Measurement of the charged particle density with the ATLAS detector: First data at $\sqrt{s} = 0.9$, 2.36 and 7 TeV

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Chapter 2

The ATLAS experiment

The ATLAS (A Toroidal LHC ApparatuS) detector [17] has been built to fully exploit the physics potential of the LHC. The goals of the ATLAS physics programme are diverse: they reach from an improved measurement of the properties of well known particles like the mass of the $W$ boson or the top quark to the search for the Higgs boson and possible discoveries of physics beyond the Standard Model as predicted by supersymmetric theories for example. This chapter outlines the key components and design of the ATLAS detector, followed by a detailed description of the inner detector.

Figure 2.1: Cut-away view of the ATLAS detector.
The ATLAS experiment

A cut-away view of the ATLAS detector, which has a length of 44 m and a diameter of 25 m, is shown in Figure 2.1. The individual detectors are arranged in cylindrical layers around the beam pipe in the central part - the barrel - and as wheels perpendicular to the beam axis in the forward parts - the end-caps. The major detector components are the inner detector, the calorimeters and the muon spectrometer. Perhaps the most striking feature of the ATLAS detector is however its magnet system. Eight air-core toroids provide the magnetic field for the muon spectrometer while the magnetic field in the inner detector is produced by a solenoid. To reach its benchmark physics goals the following demands were imposed on the detector design:

- High reconstruction efficiency and precise momentum determination of charged particles in the inner detector as well as the ability to precisely determine secondary vertices for the identification of $\tau$ leptons and jets from $b$ quarks.

- Good electromagnetic calorimetry to identify electrons and photons as well as precise hadronic calorimetry for an accurate measurements of jet energy and the missing transverse energy.

- Efficient muon identification with a good momentum resolution over a wide range of momenta and the ability to unambiguously determine the charge of high $p_T$ muons.

- Highly efficient trigger system with sufficient rejection of background events.

Table 2.1: General performance design of the ATLAS detector. For high-$p_T$ muons, the muon-spectrometer performance is independent of the inner-detector system. [17]

<table>
<thead>
<tr>
<th>Component</th>
<th>Resolution</th>
<th>$\eta$ coverage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tracking</td>
<td>$p_T/p_T = 0.05% \times p_T \oplus 1%$</td>
<td>$\pm 2.5$</td>
</tr>
<tr>
<td>EM calorimetry</td>
<td>$\sigma_E/E = 10% / \sqrt{E} \oplus 0.7%$</td>
<td>$\pm 3.2$</td>
</tr>
<tr>
<td>Hadronic calorimetry</td>
<td></td>
<td></td>
</tr>
<tr>
<td>barrel</td>
<td>$\sigma_E/E = 50% / \sqrt{E} \oplus 3%$</td>
<td>$\pm 3.2$</td>
</tr>
<tr>
<td>and end-cap</td>
<td>$\sigma_E/E = 100% / \sqrt{E} \oplus 10%$</td>
<td>$3.1 &lt;</td>
</tr>
<tr>
<td>forward</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Muon spectrometer</td>
<td>$p_T/p_T = 10%$ at $p_T = 1$ TeV</td>
<td>$\pm 2.7$</td>
</tr>
</tbody>
</table>

These requirements have also been quantified for each component of the detector and are summarised in Table 2.1. Besides these requirements, the detector has to cope with the harsh environment of high interaction rates, radiation doses and particle multiplicities at the LHC. Fast, radiation hard electronics and sensor elements that provide a high granularity for the reconstruction of physics objects and ensure a high data taking efficiency over several years are thus needed.

The measurement of the charged particle density as described in this thesis is one of the early physics measurements. The main detector components needed for this measurement are the Minimum Bias Trigger Scintillators (MBTS) and the inner detector.
2.1 General layout

The ATLAS coordinate system is a right-handed coordinate system with the nominal interaction point as origin. The positive $x$ axis is defined as pointing from the interaction point to the centre of the LHC ring and the positive $y$ axis is defined to point upwards marking the $x−y$ plane, which is transverse to the beam direction. The positive $z$ axis is then oriented parallel to the beam line in anti-clockwise direction.

Commonly a polar coordinate system is used in ATLAS. The radial component $R$ is defined in the $x−y$ plane and the azimuthal angle $\phi$ is defined as the angle in the $x−y$ plane with respect to the positive $x$ axis. The polar angle $\theta$ is the angle with respect to the positive $z$ axis. Often the pseudorapidity $\eta$ is used that is defined by

$$\eta = -\ln \left( \tan \frac{\theta}{2} \right).$$  \hspace{1cm} (2.1)

Convenient properties of the pseudorapidity are that the difference in pseudorapidity of two particles is invariant under Lorentz boosts along the beam directions if the particles are massless and that the distribution of charged particles is approximately constant as a function of $\eta$.

