Chapter 1

Charge monitoring – the ATLAS Diamond Beam Monitor

-Diamond Beam Monitor

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Particle detectors in high energy physics experiments need to meet very stringent specifications, depending on the functionality and their position in the experiment. In particular, the detectors close to the collision point are subject to high levels of radiation. Then, they need to operate with a high spatial and temporal segmentation to be able to precisely measure trajectories of hundreds of particles in very short time. In addition, they need to be highly efficient. In terms of the structure, their active sensing area has to be thin so as not to cause the particles to scatter or get stopped, which would worsen the measurements. This also means that they have to have a low heat dissipation so that the cooling system dimensions can be minimised. Finally, they need to be able to operate stably for several years without an intervention, because they are buried deep under tonnes of material and electronics.

The material of choice for the inner detector layers in the HEP experiments is silicon. It can withstand relatively high doses of radiation, it is highly efficient (of the order of $\sim$99.9 %) and relatively low cost due to using existing industrial processes for its production. Its downside is that, with increasing irradiation levels, it needs to be cooled to increasingly low temperatures to still operate stably.

The ATLAS Diamond Beam Monitor (DBM) is a novel high energy charged particle detector. Its function is to measure luminosity and beam background in the ATLAS experiment. The monitor's pCVD diamond sensors are instrumented with pixellated FE-I4 front-end chips. The pCVD diamond sensor material was chosen to ensure the durability of the sensors in a radiation-hard environment. The DBM was designed as an upgrade to the existing luminosity monitor called the Beam Conditions Monitor (BCM) [] 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. This chapter first describes the principles of luminosity measurements. It then explains how the DBM will carry out this task. Finally, some results from tests and from the real collisions are presented.

When a particle traverses a sensor plane, a hit is recorded in the corresponding pixel. Thus, a precise spatial and timing information of the hit is extracted. 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 the 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.

1.1 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. The ATLAS experiment uses the *van der Meer scan* [] 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.

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 detector has at least three layers, it can reconstruct the particle's track, which gives us more information on the particle's trajectory. This is one reason why detectors with a high time and/or spatial segmentation are more suitable for these applications. The second reason is that, with a high spatial segmentation, the detector will not saturate even at high particle fluences.

1.2 Diamond pixel module

1.2.1 Front-end electronics

The FE-I4 (front-end version four) is an ASIC pixel chip designed specifically for the ATLAS pixel detector upgrade. The newly installed pixel layer called the Insertable B-Layer (IBL) [] is equipped with 336 FE-I4 modules. The DBM uses the same chips. The FE-I4's integrated circuit contains readout circuitry for 26880 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 $\times$ 16.8 mm. This fine granularity allows for a 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 (ToT) 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.

1.2.2 Positioning

The DBM is placed in the forward region of the ATLAS detector, very close to the beam pipe. 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. Each DBM telescope houses three diamond pixel modules. Eight DBM telescopes reside approximately 1 m away from the collision region, four on each side. They are tilted with respect to the beam pipe for 10°. This is due to a specific phenomenon connected to erratic (dark) currents in diamond. Studies have shown [] that the erratic leakage currents that gradually develop in diamond can be suppressed under certain conditions. For instance, if a strong magnetic field is applied perpendicular to the electric field lines in the diamond bulk, the leakage current stabilises []. 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. The influence of the magnetic field on the particle tracks at this angle is very low as the field lines are almost parallel to the tracks. The tracks are therefore straight, which reduces the track reconstruction complexity.

1.2.3 Module assembly and quality control

Parts for the detector arrived separately and were assembled at CERN after being checked for production faults. The assembled modules underwent a series of quality control (QC) and burn-in tests to determine their quality, efficiency and stability.

Assembly

A single-chip module consists of a pixel module, a flexible PCB and the supporting mechanics (a ceramic plate and an aluminium plate). The chip arrives already bump-bonded to the sensor, be it diamond or silicon. First it is glued to the ceramic plate on one side and to the PCB on the other using either Araldite 2011 or Staystik 672/472. Then it is wire-bonded and attached to the aluminium plate.

Testing

The modules were tested in the lab using an RCE readout system and a moving stage with two degrees of freedom. They were placed onto the stage and connected to the readout system and the power supplies. After ensuring the low- and high voltage connectivity they were checked for the signal connectivity. If everything was operational, a series of automated tests was run. Each of these tests calibrates a certain value within a pixel, whether it is the signal threshold or the value for integrated charge. These are tuned in a way that the response to a predefined calibration signal is uniform for all pixels across the sensor. This procedure is referred to as *tuning*.

When the modules were tuned, they were tested using a ^{90}Sr radioactive source. Two things were tested: 1) operation of all pixels and 2) sensor efficiency. The first test was carried out by moving the module slowly under the source while taking data so that the whole surface was scanned uniformly. The resulting occupancy map revealed any pixels that were not electrically connected to the sensor via bump bonds. This was an important step in the DBM QC procedure, because it turned out that a significant portion of the flip-chipped diamond sensors exhibited very poor connectivity. The disconnected regions on the faulty modules ranged anywhere from 0.5–80 % of the overall active surface. In two cases the sensor was even completely detached from the chip. The pixel connectivity turned out to be the most important qualification factor in the QC procedure. Unfortunately the only way to check it was to fully assemble a module and test it using a radioactive source. If the module turned out to be of poor quality, it was disassembled and sent for rework. The turnover time of this operation was of the order of one month, which affected the detector installation schedule significantly. Only the sensors that passed the pixel connectivity test underwent the second test stage in which the sensor's efficiency was estimated. In principle, a scintillator placed underneath the module was used as a trigger; a particle that crossed the DBM module and hit the scintillator, triggered the module readout. In the end, the number of triggers was compared to the number of hits/clusters recorded by the module. The resulting ratio was an estimate of the sensor's detection efficiency. The real sensor efficiency can only be measured in a particle beam and using a beam telescope as a reference detector. Nonetheless, the so-called *pseudo-efficiency* gave a rough estimate of the sensors' quality. For instance, the majority of the silicon modules yielded the pseudo-efficiency of 94.3±0.2 %. Silicon sensors being 99.99 % efficient, this value vas underestimated by about 5 %. The measured pseudo-efficiency of the diamond modules was anywhere between 5–80 %, depending on the diamond quality, the set threshold and the applied bias voltage. All in all, 79 modules went through the QC procedure – 45 diamond modules and 34 silicon modules, 12 of the latter only for testing purposes. 18 diamond modules and 6 silicon modules were in the end chosen to be made up into DBM telescopes and installed into ATLAS.

1.2.4 Installation and commissioning

1.3 Performance results

1.3.1 Source tests

1.3.2 Test beam results

Spatial resolution, efficiency, ToT

1.4 Limitations

comparison between diamond and silicon modules