The top and beyond: missing energy and little Higgs in ATLAS
Rijpstra, M.

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The ATLAS Detector

This chapter describes the experimental setup that provides the data of interest: the ATLAS detector. It is one of the four particle detectors that are designed to measure physics processes that occur at collisions of hadrons produced by the Large Hadron Collider. In the first section, the Large Hadron Collider is described. The subsequent sections cover the ATLAS detector and each of its components.

2.1 The Large Hadron Collider

The Large Hadron Collider (LHC) is a circular particle accelerator situated at CERN in the tunnel where the Large Electron Positron accelerator (LEP) operated between the years 1989 and 2000. The LHC is designed to collide beams of protons with 14 TeV center of mass energy, whereas LEP collided electrons on positrons with center of mass energies from 91 GeV up to 209 GeV. The larger energy and the fact that the two beams of particles are not mutual antiparticles require a more advanced accelerator machine.

The counter-rotating beams cross each other in four points along the tunnel, where the particle detectors ALICE [28], ATLAS, CMS [29] and LHCb [30] are located. Figure 2.1 locates the detectors along the LHC ring as well as the pre-accelerators: the linear accelerator (LINAC), the Proton Synchotron Booster (PSB), the Proton Synchotron (PS) and the Super Proton Synchotron (SPS). Protons are produced by stripping electrons from hydrogen atoms and are subsequently accelerated to 50 MeV in the LINAC. The protons are then accelerated in three steps by the circular pre-accelerators to 1 GeV, 26 GeV and 450 GeV respectively. An arrangement of the protons into bunches of $10^{11}$ protons each and a 25 ns bunch separation are established. The SPS finally injects the bunches both in clockwise and counter-clockwise direction into the LHC, which accelerates them to energies up to 7 TeV.

The LHC [31] consists of eight arcs and eight straight sections, adding up to a circumference of 27 km. The two vacuum beam pipes are surrounded by several thousands of superconducting magnets, which accomplish the bending and focusing of the beams. As the radius of the accelerator is fixed by the existing tunnel, the energy of the proton beams

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1 Occasionally beams of lead ions are accelerated and collided at $\sqrt{s} = 1148$ TeV instead.
is constrained by the strength of the bending magnets. The bending is achieved by 1232 dipole magnets, which are cooled to 1.9 K by liquid helium and provide a field strength of 8.33 T. A special twin aperture design of the magnets allows the two beams to be subject to opposite magnetic fields while sharing the iron structure and helium vessel.

The actual acceleration of the proton beams is established in radio frequency cavities, where an oscillating electric field of 2 MV is generated. The oscillation frequency of 400 MHz is tuned to the bunch spacing of the beams.

In addition to the center of mass energy of the provided collisions, an important characteristic of an accelerator machine is the beam intensity or luminosity $L$. It determines the rate of proton-proton interactions and thereby the rate of interesting events that occur in the center of the ATLAS detector:

$$\frac{dN_{\text{events}}}{dt} = L\sigma_{\text{events}},$$

where $\sigma_{\text{events}}$ is the cross section of those events at a given $\sqrt{s}$. The achieved luminosity of an accelerator is described as

$$L = \frac{fNn^2}{A},$$

where $f$ is the revolution frequency, $N$ is the number of bunches per beam, $n$ is the number of particles per bunch and $A$ is the cross section of the beam. The target luminosity of the LHC, $L = 10^{34}$ cm$^{-2}$s$^{-1}$, is reached by operating at the values given in Table 2.1.

The luminosity is subject to degradation due to beam losses from collisions and imperfections, resulting in an expected beam lifetime of approximately 15 hours [31]. Refilling the LHC requires roughly 4 minutes per beam and ramping up the energy from 450 GeV to 7 TeV in the LHC machine takes an additional 20 minutes, thus defining the minimum turnaround time. In a realistic scenario, the acquired integrated luminosity is estimated at 100 fb$^{-1}$ per year when running at design luminosity.

Operating the LHC machine at design beam energies and design luminosity is a delicate procedure for which no test setup exists. Initially, in 2008, a faulty electrical connection
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<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Circumference</td>
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</tr>
<tr>
<td>Injection energy</td>
<td>450 GeV</td>
</tr>
<tr>
<td>Bunch spacing</td>
<td>25 ns</td>
</tr>
<tr>
<td>Particles per bunch $n$</td>
<td>$10^{11}$</td>
</tr>
<tr>
<td>Bunches per beam $N$</td>
<td>2808</td>
</tr>
<tr>
<td>Revolution frequency $f$</td>
<td>11 kHz</td>
</tr>
<tr>
<td>Beam radius</td>
<td>16 $\mu$m</td>
</tr>
</tbody>
</table>