2.1.1 Inner detector

The inner detector [64] as shown in Figure 2.2 provides an efficient detection of charged particles with high spatial and momentum resolutions and is capable of identifying primary and secondary vertices. It is located in a solenoidal magnetic field with a maximum field strength of $B_z = 2$ T parallel to the beam axis and provides full azimuthal coverage within the pseudorapidity range $|\eta| < 2.5$. The detector is able to detect charged particles with a transverse momentum as low as 100 MeV.

The inner detector is the component closest to the interaction point and is composed of three separate detectors: a silicon pixel detector, a silicon strip detector (SemiConductor Tracker, SCT) and a straw tube detector (Transition Radiation Tracker, TRT). The inner detector is contained within a cylindrical envelope of 7024 mm length and a diameter of 2300 mm. On average a reconstructed track has three pixel hits, eight SCT hits and approximately 35 hits in the TRT.

The hit resolutions of the three detector systems are summarised in Table 2.2 together with their required alignment precisions. The initial accuracy to which the position of the detector elements was known after they were installed in the cavern was according to plan. The relative precision within the volume of the inner detector was of $\mathcal{O}(1 \text{ mm})$ for an entire barrel or end-cap, of $\mathcal{O}(100 \text{ \mu m})$ for a single layer or disk and of $\mathcal{O}(10 \text{ \mu m})$ for individual modules [65] within a layer or disk. Track-based algorithms are used to resolve these residual misalignments. More information on the alignment procedure and the achieved hit resolutions are given in Section 4.3.
Figure 2.2: A schematic view of the inner detector. In the central part, the detector elements are arranged in cylindrical layers. In the end-caps, the modules are arranged in wheels perpendicular to the beam axis.
Table 2.2: Intrinsic measurement accuracies and mechanical alignment tolerances for the inner detector sub-systems. The quoted values refer to individual modules in the pixel and SCT detectors respectively individual straws in the TRT. [17]

<table>
<thead>
<tr>
<th>Detector component</th>
<th>Intrinsic accuracy (µm)</th>
<th>Alignment tolerances (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Radial (R)</td>
<td>Axial (z)</td>
</tr>
<tr>
<td><strong>Pixel</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Barrel layers</td>
<td>10 (R-φ)</td>
<td>115 (z)</td>
</tr>
<tr>
<td>End-cap disks</td>
<td>10 (R-φ)</td>
<td>115 (R)</td>
</tr>
<tr>
<td><strong>SCT</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Barrel layers</td>
<td>17 (R-φ)</td>
<td>580 (z)</td>
</tr>
<tr>
<td>End-cap disks</td>
<td>17 (R-φ)</td>
<td>580 (R)</td>
</tr>
<tr>
<td>TRT</td>
<td>130 (R-φ)</td>
<td></td>
</tr>
</tbody>
</table>

2.1.2 Calorimeters

Electromagnetic calorimeter

The ATLAS calorimeter system [66] is located around the solenoid as shown in Figure 2.1. The electromagnetic calorimeter precisely measures the energy and direction of electrons and photons. It is a sampling calorimeter using lead as absorber material and LAr as active or sampling material. The $\Delta \eta \times \Delta \phi$ granularity is 0.025 x 0.025 in the barrel part which covers a pseudorapidity region of $|\eta| < 1.5$ while the end-caps provide a coverage of $1.375 < |\eta| < 3.2$. An accordion shaped geometry was chosen for the absorbers and the active material to ensure a full and homogeneous coverage in azimuth without any cracks. In total, the amount of material in the electromagnetic calorimeter corresponds to 25 to 35 radiation lengths ($X_0$) and to two to four nuclear interaction lengths ($\lambda$) over the whole range of pseudorapidity. The expected energy resolution is $\sigma_E/E = 10\%/\sqrt{E} \otimes 0.7\%$.

Hadronic calorimeter

The hadronic calorimeters surrounding the electromagnetic calorimeters have a coarser granularity which is still satisfactory to meet the specifications on jet reconstruction. They are divided in the tile calorimeter, the Hadronic End-cap Calorimeters (HEC) and the Forward Calorimeter (FCal). The tile calorimeter covers the central region ($|\eta| < 1.7$) and uses steel as absorber and scintillating tiles as active material. The HEC extends up to $|\eta| = 3.2$ and relies on LAr as active material and copper as absorber material. The expected energy resolution of the barrel and end-cap hadronic calorimeters is $\sigma_E/E = 50\%/\sqrt{E} \otimes 3\%$ for single pions.

In the very forward region up to $|\eta| = 4.9$, the LAr forward calorimeters have been installed to improve the measurement of the missing transverse energy which is produced
by particles that escape the detector undetected such as neutrinos. Again LAr was chosen as active material while the absorbing material is composed of copper and tungsten. The expected energy resolution is $\sigma_E / E = 100\% / \sqrt{E} \oplus 10\%$ for single pions. The cumulative amount of material at the end of the active calorimetry region varies between 10 and 18 nuclear interaction lengths as a function of pseudorapidity.

