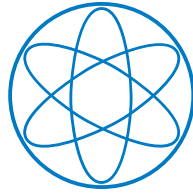


PHYSIK DEPARTMENT



Alignment of the ATLAS Muon Spectrometer Using Muon Tracks

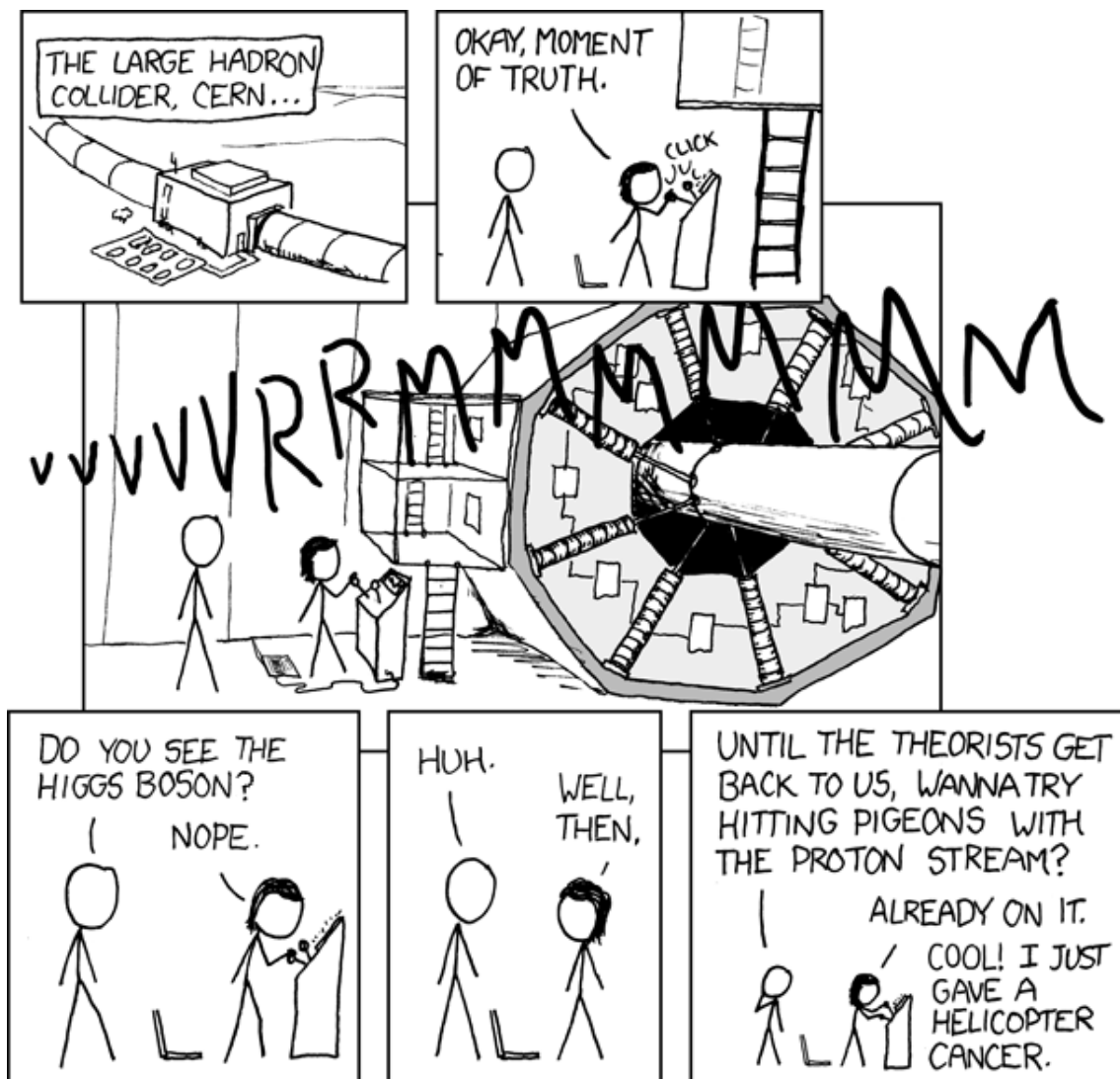
Diploma Thesis
by
Bernhard Bittner

November 28, 2008

CERN-THESIS-2008-161
30/11/2008



Max-Planck-Institut für Physik
(Werner-Heisenberg-Institut)



