD (Chemical Vapour Deposition) diamond pad sensors mounted on top of each other and connected in parallel [2]. Signals created in the diamond sensors by charged particles are amplified in two stage amplifier build of off-the-shelf components [3] which were chosen for their satisfactory performance after the irradiation. Further away from the interaction point (in radiation less harsh environment) the precise timing information and amplitude is encoded into digital signals sent to the back end electronics based on sophisticated FPGA board. The principle of operation is shown on Figure 2 where interactions at interaction point will cause the appearance of signals in modules on both sides simultaneously (“in time events”) and the background events which will cause time difference between the recorded signals on the two sides of 12.5 ns (“out of time events”), about ½ of the bunch to bunch time spacing due to adequately chosen BCM module locations.

In addition to beam condition monitoring the BCM will provide valuable complementary luminosity monitoring information which could be used for example for correcting the trigger for bunch to bunch luminosity variations. During the LHC early commissioning when the conditions will not yet be stable and the Inner Detector will most likely be switched off, the BCM might be the first detector system to report proton-proton collisions inside ATLAS spectrometer.

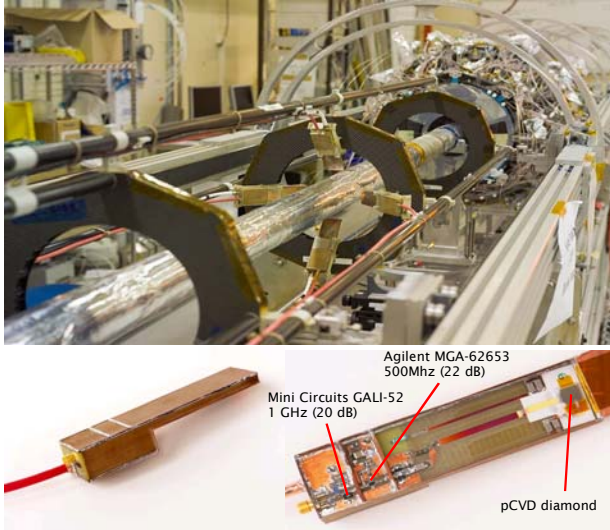


Figure 1: Four ATLAS BCM modules installed on the side-C of the ATLAS Pixel system support frame (upper picture). The beam-pipe going through the support structure as well as Pixel detector in the background can also be seen. The lower two pictures show BCM module soldered close (lower left picture) and BCM module prior to installation of the covers where pCVD diamond sensors and two stage amplifier is visible (lower right picture).

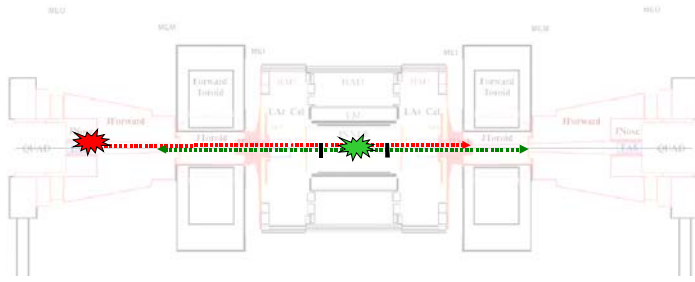


Figure 2: Principle of operation of Beam Condition Monitor. In case of the normal proton-proton interaction at interaction point (green) secondary particles would reach both sides of BCM system simultaneously. In the case of anomalous event such as proton hitting a collimator (red) one side of BCM system would detect secondary particles before the other. The $z = \pm 184\text{cm}$ defines the time difference between the two sides to $\sim 12.5\text{ ns}$ almost exactly $\frac{1}{2}$ of the time interval between two consecutive LHC bunches.

