Beam Conditions Monitor in ATLAS

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Abstract

In order to monitor beam conditions and detect signs of beam instabilities which could cause damage to their detectors, LHC experiments have decided to develop their own systems in addition to those provided by the accelerator. ATLAS Beam Conditions Monitor will consist of eight detector modules with diamond pad sensors, placed symmetrically around the interaction point along the beam axis. By use of fast electronics, time-of-flight measurements will provide unique distinction between normal beam events of colliding protons and anomalous events which induce background and could in worst case damage the ATLAS inner detector. Additionally BCM modules will be used to measure the interaction rate which will be used to monitor LHC luminosity in ATLAS.

Final modules have been assembled and subjected to qualification tests before their installation onto the ATLAS Beam Pipe Support Structure in January 2007. The final design of the BCM modules as well as the summary of results will be presented.

1 Introduction

The primary goal of Beam Conditions Monitor (BCM) is to detect the onset of beam instabilities. The BCM in ATLAS experiment at LHC is the first monitoring system that is based on single beam bunch crossing measurement rather

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than integrating the accumulated particle flux. It is designed to provide a separation between normal LHC proton collisions and anomalous events causing background (e.g. beam interactions with residual gas) or even damaging the ATLAS Inner detector (e.g. several protons hitting the beam collimator upstream the detector). This will be achieved by measuring the time difference between two successive signals. Considering two detector stations placed symmetrically around the interaction point at $\pm z_{BCM}$ we can distinguish between three classes of events (see Fig. 1). First are normal proton-proton interactions which give coincident signals every 25 ns. The second one are anomalous events, like protons hitting the collimator or beam-gas interactions occurring at $z > |z_{BCM}|$, that give signals with time difference of $\Delta t = 2z_{BCM}/c$. While beam-gas events originating from $z < |z_{BCM}|$ can give signal anywhere between two normal collision signals. Choosing Δt=12.5 ns gives the optimal separation between these types of events, which corresponds to $z_{BCM} \sim 1.9$ m.
Additionally, ATLAS BCM will be used for interaction rate measurement and luminosity monitoring [1], thus providing a complementary measurement to LUCID [2], the ATLAS main luminosity monitor.

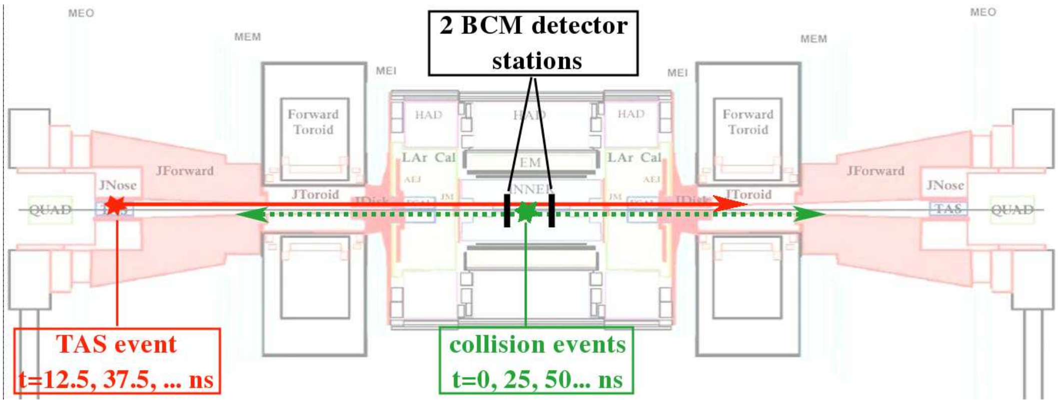

Fig. 1. Sketch of two BCM stations in ATLAS detector.

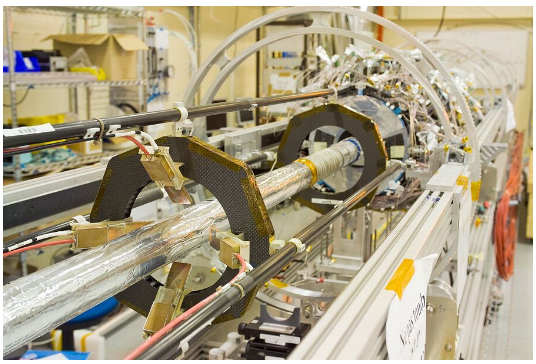

Fig. 2. Picture of four BCM modules mounted on Pixel Beam Pipe Support Structure.

2 Requirements

Hostile radiation environment and high rate of interaction at LHC pose stringent requirements for ATLAS BCM sensors and electronics. In 10 years of LHC operation the radiation field at sensor location will amount to about 10^{15} particles (mostly pions) per cm^2 and ionization dose of $\sim$30MRad. Signals from multiple interactions occurring every 25 ns induce harsh requirements for timing properties of BCM signal, namely fast rise time ($\leq$1 ns), narrow pulse width ($\leq$3 ns) and fast baseline restoration ($\leq$10 ns).
Predicted particle flux at BCM sensors location for a single 7 TeV proton hitting the TAS collimator is about 1 particle per cm^2 [3] while about half lower flux will be caused by interactions in each bunch crossing at designed luminosity of $10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ [1]. Thus a minimum ionizing particle (MIP) sensitivity is beneficial in order to be able to detect early signs of incident and estimate the luminosity as well.