When charged particles of more than 5 TeV pass through a bubble chamber, they leave a trail of candy. (<http://xkcd.com/401/>)

Contents

I	ATLAS and the LHC	1
1	Introduction and Outline	3
2	The ATLAS Detector	5
2.1	The ATLAS Coordinate System and Conventions	5
2.2	The Detector Components	5
2.3	The Magnetic Field Configuration	8
II	The ATLAS Muon Spectrometer	11
3	The Muon Spectrometer	13
3.1	The Layout of the Muon Spectrometer	13
3.2	The MDT Chambers	13
4	Commissioning of the MDT Chambers in ATLAS	19
4.1	The Noise Rate of the MDT Chambers	20
4.2	Commissioning of the MDT Chambers in ATLAS	26
4.3	Overview of the Commissioning Status	27
III	The Alignment of the ATLAS Muon Spectrometer	31
5	Alignment Concepts	33
5.1	Why Is Alignment of the MDT Chambers Needed?	33
5.2	Momentum Determination with the Sagitta Method	34
5.3	Impact of Misalignment on the Sagitta Measurement	35
5.4	The ATLAS Optical Alignment System	37
5.5	Alignment Using Muon Tracks	39
6	Segment Reconstruction	41
6.1	Segment Reconstruction for Curved Tracks	41
6.2	Tests of the Segment Reconstruction Algorithm	43
6.3	Conclusions	48
7	Alignment with Straight Tracks	51
7.1	Alignment with Straight Tracks Using χ^2 Minimisation	51
7.2	Simplified Alignment Method	53
7.3	Conclusions	56

8	Alignment with Curved Tracks, Method I	59
8.1	Momentum Measurement in the Middle Chamber	59
8.2	Momentum Measurement from Angular Deflection	59
8.3	Influence of the Calibration	60
8.4	Track Reconstruction Accuracy	60
8.5	Chamber Shift Reconstruction	62
8.6	Conclusions	63
9	Alignment with Curved Tracks, Method II	65
9.1	Alternative Alignment Method	65
9.2	Rotation Determination	66
9.3	Performance Tests with Monte-Carlo Data	67
9.4	Conclusions	69
IV	Conclusions	71
10	Summary	73
V	Appendix	75
A	Momentum Calculation	77

Part I

ATLAS and the LHC

Chapter 1

Introduction and Outline

After years of delay the *Large Hadron Collider* (LHC) at CERN¹ will finally come into operation in 2009. This 27 km long machine will extend the frontiers of particle physics with its unprecedented high energy and luminosity. Inside the LHC, bunches of up to 10^{11} protons will collide at a rate of 40 million Hertz to provide proton-proton collisions at a centre-of-mass energy of 14 TeV with the design luminosity of $10^{34} \text{ cm}^{-2}\text{s}^{-1}$.

With this new collider, physicists hope to find answers to some of the most fundamental questions in particle physics. In particular, they are interested to answer questions such as: “Are there more than 3 space dimensions?” or “How did matter behave right after the Big Bang?”. The search for the *Higgs boson*, the only particle predicted by the standard model of particle physics which has not been observed yet, also plays the most important role. An other very interesting field is the search for new particles and physics beyond the standard model such as *supersymmetric particles* or first hints for expectations from string theories like extra spatial dimensions.

Two general-purpose detectors, ATLAS and CMS, will study proton-proton collisions at the LHC. This thesis is performed in the context of the ATLAS experiment. One very important part of this detector is its muon spectrometer which makes up for more than 80% of the whole detector volume. It is equipped with a huge superconducting air-core toroidal magnet providing an average magnetic field of 0.4 T to allow for a precise muon momentum measurement with the spectrometer alone. More than 1200 precision chambers are used to measure muon trajectories in the spectrometer with high efficiency.

The high spatial resolution of the muon chambers allows for the measurement of transverse muon momenta with a resolution of $\Delta p_T/p_T < 10\%$ up to energies of 1 TeV/c muons. This momentum resolution requires the knowledge of the relative positions of the muon chambers with 30 μm accuracy. The required accuracy of the chamber position measurement is provided by an optical alignment monitoring system.

This thesis addresses two import aspects of the muon spectrometer. In the first part, the focus is on the commissioning of the muon chambers with focus on noise reduction in the readout electronics. The second part studies the alignment of the muon spectrometer with muon tracks as a complement to the optical system.