2.1.3 Muon spectrometer

The muon spectrometer [67] is the outermost part of the ATLAS detector as shown in Figure 2.1. It provides a transverse momentum resolution of approximately 10% for muons with a $p_T$ of 1 TeV. The detection efficiency for muons up to 100 GeV is well above 90%. In addition, it is used to trigger on events containing high-$p_T$ muons. The muon spectrometer covers a radial distance from 5 m to approximately 11 m and a pseudorapidity region of $|\eta| < 2.7$.

The momentum resolution is determined by the magnetic field integral $\int |\vec{B} \times \vec{d}|$ - often referred to as the bending power. The magnetic field to deflect the muons is provided by a toroidal magnet system. In contrast to a solenoidal field, the direction of flight is almost perpendicular to the direction of the magnetic field guaranteeing the highest possible bending power even for particles in the forward direction. The eight air-core coils in the barrel part provide a bending power between 1.5 Tm to 5.5 Tm over the pseudorapidity range $|\eta| < 1.4$. In the forward region, the end-cap toroid magnets produce a bending power of approximately 1 Tm to 7.5 Tm. In the transition region between barrel and end-caps, the bending power is lower.

Four different detector types are used to reconstruct muon trajectories. Monitored Drift Tubes (MDTs) chambers provide a precision measurement of the coordinate in the bending direction of the particles in the central part of the detector. Due to the higher background rate in the forward region, Cathode Strip Chambers (CSCs), which have a higher granularity with respect to the MDTs, have been installed here. Furthermore, Resistive Plate Chambers (RPCs) and Thin Gap Chambers (TGCs) are used for triggering and the measurement of the coordinate orthogonal to the bending direction. The properties of the four muon chamber types are summarised in Table 2.3.

2.1.4 Trigger system

Proton-proton collision events are expected to take place every 25 ns once the LHC is operating at its design parameters. Bearing in mind that approximately 1.3 Mbyte of space are needed to store the detector response of a single event, a data flow of 50 Tbyte/s would be imposed on the data acquisition system if all events were saved for further processing. To reduce the amount of data and reach the desired event rate of about 200 Hz, ATLAS makes use of a three level trigger system composed of Level 1 (L1), Level 2 (L2) and the Event Filter (EF).

At Level 1, the information from on-detector readout electronics in the calorimeters and the muon system is processed to identify events containing high transverse momentum muons, electrons, photons or jets as well as events with large missing or large total
Table 2.3: Summary of the main parameters of the ATLAS muon spectrometer chambers. [17]

<table>
<thead>
<tr>
<th>Monitored Drift Tubes</th>
<th>MDT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coverage</td>
<td>$</td>
</tr>
<tr>
<td>Readout channels</td>
<td>354,000</td>
</tr>
<tr>
<td>Function</td>
<td>Precision tracking</td>
</tr>
<tr>
<td>Cathode Strip Chambers</td>
<td>CSC</td>
</tr>
<tr>
<td>Coverage</td>
<td>$2.0 &lt;</td>
</tr>
<tr>
<td>Readout channels</td>
<td>31,000</td>
</tr>
<tr>
<td>Function</td>
<td>Precision tracking</td>
</tr>
<tr>
<td>Resistive Plate Chambers</td>
<td>RPC</td>
</tr>
<tr>
<td>Coverage</td>
<td>$</td>
</tr>
<tr>
<td>Readout channels</td>
<td>373,000</td>
</tr>
<tr>
<td>Function</td>
<td>Triggering, second coordinate</td>
</tr>
<tr>
<td>Thin Gap Chambers</td>
<td>TGC</td>
</tr>
<tr>
<td>Coverage</td>
<td>$1.05 &lt;</td>
</tr>
<tr>
<td>Readout channels</td>
<td>318,000</td>
</tr>
<tr>
<td>Function</td>
<td>Triggering, second coordinate</td>
</tr>
</tbody>
</table>

transverse energy. The trigger decision is made in less than 2.5 µs and the event rate is reduced to about 75 kHz. At Level 2 and the Event Filter, software algorithms on large computer clusters are used to further select interesting events and to reduce the rate of stored events. The Level 2 trigger algorithms reduce the event rate to 3.5 kHz in approximately 40 ms. The analysis methods used in the Event Filter level further reduce the event rate to reach a maximum of 200 Hz within the allocated processing time of roughly four seconds.

Minimum Bias Trigger Scintillators

For an optimal measurement of the charged particle density, it is vital that the trigger selects as many events from pp collisions as possible while efficiently rejecting background events. Those background events arise from events where protons interact with the gas inside the beam pipe (beam gas events) or when outlier particles hit parts of the detector and cause a spray of particles (beam halo events).

