The ATLAS SemiConductor Tracker Endcap
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Chapter 2

The Large Hadron Collider and the ATLAS experiment

“I do not feel obliged to believe that the same God who has endowed us with sense, reason, and intellect has intended us to forget their use.”

Galileo Galilei

This section starts with an overview of modern-day colliders and motivates the critical technology choices made for the LHC, and gives some details of it. Next, it describes ATLAS, going briefly through each of the main-detector systems and their associated magnets. The intention is to introduce some of the terminology needed and to show where the SCT sub-detector fits in. The SCT itself is described in more detail in the next chapter.

2.1 The Large Hadron Collider

2.1.1 An overview of present and near-future colliders

The predecessor of the Large Hadron Collider (LHC) was the Large Electron-Positron collider (LEP). Both machines are circular colliders: at each collision, only a few particles interact and the bunches are re-used. The beam energy of the LEP machine was limited by synchrotron radiation: the particles radiate photons and so lose energy. This energy has to be replaced by accelerating cavities distributed around the ring. A small increase in energy requires a very much bigger input of energy: the lost energy $\Delta E$ relates to the particle’s energy $E$ and mass $m$ and accelerator radius $R$ as $\Delta E \propto 1/R (E/m)^4$. At LEP ($R = 3100$ m), when running at its maximum energy ($E_{\text{beam}} = 104.4$ GeV), an electron lost approximately 3.5 GeV per turn. There are two ways to avoid this.

First, one can give up the advantages of a circular accelerator and build a linear accelerator. However, this will require certain technological developments to reach high enough energies
and luminosities. The feasibility of this was only proved recently and formed the basis of the TESLA proposal: a linear collider at DESY (Germany), with total collision energy of 500 to 800 GeV (Brinkmann et al. 1995).

Second, one could accelerate heavy particles such as protons instead of electrons, since the mass of a proton is 2000 times that of an electron, thus reducing enormously the energy loss.

This second approach has been followed by Fermilab, USA, where the Tevatron collider was built and became operational in 1983. This machine accelerates protons and antiprotons and collides them, now at an interaction energy of 1.96 TeV. The advantage of accelerating both particle and anti-particle is that only one ring is needed to accelerate both beams in opposite directions. The disadvantage is that antiprotons are difficult to produce, which limits the luminosity of this machine. The peak-luminosity reached with the Tevatron is typically 0.016 nb$^{-1}$s$^{-1}$ (Witherell 2002).

The LHC also follows the second approach, except it will collide protons onto protons to achieve high luminosities: it is expected to reach a nominal luminosity of 10 nb$^{-1}$s$^{-1}$. Since the energy loss of the proton beams is relatively small and the radius of the accelerator is defined by the LEP-tunnel, the strength of dipole magnets used to guide the beams into a circular orbit is the limiting parameter for the maximum beam energy that can be reached. The LHC dipole-magnets

Figure 2.1: The principle of the LHC dipole magnet. The two beam pipes and the magnets are shown and the magnet field-lines are indicated.
are super-conducting and produce an intense magnetic field: 8.37 T\(^1\). The extra costs needed to build two rings to accelerate both proton bunches in opposite directions is partly solved by a clever dipole-magnet design: one ring uses the return field of the other ring (see Figure 2.1). The expected interaction energy is 14 TeV: almost an order of magnitude higher than the Tevatron.

A disadvantage of using protons instead of electrons is that electrons are elementary particles, so all the energy is available in a collision, whereas protons are composite particles and it is the 'parton' constituents that collide. To be able to understand the physics processes that will occur at the LHC, the collision itself and thus the internal sub-structure of the protons should be well understood. This sub-structure has been well measured at (mainly) the HERA ep-collider at DESY. The measurements at the Tevatron have helped to further understand the internal sub-structure of protons.