3 Design

In ATLAS, BCM modules were mounted on the Pixel Beam Pipe Support Structure with sensors at optimal position z_{BCM}=±183.8 cm and r∼55 mm, corresponding to pseudo-rapidity η∼4.2. There are four modules on each side of interaction point at ϕ=0^o, 90^o, 180^o and 270^o, mounted at 45^0 towards the beam-pipe (see Fig. 2).
For active sensor material polycrystalline Chemical-Vapor-Deposition (pCVD) diamonds are used due to their radiation hardness and fast signal. Sensors were developed by CERN RD42 collaboration [4] in cooperation with Element Six Ltd. [5]. They are approximately 500 μm thick with 1 cm ×1 cm surface that has 8 mm ×8 mm metal contacts made at Ohio State University. In the module box two pad sensors are assembled back to back onto alumina oxide ceramic inserts that merge the signal planes. This assembly is glued to ceramic baseboard. High voltage is connected through vias to the lower plane of the bottom diamond, via wire bonds directly to the top plane of upper diamond and redundantly through additional gold pad with wire bonds (see Fig. 3). The timing properties of sensors are determined by high velocity of charge carriers and short trapping times even before irradiation in pCVD diamond. They will be operated at unusually high electric field of 2 V/μm (bias voltage of ±1000 V), close to saturation velocity, in order to achieve high and narrow current pulse. In addition pCVD diamond exhibits very low leakage current, allowing operation at room temperature without cooling. Typical characteristics of the sensors used are leakage current of less than 100 pA at ±1000 V and charge collection distance of around 220 μm. Radiation hardness of sensors was tested

for fluences up to 2.2×10^{15} protons per cm^2 with signal degradation of only 15% [6].
Signal is transmitted through 5 cm long transmission line to the front-end amplifier in order to decrease the radiation field by ~30% at location of front-end electronics (Fig. 4). The front-end was designed by Fotec [7] and is based on two stage RF amplifier using 500MHz Agilent NGA-62563 GaAs MMIC low noise amplifier for the first stage and Mini Circuits 1 GHz Gali 52 InGaP HBT amplifier for the second stage, each isolated in separate compartment. Each amplification stage and output are all AC coupled. Input is protected against discharges with diodes. Further processing of the signal will be done after ~14 m of coaxial cable (1.4m Gore 41 0.19" and 12m Heliax FSJRN-50B$\frac{1}{4}$" from ANDREW) at region of less hostile radiation environment (ionization dose ~100kRad in 10 years) where NINO [8], a time-over-threshold ASIC developed by MIC at CERN, can be used. Optically transmitted signal will be routed to USA15 service cavern where they will be processed with the use of FPGA system. The resulting signal will then be included into the LHC beam abort system.

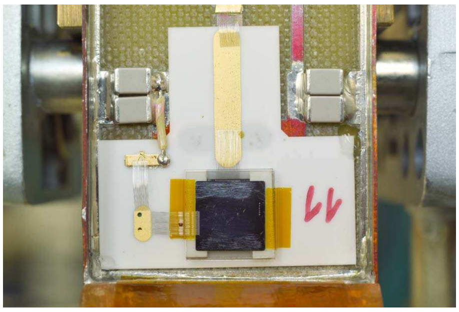

Fig. 3. Ceramic assembly with two back–to-back pCVD diamond sensors.

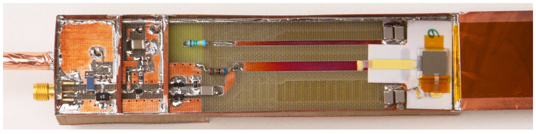

Fig. 4. Top view of ATLAS BCM module. On the right ceramic assembly with two pCVD diamond mounted on top of each other are visible. Left part of module contains two stage fast amplifier, each stage being in a separate compartment.

4 Results

So far detector modules were tested in various stages of development with low energy protons (125 and 200 MeV) at MGH Boston, high energy pions in KEK and CERN and electrons from ^{90}Sr in on-the-bench setup. The details about results of these tests can be found in Refs. [9]-[12]. Here only a short summary of most relevant results is presented. It was confirmed that inclining the modules by 45^o to the beam increases signal by expected factor of $\sqrt{2}$. Further it was also established that it is beneficial to use modules with two back-to-back diamonds which give double signal while the noise was increased only by ~30% compared to modules with only one sensor, improving signal to noise ration (SNR) by ~50%. With 200 MHz bandwidth limit SNR was improved by factor of ~1.3. Off-line analysis of recorded wave-forms confirmed that optimal SNR is reach when applying a low-pass filter with pole at 200-

300 MHz. Noise was found to be independent of electric field up to 3 V/μm. It was also measured that using sensors thinned to 300 μm, shows no benefit in terms of SNR even at higher electric fields. Radiation hardness of Agilent amplifier was also tested since degradation of amplification is governed by the first stage. It was observed that irradiation of mixed fluence of 5×10^{14} protons and 5×10^{14}neutrons/cm^2 results in amplification loss of 20% with no change in noise. We also observed that rising of leakage current of BCM module by factor 100 on time scale of days vanishes if the module inclined by 45^o is placed in a strong magnetic field like 2 T, which will be present in ATLAS Inner Detector. This made the current stay well below 10 nA on a time scale of about 3 days. Efficiency as function of NINO threshold was measured during beam test in CERN PS. The result is shown on fignure 5.

