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The ATLAS Diamond Beam Monitor

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ABSTRACT: The ATLAS Diamond Beam Monitor is a novel charged-particle detector. It will be used in the ATLAS experiment to measure luminosity and beam background. The monitor’s pCVD diamond sensors are instrumented with pixellated FE-I4 front-end chips. The CVD diamond sensor material was chosen to ensure long-term durability of the sensors in a radiation-hard environment. This document describes the principles of luminosity measurements. It then explains how the Diamond Beam Monitor will carry out this task.

KEYWORDS: Radiation-hard detectors; Particle tracking detectors; Diamond Detectors; Detector design and construction technologies and materials

On behalf of the ATLAS DBM collaboration.
1 Introduction

This paper provides a general description of a novel particle detector called the Diamond Beam Monitor (DBM) which will be installed in the ATLAS experiment [1]. Section 3 provides basic information on luminosity measurements at high-energy physics experiments. Subsequent sections 4, 5 and 6 describe how the new detector tackles the problem of performing these measurements in a radiation-hard environment. Later, some insight on its development, integration and testing is given.

The Large Hadron Collider (LHC) at CERN has been running with an energy of 8 TeV, which is planned to increase to 14 TeV in 2015 following a two-year shutdown. Currently the maximum instantaneous luminosity reached is \( \sim 8 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1} \). However, it is estimated that it will increase by up to 3 times the current value in the next five years. Moreover, the bunch spacing will decrease by a factor of two from the current 50 ns. In addition, the number of particle collisions per bunch crossing will increase due to increased bunch density.

All these factors might cause saturation of the luminosity detectors currently installed. Hence, a new detector called the Diamond Beam Monitor (DBM) has been designed to cope with the increased number of collisions taking place in the ATLAS experiment.
2 Purpose

The DBM was designed as an upgrade to the existing luminosity monitor called the Beam Conditions Monitor (BCM) [2, 3]. The BCM is a particle detector consisting of eight diamond pad detectors. It is able to perform precise time-of-flight (ToF) measurements. The DBM complements the BCM’s features by implementing tracking capability. Its pixelated front-end electronics significantly increase the spatial resolution of the system. Furthermore, the DBM is able to distinguish particle tracks originating in the collision region from the background hits. This capability is a result of its projective geometry pointing towards the interaction region.

Finally, the choice of diamond as a radiation-hard sensor material ensures the stability and durability of the detector throughout its lifetime.

3 Luminosity measurements

Luminosity is one of the most important parameters of a particle collider. It is a measurement of the rate of particle collisions that are produced by two particle beams. It can be described as a function of beam parameters, such as: the number of colliding bunch pairs, the revolution frequency, the number of particles in each bunch and the transverse bunch dimensions. The first four parameters are well defined. However, the transverse bunch dimensions have to be determined experimentally during calibration, as summarised in section 3.1 [4].

3.1 Calibration

The ATLAS experiment uses the van der Meer scan [5] during low-luminosity runs to calibrate the luminosity detectors. This scan is performed by displacing one beam in a given direction and measuring the rate of interactions as a function of the displacement. Transverse charge density of the bunches can be estimated on the basis of the interaction rate. The calibrated luminosity detectors can then operate during high-luminosity runs.

3.2 Monitoring

One approach to luminosity monitoring is to count the number of particles produced by the collisions. The luminosity is then proportional to the number of detected particles. A detector has to be capable of distinguishing individual particles that fly from the interaction point through the active sensor area. If the number of particles reaching the sensors is too high, the detectors may saturate. It is hence important to design detectors with a high time and/or spatial resolution.

4 Detector description

The DBM is a charged-particle detector. Its purpose is to monitor the instantaneous (bunch-by-bunch) luminosity and bunch-by-bunch position of the beam spot in the ATLAS experiment.

When a particle traverses a sensor plane, a hit is recorded in the corresponding pixel. Thus, precise spatial and timing information of the hit is extracted. Moreover, with three or more sensors stacked one behind the other, it is also possible to define the particle’s trajectory. This is the case with the DBM. Its projective geometry allows particles to be tracked if they traverse the sensor
planes. The DBM relates the luminosity to the number of particle tracks that originate from the collision region of the ATLAS experiment. Particles that hit the DBM from other directions are not taken into account.