### 2.1.2 The Large Hadron Collider Characteristics

<table>
<thead>
<tr>
<th>parameter</th>
<th>value</th>
<th>unit</th>
</tr>
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<tbody>
<tr>
<td>circumference</td>
<td>27</td>
<td>km</td>
</tr>
<tr>
<td>proton energy</td>
<td>7</td>
<td>TeV</td>
</tr>
<tr>
<td>number of bunches</td>
<td>2835</td>
<td></td>
</tr>
<tr>
<td>bunch separation</td>
<td>24.95</td>
<td>ns</td>
</tr>
<tr>
<td>number of protons per bunch</td>
<td>(1.1 \times 10^{11})</td>
<td></td>
</tr>
<tr>
<td>beam current</td>
<td>0.54</td>
<td>A</td>
</tr>
<tr>
<td>stored beam energy</td>
<td>334</td>
<td>MJ</td>
</tr>
<tr>
<td>radiated power per beam</td>
<td>3.7</td>
<td>kW</td>
</tr>
<tr>
<td>beam lifetime</td>
<td>10</td>
<td>hour</td>
</tr>
<tr>
<td>expected run time per year</td>
<td>(10^7)</td>
<td>s</td>
</tr>
<tr>
<td>interaction point diameter (1 (\sigma))</td>
<td>15</td>
<td>(\mu m)</td>
</tr>
<tr>
<td>interaction point length (1 (\sigma))</td>
<td>5.6</td>
<td>cm</td>
</tr>
<tr>
<td>luminosity</td>
<td>10</td>
<td>nb(^{-1}) s(^{-1})</td>
</tr>
<tr>
<td>number of dipoles</td>
<td>1,296</td>
<td></td>
</tr>
<tr>
<td>dipole field</td>
<td>8.36</td>
<td>T</td>
</tr>
<tr>
<td>number of other magnets</td>
<td>2,500</td>
<td></td>
</tr>
</tbody>
</table>

Figure 2.2: A schematic overview of the LHC accelerator complex and its main parameters.

Figure 2.2 shows an overview of the accelerator complex at CERN. One of the large advantages of building such a machine at CERN is that a lot of elements in Figure 2.2 are present: the tunnel to build the LHC in (the old LEP tunnel) and all the pre-accelerators, which accelerate the protons to 450 GeV.

The table in Figure 2.2 summarises a few key parameters of the LHC. The proton beams are bunched in packets (bunches), at some distance from each other (bunch spacing). The more bunches in the machine the higher the intensity or luminosity of the beam is, but if there are too many in the beam they distort each other. At four points around the ring the beams are

\(^{11}\) T (Tesla) is equal to 10000 Gauss (which is an old unit for the strength of a magnetic field). The strength of the earth's magnetic field is approximately 0.5 Gauss.
collided, at the so-called ‘interaction points’. The collision frequency is determined by the bunch spacing, which drives the speed of the electronics reading out the LHC detectors. Due to beam losses caused by imperfections of the beam line and the collisions, the luminosity of the beam decreases, limiting the lifetime of the beam.

The expected nominal luminosity is $10 \, \text{nb}^{-1}\text{s}^{-1}$, which probably will be achieved after an initial period of three years, during which the LHC is expected to run at one-tenth of the final luminosity.

The LHC will have four interaction points. Large experimental halls located at these points will accommodate the four experiments. The experiment called ALICE (ALICE Collaboration 1995) is dedicated to the study of the quark-gluon plasma. The experiment called LHCb (LHCb Collaboration 1998) will study CP-violation in the B-system. The two remaining interaction points serve multi-purpose experiments: ATLAS (ATLAS Collaboration 1994) and CMS (CMS Collaboration 1992).

### 2.2 The ATLAS detector

This section starts with the definition of the ATLAS coordinate-system, which will aid the description. The opportunity is used to define some typical LHC physics-parameters. Next, it describes the layout and the main components of the ATLAS detector. Since the collision rate of almost 1 GHz makes it impossible to permanently store all the data, an event selection is implemented, based on a three-level trigger system, described at the end.