¹CERN - Conseil Européen pour la Recherche Nucléaire

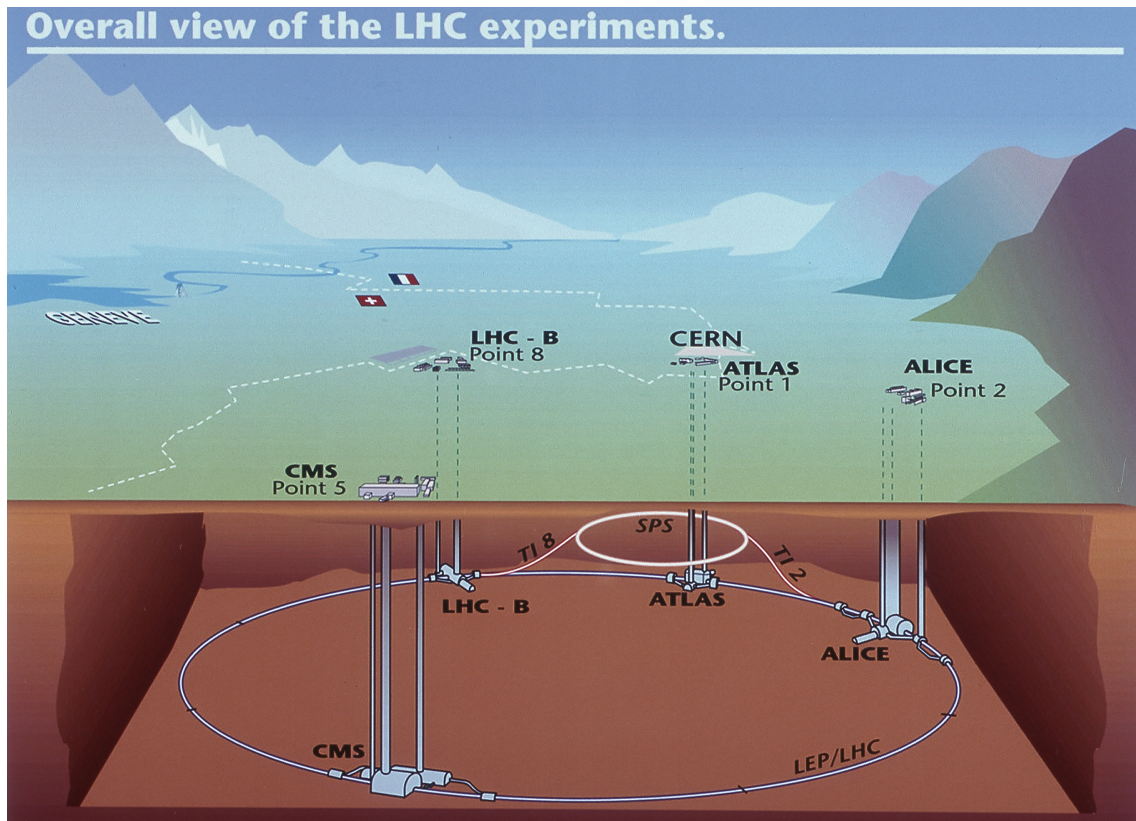


Figure 1.1: The Large Hadron Collider and its four large detectors: ALICE (A Large Ion Collider Experiment), ATLAS (A Toroidal LHC ApparatuS), CMS (Compact Muon Solenoid) and LHCb (Large Hadron Collider beauty experiment).

Chapter 2

The ATLAS Detector

There are four big detectors at the LHC: ALICE, ATLAS, CMS and LHCb. Two of them (ATLAS and CMS) are so-called *multi purpose detectors* and will exploit the whole range of physics available at the LHC. The other two will focus on certain specific physics processes. ALICE will study the formation of a quark-gluon-plasma resulting from colliding lead nuclei, LHCb will focus on b-quark physics and related CP violation.

The ATLAS detector is 44 m long and 25 m in height. It has an overall weight of about 7,000 tones. The cavern of the LEP¹ experiment that was situated at the same point was too small for the new detector and therefore a new cavern was build. The assembly of the detector started in 2003 and is about to be finished end of 2008.

