The ATLAS Beam Conditions Monitor

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***Abstract*– The ATLAS Beam Conditions Monitor is being developed as a stand-alone device allowing to separate LHC collisions from background events induced either on beam gas or by beam accidents, for example scraping at the collimators upstream the spectrometer. This separation can be achieved by timing coincidences between two stations placed symmetric around the interaction point. The 25 ns repetition of collisions poses very stringent requirements on the timing resolution. The optimum separation between collision and background events is just 12.5 ns implying a distance of 3.8 m between the two stations. 3 ns wide pulses are required with 1 ns rise time and baseline restoration in 10 ns. Combined with the radiation field of 10^{15} cm^{-2} in 10 years of LHC operation only diamond detectors are considered suitable for this task.**

pCVD diamond pad detectors of 1 cm^2 and around 500 µm thickness were assembled with a two-stage RF current amplifier and tested in proton beam at MGH, Boston and SPS pion beam at CERN. To increase the S/N ratio two back-to-back diamonds were read out by a single amplifier and the detectors inclined to 45 degrees. Limiting the bandwidth at the readout to 200 MHz provided further improvement; S/N ratio of nearly 10:1 could be achieved with MIP's. Amplifiers of the two stages were irradiated with protons and neutrons to 10^{15} cm^{-2}. Evaluating the irradiated electronics with silicon pad detectors, 20 % degradation in S/N ratio was observed.

Ten detector modules are being assembled and tested at CERN for their final installation into the ATLAS pixel support structure in the beginning of 2006.

I. Introduction

ONE of the worst-case scenarios to be considered during LHC operation is the case where several proton bunches hit the collimators designed to protect the detectors. Although doses from such unlikely accidents still amount only to those accumulated during days of normal operation, and as such pose no major contribution to the integrated dose, the enormous instantaneous rate might provoke detector damage. An early detection of such a disaster developing could provide an abort signal to the LHC machine, preventing it to happen.

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On the other hand, beam gas interactions are also a worry, especially in the early days of LHC running. Common to both of these backgrounds is they predominantly result in showers originating well up- or down-stream of the interaction point. Given two detector stations placed symmetric along the beam pipe on both sides of the interaction point at $\pm z$, shower particles hit the detectors with a time difference $\Delta t = 2z/c$. Collisions at high luminosity add coincident signals in these detectors every 25 ns. Thus distinction between these two classes of events is best achieved by placing the two stations ~3.8 m apart at $z = \pm 1.9$ m, resulting in a Δt of 12.5 ns.

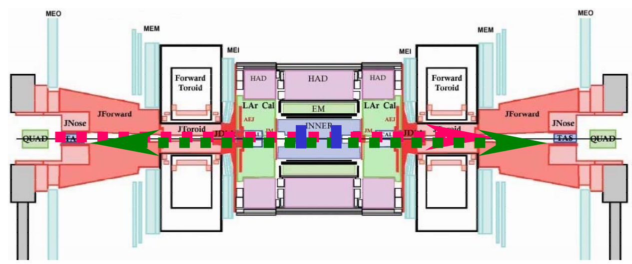

Fig. 1.: Sketch of ATLAS detector with two BCM stations (blue) at $z = \pm 1.9$ m and a sketch of a background (magenta) and interaction (green) induced event.

In the scope of luminosity measurements [1] the Beam Conditions Monitor (BCM) can provide valuable complementary measurements to LUCID, the main ATLAS luminosity monitor. Also during the commissioning of the LHC collider, when tracking detectors are likely to be switched off, BCM might well be the first detector to report 14 TeV proton collisions inside ATLAS.

II. Requirements

The engineered location of the BCM is inside the Pixel Support Tube (PST), with the sensors at a radius of r ~ 55 mm, about 20 mm from the beam pipe, and $|z|$ = 183.8 cm upstream and downstream of the interaction point. One should note that such Δz results in an almost ideal Δt of 12.3 ns.