#### 2.2.1 Nomenclature

The coordinates are defined to form a right-handed Cartesian coordinate-system. The beam line defines the $z$-axis. The positive $z$-direction points in the direction of LHC-b (see Figure 2.2). The $x$-axis points in the direction towards the centre of the LHC ring. The positive $y$-direction points (almost) upwards. Note that, due to the geological conditions around Geneva, the tunnel does not lie in a horizontal plane and therefore the $y$-axis has a small angle with the vertical (0.704°).

The symmetry of the detectors is cylindrical, making cylindrical coordinates useful with the usual definition: the $z$-axis is the same as for the Cartesian coordinate-system, the azimuthal-angle symbol is $\phi$ and the radial symbol is $R$. When using polar coordinates, the radial-coordinate symbol is $r$ and the polar angle symbol is $\theta$. For hadron colliders one often uses the pseudorapidity instead of $\theta$:

$$\eta \equiv -\ln (\tan (\theta/2))$$  \hspace{1cm} (2.1)

because the particle multiplicity-distribution in pseudorapidity ($dN/d\eta$) is basically flat.

High transverse momentum particles are a signature of hard scattering, and so the transverse momentum of a particle, $p_T \equiv \sqrt{p_T^x + p_T^y}$, is an important quantity. If measured in the calorimeter, especially for a jet, the corresponding quantity is the transverse energy: $E_T \equiv E_{\text{deposited}} \times \sin \theta$. Since the momentum fractions of the partons taking part in the collision are not a priori known, momentum conservation cannot be used in the analysis of the events. However, it is known that before the reaction there was (almost) no momentum in the plane transverse to the beam. Therefore the missing transverse-energy $E_T^{\text{miss}}$ of the event, $E_T^{\text{miss}} \equiv \sqrt{(\sum E_T \cos \phi)^2 + (\sum E_T \sin \phi)^2}$
(summed over all energy deposits in the calorimeter), is very important. A large value can be a signature for neutrino’s or physics beyond the Standard Model.

2.2.2 Overview

![Diagram of the ATLAS detector](image)

Figure 2.3: The ATLAS detector, with parts left out to be able to view the inside. The humpback whale and calf on the left are drawn to indicate the size. The whale is an average female of 15 m length. The calf measures almost 7 m.

The ATLAS detector surrounds the interaction point (IP) of the LHC as much as possible. The structure of the ATLAS detector is typical for a multi-purpose (symmetric) collider-experiment: it has a layered structure (see Figure 2.3) and each layer has its own specific purpose. ATLAS consists of three subsystems. The inner-most layer is the Inner Detector, which will sit in a 2 T solenoidal magnetic-field. The Inner Detector will be surrounded by the calorimeters. The only (known) charged particles that are likely to pass through the calorimeters are muons. To identify the muons and measure their momentum accurately, the calorimeters will be surrounded by the muon system. The magnetic field for this system will be provided by large air-core toroids.

2 All drawings of ATLAS detector systems in this thesis have been made using the program PERSINT (Virchaux & Pomarede 2001)
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consisting of independent coils arranged with an eight-fold symmetry outside the calorimeters.

The main difference with other collider experiments is its enormous size: the ATLAS experiment is approximately eight times as big as the L3 (L3 Collaboration 1991) experiment, which is until now the largest collider experiment ever built. The ATLAS detector will be 22 m high, 44 m long, and will weigh 7000 tons. This enormous size is a direct consequence of both the high luminosity and the large centre-of-mass energy of the LHC beams.

Each bunch crossing is expected to produce a large number of charged particles, neutral particles, and jets, which can have an enormous energy (see Figure 1.1). Due to the boost of a high-energy jet, the detector will be hit with a high-density spray of particles. To be able to distinguish the individual particles of which a jet is composed, a detector with high-granularity is required. Since the particle density decreases with $1/r^2$, the detector elements can have a reduced granularity at larger distances.

The energies of the particles produced by the LHC will be almost ten times higher than in earlier collider experiments. The momentum of a (charged) particle is measured by reconstructing its track in a magnetic field and measuring the bend. This measurement improves by a large lever arm and thus a large detector.