A. Beam Accidents simulation and past experiences

The ATLAS experiment is rated to be as the 'safest' of all interaction points in terms of possible beam failure scenarios because it is located furthest away from beam extraction and injection points. ATLAS is also shielded with so called Target Absorber Secondaries (TAS) collimators which are 1.8m long copper block located at $z = \pm 18\text{m}$ from the interaction point and are intended to protect the inner triplet of cryogenic quadrupoles from excessive heat load due to particles from collisions. Additionally, TAS also protects the Inner Detector from a variety of beam failures. The beam interlock system

(BIS) at LHC comprises two redundant optical loops per beam, which transport BeamPermit signal around the LHC ring. In each insertion region two beam interlock controllers (BIC) are used to make a logical AND of many UserPermit signals provided by user systems (experiment BCMs, machine beam loss or beam position monitors...). If BeamPermit signal is set to false the beam dump is initiated or beam is not allowed to be injected from SPS. The extraction of beam is triggered by the BIS and is completed within $270\text{ }\mu\text{s}$ after the UserPermit signal was removed at the BIC. Each user system is connected to BIS through user interface CIBU (Controls-Interlocks-Beam-User), which takes the UserPermit signal and transmits it to the nearest BIC. The most likely beam losses are due to failures or wrong settings in the magnet and powering system with about 8000 magnets powered in 1700 electrical circuits. Beam losses occur at different time scales. They can happen either in a single-turn (or a fraction of turn) with a sudden beam loss or during several turns resulting in progressive losses. Figure 3 shows possible scenario of a beam hitting a collimator and causing showers that can be a potential risk to the Inner Detector.

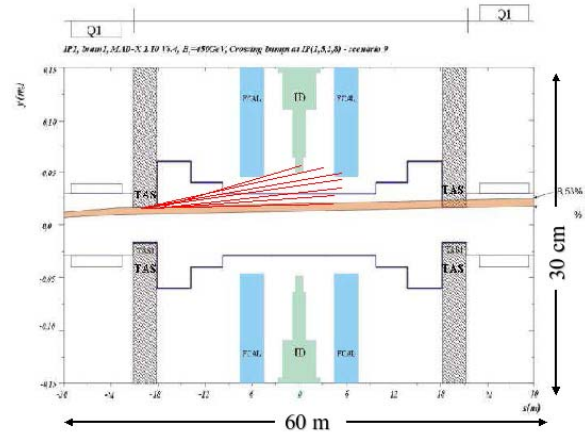


Figure 3: An example of one of the possible scenarios, where beam hitting a TAS collimator at beam injection causes a shower in Inner Detector.

LHC will circulate 2808 bunches per colliding beam, each bunch consisting of 1.1×10^{11} protons at energy of 7 TeV – about 200-times more energy stored in beams compared to maximum value in previous accelerators like HERA or Tevatron. Already at Tevatron accidents happened such as the one depicted in Figure 4 where the proton beam caused damage to a collimator due to misfiring kicker magnet.

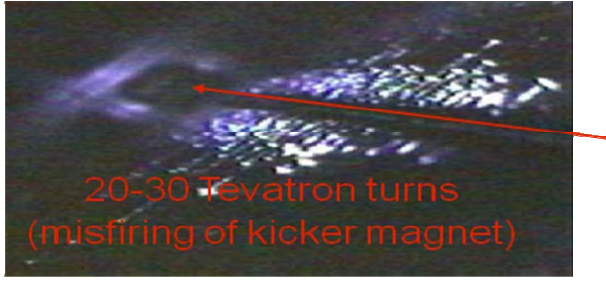


Figure 4: An accident that happened at Tevatron due to misfiring of the kicker magnet.

II. THE ATLAS BCM SYSTEM

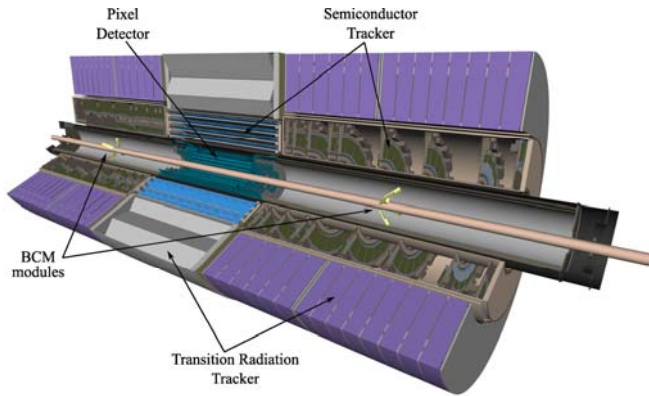


Figure 5: Schematic view of location of BCM detector modules within ATLAS Inner Detector.