An estimate [2] predicts particle fluxes of ~ 1 cm^{-2} from a single proton hitting the TAS collimator. A slightly lower flux results from interactions of each bunch crossing at LHC design luminosity of 10^{34} cm^{-2}s^{-1} [1]. Thus minimum ionizing particle (MIP) sensitivity is indicated for an early detection of incidents, and is a prerequisite for a luminosity assessment. Due to interactions inducing signals almost every 25 ns, timing properties of the signal are paramount: fast rise time (~1 ns), narrow pulse width (~3 ns) and base line restoration in

10 ns to prevent pile-up are sought. The radiation field at this location amounts to about 10^{15} particles, mostly pions, per cm^2 and an ionization dose of ~500 kGy in 10 years of LHC operation.

An additional constraint stems from the fact that BCM will be integrated into the PST and covered with layers of pixel services. This will render it almost inaccessible, with any intervention requiring a disassembly of a substantial part of services, an action unlikely to be approved. The design therefore has to remain simple and robust with no risky components built in.

III. Sensors and FE electronics

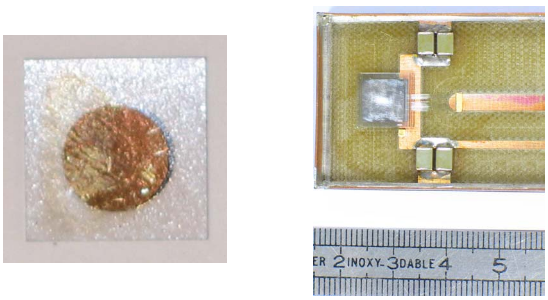

Fig. 2: pCVD diamond sensor with test Au metallization (left) and back-to-back sensors mounted in the module box (right).

Poly-crystalline chemical vapor deposition diamonds were chosen as the only sensor material up-to-date believed to fulfill our requirements in terms of signal speed and radiation hardness. The sensor of choice is the pCVD diamond developed by RD42 [3] and produced by Element Six Ltd. [4]. The timing properties of the ionization current signal are given by high velocity of carriers in the envisaged 2 V/µm electric field and short trapping times even before irradiation. A clear benefit is also the very low leakage current of less than 1 nA/cm^2, allowing operation at room temperature without cooling. Radiation hardness is proven up to fluences of 2.2×10^{15} p/cm2 with a signal degradation of only 15 % [5]. Proprietary radiation hard metallization of the diamonds is applied at Ohio State University.

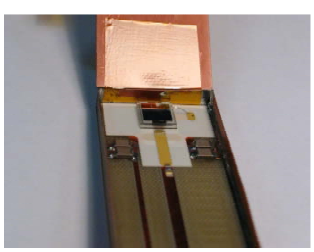

Fig. 3: Back-to-back pCVD diamond sensors assembled on ceramics.

The sensor (Fig. 2) dimensions are 1 cm x 1 cm with the metallization covering 8 mm x 8 mm. Their thickness is around 520 µm, which at a bias of 1000 V provides the sought electric field of 2 V/µm. At 1000 V typical characteristics of the sensors used are leakage current of less than 100 pA and charge collection distance (CCD) around 220 µm [6].

Two back-to-back sensors are assembled (Fig. 3) onto alumina ceramic inserts shorting the signal planes at ground potential [6]. The assembly is glued to a ceramic baseboard supplying high voltage via conducting glue to the bottom diamond backplane and via wire bonds to the top diamond backplane.

Signal is fed through a 5 cm long 50 Ω transmission line to the front end amplifier. In this way the radiation field at the amplifier location is decreased by about 30 %. The front-end [7] designed by Fotec [8] is a two-stage RF amplifier utilizing 500 MHz Agilent MGA-62563 GaAs MMIC low noise amplifier in the first and Mini Circuits Gali 52 InGaP HBT broad-band micro-wave amplifier in the second stage (Fig. 4). Each stage provides an amplification of about 20 dB, with the first stage exhibiting an excellent noise factor of only 0.9 dB.