The basic design criteria of the ATLAS detector are (ATLAS Collaboration 1999a):

- Very good electromagnetic calorimetry for electron and photon identification and measurement, complemented by full-coverage hadronic calorimetry for accurate jet and missing transverse-energy measurements;
- High-precision muon momentum measurements, with the capability to guarantee accurate measurements at the highest luminosity using the external muon spectrometer alone;
- Efficient tracking at high-luminosity for momentum measurement of high $p_T$ leptons, electron and photon identification, $\tau$-lepton and heavy-flavour identification, and full event-reconstruction capability at lower luminosity;
- Large acceptance in pseudorapidity with almost full azimuthal angle coverage everywhere;
- Triggering and measurements of particles at low-$p_T$ thresholds, providing high efficiencies for most physics processes at the LHC.

2.2.3 The Inner Detector

Figure 2.4 shows an overview of the Inner Detector (ATLAS Inner Detector Collaboration 1997a, ATLAS Inner Detector Collaboration 1997b). The Inner Detector consists of three sub-systems: the Pixel detector on the inside; a silicon-strip detector called the Semi-Conductor Tracker (SCT); and a straw tube tracker on the outside called Transition-Radiation Tracker (TRT). Table 2.1 gives an overview of the main parameters of the sub-detectors of the Inner Detector.

The solenoid gives a 2 T field. It is shorter than the TRT and the SCT. Consequently, the field deviates significantly from uniformity. Figure 2.5 shows the field distributions. It can be seen that $B_z$ drops to almost 1 T at the end of the tracker, while $B_R$ has a maximum of 0.6 T near the end of the coil. This is not a problem, since first, this magnetic field will be well measured and second, the tracks at large $|\eta|$ will only see the reduced field near the end of their passage through the Inner Detector.
The Pixel detector is designed to provide a very high-granular, high-precision set of measurements as close to the interaction point as possible. The entire system consists of 2586 modules. Each module consists of 16 chips, with $160 \times 24$ pixels each. The pixels measure $50 \, \mu m$ in $R\phi$ and $300 \, \mu m$ in $z$ in the three barrel layers or $R$ in the three discs of each end-cap. It is designed to provide three precision points over its full acceptance and contributes the most to the impact parameter resolution. The inner-most layer is called the ‘b-layer’. This receives a particle flux five times higher than the next layer. It will have to be replaced every few years, due to damage by this high level of radiation.

The Semi-Conductor Tracker consists of a barrel system and two end-cap systems. The barrel detector consists of four barrel-shaped layers and the end-cap consists of nine disks. In this way the SCT provides four precision points per track in the intermediate radial range of the Inner Detector. Each precision point is provided by two back-to-back silicon-strip sensors, which have a small stereo angle (about $2.3^\circ$) with respect to each other. Each sensor has 768 strips with

<table>
<thead>
<tr>
<th>System</th>
<th>Position</th>
<th>$\eta$-coverage</th>
<th>Layers</th>
<th>Hits</th>
<th>Resolution ($\mu m$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pixel</td>
<td>B-layer</td>
<td>$\pm 2.5$</td>
<td>1</td>
<td>1</td>
<td>$R\phi = 12, z = 66$</td>
</tr>
<tr>
<td></td>
<td>barrel layers</td>
<td>$\pm 1.7$</td>
<td>2</td>
<td>2</td>
<td>$R\phi = 12, z = 66$</td>
</tr>
<tr>
<td></td>
<td>end-cap discs</td>
<td>$1.7 - 2.5$</td>
<td>3</td>
<td>3</td>
<td>$R\phi = 12, R = 77$</td>
</tr>
<tr>
<td>SCT</td>
<td>barrel layers</td>
<td>$\pm 1.4$</td>
<td>4</td>
<td>4</td>
<td>$R\phi = 23, z = 580$</td>
</tr>
<tr>
<td></td>
<td>end-cap discs</td>
<td>$1.4 - 2.5$</td>
<td>9</td>
<td>4</td>
<td>$R\phi = 20-26, R = 580$</td>
</tr>
<tr>
<td>TRT</td>
<td>barrel straws (axial)</td>
<td>$\pm 0.7$</td>
<td>73</td>
<td>36</td>
<td>$R\phi = 170$</td>
</tr>
<tr>
<td></td>
<td>end-cap straws (radial)</td>
<td>$0.7 - 2.5$</td>
<td>224</td>
<td>36</td>
<td>$R\phi = 170$</td>
</tr>
</tbody>
</table>