Table 2.1: Properties of the LHC at $\sqrt{s} = 14$ TeV proton-proton operation and design luminosity $L = 10^{34}$ cm$^{-2}$s$^{-1}$.

between two magnets caused severe damage to the accelerator and a full year was needed for recovery. At the next attempt, in November 2009, the beams were maintained at injection energy to get acquainted with the steering and stabilizing. Thousands of events were recorded with the ATLAS detector at $\sqrt{s} = 900$ GeV and provided the first opportunity to test reconstruction algorithms and detector performance with proton collisions. The energy was gradually ramped up to reach the world record center of mass energy of 2.36 TeV on December 8th, 2009. The collision energies were expected not to exceed 10 TeV until 2012, after a scheduled maintenance shutdown, which is therefore the focus of the studies in this thesis.

Ultimately, during summer 2010, a center of mass energy of 7 TeV was maintained and a total integrated luminosity of 3.46 pb$^{-1}$ was recorded by ATLAS up until the sixth of September. The instantaneous luminosity reached a maximum of $10^{31}$ cm$^{-2}$s$^{-1}$, which is a thousandth of the design luminosity. Figure 2.2 displays the course of integrated luminosity delivered by the LHC as well as the part recorded by the ATLAS detector. The recorded collisions are investigated in Chapter 8.

2.2 The ATLAS Detector

The ATLAS detector was designed to observe the wide range of particles that are expected to be created in proton-proton collisions at the unprecedented energies and luminosity. To this end, it is built up of several subdetectors, configured in concentric layers around the interaction point, each optimized for the detection of a specific type of particles. Charged particles leave traces in the tracking detectors and all particles except for muons and neutrinos deposit their energy in the calorimeters. Muons are detected by the muon detectors in the outermost layer, whereas neutrinos escape the detector without leaving a trace.

From the interaction point outwards, the first subdetector of ATLAS is the inner detector, one of the two tracking detectors. The subsequent subdetector is the calorimeter system, divided into an electromagnetic and a hadronic component, which measures

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2 During 2008 several runs of cosmic muon data were taken with ATLAS.
3 Their transverse momenta can nevertheless be reconstructed by means of momentum conservation in the transverse plane. This procedure is addressed in detail in Section 4.6 and Chapter 6.
Figure 2.2: Integrated luminosity delivered by the LHC (blue) and recorded by ATLAS (yellow) up to September 6, 2010 during stable beams with $\sqrt{s} = 7$ TeV. Figure taken from [32].

The energy of particles by total absorption. The outer tracking detector is the muon spectrometer, designed to measure tracks of muons in particular. Both tracking detectors operate in a magnetic field, provided by a solenoidal and a toroidal magnet system respectively. Figure 2.3 illustrates the arrangement of the subdetectors and magnets that compose the ATLAS detector. In addition, the dimensions are shown, which indicate that it is the largest particle detector ever built for an accelerator experiment. The detector was installed in the underground cavern between 2003 and 2008 after many years of research, preparation and construction.

The Coordinate System

The origin of the ATLAS coordinate system is defined as the nominal interaction point in the center of the detector. The $z$-axis runs parallel to the beam line in counterclockwise direction. The half of the detector that corresponds to positive values of $z$ is referred to as side $A$ and the other half as side $C$. The $x$-axis points to the center of the LHC ring and the $y$-axis points upwards to the surface, resulting in a righthanded orientation. The $xy$-plane is referred to as the transverse plane.

The ATLAS detector has a global cylindrical structure, where each subdetector consists of concentric layers around the beam axis, the barrel component, and two endcaps formed by disks perpendicular to the $z$-axis on each side of the interaction point. A coordinate system closely related to cylindrical coordinates is convenient. The radial distance is given by $R = \sqrt{x^2 + y^2}$. The azimuthal angle $\phi \in [-\pi, \pi]$ is the angle with the positive $x$-axis and increases in clockwise direction when looking down the positive $z$-axis. The polar angle $\theta \in [0, \pi]$ is defined as the angle with the positive $z$-axis, albeit generally replaced by the...
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Figure 2.3: Computer generated image of the ATLAS detector. A part is cut away in order to reveal the structure of concentric subdetectors that constitute the detector.