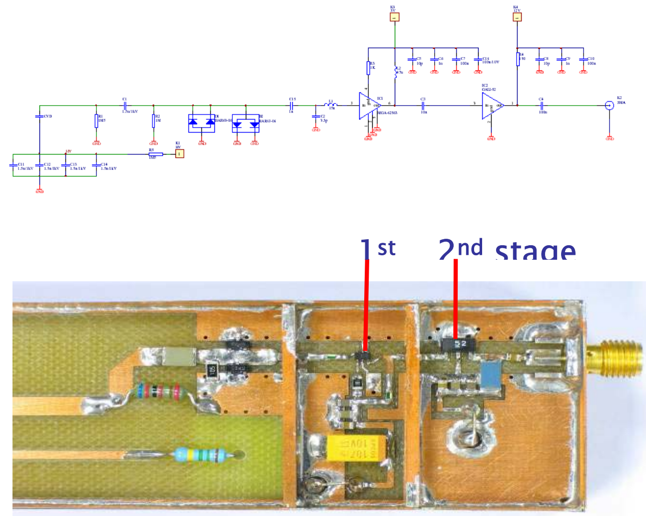

Fig. 4: FE amplifier. Top: amplifier schematics. Bottom: layout of the two amplification stages in BCM module box.

Sensors and FE electronics are mounted in a module box (Fig. 5) designed to RF specifications. Each of the amplification stages is isolated in a separate shielded compartment

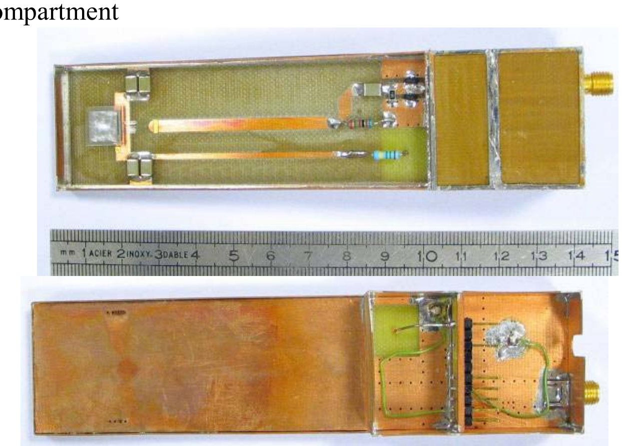

Fig. 5 BCM module box. Top: view exhibiting sensors (left) and HV supply line in parallel to signal transmission line. The compartments containing amplification stages are sealed by soldering. Bottom: isolated HV feed in the left and signal (SMA) and power connectors in the right compartment.

IV. Test Results

The prototype assemblies were tested with electrons from ^{90}Sr source, 125 and 200 MeV protons at MGH Boston, and high energy pions from CERN SPS.

The proton beam at MGH provided signals in diamonds in excess of 2.3 minimum-ionizing particle (MIP) signals. One double-sensor and one single-sensor module were used to investigate signal and timing properties (Fig 6)

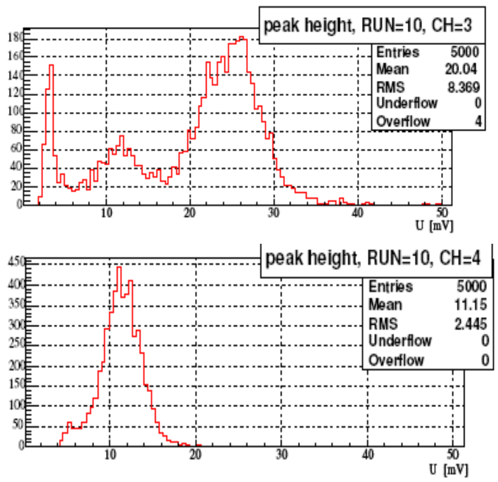

Fig. 6: Signals from double- (top) and single-sensors (bottom) inclined at 45º in 200 MeV proton beam. Because of imperfect sensor matching, both single and double sensor peaks can be observed in the double-sensor module (top).

Inclining sensors to 45º did result in the expected √2 increase of the signal and no effect on the noise. Doubling the sensors on the same amplifier input doubled the signal, with the noise increasing by ~30 %, so the S/N ratio improved by ~50 %. One should note that all sensors had thicknesses (490 µm for the single, 360 µm for each of the double) well in excess of their respective charge collection distances (220 and 160 µm). The signal thus does not scale with detector thickness, so the back-to-back configuration of the sensors with a common readout electrode is crucial for doubling the induced current signal.