2.1 The ATLAS Coordinate System and Conventions

The ATLAS coordinate system is a right-handed system. The x axis is pointing to the center of the LHC ring, the y axis is pointing upwards and the z axis is parallel to the beam, pointing towards the LHCb experiment at point 8 of the LHC (see Fig. 1.1). The polar angle ϑ is measured from the positive z axis. The pseudo-rapidity η is defined as

$$\eta = -\ln \tan \left(\frac{\vartheta}{2} \right) . \quad (2.1)$$

The transverse momentum p_T of a particle is defined as the momentum component perpendicular to the LHC beam axis. ATLAS is divided into two parts: the barrel region (with $|\eta| < 1.05$) and the endcap region ($1.05 < |\eta| < 2.7$).

2.2 The Detector Components

ATLAS, like all 4π collider detectors, consists of several layers of subdetectors. A cut-away view of the detector is shown in Figure 2.1. Following is a short description of the different detector parts. Since this thesis is concerned with the muon spectrometer, this part is described in more detail.

¹LEP - Large Electron-Positron Collider

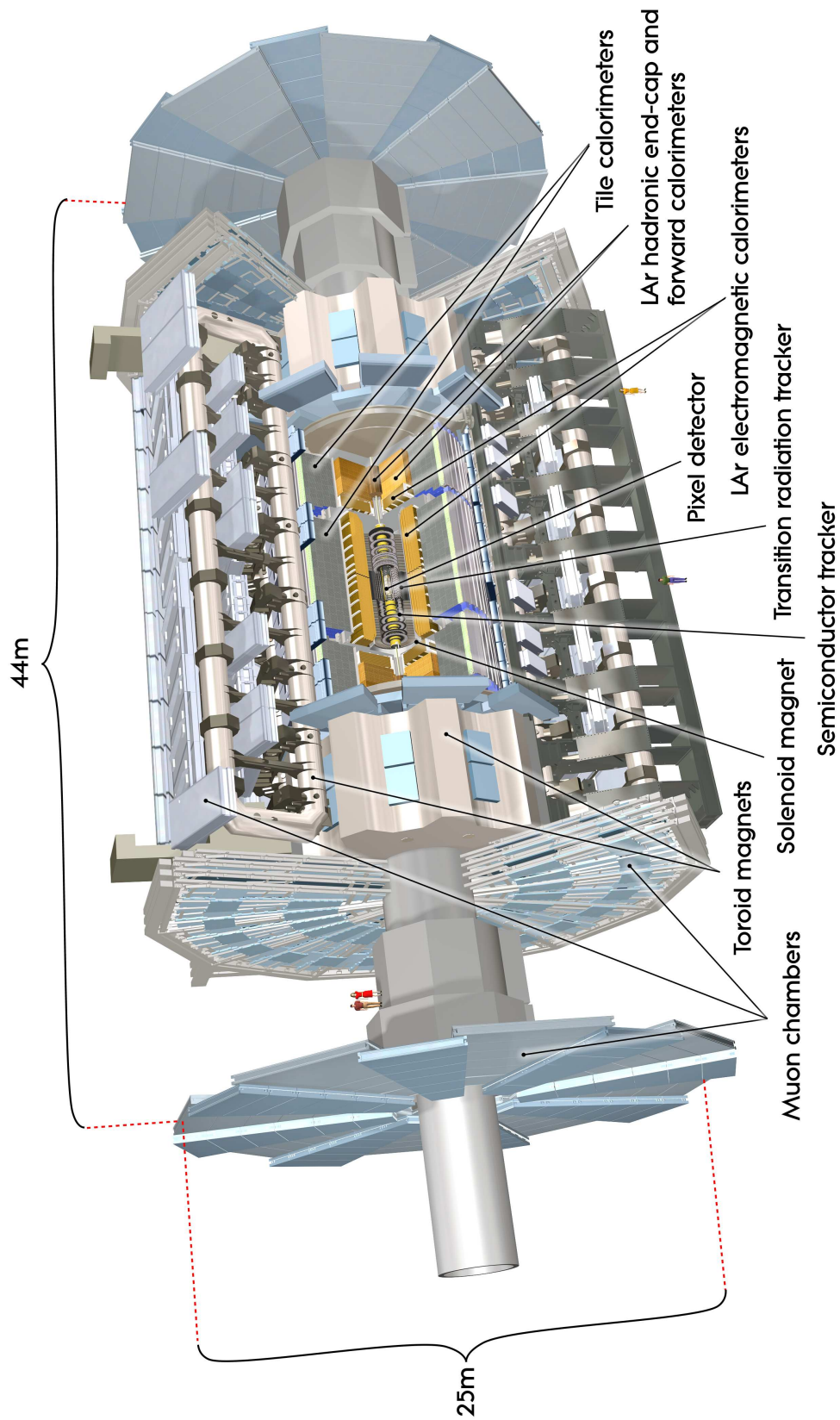


Figure 2.1: Cut-away view of the ATLAS detector. The dimensions of the detector are 25 m in height and 44 m in length. The overall weight of the detector is approximately 7000 tones.