**Pseudorapidity** $\eta$, which is given by

$$\eta = -\ln \left[ \tan \left( \frac{\theta}{2} \right) \right]. \quad (2.3)$$

The preference for this quantity is motivated by the particle flux being roughly constant as a function of $\eta$. A direction ($\eta, \varphi$) is assigned to reconstructed final state objects and the opening angle between two of them is denoted $\Delta R$, i.e.

$$\Delta R = \sqrt{(\Delta \eta)^2 + (\Delta \varphi)^2}. \quad (2.4)$$

**Requirements**

The performance requirements for the design of the ATLAS detector are based on the processes that may be observed at this new energy scale, such as the production of the Higgs boson, SUSY particles or heavy gauge bosons $W'$ and $Z'$. The extensive variety of objects to be detected, the broad energy range of particles to be measured, the high radiation conditions and the high collision rate impose strict requirements on the detector’s precision, speed, performance, radiation hardness, efficiency and acceptance. The performance requirements in terms of resolution as well as the acceptance of each subdetector are summarized in Table 2.2. An additional challenge is the instantaneous
selection of collisions to be stored, which is taken care of by the trigger system. This is addressed in Section 2.2.5, after the three subdetectors and the magnet system are described in more detail in Sections 2.2.1 through 2.2.4.

<table>
<thead>
<tr>
<th>Subdetector</th>
<th>Required Resolution</th>
<th>( \eta ) coverage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inner Detector</td>
<td>( \sigma(p_T)/p_T = 0.05% \ p_T \oplus 1% )</td>
<td>(</td>
</tr>
<tr>
<td>Electromagnetic Calorimeter</td>
<td>( \sigma(E)/E = 10%/\sqrt{E(\text{GeV})} \oplus 0.7% )</td>
<td>(</td>
</tr>
<tr>
<td>Hadronic Calorimeter</td>
<td>( \sigma(E)/E = 50%/\sqrt{E(\text{GeV})} \oplus 3% )</td>
<td>(</td>
</tr>
<tr>
<td></td>
<td>( \sigma(E)/E = 100%/\sqrt{E(\text{GeV})} \oplus 10% )</td>
<td>( 3.1 &lt;</td>
</tr>
<tr>
<td>Muon Spectrometer</td>
<td>( \sigma(p_T)/p_T = 10% ) at ( p_T = 1 \text{ TeV} )</td>
<td>(</td>
</tr>
</tbody>
</table>

Table 2.2: Performance requirements for the subdetectors of the ATLAS detector [33].

### 2.2.1 The Inner Detector

The inner detector is the subdetector closest to the interaction point, where the density of particles is largest. High granularity and good radiation tolerance are required. With an inner radius of 45 mm it is as close as 10 mm to the beam pipe and it extends to a radius of 1150 mm. It is contained inside a solenoidal magnetic field of 2 T (cf. Section 2.2.4) and designated to the reconstruction of tracks of charged particles. In order to achieve high momentum resolution over the entire range of momenta as well as precise vertex measurements, the inner detector consists of three complementary tracking devices: the pixel detector, the semi-conductor tracker (SCT) and the transition radiation tracker (TRT). Their configuration is illustrated in Figure 2.4.

#### The Pixel Detector

The innermost part of the inner detector is the pixel detector, consisting of three concentric layers around the beam axis and three discs perpendicular to the beam axis on each side of the interaction point. The 1744 modules that constitute the pixel detector each consist of a 250 \( \mu \)m layer of silicon implanted with readout pixels that measure 50 \( \times \) 400 \( \mu \)m\(^2\), adding up to a total of 80 million pixels. Electron-hole pairs are created in the silicon when charged particles pass through and a current is induced due to the p-n junction in the doped silicon, which is read out by the pixels. The pixel detector primarily contributes to the precise identification of the primary vertex and secondary vertices.

#### The Semi-Conductor Tracker

The middle component of the inner detector is the SCT, which is composed of four concentric barrels around the beam axis and nine endcap disks along the beam line on each side. It thus extends radially from 255 mm to 549 mm and longitudinally from 810 mm to 2797 mm from the interaction point. Its detection principle is similar to that of the pixel.
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Figure 2.4: The inner detector and the configuration of its three components: the pixel detector, the SCT and the TRT.

detector, although the lower particle density allows for long, narrow silicon strips rather than small rectangular pixels. The strips are configured in two layers under a small angle with respect to each other, such that a position measurement along the strip length can be obtained from hits in overlapping strips.

The Transition Radiation Tracker

The technology employed in the outer component of the inner detector, the TRT, is twofold: gaseous straw tubes are interleaved with transition radiation material. The barrel contains 73 such layers and the 20 wheels on each endcap are covered with 160 such planes, adding up to approximately 350k readout channels.

When charged particles pass through, the gas inside the tubes is ionized and a voltage difference between the tube and the anode wire in its center causes the free electrons to drift towards the wire. The drift time is converted into the distance of the track to the wire.

Transition radiation is emitted when highly relativistic charged particles pass the transition between two materials with different dielectric constants. The intensity of the transition radiation photons is proportional to the Lorentz factor of the traversing particle, which is much higher for electrons than for pions, at equivalent energies, due to their mass difference. The gas mixture inside the straw tubes contains xenon, which absorbs the radiation photons and thus produces a signal with a high amplitude when an electron passes through.