Table 2.1: The main parameters of the Inner Detector. In the end-cap SCT, the resolutions vary, only a typical number is indicated.
80 $\mu$m pitch. Binary (hit or no hit) read-out is used, which gives only a list of which strips are hit and no charge measurement, limiting the resolution to about 23 $\mu$m. The SCT contributes to the measurement of the momentum, impact parameter and vertex z-position. It contributes to the pattern recognition with its high-granularity at large radius.

The Transition Radiation Tracker uses straw detectors, which can be operated at the high LHC-rates due to the small radius of 4 mm with a 30 $\mu$m wire. The non-flammable gas used consists of 70% Xe, 27% CO\textsubscript{2} and 3% O\textsubscript{2} and is operated as a proportional counter. The layers are interleaved with a radiator material. This radiator material produces transition-radiation photons, with a probability proportional to the Lorentz boost ($\gamma \equiv E/m$) of the traversing particle. The xenon in the tubes is sensitive to these photons. This allows electron identification, since electrons have high boost. For a $p_T$ of 20 GeV, the pion rejection factor varies with $|\eta|$ from 20 to 100 at 90% electron efficiency.

The Inner-Detector resolution can be parameterised for the barrel region as:

$$
\frac{\sigma_{p_T}}{p_T} = 0.032\% \cdot p_T \oplus \frac{1.30\%}{\sqrt{\sin \theta}} (p_T \text{ in GeV})
$$

(2.2)

and for the forward region as:

$$
\frac{\sigma_{p_T}}{p_T} = 0.045\% \cdot p_T \oplus \frac{1.80\%}{\sqrt{\sin \theta}} (p_T \text{ in GeV})
$$

(2.3)

This parameterisation has been shown to describe the results from a full simulation well (Lavrijsen 2002). The first terms in the above equations represent the intrinsic tracker resolution, depending on the resolutions of the detector elements and the magnetic field. The second terms represent the resolution degradation due to multiple scattering. The $1/\sqrt{\sin \theta}$-term is due to the barrel

Figure 2.5: The solenoidal field. Figure (a) shows the field along the beam line. Figure (b) shows the field perpendicular to the beam line.
structure that is traversed by the particles: when the angle with the beam becomes smaller, more material has to be traversed due to the angle of incidence. Since in the end-cap detector most of the material is due to the support cylinder and services, the same relation holds for the forward region.

The same dependence is reflected in the total amount of material in the Inner Detector, shown in Figure 2.6. The SCT contributes approximately 10% $X_0$ (radiation length, see Section 3.2.1) at $|\eta| = 0$ to 30% $X_0$ at larger pseudo-rapidities. Most of the radiation length is due to services and support: the total material of an end-cap module only amounts to 1.3% $X_0$ (Feld 2001a).

Figure 2.6: The total material budget of the Inner Detector, compared to the budget estimated for the Physics Performance studies (May 1999).
2.2.4 The calorimeters

![Diagram of calorimeters]

**Figure 2.7:** An overview of the calorimeters. The baby whale (7 m long) that is shown for comparison, is the same as shown in the ATLAS overview.

A likely way of observing SUSY, if it exists, is to measure a large amount of missing transverse energy in the detector. Therefore it is important to have a calorimeter which has a coverage as close as possible to $4\pi$, so all energy is likely to be measured.

ATLAS has separate electromagnetic and hadronic calorimeters up to a pseudorapidity of $|\eta| < 3.2$. A special combined electromagnetic and hadronic calorimeter extends the energy measurement to $|\eta| = 4.9$ (see Figure 2.7 for an overview).