2.2.1 The Inner Detector

The Inner Detector (ID) starts at a radial distance of 4.6 centimetres from the proton beam axis, extends to a radius of 1.2 metres, and is seven metres in length along the beam. The ID can determine track coordinates with an accuracy better than $20\ \mu\text{m}$ in the r - ϕ plane perpendicular to the beam. With this high accuracy it is possible to associate the detected particles to a common vertex.

The ID is built inside a superconducting solenoid magnet. From the measured track curvature the momentum of the particles can be calculated. To fulfill this task at the LHC, the detector has to cope with very high track densities and event rates. At the nominal luminosity of $10^{34}\ \text{m}^{-2}\text{s}^{-1}$, 28 proton-proton interactions every 25 ns are expected, each event consisting of up to about 2000 particles. This requires a very fast detector with high granularity.

The ID is a combination of three subsystems: two segmented silicon detector trackers (the Pixel Detector and the Semiconductor Tracker (SCT)) and a gas tracking detector, the Transition Radiation Tracker (TRT).

The Pixel Detector is the innermost part of the ID. Its 80 million electronics channels are distributed over 1744 modules with about 47,000 pixels each. The resolution in the *precision plane*² is as small as $10\ \mu\text{m}$.

It is surrounded by the SCT. This detector covers a larger η area, namely $|\eta| < 2.5$. The resolution in the precision plane is with $17\ \mu\text{m}$ almost as good as for the Pixel Detector, and it provides track points over a large volume. The modules are equipped with silicon strip detectors. Each strip has a width of $80\ \mu\text{m}$ and a length of 12.6 cm.

Subsequent is the TRT, a combination of straw-tube tracker and transition radiation detector. It consists of straw tubes (tiny drift tubes) and a transition medium inbetween and provides on average 36 spacepoints per track with a resolution of about $170\ \mu\text{m}$. Electrons are identified by their characteristic transition radiation.

2.2.2 The Calorimeters

The calorimeters are starting right outside the solenoid magnet, at a distance of 1.5 meters from the beam axis. Their purpose is the determination of the total energy of a particle. This is done by stopping the particles and their decay products and measuring the deposited energy in the calorimeters. Since the interaction of hadrons, leptons and photons with matter is very different, there is one part dedicated to measure hadron energies and another part designated to determine the energy of electro magnetically interacting particles.

Except for muons, all particles are absorbed in the calorimeters.

The Liquid Argon Calorimeter

The *Liquid Argon* (LAr) Calorimeter is divided into several components: an electromagnetic sampling calorimeter with 'accordion-shaped' lead absorbers in the barrel and in the endcaps, a hadronic calorimeter using flat copper electrodes in the endcaps, and a forward calorimeter close to the beampipe in the endcaps made of copper and tungsten as absorber material. In addition, LAr presampling calorimeters in

²The so-called *precision plane* is the r - ϕ plane, providing the measurement of the important transverse momentum p_T of a track.

front of the electromagnetic calorimeter help to correct for the energy loss in front of the calorimeter (mainly due to LAr cryostat walls and the barrel solenoid).

The Tile Calorimeter

The *Tile Calorimeter* is a large hadronic sampling calorimeter which uses steel as absorber material and scintillating plates read out by wavelength shifting fibres as active medium. It covers the central region $|\eta| < 1.7$. A special feature in its design is the orientation of the scintillating tiles which are placed in planes perpendicular to the colliding beams and are staggered in depth resulting in a good sampling homogeneity. The thickness of the calorimeter is equivalent to a total of about two hadronic interaction lengths. It has a cylindrical structure with an inner radius of 2.3 m and an outer radius of 4.2 m and is subdivided into a 5.6 m long central barrel and two 2.9 m long extended barrel parts. The total number of readout channels is about 10,000.