Minimum Bias Trigger Scintillators (MBTS) [68] are used to select the desired minimum bias events. The MBTS consist of 32 scintillator counters of 2 cm thickness each that are arranged in two disks. At each side of ATLAS, one MBTS disk is mounted on the inside of the liquid argon end-cap calorimeters at $z = \pm 3560$ mm shown in Figure 2.3(a). The disks are divided in an inner and outer ring as illustrated in Figure 2.3(b) covering the pseudorapidity region of $2.09 < |\eta| < 2.82$ and $2.82 < |\eta| < 3.84$.
The ATLAS experiment

respectively. Light emitted by each scintillator counter is collected by optical fibres and transmitted to a photomultiplier tube (PMT). The PMT signals are read out, amplified and shaped by the electronics of the hadronic tile calorimeter. The signal is then transmitted to the Central Trigger Processor (CTP) where the trigger decision is made well within the allocated time for the L1 trigger of 2.5 $\mu$s.

Figure 2.3: (a) Photograph of a MBTS disk mounted on the inside of a LAr calorimeter end-cap. (b) Schematic view of a MBTS disk indicating the 16 scintillator counters per disk.

The requirements on the Minimum Bias trigger system differ substantially from the ones during long time detector operation explained in the previous paragraph. Due to the low instantaneous luminosities, which have been measured to be between $10^{26}\text{cm}^{-2}\text{s}^{-1}$ and $10^{29}\text{cm}^{-2}\text{s}^{-1}$ [69] for the data sets used in Chapters 5 and 6, the MBTS were operated without scaling their acceptance during this period. The trigger system thus recorded all potential collision events while the maximum event rate is not superseded.

The trigger criterion for the measurement of the charged particle density requires the presence of both proton beams confirmed by the beam pick up trigger system (BPTX, [70]) and at least one hit on one MBTS disk. Figure 2.4(a) shows a comparison between data and simulation of the measured charge deposit in a typical scintillator with at least one MBTS above threshold. Noise in the MBTS was emulated by adding a Gaussian contribution with a width of 0.02 pC around zero to the simulation of pp collisions. The two distributions are in good agreement although some residual differences remain. The detector simulation is however only used for studying possible correlations with other triggers. The MBTS signal and trigger efficiencies for the final analysis are purely obtained from data. The discriminator threshold for the MBTS was set to a charge deposit of 0.18 pC which is a compromise between suppressing noise hits and retaining a high trigger efficiency. Although some signal events are discarded per

\[^1\text{This is denoted as } L1_{MBTS,I} \text{ trigger signal.}\]
individual counter, typically various scintillators are above threshold in pp collisions, which guarantees a high trigger efficiency as will be shown in Section 5.2.

Figure 2.4: (a) Comparison of the charge deposit in an individual scintillator between data and simulation with an additional term added for the noise in simulation. [71] (b) Time difference between the passthrough of a proton bunch and the recorded MBTS signal for LHC fills with one beam (beam1 and beam2) and two beams (beam1 & beam2). [68]

A simple method to reduce the contribution from background events is to study the time difference between the time of a bunch crossing in the detector and the arrival time of a signal in the MBTS detectors. The time at which a bunch of protons passes through the detector is measured by the LHC clock. For collision events, all scintillators measure roughly the same arrival time of the signal, whereas for background events this time is considerably smaller on one side than on the other. The measured time difference is shown in Figure 2.4(b) for periods where the LHC was filled with either one or two proton beams. At ± 30 ns, peaks originating from the passthrough of only one beam are clearly identified. Consequently only events with a time difference below 10 ns are considered to originate from pp collisions.

2.2 Pixel detector

The pixel detector [72] is the component closest to the beam pipe and it therefore has to cope with a higher particle flux than any other detector in ATLAS. This requires a high granularity to disentangle tracks from individual charged particles with a high efficiency and purity. The fine granularity also enables the identification of primary and secondary vertices.
Figure 2.5: View of a quarter-section of the inner detector showing each of the major detector elements with its active dimensions and envelopes. The lower graphic shows a zoomed-in view on the pixel detector.
The pixel detector consists of 1744 modules that are grouped in three layers in the barrel and three disks in each end-cap. The barrel layers are arranged in 112 staves and the end-cap disks are comprised of a total of 48 end-cap sectors (eight sectors per disk) resulting in a total active area of silicon of approximately 1.7 m$^2$ with 80M readout channels. A schematic view of the inner detector showing the positions of the detector elements including a zoomed-in view on the pixel detector is presented in Figure 2.5.

Throughout the pixel detector the same module design has been used. The size of an individual pixel is $50 \times 400 \, \mu m^2$ in the local $x$ and $y$ direction. This size is dominated by the dimensions of the readout cells which are integrated in the front end ASICS. The hit resolution of a single pixel is estimated to be $(\text{pixel pitch})/\sqrt{12} = 14 \, \mu m \times 173 \, \mu m$. The actual design hit resolution is better with $10 \, \mu m \times 115 \, \mu m$ as quoted in Table 2.2. This is due to the fact that the recorded time over threshold allows to calculate the central position of a pixel cluster as explained below.