4.1 CVD diamond sensors

The DBM will be exposed to high radiation levels during operation. Hence, CVD diamond has been chosen as the sensor material due to its high radiation hardness [6]. Only polycrystalline CVD diamonds are commercially available in the required sizes (21 mm × 18 mm, 500 µm thickness). The diamonds used for the DBM have been produced by two companies: II-VI [7] and E6 [8].

CVD diamond is an insulating material due to the large energy gap $E_g \sim 5.5 \text{ eV}$. The principle of operation is similar to that of an ionisation chamber. When a minimum ionising particle (MIP) traverses the sensor plane, it deposits some of its energy. The deposited energy creates electron-hole pairs in the sensor. These then drift in an externally applied electrical field ($\sim 2 \text{ V/µm}$) and induce a current signal on the electrodes at the surface of the diamond [9]. In the case of the DBM, the electrons are pulled into the larger weighting field region and collected by the front-end pixel electrodes.

There are several advantages to using CVD diamond rather than silicon. First, diamond is a highly resistive material. It does not need a reverse-biased p-n junction as is the case with silicon. Furthermore, due to its high $E_g$, there are no free carriers to contribute to noise. This also results in a low leakage current — in the order of 1 nA/mm$^3$ in the $\sim 2 \text{ V/µm}$ electric field for the DBM modules. Moreover, the pixel capacitance is lower for the diamond pixels than for the silicon pixels (35 fF and 120 fF, respectively) [10]. This is a result of the diamond having a smaller dielectric constant and a simpler structure.

In addition, diamond has an excellent thermal conductivity: 2000 W/m·K with respect to 150 W/m·K for silicon. Together with a low generation current, chances of a thermal runaway are minimised. This reduces the need for an extensive cooling system.

Finally, as stated above, diamond is significantly less affected by the radiation than silicon [10]. The use of diamonds thus extends the detector lifetime in a radiation-hard environment.

4.2 Front-end electronics

Currently, the ATLAS pixel detector consists of three layers of silicon pixel sensors utilising the FE-I3 front-end ASIC pixel readout chips. In order to increase the impact parameter resolution of the detector, a fourth layer of sensors will be installed around the beam pipe. A new pixel front-end chip, the FE-I4, has been designed for this upgrade. The newly installed pixel layer is called the Insertable B-Layer (IBL) [11] and is equipped with FE-I4 chips [12]. The DBM will use the same chips.

The FE-I4’s integrated circuit contains readout circuitry for 26 880 pixels arranged in 80 columns on a 250 µm pitch and 336 rows on a 50 µm pitch. The size of the active area is therefore 20.0 mm × 16.8 mm. This fine granularity allows for high precision particle tracking. The chip operates at 40 MHz with a 25 ns acquisition window, which corresponds to the spacing of the particle bunches in the LHC. It is hence able to correlate hits/tracks to their corresponding bunch. Furthermore, each pixel is capable of measuring the deposited charge of a detected particle by using the Time-over-Threshold method. The pixels are designed to collect the negative charge.
Finally, the FEI4 has been designed to withstand a radiation dose up to 300 MGy. This ensures long term stability in the radiation hard forward region of the experiment.

4.3 Data acquisition and triggering

The DBM is instrumented with the same front-end chips as the IBL. As a result, it will make use of the data acquisition (DAQ) hardware and firmware provided for the IBL, reducing the development time and costs. In particular, the IBL employs two 9U VME cards for the readout: the Back of Crate card (BOC) and the Read-Out Driver card (ROD), each housing three FPGAs [13]. One or two ROD-BOC sets will be used to read out the entire DBM, depending on the space available in the FPGAs. The DBM has 32 output channels — 24 160 Mbit/s channels from the 24 DBM modules and eight 320 Mbit/s channels from four Hitbus chips (described below). After the readout, the processed data is sent via optical link to the readout subsystem PCs (ROS), as shown in figure 1.