The readout electronics of the tubes apply two distinct thresholds: a lower one that
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detects the ionization clusters and a higher one that is optimized for transition radiation from electrons and allows for rejection of tracks from $\pi^\pm$ background.

A particle originating from the interaction point, given that it satisfies $|\eta| < 2.0$ and $p_T > 5.0$ GeV, typically gives rise to three pixel hits, four SCT measurements and around 30 TRT hits. The semiconductor trackers provide three-dimensional space points with high precision, yet the high number of TRT hits over the larger part of the track length contributes significantly to the momentum measurement. In addition, efficient electron identification is provided by the TRT. The expected inverse transverse momentum resolution on a reconstructed track with $0.25 < |\eta| < 0.50$ is

$$\sigma(1/p_T) = 0.34 \text{ TeV}^{-1}(1 \oplus 44 \text{ GeV}/p_T), \quad (2.5)$$

where the first term indicates the expected asymptotic resolution at infinite transverse momentum and the second term represents the impact of multiple scattering at low momenta. The expected resolution on the transverse impact parameter is

$$\sigma(d_0) = 10 \text{ \mu m}(1 \oplus 14 \text{ GeV}/p_T). \quad (2.6)$$

2.2.2 The Calorimeters

After having traversed the inner detector, particles enter the calorimeter system, which is situated outside the solenoidal magnet that surrounds the inner detector. It extends from approximately 1.4 m to 4.2 m from the interaction point in the transverse plane. Firstly encountered is the electromagnetic calorimeter, which is optimized for the identification and energy determination of photons and electrons. The hadronic calorimeter is dedicated to the reconstruction of hadronic showers from quarks, gluons and hadronically decaying taus. Altogether, the calorimeter system covers the full azimuth and the pseudorapidity range $|\eta| < 4.9$. The configuration of the calorimeters is depicted in Figure 2.5.

Muons generally deposit a mere fraction of their energy in the calorimeters and continue to be detected by the muon spectrometer (cf. Section 2.2.3). Neutrinos remain undetected entirely. The transverse component of the undetected energy can be nevertheless estimated by means of the expected energy balance in the transverse plane. The performance of the calorimeters is of direct influence on this quantity, the missing transverse energy, which will be discussed in more detail in Chapter 5.

Both the electromagnetic and the hadronic calorimeter consist of sampling detectors, i.e. layers of passive, dense material alternated with layers of active material. The passive material causes incident particles to initiate a shower or cascade of secondary particles, which are detected in the active material. In sufficient successive layers, the primary particle will have transferred all its initial energy.

Electromagnetic showers are the result of Bremsstrahlung and $e^+e^-$ pair production and the characteristic interaction distance is the radiation length $X_0$ of the material. Hadronic showers are the result of nuclear interactions and develop over larger distances. The required

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1. $X_0$ is the mean distance over which an electron loses all but $1/e$ of its energy.
depth of the material for complete containment of the shower is larger and is expressed in terms of the nuclear interaction length $\lambda$ of the passive material.

![Figure 2.5: Configuration of the ATLAS calorimeters, indicating the electromagnetic components as well as the tile calorimeters.](image)

**The Electromagnetic Calorimeter**

The electromagnetic calorimeter consists of a barrel that covers $|\eta| < 1.475$ and two endcap wheels at $1.375 < |\eta| < 3.200$. The passive material employed in the electromagnetic calorimeter are lead plates folded into an accordion shape. The space between the plates contains a honeycomb structure that is filled with liquid argon. Charged particles produced in showers induce free charge by ionizing the liquid argon, which is collected on the readout electrodes. The barrel component shares its cryostat vessel with the solenoid magnet (cf. Section 2.2.4) in order to minimize the amount of inactive material. Between the barrel and each endcap wheel, around $|\eta| = 1.4$, some space is available for cables and services for the inner detector. The thickness of the electromagnetic calorimeter varies from $22X_0$ to $33X_0$.

The modules of which the electromagnetic calorimeter is composed are divided into three longitudinal layers, as illustrated in Figure 2.5. The front layer is finely segmented in $\eta$, which facilitates $\gamma/\pi^0$ separation. The middle layer is thickest and receives the larger part of the energy deposited by electromagnetic showers. The third layer has a coarse granularity and is mainly used to recover the tails of highly energetic electromagnetic showers and to discriminate between hadronic and electromagnetic showers based on the larger energy deposit by the former.
The achieved resolution on the energy $E$ as measured in a test beam of electrons is

$$\sigma(E) = \frac{10\%}{\sqrt{E \text{(GeV)}}} \oplus 0.17\%. \quad (2.7)$$

The first term represents the stochastic response of the calorimeter, whereas the constant term is due to systematic effects, such as non-uniformity and stability.