### 2.2.4.1 The electromagnetic calorimeter

The electromagnetic calorimeter consists of a barrel and two end-caps and is the most inner part of the calorimeter system. It is expected to achieve an excellent energy-resolution (see Figure 2.8 (ATLAS Collaboration 1999a)). It uses the LAr-technology in combination with Kapton electrodes and lead absorber plates. The absorber plates will be placed in an accordion geometry, providing complete $\phi$-coverage without azimuthal cracks (see Figure 2.10 (ATLAS Collaboration 1999a)). The barrel is contained in a cryostat, surrounding the Inner-Detector cavity, which also holds the Inner-Detector solenoid. The electromagnetic calorimeter has more than 24 radiation lengths in the barrel region ($X_0$, see Section 3.2.1), and more than 26 $X_0$ in the forward region.
2.2. The ATLAS detector

Figure 2.8: The electron energy-resolution of the electromagnetic calorimeter system at two different inclination angles, as measured in a testbeam.

Figure 2.9: The electron energy-resolution as function of pseudorapidity for different transverse electron momenta, from simulation.

In the region devoted to precision physics (|\eta| < 2.5), the electromagnetic calorimeter is segmented in three longitudinal sections. The most inner section has a fine granularity in the \eta-direction, which enhances the \gamma/\pi^0 and e/\pi separation and also provides a precision \eta-measurement.

The electron and photon energy-resolution is aided by the presampler, which corrects for energy-loss in the Inner Detector in the region where the amount of material exceeds about 2X_0. In the transition region between the barrel and end-cap cryostat, the material in front of the calorimeter exceeds 7X_0. In this region the presampler is aided by a scintillator slab inserted in the crack between the two cryostats.

2.2.4.2 The hadronic calorimeter

The hadronic calorimeter surrounds the electromagnetic calorimeter. It consists of plastic scintillator tiles interleaved with iron absorber tiles in a non-standard orientation: the tiles are placed in the radial direction and staggered in depth (see Figure 2.11). Its longitudinal segmentation consists of three samples. The expected energy-resolution is:

\[
\frac{\sigma_E}{E} = \frac{50\%}{\sqrt{E}} \oplus 3\% \ (E \text{ in (GeV)})
\]

with a segmentation of \Delta\eta \times \Delta\phi = 0.1 \times 0.1.

The end-cap hadronic calorimeter receives a much higher radiation-dose than the barrel, and therefore uses the intrinsically radiation-hard Liquid Argon (LAr) technology. The hadronic end-cap uses copper absorbers in a parallel-plate geometry.
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2.2.4.3 The forward calorimeter

The Forward CALorimeter (FCAL) provides electromagnetic and hadronic calorimetry in the range $3.2 < |\eta| < 4.9$. It uses liquid Argon technology. It is split longitudinally in an electromagnetic part with copper absorber and two hadronic parts with tungsten absorber. The absorber has longitudinal holes to accommodate the electrodes, which are tubes and rods separated by the LAr.

To avoid that neutrons are backscattered into the Inner Detector volume, it is placed 1.2 meter further away from the interaction point, compared to the electromagnetic end-cap calorimeter.

2.2.5 The muon system

The muon system (ATLAS Muon Collaboration 1997) is the largest part of the ATLAS detector. Figure 2.12 shows an overview. High-$p_T$ muons are a signature of interesting physics, making the muon trigger very important. Muons can be easily observed, because they are the only particles that have a good chance of penetrating through the calorimeter system described in the previous section. However, the calorimeters produce a large background of low-momentum particles.

A magnetic field is used to determine the muon momenta. The magnet technology that will be used is an air-core super-conducting toroid magnet. It consists of three parts: a barrel toroid and the two end-cap toroids. The low average density of such a structure minimises scattering of the tracks by material. Although the typical field strength will be low (approximately 0.6 T) the large size gives a large bending power (typically 3 Tm).

This magnet system will be complemented with low resolution detectors for triggering: Re-
2.2. The ATLAS detector

Figure 2.12: Three dimensional view of the muon spectrometer indicating the areas covered by the four different chambers technologies.