In November 2006 extensive qualification tests of final modules were preformed in order to select eight most reliable ones for the installation. Before assembling, all module PCBs were cleaned with Vigon EFM solution in order to remove remnants of soldering flux and organic pollutants. Afterwards modules were subjected to thermo-mechanical test. Before and after this test, measurements with ^{90}Sr as source of MIP signal were preformed. The source was mounted above the module with a 2 mm thick aluminum collimator with round opening of 2 mm aligned to the center of diamond assembly. A scintillator mounted below module provided a trigger for electrons penetrating the diamond assembly. Signals from BCM module were recorded by 1GHz LeCroy LC564A oscilloscope with a 200 MHz bandwidth limit applied. A typical MIP signal pulse recorded is shown on Fig. 6. Signal was extracted as the maximum value found in a 2 ns interval around the peak of average signal while the noise was extracted from baseline fluctuations in a 20 ns interval well before the signal. Typical signal and noise spectrum obtained is shown on Fig. 7.

For one of the final modules accelerated aging was preformed, keeping it at 140^oC for 14 hours, which simulates more than 10 years at 20^oC (if activation energy of 0.8 eV is used). No change in terms of SNR was observed. Other modules were kept at 80^oC for 12 hours for infant mortality test. This was followed by thermal cycling in order to generate stressing due to thermal coefficient of expansion mismatch between components. There were 10 temperature cycles with humidity set to zero and temperature range between -25^OC and 40^oC, which is more extreme than expected in the real experiment. Comparison of results from on-the-bench measurements with ^{90}Sr before and after thermo-mechanical treatments shows no change in SNR. Results for the relevant polarity of bias voltage of eight modules that were selected for installation are summarized in table 1.

Module	**F410**	**F413**	**F420**	**F422**	**F404**	**F405**	**F408**	**F424**
Bias [V]	+1000	+1000	-1000	-1000	+1000	+1000	-1000	-1000
Current [nA]	20	200	200	40	80	40	20	10
SNR	7.8	7.0	7.8	7.3	6.5	7.0	7.0	8.0

Table 1
Results of qualification tests of eight final modules in a on-the-bench setup with ^{90}Sr as a source of MIP signals. Current reading was taken after 10h at bias voltage of $\pm$1000V.

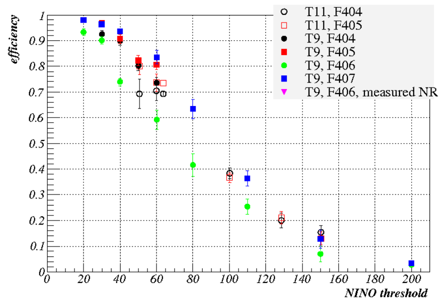

Fig. 5. Efficiency versus NINO threshold measured in CERN PS beam.

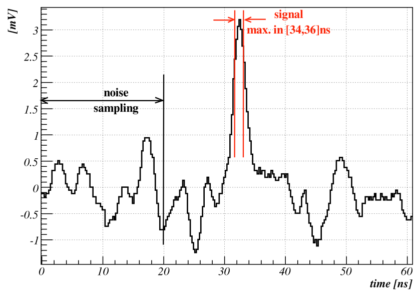

Fig. 6. Typical MIP signal pulse from BCM module recorded by LeCroy oscilloscope in a ^{90}Sr test.

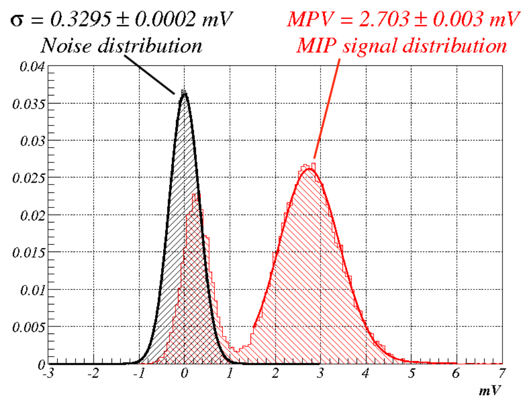

Fig. 7. Normalized MIP signal distribution (hatched red), and noise distribution (hatched black) measured in a ^{90}Sr test for one of the BCM modules. Most Probable Value (MPV) of 2.8 mV was obtained from the fit of Landau-Gauss convolution to signal spectrum, while σ=0.33 mV was extracted from the fit of Gauss function to noise spectrum.

5 Summary

Final BCM modules were subjected to qualification tests before their installation on Beam Pipe Support Structure. No change in SNR, measured with ^{90}Sr as MIP source in on-the-bench setup, was observed after thermo-mechanical treatment of final BCM modules. Typical SNR measured was ~7.5.

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