![Diagram of a module in the electromagnetic calorimeter](image)

**Figure 2.6:** Schematic view of a module in the electromagnetic calorimeter, showing the typical accordion shape and the granularity of the different layers.

### The Hadronic Calorimeter

The hadronic calorimeter surrounds the electromagnetic calorimeter and constitutes a scintillator tile calorimeter at $|\eta| < 1.7$ and two endcap wheels at $1.5 < |\eta| < 3.2$. The tile calorimeter in turn is divided into a central barrel at $|\eta| < 1$ and two extended barrels at $0.8 < |\eta| < 1.7$. The gap in between contains cables, services and power supplies for the inner detector as well as for the electromagnetic calorimeter. The passive material is steel, which functions simultaneously as return yoke for the solenoid magnet. The active medium is formed by scintillating plastic tiles that emit the absorbed energy in the form of light. The scintillation light is picked up by wavelength shifting fibers and propagated to photomultiplier tubes, where the signal is amplified and detected. The thickness of the hadronic calorimeter is approximately $10 \lambda$. It follows from pion test beam results that the achieved energy resolution meets the requirement

$$\sigma(E) = \frac{50\%}{\sqrt{E \text{(GeV)}}} \oplus 3\%. \quad (2.8)$$
Hadronic showers are more complex than electromagnetic showers and the resolution is limited by binding energy losses and non-compensation, i.e. the electromagnetic component of the shower is detected more efficiently than the hadronic component. The electromagnetic fraction is energy dependent and its fluctuations contribute to the resolution. The ratio of the electron response and pion response is determined as a function of energy in test beams and used in the calibration (cf. Section 4.2).

In the hadronic endcap wheels the passive layers are made of copper and the active medium in between is liquid argon. The readout cells measure $\Delta \eta \times \Delta \phi = 0.1 \times 0.1$ in the region $1.5 < |\eta| < 2.5$ and $0.2 \times 0.2$ in the more forward region.

### The Forward Calorimeter

In order to estimate the missing transverse energy, as large hermetic calorimeter coverage as possible is pursued. The coverage in the very forward region, $3.1 < |\eta| < 4.9$, is provided by three wheels on either side: one electromagnetic component and two hadronic components. With inner radii of approximately 8 cm, they are situated close to the beam and the expected radiation level is high. Closest to the interaction point is the electromagnetic component in which copper acts as the passive material. The two hadronic components employ tungsten and the active material in all three of them is liquid argon. On each side, the forward calorimeter wheels share the liquid argon cryostat with the electromagnetic and hadronic endcaps.

#### 2.2.3 The Muon Spectrometer

The muon spectrometer is the largest and outermost subdetector of ATLAS. With inner and outer radii of approximately 4.5 m and 11 m respectively and stretching out from about 7 m to 23 m from the interaction point on each side in the longitudinal direction, it occupies a volume of around 16000 m$^3$. It was designed to trigger on muons with high momenta, which play a role as a distinguishing feature in several interesting physics channels, as well as to reconstruct the tracks of muons that pass through with high precision. The components providing the first functionality are the Resistive Plate Chambers (RPC) and the Thin Gap Chambers (TGC), while the latter is achieved by the Monitored Drift Tube (MDT) chambers and the Cathode Strip Chambers (CSC). A three-dimensional representation of the muon spectrometer is shown in Figure 2.7(a), indicating the four different types of components. The arrangement is such that a particle originating from the interaction point will traverse three layers of muon stations as it is bended by the magnetic field (cf. Section 2.2.4).

### The Barrel

The barrel of the muon spectrometer consists of three concentric cylindrical layers of muon stations that cover space up to a pseudorapidity of $|\eta| = 1$ and in nearly full azimuth. The stations are organized in sixteen sectors, alternating small (S) and large (L), thus following the structure of the eight barrel toroid magnet coils (cf. section 2.2.4). Muon stations in the innermost layer are single MDT chambers located just outside the hadronic calorimeter and named Barrel Inner (BI) chambers. Stations in the middle layer consist of a Barrel Middle
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Chambers

(a) A three-dimensional schematic view of the muon spectrometer.

(b) A schematic view of the transverse cross section of the muon spectrometer, indicating the numbering convention of the sectors as well as the arrangement of the muon stations around the barrel toroid magnet.

Figure 2.7: The muon spectrometer.

(BM) MDT chamber with a RPC on either side and are situated inside the barrel toroid magnet. The outer layer consists of stations that each comprise a Barrel Outer (BO) MDT chamber and a RPC and are positioned just outside the barrel toroid magnet. A transverse cross section of the barrel of the muon spectrometer is shown in Figure 2.7(b) indicating the numbering scheme of the sixteen sectors.