Despite the similarities between the IBL and the DBM readout, major modifications to the BOC firmware will be necessary to implement the triggering for the DBM luminosity measurements. In particular, a DBM-specific processor in the FPGA will need to trigger the readout with a higher rate than the one from ATLAS. A major task for the DBM processor will be to handle both the DBM-specific triggers and the ATLAS triggers. The latter will always have priority over the former, but their rate will be lower (∼ 100 kHz as compared to ∼ 500 kHz for the DBM-specific triggers). Two options are being studied for generating the triggers for the luminosity measurements. The first one is to generate pseudorandom triggers. In this case, the DBM processor triggers the readout in the way that it tries to measure all bunches in the LHC uniformly. The second option is to use the Hitbus chips installed on the circuit board close to the telescopes. Their programmable logic allows them to send a flag to the DBM processor on specific events (e.g. there is at least one hit in every DBM module in a telescope). The processor then decides whether to read out the detector or not.

4.4 Positioning

The DBM is placed in the forward region of the ATLAS detector — close to the beam pipe (see figure 2). The mechanical structure that holds the sensor planes is, due to its shape, referred to as a DBM telescope. A telescope is a system that consists of several pixel sensors placed in series one behind the other. It is capable of carrying out position-resolved measurements by performing high-precision particle tracking.
Figure 2. This sketch shows the positioning and the alignment of a DBM telescope in the ATLAS experiment.

Each DBM telescope houses three diamond pixel modules. Eight DBM telescopes reside approximately 1 m away from the collision region, four on each side.

Studies have shown [14] that the erratic leakage currents that gradually develop in diamond can be suppressed under certain conditions. If a strong magnetic field is applied perpendicular to the electric field lines in the diamond bulk, the leakage current stabilises [14]. The DBM was designed to exploit this phenomenon. The magnetic field lines in the ATLAS experiment are parallel to the beam. Hence, an angular displacement of the sensor with respect to the beam allows for the leakage current suppression. However, the DBM telescopes still need to be directed towards the interaction region. Taking these considerations into account, a 10° angle with respect to the beam pipe was chosen (see figure 2).

The particle tracks are not significantly affected by the magnetic field given that the field lines are almost parallel to the tracks. This reduces the track reconstruction complexity.

5 Development

The DBM is the product of a collaboration between European and North American institutes. Each institute is in charge of a specific task, whether it is the production, assembly, or testing of detector parts. Part of the production pipeline is shared with the IBL.

5.1 Module assembly

The production of the DBM modules consists of three main steps: diamond sensor preparation, flip chip assembly to FE-I4, and assembly by gluing and wire-bonding.

The polycrystalline CVD diamond is first grown in six inch wafers and thinned down to the required thickness. To measure the quality of the wafer, electrodes are placed across the surface as shown in figure 3. Then a high voltage is applied and the response to high energy particles from a radioactive source is measured. A reliable way to characterise the diamond material for detector applications is to measure the charge collection distance (CCD). This value represents the average distance an electron-hole pair travels in diamond. A higher CCD indicates that a larger electrical signal is produced by the deposited energy of a particle [15]. The DBM specification is $CCD > 200 \mu m$.

After characterisation, the wafer is diced into rectangles of the required size. Only the areas exhibiting the best properties are used. Backside and pixel metallisation is applied on individually diced pieces. The sensor pixel pitch corresponds to that of the FE-I4.
The diamonds with the applied metallisation are bump-bonded to the FE-I4 front-end electronics. During this procedure, known as flip chip, small solder bumps are deposited onto pixels of the FE-I4. Then, the sensor is flipped and the pixel metallisation is aligned to the FE-I4 pixel pattern. Finally, the sensor and FE-I4 are bonded by heating the solder and pressing the two together.

The bump-bonded diamond-chip assemblies are then sent to CERN where they are glued to the mechanic support and wire-bonded to a flex PCB.

5.2 Testing

After assembly, every DBM module is subject to a series of qualification tests. First, the basic chip operations are checked: current consumption, chip configuration, chip readout. Then, a series of procedures is carried out to adjust every pixel to a specific threshold setting (see figure 4). Afterwards, the high-voltage behaviour of the diamond sensor is investigated.

The next step is to check the detector response to high-energy particles. To carry out this test, a scintillator is placed under the module and used as a trigger. When a $^{90}$Sr radioactive source is placed above the module, high-energy electrons traverse the module and hit the scintillator, triggering the chip readout. This way it is possible to check the full sensor area for pixel disconnections or other imperfections (see figure 4). The source test is also used to compare the response of the module at various thresholds and high-voltage settings.