The hit efficiency and the corresponding noise occupancy are important characteristics of the pixel detector. In Figure 2.6(a), the efficiency of associating a hit to a track that crossed a detector layer or disk is shown. A high efficiency of approximately 99% is reached for all layers except for the two outermost end-cap disks where the efficiency is slightly lower. Figure 2.6(b) shows that an extremely low probability of recording random hits of $10^{-10}$ is achieved.

![Figure 2.6: (a) Hit to track association efficiency per barrel layer or end-cap disk. (b) Noise occupancy in the pixel detector as a function of various data taking periods for different levels of the event reconstruction. The bulk reconstruction composes the last step where noisy readout channels have already been excluded.](image)

The pixel sensors are made of n$^+$-in-n silicon and have a thickness of approximately 250 $\mu m$. The sensors are fully depleted at a bias voltage of approximately 20 V and will be operated at 150 V being affected by radiation damage. Irradiation of the modules due to the high flux of charged particles will lead to a type inversion of the n-bulk material into n$^-$.

\[\text{Approximately 10\% of the pixels have the size } 50 \times 600 \, \mu m^2.\]
an effective p-type material after several years of operation. This is expected to happen after an irradiation of a fluence \( F_{\text{neq}} \) of \( 10^{13} \text{ neq cm}^{-2} \). After type inversion the effective concentration will grow continuously with time and the depletion voltage will rise up to 600 V after ten years of operation corresponding to an integrated luminosity of 700 fb\(^{-1}\). To mitigate the effects from radiation damage the pixel detector is operated at low temperatures. The pixel detector has been designed to withstand a total fluence \( F_{\text{neq}} \) of approximately \( 1 \cdot 10^{15} \text{ neq cm}^{-2} \). The hit efficiency in the innermost layer (Layer 0) is however expected to significantly decrease after approximately three years of operation and an additional pixel layer mounted on a new beam pipe will be inserted.

The expected radiation damage also influenced the development of the read out electronics. In the readout cells the signal is amplified and compared to a discriminator threshold. When the signal is above threshold, the pixel address, a hit time stamp and the recorded time over threshold are transferred to the module control chip for further processing. The communication with the off-detector data acquisition system is then performed via optical links. Laser diodes (VCSELs, \cite{77,78}) are used for the conversion from electronic to optical signals.

As mentioned above, the recorded time over threshold allows for a better hit resolution compared to a completely binary readout. In general not only a single pixel fires when a module is traversed by a charged particle, but clusters of neighbouring pixels over threshold are formed. This is illustrated in Figure 2.7(a) where the average cluster size is shown as a function of the track incidence angle from cosmic ray data with and without magnetic field. The time over threshold signal is related to the deposited charge in the pixels and the charge sharing ratio \( \Omega_{x,y} \) for a cluster of two fired pixels is computed according to

\[
\Omega_{x,y} = \frac{Q_{\text{last pixel}}}{Q_{\text{last pixel}} + Q_{\text{first pixel}}},
\]

where \( Q \) is the measured charge per pixel in the local \( x \) or \( y \) direction. A straight line is fit to the residual of the position of the extrapolated track on the module and the average position of the two pixels as a function of \( \Omega_{x,y} \), which is shown in Figure 2.7(b). The position of the cluster centre is corrected by the slope of the straight line to obtain a better estimate of the actual cluster centre.

The average cluster size as a function of the track incidence angle as shown in Figure 2.7(a) is also used to measure the Hall angle. In the presence of a magnetic field the drift path of the created electron hole pairs in a silicon detector is deflected by the Lorentz force and the resulting drift angle is called the Hall angle \cite{80}. A precise knowledge of the Hall angle is vital for the detector alignment and to fully exploit the spatial resolution of the detector. The Hall angle is given by the incidence angle at the minimal average cluster size. A clear shift of the minimal cluster size from zero is visible in presence of a magnetic field. The value is obtained by fitting a convolution of a geometrical function and a Gaussian distribution to the data points \cite{79}. The resulting Hall angle for the pixel detector is \( 11.77^\circ \pm 0.03^\circ \) (stat) \( ^{+0.13^\circ}_{-0.23^\circ} \) (syst). The dominant source of the systematic uncertainty is the range to which the fit was applied. The measured value is consistent with the predicted value of \( 12.89^\circ \pm 1.55^\circ \) (syst). The rather high uncertainty
2.2 Pixel detector

![Graph showing average cluster size vs. track incident angle](image)

**Figure 2.7:** (a) Average cluster size as a function of the track incidence angle. [79] (b) The residual between the track extrapolation and the cluster centre as a function of the charge sharing ratio $\Omega_y$ in different regions of pseudorapidity. [74]

...on the prediction arises from the uncertainties on the mobility of the charge carriers and on the non-uniformity of the electric field in the readout sensors. Strictly speaking, the non-uniform electric field is a systematic uncertainty affecting the measurement rather than the prediction.