The chamber coverage is limited in the region $|\eta| < 0.1$ to accommodate inner detector and calorimeter services as well as in the barrel/endcap transition region where most of the middle stations are not installed yet for first operation. In sectors 12 and 14, around $\varphi \sim -\frac{9}{24}\pi$ and $\varphi \sim -\frac{15}{24}\pi$, the support feet of the toroidal magnet system prevent full azimuthal coverage.

The Endcaps

The two endcaps of the muon spectrometer consist of four disks each and cover a pseudorapidity range of $1.0 < |\eta| < 2.7$. The greater part of the disks consists of trapezoidally shaped MDT chambers, yet the innermost disk of the innermost layer of each endcap is equipped with CSCs. Thus, in the pseudorapidity range $2.0 < |\eta| < 2.7$ in which the largest particle flux is expected, a better spatial resolution and faster measurements are accomplished. The trigger information in the forward regions is provided by three planes of TGCs in each endcap, which cover $1.05 < |\eta| < 2.4$. 

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Precision Chambers

The precision measurement of muon trajectories is accomplished by MDTs and CSCs, designed to reach a transverse momentum resolution of approximately 10% for muon momenta of 1 TeV.

MDTs consist of two multilayers of aluminium tubes and a support structure, as shown in Figure 2.8. The cathode tubes of 30 mm diameter are filled with a gas mixture and contain an anode wire to which a voltage is applied during operation. When a charged particle passes through, ionization clusters are created in the gas, which will drift to the anode wire where the signal is propagated to the readout electronics. The position of the incident particle is derived from the timestamp corresponding to the signal pulse passing a threshold of five times the noise level by making use of the relation between the drift time and the distance of the particle to the wire.

CSCs consist of four planes of anode wires and two cathode planes equipped with strips. The coordinates of a traversing charged particle are obtained from the relative measurement of induced charge on adjacent cathode strips. The strips on each of the two cathode planes are positioned orthogonally, thus allowing for determination of two coordinates.

The actual reconstruction of muon tracks is further described in Section 4.5.

Trigger Chambers

Trigger chambers serve the purpose of providing rapid information about charged particles traversing the muon system.

RPCs are gaseous detectors with a time resolution of 1.5 ns and a typical spatial resolution of 1 cm. They consist of two rectangular detectors, contiguous to each other, each composed of two gas volumes and two readout strip panels. A gas volume is enclosed

Figure 2.8: Schematic layout of a monitored drift tube chamber.
by two resistive plates separated by 2 mm to which a voltage is applied, such that avalanches
induced by ionizing tracks are accelerated towards the anode plane, where the signal is read out.

TGCs are based on the same technology as CSCs, although the spacing between the wires and the cathodes is relatively small in order to guarantee a drift time that does not exceed the 25 ns LHC bunch separation.

2.2.4 The Magnet System

The ATLAS magnet system generates a magnetic field configuration such that the trajectories of charged particles are bented when traversing the tracking devices, the inner detector and the muon spectrometer. It consists of two superconducting magnet systems, a toroidal system and a central solenoid, that add up to a diameter of 22 m and a length of 26 m. The toroidal magnet system provides a magnetic field inside the volume of the muon spectrometer, while the solenoidal magnet generates a homogeneous field parallel to the beam axis inside the inner detector. The curvature of the trajectory followed by a charged particle when passing through the field is used to determine its momentum. A schematic view of the configuration of the toroidal and solenoidal magnets in ATLAS is depicted in Figure 2.9.

![Schematic view of the magnet system](image)

Figure 2.9: Three dimensional schematic view of the magnet system, showing the eight rectangular barrel coils, eight endcap coils on either side and the solenoid in the center.

The Toroidal Magnet System

The toroidal magnet system is built up of a barrel toroid and two endcap toroids.

The barrel toroid consists of eight superconducting rectangular coils, each encased in a cryostat. The total assembly weighs 830 tons and adds up to 25.3 m axial length and inner and outer diameters of 9.4 m and 20.1 m respectively. Cooling down to the nominal
operational temperature of 4.6 K takes 5 weeks. The field strength provided by the barrel toroid at the nominal operational current of 20.5 kA varies from 0.15 T to 2.5 T.

The endcap toroid systems consist of eight coils each, which are located interleaved with the barrel toroid coils on either side, thus generating a magnetic field in the endcap regions of the muon spectrometer. With an inner and outer diameter of 1.65 m and 10.7 m and an axial length of 5.0 m each endcap toroid weighs 239 tons. Powered in series with the barrel toroid, the endcap toroids generate a field strength that varies from 0.2 T to 0.35 T at nominal operational current.

The Central Solenoid

The solenoidal magnet system is aligned with the beam axis and produces an axial field throughout the volume of the inner detector. At the 7.730 kA nominal operational current, the strength of the field varies from 2 T at the interaction point to 0.9 T. With an axial length of 5.8 m and a diameter of about 2.5 m, it is embedded inside the electromagnetic calorimeter. In contemplation of a minimal amount of material in front of the calorimeters, the solenoid shares its cryostat with the electromagnetic calorimeter.