2.2.3 The Muon Detectors

The muon spectrometer forms the outermost layer of ATLAS. the fact that muons are the only long living particles that don't get stopped in the calorimeters, is used for particle identification. A toroidal magnetic field of 1.5 T bends the muon tracks a second time after the ID and provides the possibility to independently determine the momentum of the particle.

ATLAS uses four different muon detector types: Monitored Drift Tube chambers (MDT), Resistive Plate Chambers (RPC), Thin Gap Chambers (TGC) and Cathode Strip Chambers (CSC). RPCs and TGCs are very fast responding chambers, but have only a poor spatial resolution. They are used to provide a muon trigger and the so-called second coordinate³. RPCs are used in the barrel part, TGCs in the endcaps. The MDT and CSC chambers provide a very high spatial resolution in the track bending plane, but are relatively slow. The combination of all four detector types provides the desired resolution in space and time.

In the very forward direction, the rate of muons is very high and only the CSCs are fast enough to detect them with high efficiency. A schematic view of the locations of the different chamber types is shown in Figure 3.1. The combination of a MDT and a RPC chambers in the barrel is called a muon station.

The muon spectrometer is discussed in detail in the following section.

2.3 The Magnetic Field Configuration

As discussed before, there are two independent superconducting magnets in ATLAS: a central solenoid producing a field of 2 T surrounding the inner detector and a toroidal magnet system with a maximum field of 1.5 T in the muon spectrometer (see Fig. 2.2). The toroidal magnet system consists of a barrel part and two endcap magnets. The outer endcap parts of the muon spectrometer are outside the magnetic field.

³The direction perpendicular to the precision plane.

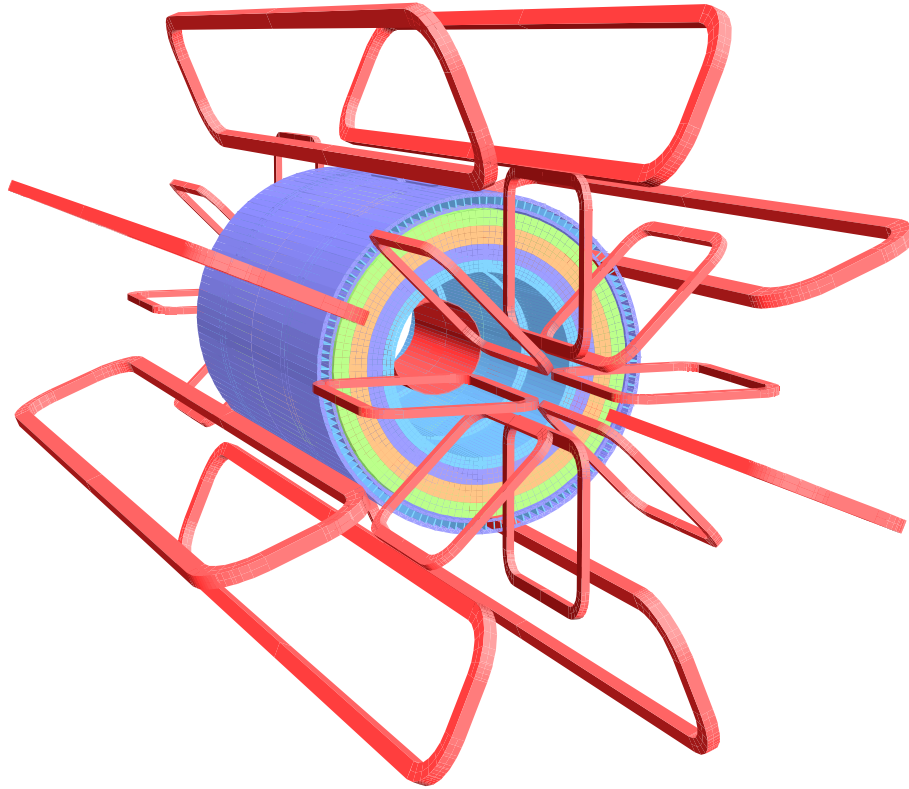


Figure 2.2: Geometry of the magnet coils and tile calorimeter steel. The eight race-track shaped barrel toroid coils, with the end-cap coils interleaved, are visible. The solenoid magnet lies inside the cylindrical calorimeter volume. The tile calorimeter serves also as return yoke for the solenoid magnet.