By the time of writing of this thesis, the pixel detector has been operated for more than two years in the ATLAS cavern taking both data from cosmic ray and pp collisions. By now the focus lies on stable detector operation during collision data taking. Approximately 97% of the modules have been operational since the first collisions were recorded at $\sqrt{s} = 900$ GeV in November 2009 [81]. The main reasons for disabled modules are failures in the data transfer system or in the high voltage supply. Furthermore, 0.16% of the remaining front end chips are disabled. As mentioned above, VCSELs are used for the generation of optical signals to and from the detector. The same design has been used for VCSELs located close to the modules (on-detector) and in the data acquisition racks (off-detector). Problems were encountered with the data transmission boards where the VCSELs are located on the off-detector site. As these boards are accessible and failing boards have been replaced, the data taking efficiency has only been marginally influenced so far. Failures of the on-detector VCSELs have not been observed yet, probably because the on-detector diodes are only in use if a L1 trigger signal was received whereas the off-detector VCSELs are operated at the 40 MHz design collision rate of the LHC.
2.3 Semiconductor Tracker

The SemiConductor Tracker (SCT) is a silicon strip detector which is located around the pixel detector. Its main purpose is to contribute to a precise and efficient identification of charged particles. In addition, it is possible to perform pattern recognition and track reconstruction exclusively from SCT hits (stand-alone), which will be used in Chapter 5 and for studies investigating the detector performance as presented below.

Figure 2.8: Photograph of the fully assembled SCT barrel prior to its insertion in the TRT barrel.

The SCT consists of one barrel and two end-caps. The barrel, which is shown prior to its insertion into the TRT in Figure 2.8, is composed of four cylindrical layers containing 2112 detector modules and each end-cap is made of nine disks containing 988 detector modules. Depending on the particular layer the barrel covers $|\eta| < 1.1$ to 1.4 and the end-caps cover the region up to $|\eta| = 2.5$. The exact position of the detector elements is shown in Figure 2.5. The SCT was designed to contribute with at least four precision measurements to each track within $|\eta| < 2.5$.

An SCT detector module [82, 83] consists of two sensors glued back-to-back under a small stereo angle of 40 mrad to provide a two-dimensional measurement. The same design is used for all barrel modules whereas three different module types varying in external dimensions and strip pitch are used in the end-caps. Photographs of a barrel and of a end-cap module are shown in Figure 2.9.

The sensors are manufactured using p-type readout strips on n-type bulk silicon. The strip pitch is 80 $\mu$m in the barrel and varies in the end-caps between 57 $\mu$m and 94 $\mu$m due to a fan geometry. A spatial resolution of approximately 17 $\mu$m in R-$\phi$ as mentioned in Table 2.2 can be achieved. A smaller strip pitch would imply larger clusters and less deposited charge per strip. After irradiation of the modules, the deposited charge might not satisfy the readout threshold any more and a lowering of the threshold would in turn
2.3 Semiconductor Tracker

Figure 2.9: Photographs of an SCT barrel (a) and end-cap (b) module.

imply an increase of noise hits. In total, there are 768 active readout strips per module side with a length of typically 126 mm.

As the number of readout channels is considerably smaller than in the pixel detector, a higher noise occupancy in the SCT is acceptable. It is required to be below $5 \cdot 10^{-4}$ at a hit efficiency of 99%. Figure 2.10 shows the noise occupancy as measured from cosmic ray data averaged per readout chip (128 channels) in the barrel and end-cap regions. The few readout chips that did not satisfy the specification limit are not displayed. The slight variations of strip length and readout pitch cause the different behaviour of the various module types.

Figure 2.10: Noise occupancy averaged over the number of readout chips as measured in cosmic-ray data. Due to their shorter strip length the noise occupancy of the inner end-cap modules is below the displayed range. [79]

The hit association efficiencies are measured by computing the ratio of the actual and expected number of hits in the ideal case. This means that a stringent track selection has been applied and disabled modules and readout chips have been eliminated from
the analysis. The efficiencies are either measured with tracks reconstructed stand-alone with the SCT or with the full inner detector information as shown in Figure 2.11 for the barrel and one end-cap (end-cap A). Independent of the method all barrel layers and end-cap disks meet the specification of 99% efficiency.

Figure 2.11: Hit efficiencies in the SCT barrel (a) and end-cap A (b) per module side of a layer or disk in $\sqrt{s} = 900$ GeV data. [84]

The SCT sensors have a thickness of approximately 300 µm and are fully depleted at a bias voltage of approximately 70 V. Similar to the pixel detector, irradiation is expected to influence the performance of the modules and the bias voltage will be adjusted accordingly. The maximal voltage will be reached at 500 V after an integrated luminosity of 700 fb$^{-1}$ has been collected. The SCT is using the same evaporative cooling system as the pixel detector to slow down effects from radiation damage and to dissipate the heat produced by the modules. The operating temperature of the modules is approximately 0°C. The detector has been designed to withstand a fluence $F_{\text{neq}}$ of approximately $2 \cdot 10^{14}$ neq cm$^{-2}$ [76].