In order to monitor the magnetic field inside the inner detector, four NMR (Nuclear Magnetic Resonance) probes are mounted on the wall of the vessel at $z=0$, equally spaced in $\phi$, that measure the magnitude of the magnetic field, $|B|$, with an accuracy of 10 $\mu$T.

Magnetic Field Sensors in the Muon Spectrometer

A precise knowledge of the strength of the magnetic field, $B$, at each given point inside the volume of the muon spectrometer is required to reconstruct a muon’s momentum. To this end a magnetic field map is computed from contributions to the Biot-Savart integral from the toroidal and solenoidal magnet systems as well as other ferromagnetic material present in the various detector systems. During operation however, the exact position of these components is continuously influenced by temperature fluctuations and material-induced magnetic forces. Therefore approximately 1800 magnetic field sensors are installed throughout the MDT system to support the calculation of the magnetic field. Their position in ATLAS is displayed in Figure 2.12(c). Each sensor is equipped with Hall probes on three of its orthogonal faces that determine the components of the magnetic field from the induced voltage due to the Hall effect. The number of sensors mounted on a MDT chamber varies from zero to four, each including its own readout electronics and a temperature sensor to allow for local calibration. By measuring the response of each Hall probe as a function of field strength, field orientation and temperature $T$ in test stands at CERN [35], the Hall voltage of each sensor was calibrated. The achieved accuracies on the magnitude $|B|$ of the magnetic field are 0.2 mT up to $|B|=1.4$ T and 1 mT up to 2.5 T. In addition, two NMR probes are mounted on the barrel toroid system in order to monitor potential long-term drifts in the response of the Hall probes.

A number of criteria are defined in order to assess the quality of the value read out by each magnetic field sensor. The criteria include, amongst other,

- $|T - 20^\circ C| < 10^\circ C$;
- $|B| < 2.0$ T in the endcaps and $|B| < 3.0$ T in the barrel;
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- RMS ($|B|/I$) < 1.0 T/A;
- RMS ($T$) < 2°C;
- $|B_i - \langle B_i \rangle| < 3 \sigma(B_i)$ for each component $i \in \{x, y, z\}$, where the average is taken over all sensors;
- $|T - \langle T \rangle| < 3 \sigma(T)$ where the average is taken over all sensors.

In case any of the criteria is not satisfied, the sensor is flagged and disregarded in the field map calculation.

**Magnet Operation**

After installation in ATLAS, the barrel toroid, each of the endcap toroids and the solenoid were cooled down to 4.6 K and ramped to their nominal current during separate standalone tests. In 2008, the barrel toroid and endcap toroids were powered in series and commissioned as an assembly. During the first duration test of the combined configuration, the current was initially ramped up to 20400 A in about three hours time, subsequently ramped up to slightly over the 20500 A nominal operational current and finally the magnets were slowly discharged. The behaviour of the toroid current and the magnetic field sensors mounted on MDT chambers of type BOL (Barrel Outer Large) is shown in Figures 2.10(a) and 2.10(b) respectively.

Figure 2.10: The first duration test of the toroidal magnet system.

In case any of the criteria is not satisfied, the sensor is flagged and disregarded in the field map calculation.

Figure 2.11 displays the RMS of the magnitude of the magnetic field as read out by the magnetic field sensors during the current plateau of 20504.8 A that was part of the duration
test. The figure contains the measurements of all 95% of the magnetic field sensors that passed the quality criteria at that moment. In addition, the distribution is displayed for measurements taken in 2010 during full operation. The number of sensors passing all criteria has increased to 100% and the RMS values of the measurements have not degraded in two years time. The relative RMS values with respect to the mean value of \(|B|\) are of the order \(O(10^{-5})\), which meets the requirement \(5 \cdot 10^{-4}\) from muon reconstruction performance [33].

![Figure 2.11: The RMS of the magnitude of the magnetic field during constant current as read out by the magnetic field sensors throughout the MDT system.](image)

Figure 2.11: The RMS of the magnitude of the magnetic field during constant current as read out by the magnetic field sensors throughout the MDT system.

Figure 2.12(c) shows the magnitude \(|B|\) of the magnetic field measured by each sensor during operation, i.e. at 7.730 kA solenoid current and 20.5 kA toroid current.

The temperature fluctuations of the four sensors on a MDT chamber in the top sector, BIL2C05, are displayed in Figure 2.13. The temperature decreases slightly during the night and starts incrementing again around 7:00. It turns out that the temperature difference between the sensor locations on a chamber is considerable. The fluctuations of the temperature are accounted for in the calibration of the magnetic field components being read out by the Hall probes. The RMS on the temperature measurement is well within the allowed range not to be flagged for each of the sensors in the figure.