Figure 5 shows schematic view of positions of the 8 BCM modules inside the ATLAS Inner Detector. The location is conveniently chosen to make the time of flight between the two sides approximately $\frac{1}{2}$ of the bunch to bunch spacing in LHC.

A. Detector module

The polycrystalline CVD diamond sensors of $1\text{ cm} \times 1\text{ cm}$ size and $500\text{ }\mu\text{m}$ thickness were developed by a collaboration of RD42 [5] and Element Six Ltd. [6] (later named Diamond Detectors Ltd.). They were proven to be radiation hard and to produce very fast signals (rise time $< 1\text{ ns}$, signal width $\sim 2\text{ ns}$). They are also attractive choice due to low leakage currents even after irradiation which does not exceed 1 nA/cm^2 thus no active cooling is required to cool the sensors. Two pad sensors are assembled back to back on a Al_2O_3 ceramic baseboard which brings high voltage ($\pm 1000\text{ V}$) to the lower surface of the bottom diamond sensor and to the pad on the side which is used to connect the high voltage to the upper side of the top diamond sensor through several bond wires. The middle surfaces of the two sensors are conductively glued together with small pieces of ceramic distance holders and connected to the signal line on the ceramic baseboard through multiple bonds (see Figure 7). All parts are glued together with thermoplastic conductive adhesive pads (Staystik 571, a material proven to be radiation hard).

Ceramic module with two diamond sensors was assembled into the front end electronics box [3] based on commercially available 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. The first stage Agilent amplifier has an excellent noise performance with its noise figure below 1 dB in most of its frequency range.

To avoid electrical interference and pick-up each module was closed by soldering covers to each of the three compartments on the upper side (respectively containing two diamond sensors, first stage Agilent amplifier and second stage Gali amplifier, see Figure 6) and the compartment on the lower side containing the LV/HV power cable connector and temperature sensor.

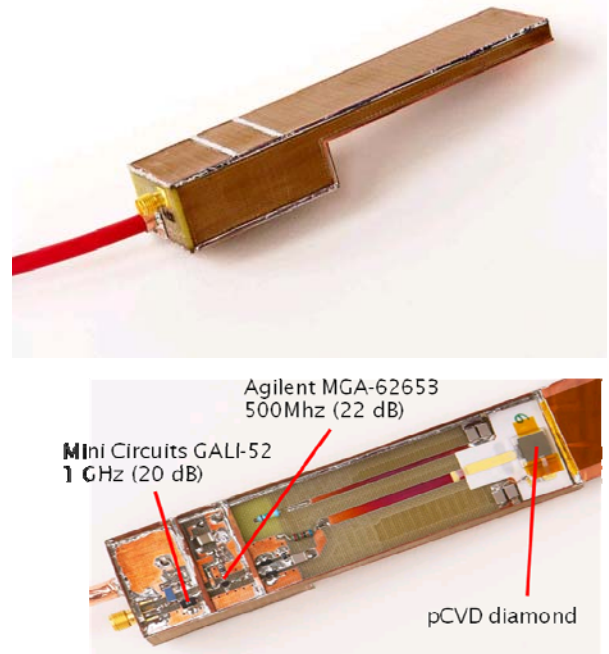


Figure 6: The two pictures show BCM module soldered close (upper picture) and BCM module prior to installation of the covers where pCVD diamond sensors and two stage amplifier is visible (lower picture).

B. The BCM Readout Chain

The ATLAS BCM will measure the arrival times of the signals and their time over threshold (TOT) for each of the 8 modules. These signals will be processed in real-time into rates, trends of rates for individual modules as well as for different logical combinations of signals taking into account also the timing within 25ns (“in time” and “out of time” signals). The Figure 8 schematically shows the BCM system architecture. BCM system functionality can be summarized as follows:

- **LHC Beam Abort.** Two redundant signals indicating that beam conditions in ATLAS Inner Detector have reached the beam abort levels are sent to LHC through ATLAS “CIBU” system and will eventually cause that all LHC bunches being dumped in a controlled manner.