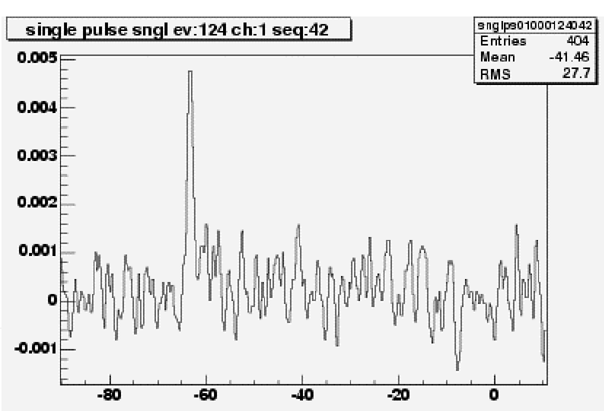

Fig. 7: Typical minimum-ionizing particle signal superimposed on base-line fluctuations as recorded by LeCroy oscilloscope.

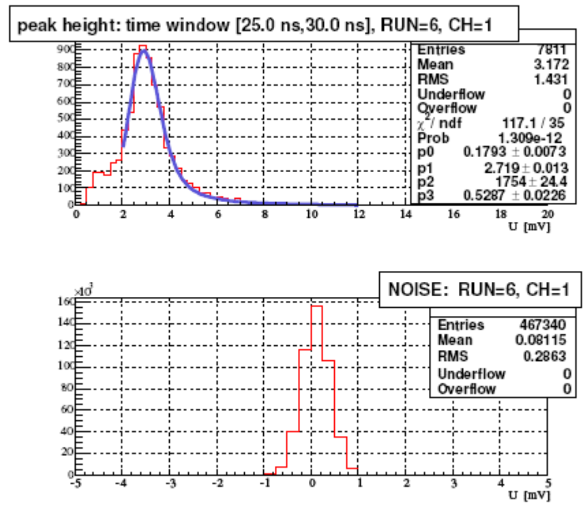

Fig. 8: Signal (top) and noise for double-sensor module at 45º in SPS pion beam read with 200 MHz bandwidth limit on the LeCroy oscilloscope.

The CERN SPS pion beam provided true MIP signals (Fig. 7) and could be used for an absolute calibration of S/N. In addition to the double sensor of CDS 154 and CDS 155 diamonds (360 µm thick) already tested at MGH, production-type CDS 159 and CDS 160 (515 µm thick, CCD 224 and 230 µm @ 1000 V) formed the second double-diamond detector.

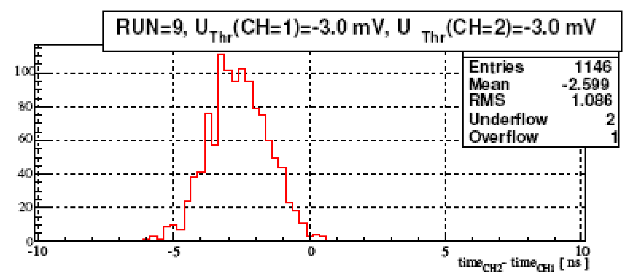

Fig. 9: Time difference between two BCM modules in SPS beam.

Figs. 8 and 9 show the most relevant results. A signal-to-noise (S/N) figure of 7.5:1 could be achieved placing the 1 GHz LeCroy oscilloscope read out at the end of a 16 m long coaxial cable (HELIAX FSJ1 1/4" series from Andrews). The timing difference between the two modules shows a FWHM of 2.5 ns, much better than needed for the final application. It was observed that a 200 MHz bandwidth limit at read-out further improves the S/N to 9.2:1 at the expense of 10 % worse timing. The most probable signal value is referred to as "signal" and RMS of base-line fluctuations as "noise" in S/N ratios throughout this paper.

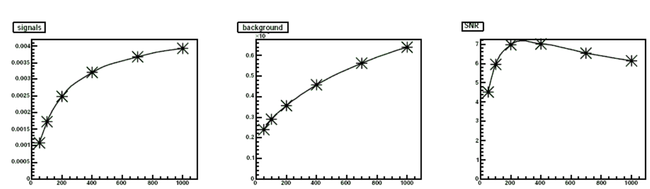

Fig. 10: Off-line analysis of recorded signal wave-forms applying a low pass filter: signal (left), noise (middle) and S/N (right).