### 2.2.5 The Trigger System

Operating at a bunch crossing frequency of 40 MHz, with approximately 23 interactions occurring per bunch crossing, the LHC will produce as many as one billion events per second. Merely a fraction of these events are of interesting nature as most of the interactions are so called minimum bias events, i.e. partonic interactions with transverse momenta too small for perturbation theory to be valid. Moreover, it is not feasible to store the corresponding amount of data, approximately 1 PB s\(^{-1}\), on technical grounds. Therefore, a highly efficient selection of interesting events within a minimal time span is required. To this end, a complex trigger system is developed that reduces the rate of events to be stored by a factor of \(O(10^7)\). The event rejection procedure takes place in three subsequent stages: the Level-1 Trigger, the Level-2 Trigger and the Event Filter.
Figure 2.12: The magnitude of the magnetic field during operation as read out by sensors throughout the MDT system.

The Level-1 Trigger

The first level of the trigger system bases its decision on coarse granularity information from the calorimeters and information from the muon trigger chambers only. The decision time is constrained to 2 μs by the pipeline memory in which all detector channel data of a bunch crossing are stored until a decision is reached. In order to minimize the propagation time through cables, the dedicated electronics are located as close as possible to the ATLAS detector. The Level-1 Trigger defines Regions of Interest (RoIs) in (η, φ) space where object
candidates satisfy certain energy thresholds. Based on the multiplicity of RoIs, an event is passed on to the Level-2 Trigger or rejected, which results in a reduction of the event rate to 75 kHz.

The Level-2 Trigger

The second level of the trigger system refines the Level-1 Trigger decision by using full granularity information from all detectors, including the inner detector. Dedicated software examines the previously defined RoIs in more detail and attempts to reconstruct physics objects, i.e. electrons, photons, muons and jets, and it calculates the missing transverse energy from the information from the calorimeters. Subsequently, a set of selection criteria is applied and the resulting event rate is 2 kHz.

The Event Filter

The Event Filter is designed to reduce the event rate from 2 kHz to the 200 Hz permanent storage acceptance. In addition, it organizes the data into streams based on physics object candidates, as further described in Section 4.1. It accesses the full precision data from the complete detector and generally makes use of the same sophisticated algorithms as the reconstruction of the events that are eventually stored (cf. Chapter 4), yet looser criteria are applied. The available processing time per event is approximately 4 s.

The sequence of algorithms that define a certain object candidate at each stage will be referred to as a trigger chain. The final energy threshold and quality requirements are naturally determined by the last stage, the Event Filter. The naming convention for a trigger chain is $[N][TYPE][THRESHOLD]_i(QUALITY)$, where TYPE specifies the object candidate (as indicated in Table 2.3), $N$ indicates its multiplicity, THRESHOLD is a number corresponding to a (transverse) momentum threshold, $i$ indicates isolation and QUALITY
refers to the severity of requirements in the algorithm (e.g. loose, medium or tight in case of electrons, cf. Section 4.4).

<table>
<thead>
<tr>
<th>Object</th>
<th>TYPE</th>
</tr>
</thead>
<tbody>
<tr>
<td>muon</td>
<td>mu</td>
</tr>
<tr>
<td>electron</td>
<td>e</td>
</tr>
<tr>
<td>photon</td>
<td>g</td>
</tr>
<tr>
<td>electron/photon</td>
<td>em</td>
</tr>
<tr>
<td>jet</td>
<td>j</td>
</tr>
<tr>
<td>forward jet</td>
<td>fj</td>
</tr>
<tr>
<td>tau</td>
<td>tau</td>
</tr>
<tr>
<td>total energy</td>
<td>te</td>
</tr>
<tr>
<td>total jet energy</td>
<td>tj</td>
</tr>
<tr>
<td>missing energy</td>
<td>xe</td>
</tr>
<tr>
<td>minimum bias</td>
<td>mb</td>
</tr>
</tbody>
</table>

Table 2.3: The naming convention for TYPE in trigger chains.

The trigger chain e20_loose for instance, which is used in the following chapters, is designed to trigger on electrons. The algorithms in this chain aim to be as efficient as possible for electrons with a transverse momentum larger than 20 GeV and which satisfy the loose requirements defined in the reconstruction algorithm.

The available trigger chains are defined in terms of a trigger menu, which varies in time with increasing instantaneous luminosity. The events that pass any trigger chain in the given menu are arranged in luminosity blocks, each containing typically a couple of minutes of data taking, and stored. The beam conditions and detector performance are stored per luminosity block. Subsequently, the collected data is passed on to the reconstruction software, which is described in Chapter 4.