- *ATLAS Detector Safety System.* 4 signals are sent to ATLAS DSS, the hardware interlock system, which will allow for the ATLAS Inner Detector components to react in order to protect their hardware.
- *ATLAS Detector Control System.* In less severe cases and in addition to the hardware based DSS the warnings and alarms will be sent also through the ATLAS DCS. More sophisticated information and histograms will also be available through DCS system to ATLAS and LHC control. All recent information from BCM stored in circular buffer of the back end electronics will also be dumped through this channel.
- *ATLAS Level 1 trigger information.* ATLAS BCM will provide also a 9-bit information for the ATLAS Level 1 trigger system, allowing for triggering on topologically interesting events. BCM can provide in real time bunch to bunch luminosity variation information – a valuable input to the trigger system.
- *ATLAS DAQ stream.* Digitized information of signal arrival times and their widths will be stored into special buffer in the ATLAS DAQ data stream. BCM data bits will be also recorded in the trigger data block.

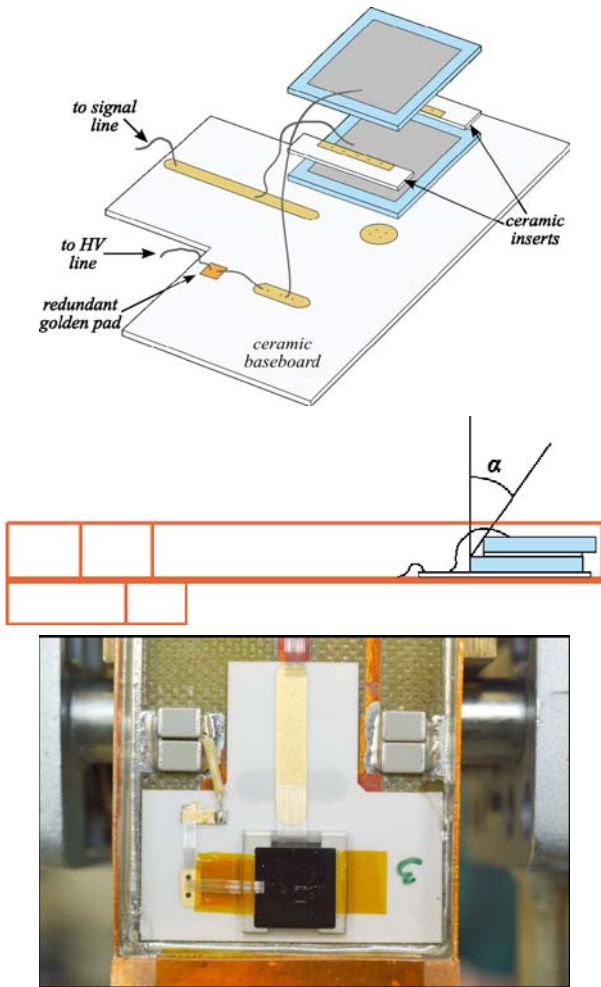


Figure 7: Schematic view of two diamonds assembly onto ceramic board (upper picture). Since modules are mounted under 45° towards the beam-pipe the two diamond sensors are mounted with slight displacement to mimic this. The two pictures show BCM module soldered close (upper picture) and BCM module prior to installation of the covers where pCVD diamond sensors and two stage amplifier is visible (lower picture).