Further off-line processing of recorded wave-forms confirmed that optimum S/N is indeed reached applying a low-pass filter with a pole at 200-400 MHz (Fig. 10).

Additional tests were performed with electrons from a ^{90}Sr source. A voltage scan of signal and noise for three assembled BCM modules is shown in Fig. 11. One of the modules had diamonds thinned to 300 µm, and therefore higher electric fields in the diamond could be reached. The band-width limit of 200 MHz implies, however, the amplifier being sensitive more to charge than to (initial) current. Thus the thin diamond performance was measured inferior to those of the thick ones even at higher fields.

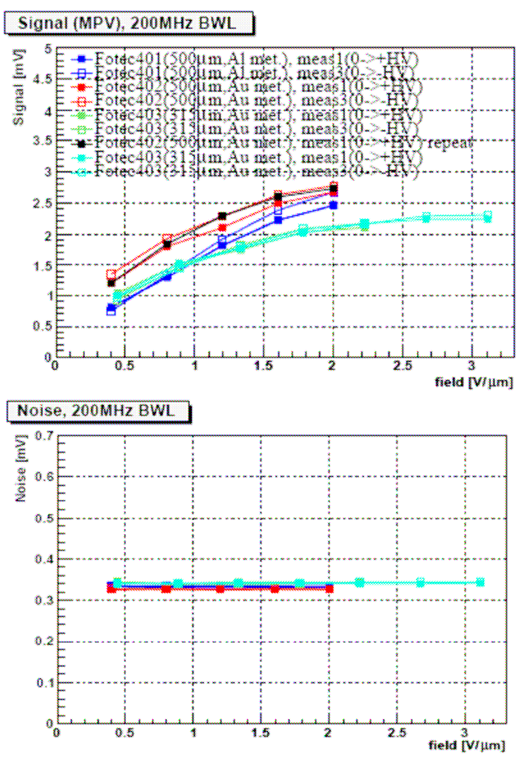

Fig 11: Signal and noise versus voltage during tests with ^{90}Sr source at CERN. Full markers refer to positive and open markers to negative voltages. The diamonds of Fotec 403 (cyan) were thinned down to 300 µm.

To verify radiation hardness of the amplifiers, several of them were irradiated with protons, neutrons and gammas, and subsequently tested. Degradations of amplification at the level of 0.5 dB were observed with the second-stage Gali amplifier. A crucial test was performed by exchanging the first-stage Agilent amplifier of a BCM module with one irradiated to a mixed fluence of $5x10^{14}$ protons and $5x10^{14}$ neutrons/cm^2. Comparing both assemblies with ^{90}Sr source signals from a standard float-zone silicon diode, an amplification loss due to radiation of 20 % was observed with no change in the noise (Fig. 12).

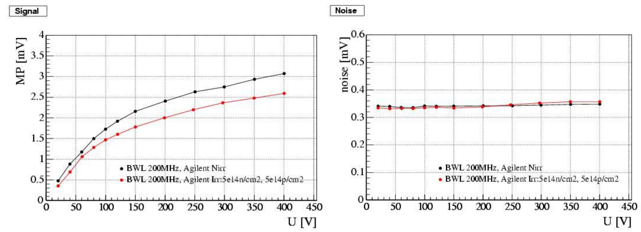

Fig 12: Comparison of signal (left) and noise (right) of BCM amplifier coupled to silicon diode. Black – non-irradiated amplifiers, red – first-stage amplifier irradiated with $5x10^{14}$ protons and $5x10^{14}$ neutrons/cm^2.

V. INTEGRATION

BCM modules are mounted into brackets and fixed to the cruciform of the PST (Fig. 13). Signals are routed via coaxial cables (first 2 m Gore 41, 12 m HELIAX FSJ1) to a region where digitization by radiation tolerant electronics can be applied. The ASIC of choice is the time-over-threshold NINO chip [9] developed for TOF measurements of the ALICE RPC by CERN-MIC. NINO is a differential timing amplifier-discriminator (1 ns peak, 25 ps jitter) with LVDS output width proportional to time-over-threshold. It features radiation tolerant design fabricated in ¼ µm IBM process. The BCM signal is split in a 1:12 ratio into two NINO inputs to increase dynamic range.