Resistive plate chambers

Cathode strip chambers

Thin gap chambers

Monitored drift tube chambers

Figure 2.12: Three dimensional view of the muon spectrometer indicating the areas covered by the four different chambers technologies.

Resistive Plate Chamber (RPCs) and Thin Gap Chambers (TGCs) in the high-rate end-cap regions. The RPCs are gaseous, self-quenching parallel plate detectors. The TGCs are multi-wire proportional chambers. Both chambers will be arranged in three layers, allowing the trigger system to make a coincidence for channels in the same $\eta$-region and thus determining whether a track had a high momentum or not.

Monitored Drift Tube (MDT) detectors provide precision muon tracking and momentum measurement. The basic detection element is a 30 mm diameter aluminium tube with a central wire. The tube is filled with a gas mixture of \text{Ar} (7\%) and \text{CO}_2 (93\%) at 3 bar absolute pressure. The tube is operated as a proportional wire chamber and measures the time taken for ionisation created along the muon track to arrive at the wire. This varies from 0 ns for tracks passing through the wire to a maximum drift time of 700 ns for tracks just inside the tube. The measured drift time can be converted into the distance from the wire to the track with an average resolution of 80 \text{\mu}m. In the forward region the drift tubes are replaced by the more radiation-resistant Cathode Strip Chambers. These chambers are based on a multi-wire proportional-chamber technique.

The tubes are arranged in chambers as illustrated in Figure 2.13. Tracks typically cross three such chambers, each of which measures the track position with a precision better than...
50 $\mu$m, allowing the track sagitta to be measured with 50 $\mu$m error. The sagitta of a 1 TeV track is typically 0.5 mm giving approximately 10% momentum resolution even at these very high momenta, far better than the Inner Detector. Figure 2.14 shows the resolution as function of muon momentum. The muon system is important at and above 40 GeV where its resolution is comparable to the Inner Detector.

### 2.2.6 Triggering

At full luminosity, each bunch crossing contains on average 23 inelastic pp-scattering collisions (minimum bias) and the bunch crossing rate is 40 MHz: the average total collision rate is therefore close to 1 GHz. As can be seen from Figure 1.1, the event rate of the interesting physics is much lower. Since is is only possible to record about 100 events per second, the data output is reduced by a three-level trigger system.

Figure 2.15 shows an overview of the ATLAS trigger system. The first level trigger (LVL1) receives information from the calorimeter (in reduced granularity) and the muon system. It looks for high-$p_T$ muons, electrons, photons, jets and $\tau$-leptons decaying into hadrons, as well as large missing and transverse energies. The expected LVL1 rate is 75 kHz, and can be upgraded to 100 kHz. The latency (decision time) of the system is 2 $\mu$s. During this time, the information of all detector channels is stored. Upon receipt of a LVL1 signal, the information is transferred to derandomising buffers, from which it is read-out. The derandomising buffers ensure that no events are lost when a second event arrives before the first one is read out.

The LVL1 data is read-out by Read-Out Drivers (RODs) and then stored in Read-Out Buffers (ROBs). The second level trigger (LVL2) makes use of the LVL1 output to define Regions-Of-Interest (RoIs). Using this information, the LVL2 uses the data stored in the ROBs corresponding to the selected RoIs to make the LVL2 trigger decision. It is expected that the LVL2 trigger will further reduce the data to a 1 kHz rate. The data reduction can be achieved due to the availability of more precise information. The latency is event dependent and varies
between 1 ms and 10 ms. For the events that are accepted by LVL2, the entire event is transferred to the Event Filter, via the Event Builder.

The Event Filter reduces the data rate further to 100 Hz by making use of more complex algorithms, such as Bremsstrahlung recovery for electrons and vertex finding, running on processor farms. It also benefits from accessing the entire event.

The event size is 1 MB, and thus the data rate that has to be stored is 100 MB/s. One nominal ATLAS year ($10^7$ s) amounts to a total data volume of 1 PB ($10^9$ MB).

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*Figure 2.15: An overview of the ATLAS trigger. A description is given in the text.*
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