Signals from BCM modules are taken through 14 m (2 m of Gore 41 in the inside and 12 m of Andrew HELIAX FSJ1 on the outside of the Pixel volume) of coaxial cables to a region with lower radiation where radiation tolerant electronics can be used. This electronics is based on NINO chip [4] designed by CERN-MIC for ALICE RPC detector for time of flight measurement. The NINO ASIC has 8 channels and features differential input amplifier (1 ns peaking time, 25 ps jitter), discriminator and the time over threshold measurement. It is built in radiation tolerant $\frac{1}{4} \mu\text{m}$ IBM technology. The NINO electronic board first filters (low-pass fourth order filter with bandwidth of $\sim 300\text{MHz}$) and splits the signals from each of the BCM FE modules into two parts in ratio of approximately 1:11 to increase the dynamic range of the BCM system. These signals are then fed into two input channels of NINO chip. The ground of each BCM channel separately (BCM module, NINO electronics, HV and LV power supply channel) is kept electrically floating with connection only to the Pixel reference ground through a $1\text{k}\Omega$ resistor close to BCM modules. The TOT digital outputs of the NINO chip is converted into optical signals using radiation tolerant laser diodes (Mitsubishi FU-427SLD-FV1) and taken with 70 m optical fibres to the ATLAS counting room where they are received by photo diodes (Lightron LP3A4-SNC1) converted to PECL electric levels and fed into two Xilinx ML410 development boards based on Xilinx Vitrex-4 FPGA chip. Optical receiver board also provides monitoring NIM level outputs. Each Xilinx ML410 boards features 8 RocketIO serial input/output channels that will sample signals received at frequencies of 2.56 GHz. The onboard RAM memory banks act as ring buffers to store the BCM signal information for the time of the last several hundreds of LHC bunch crossings. This information will be used for the post-mortem analysis after a potential beam dump. The processed data from the Xilinx ML410 will be sent through ATLAS standard optical link ("S-LINK") to the ATLAS DAQ system, via Ethernet to the ATLAS DCS system and electrically to the ATLAS interlock (DSS) system.

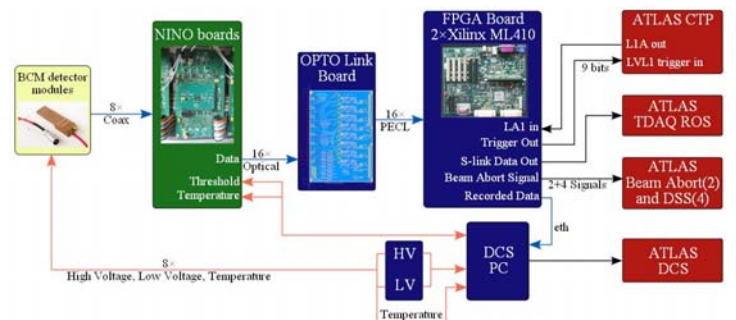


Figure 8: Symbolic BCM connectivity diagram.

III. RESULTS OF INSTALLED DETECTORS

Figure 8 shows the measured noise rate sampled at the outputs of the optical receiver (just in front of the signal input into the backend). The measurements show the RMS of the noise to be in the range from 50 mV to 70 mV as expected from the QA measurements [7,8]. Table 1 summarizes these results.

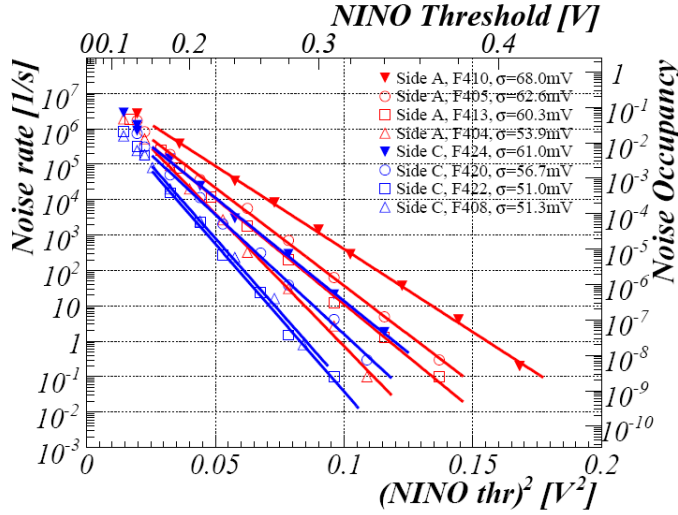


Figure 9: Noise rate of individual channels as measured in the pit.

Table 1: Summary of RMS noise measured using the detectors as installed in their final position in the pit.

Module	Position [Side, (x,y)]	Noise σ [mV]
F410	A, (+x,0)	68.0
F405	A, (0,+y)	62.6
F413	A, (-x,0)	60.3
F404	A, (0,-y)	53.9
F424	C, (+x,0)	61.0
F420	C, (0,+y)	56.7
F422	C, (-x,0)	51.0
F408	C, (0,-y)	51.3

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