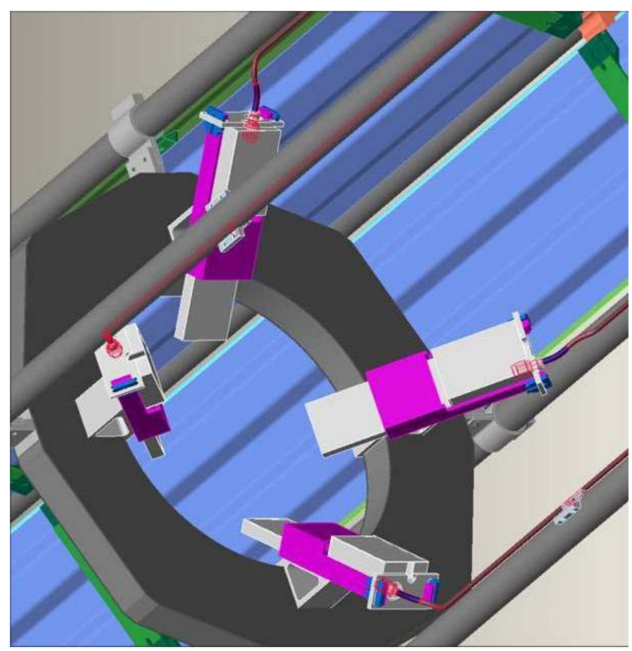

Fig 13: CAD drawing of one of the two BCM stations. Four BCM modules are mounted in brackets and attached to the PST cruciform. The routing of coaxial signal cables is visible.

Tests confirmed the suitability of NINO as BCM back-end chip. Although the threshold circuitry exhibits an offset and limited dynamic range, results in Fig. 14 show that a clear separation of MIP signal from noise can be achieved.

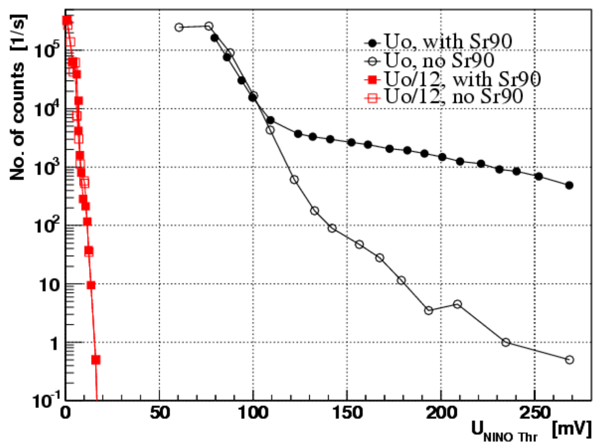

Fig 14: NINO counting rates for the two inputs as a function of threshold. Closed markers were recorded in presence of ^{90}Sr source, open denote observed noise rates.

VI. Conclusions

Tests of BCM module prototypes have demonstrated that adequate performance in terms of S/N and timing can be achieved with pCVD diamond sensors and fast RF current amplifiers. The central activity is now shifting towards assembly ant testing of ten BCM modules, of which eight have to be installed onto the PST structure in spring 2006.

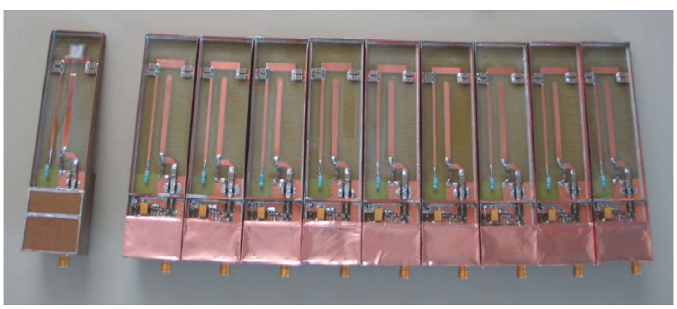

Fig.15: Ten BCM modules, one with mounted diamond detectors, ready for final assembly at CERN

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