The SCT sensors are read out by radiation hard ASICs named ABCD chips [85]. The readout is binary and the default threshold was chosen to be 1 fC. At this threshold the hit efficiency and the noise occupancy are within the specification limits as the most probable charge deposition of a minimum ionising particle is about 3.5 fC (22000 electrons) traversing 300 µm of silicon. Additionally, the noise was found to be significantly below 1 fC. Six ABCD chips per module are used to read out the strips. The readout is performed by amplifying the detector signals, discriminating the signals from background noise and then storing the binary signals in an on-chip pipeline memory. This memory is capable of holding the information from 128 bunch crossings. If a L1 trigger signal is received, the data of typically three bunch crossings is compressed and transferred to the off-detector readout electronics via optical links. For the conversion of electronic to optical signals VCSELs are used. VCSELs following the same design as in the pixel detector are used for transmitting control and clock signals to the modules. The VCSELs responsible for transferring the readout signal to the off-detector site were however constructed according to a different design [86].
2.3 Semiconductor Tracker

Figure 2.12: (a) The fraction of recorded hits as a function of the 25 ns read out time bins in the SCT as measured on cosmic ray data. (b) Average cluster size as a function of the track incidence angle. The incidence angle at the minimal cluster size provides the Hall angle. [79]

Similar to the pixel detector, the measurement of the Hall angle is important. The same procedure as described in the previous section is used to fit the average cluster size per hit as a function of the track incidence angle, which is shown in Figure 2.12(b). In general the average cluster size in the SCT is smaller than in the pixel detector due to the wider strip pitch. The resulting Hall angle was determined to be \(-3.93^\circ \pm 0.03^\circ\) (stat) \(\pm 0.10^\circ\) (syst) in presence of the magnetic field which is in good agreement with the theoretical prediction of \(-3.69^\circ \pm 0.26^\circ\). The main systematic uncertainty on the measurement arises again from the range to which the fit function was applied. It is not surprising that different absolute values and signs were determined for the Hall angles in the SCT and pixel detectors as the mobility and the sign of the charge carriers differ; positively charged holes provide the dominant signal in the SCT and negatively charged electrons in the pixel detector.

By October 2010 the SCT has been operated for more than two years since its installation in the ATLAS cavern. The fraction of active readout channels is very high at 99.3\% with only few disabled readout channels (see Table 2.4). In end-cap C 13 modules suffer from a leaking cooling pipe and are excluded from data taking. A few other modules are disabled due to failures of either the high or low voltage supply. Problems have also been encountered with the evaporative cooling system. During its operation it became clear that the design temperature of \(-7^\circ\) C will not be reached and the modules will be operated at \(0^\circ - 5^\circ\) C instead [87]. This may affect the lifetime of the detector due to increased effects from radiation damage. Failures of the data transmission boards, which use the same design for the optical readout links on the off-detector site as in the pixel detector, were also observed in the SCT and disabled data transmission boards have been replaced. The on-detector VCSELs in the SCT follow a different design that seems to work more reliably.
Table 2.4: Configuration of the SCT detector as of 2010. In total, more than 99% of the SCT readout channels are operational. [84]

<table>
<thead>
<tr>
<th>Disabled component</th>
<th>Barrel</th>
<th>End-cap A</th>
<th>End-cap C</th>
<th>Fraction (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Modules</td>
<td>10</td>
<td>5</td>
<td>15</td>
<td>0.73</td>
</tr>
<tr>
<td>Chips</td>
<td>24</td>
<td>5</td>
<td>4</td>
<td>0.07</td>
</tr>
<tr>
<td>Strips</td>
<td>3,186</td>
<td>3,364</td>
<td>3,628</td>
<td>0.17</td>
</tr>
<tr>
<td><strong>Total disabled components</strong></td>
<td><strong>0.97</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

2.4 Transition Radiation Tracker

The Transition Radiation Tracker (TRT) is the outermost sub-system of the inner detector covering a radial distance between 0.55 m and 1.1 m. It is a drift tube detector with the additional capability of generating and detecting transition radiation. The main goals of the TRT are to improve the transverse momentum resolution and to enhance the separation between electrons and pions. The design of a straw tube detector was chosen because straw tube detectors are more cost-efficient than silicon detectors, provide many hits per track and reduce the amount of material in front of the calorimeter compared to an all silicon tracker. However, only one coordinate is measured precisely compared to the two dimensional measurements of the pixel and SCT detectors. Figure 2.13 shows a drawing of the inner detector traversed by a track with a $p_T$ of 10 GeV where the lay-out of the individual straw layers in the TRT barrel is illustrated.