Finally, all modules undergo a mechanical stress test. They are put in a climate chamber where they are subject to thermal cycling. During this procedure, the temperature changes ten times from $-40^\circ C$ to $+20^\circ C$ and back. Then, a second source scan is carried out to check if the thermal cycling has affected the detector operation.

5.3 Installation

The modules that passed the qualification tests are mounted in the DBM telescopes. Each DBM telescope contains three modules which share a common high voltage line. Hence, the modules with matching high-voltage properties are installed together to maximise the tracking efficiency.
Figure 4. The aim of the module test is to tune the pixels to a specific threshold and to check the full sensor area using a radioactive source. These plots have been produced after tuning a module to a 1100 electron threshold. The histograms show the threshold and noise distribution for all 26,880 pixels after tuning the FE-I4. The threshold requirements for the diamond module are very stringent due to the low average electron-hole production in diamond as compared to silicon. In particular, the thresholds need to be of the order of 1000 electrons in order not to cut into the signal produced by MIPs. In addition, average noise in the FE-I4 increases at lower tunings. This prevents the chip to be tuned to extremely low thresholds. In this case, the noise is still far below the threshold. The last plot is a result of a three-hour occupancy scan using a $^{90}$Sr radioactive source. Every bin on the plot corresponds to one pixel in the matrix. There are areas with low hit occupancy. This is owing to an overlaying PCB with mounted passive elements that stop the low energy electrons from hitting the sensor.

Figure 5. Four installed DBM telescopes. The IBL inner support tube (dark cylinder) is clearly visible. DBM is enclosed by the pixel detector services.

When the DBM telescopes are ready, they are installed inside the pixel detector services (see figure 5). Then, a basic set of tests is carried out for each DBM telescope to check if the modules are still intact after mounting. Finally, the whole readout chain is again subject to a full test procedure, with four DBM telescopes (12 modules) being read out at the same time.

6 First test beam

The properties of particle detector prototypes are best evaluated in test beams. A test beam is a beam of particles with well-defined properties. Generally, the particle flavour, rate, and momentum
Each bin corresponds to a single pixel. The statistics are low (∼ 10 hits/pixel) as the data was collected during a short run. The triggering scintillator of the Kartel telescope was smaller than the DUT. Hence, the recorded hits can only be seen in the top half of the sensor. The pixel efficiency distribution is presented in the histogram on the right. The data in these plots is preliminary.

The devices under test (DUTs) are often put in the test beam together with a telescope capable of carrying out very precise position-resolved measurements.

The prototypes were evaluated in a test beam of 5 GeV electrons at DESY, Hamburg, in April 2013. The test beam setup used two telescopes to provide precision measurements of the trajectory of the test beam particles (EUDET Aconite [16] and Ljubljana Kartel [17]), as well as an IBL planar silicon module which was added as a reference to compare results.

The test beam prototypes did not meet the acceptance criteria for production DBM modules in the following areas: first, the CCDs were slightly below 200 μm (the DBM standard). Secondly, the applied bias voltages ranged from 1–2 V/μm. In addition, the threshold cut was set to 1500 electrons, which is higher than the DBM standard (1000 e). Nonetheless, the module efficiencies measured were in the range of 75–85%. A sample of the analysed data is shown in figure 6. An in-depth data analysis is ongoing. Judith software [18] is used to reconstruct and analyse the acquired Kartel test beam data.

7 Conclusion

The Diamond Beam Monitor has been designed as an upgrade to the existing luminosity detectors in the ATLAS experiment. It is the first diamond pixel tracking detector installed in a high-energy physics experiment. The pixelated front-end electronic chips ensure precise spatial detection of the charged high-energy particles. The projective geometry allows for particle tracking and background rejection.

The detector is placed in a high-radiation forward region of the experiment. Therefore, radiation hardness of the chosen pCVD diamond sensors is an important requirement.

The tests carried out in the test beam and in the laboratory confirm that the DBM modules are ready to be installed in the experiment. However, further investigations have to be made to better understand the tracking performance.
At present, the DBM has been installed inside the services of the ATLAS pixel package and the DBM telescopes have passed the final acceptance tests. Due to shortage of good diamond modules, two of the telescopes were built with planar silicon sensors. The pixel detector with its services will be transported below ground and inserted into ATLAS at the beginning of 2014 with back-end services being installed in the following months. The readout firmware is under development. The first collision data are expected in mid-2015.

References