The barrel is divided into three layers of 32 sectors each and has a maximal number of 73 straw layers covering a pseudorapidity region of up to $|\eta| = 1$. In each end-cap 160 straw layers oriented perpendicular to the beam axis are arranged in 20 wheels which extend up to $|\eta| = 2$. The TRT consists of more than 170,000 straws in total.

The straw drift tubes are made of thin Kapton-based multilayer material filled with a Xenon gas mixture as active medium (70% Xe, 27% CO$_2$, 3% O$_2$). They have a diameter of 4 mm and contain a gold-plated tungsten anode wire in the centre with a diameter of 30 µm. When a high energy charged particle transits a straw, some atoms of the gas mixture are ionised and the created free electrons are multiplied after they drifted close to the anode wire. The positive ions on the other hand are attracted to the cathode and the resulting current is detected. The hit resolution in the TRT is 130 µm as quoted in Table 2.2. The maximal length of an individual straw is 144 cm in the barrel and 37 cm in the end-caps, which has been chosen such that the counting rate per wire does not exceed 20 MHz at the LHC design luminosity.

To achieve the best hit resolution it is crucial to determine the distance in a straw from the measured drift time of the ionised electrons towards the anode. Figure 2.14(a) shows the drift-time $(r - t)$ relation as measured on cosmic ray data fitted by a third order polynomial. The actual measurement used in the track fit is a circle around the anode
2.4 Transition Radiation Tracker

Figure 2.13: Drawing of parts of the inner detector barrel and of the beam pipe. The arrangement of the TRT straws in layers within their support structures is illustrated.

wire with the radius of the calculated drift distance.\(^3\) In Figure 2.14(b), the distance from the predicted track position to the measured hit position in the module is shown for TRT barrel modules. The intrinsic hit resolution and uncertainties from the track extrapolation contribute to the width of this hit residual distribution. The consistency of the data with the predictions from simulation proves the excellent understanding of the hit resolutions.

An important figure of merit is the association efficiency of a hit to a track which is calculated as the ratio of the number of hits associated to a track and the number of straws crossed by a charged particle. Figure 2.15(a) shows that the efficiency is highest at approximately 95% if the track crosses the straw about 0.5 mm away from its centre while the efficiency decreases with increasing distance from the centre. The efficiencies measured in data closely follow the predicted values from simulation. In general the hit

\(^3\)This circle is also known as drift circle.
efficiency in the TRT is lower than in the silicon detectors. The impact on the track reconstruction is however marginal as there are approximately 35 TRT hits per track compared to only three respectively eight hits from the pixel and SCT detectors.

Figure 2.14: (a) Drift-time relation fitted with a third order polynomial on cosmic ray data. [79] (b) Comparison of hit residuals between data and simulation for all TRT barrel modules. The two sets of alignment constants on data were derived from cosmic-ray (Pre-Collisions Alignment) and collision data (Post-Collisions Alignment) respectively. [88]

Figure 2.15: (a) Hit efficiency as a function of the distance to the anode wire. [89] (b) The probability of a high threshold hit as a function of the $\gamma$. [89]

The capability of separating electrons from pions is based on the installation of material layers with different dielectric constants. When a high energetic charged particle crosses the boundaries between these layers, transition radiation photons with an energy between approximately 5 keV and 10 keV are produced in a cone around the particle.
The amount of transition radiation depends on the Lorentz $\gamma$ factor which is given by $\gamma = E/m$. As the pion mass is more than 250 times bigger than the electron mass, electrons in the energy range between 1 GeV and 200 GeV produce much more transition radiation photons that are in turn absorbed by the Xe gas mixture. In order to identify these transition radiation hits, the read out electronics are equipped with two thresholds: one high threshold of approximately 6 keV and one low threshold of a few hundred eV.

The probability of a high threshold hit in the barrel is shown as a function of the Lorentz $\gamma$ factor in Figure 2.15(b). For $\gamma$ factors above $10^3$ the probability starts to rise and reaches a plateau at approximately 0.25 for $\gamma > 10^4$. This behaviour can be understood by looking at the yield of transition radiation as a function of the $\gamma$ factor. Whereas for $\gamma$ values between $10^3$ and $10^4$ the yield rises linearly with $\gamma$, the radiation spectrum of a periodic radiator does not become harder as the energy of the particle increases further and a saturation effect occurs for $\gamma$ factors above approximately $2 \cdot 10^4$ [90].

The TRT has been operated reliably since its first turn-on in the ATLAS cavern in fall 2008. 97.1% of the 350k readout channels are in operation [91]. Problems were encountered when ATLAS switched from its internal clock to the LHC clock at the beginning of a data taking period as parts of the detector loose synchronisation. Automatic recovery processes were installed to re-synchronise the detector and guarantee a good timing [92].