Part II

The ATLAS Muon Spectrometer

Chapter 3

The Muon Spectrometer

After the quick overviews of all subsystems in ATLAS, the muon spectrometer shall now be discussed in detail. ATLAS puts much emphasis on a very precise muon reconstruction since there are many physics processes with muons in the final state. The muon spectrometer is also the largest part of ATLAS and therefore responsible for the huge dimensions of the detector (see Fig. 2.1).

3.1 The Layout of the Muon Spectrometer

The muon spectrometer consists of 3 layers of chambers in the barrel and in the endcaps as shown in Figure 3.1. There are also additional chambers (e.g. mounted on the endcap toroids) to close acceptance gaps.

The magnet system of the muon spectrometer contains no iron in order to minimize scattering of the muons. With a solid iron core it would have been possible to achieve a stronger magnetic field, but at the cost of much higher deflection of muon tracks due to multiple scattering.

Without contribution from the inner detector the aim for the momentum resolution of the muon spectrometer is

$$\frac{\Delta p_T}{p_T} < 3\% \quad \text{for } E_\mu < 200 \text{ GeV} \quad \text{and} \quad \frac{\Delta p_T}{p_T} \approx 10\% \quad \text{for } E_\mu \approx 1 \text{ TeV} . \quad (3.1)$$

The muon momentum is determined from the sagitta of the muon track and the magnetic field strength along the track. To achieve the desired momentum resolution the muon chambers have to provide a spatial resolution of about $40 \mu\text{m}$ and the relative positions of the chambers have to be known with an accuracy of about $30 \mu\text{m}$ in the bending plane.

The precision tracking detectors of the ATLAS muon spectrometer are mostly drift-tube detectors, the so-called *Monitored Drift Tube* (MDT) chambers. A small forward region of the spectrometer is covered by CSC chambers.

3.2 The MDT Chambers

The monitoring by optical sensors (discussed in detail in Chapter 3.2.2) serves for the measurement of torsions and expansions induced by the magnetic field and

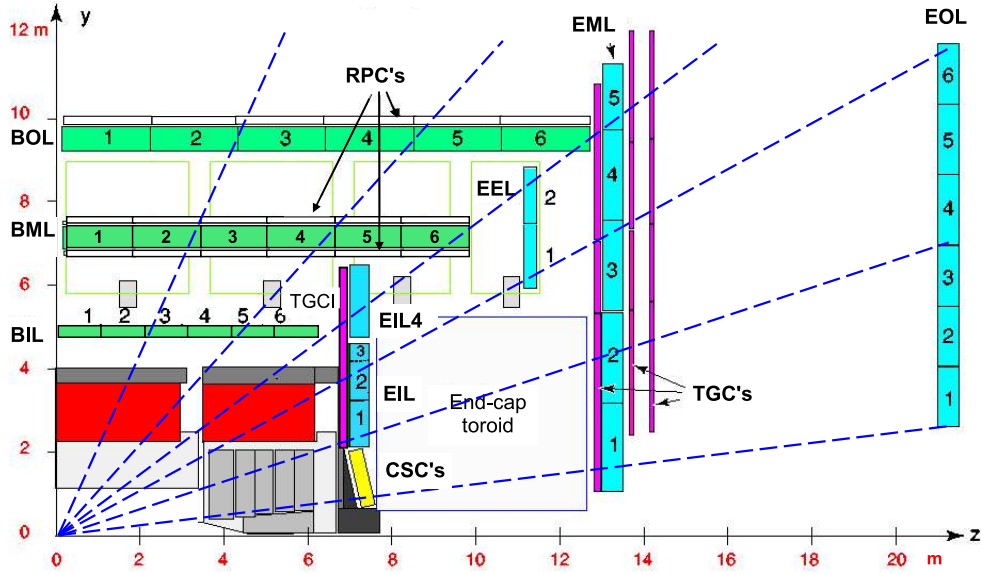


Figure 3.1: Schematic view of one quadrant of the muon system in the r - z plane (track bending plane). The dashed lines indicate tracks of muons with infinite momentum. They typically traverse three muon stations allowing for a track sagitta measurement (see text). The different detector types in the muon system, MDT (in BIL, BML, BOL, EIL, EEL, EML and EOL layers), CSCs, RPCs and TGCs are indicated.

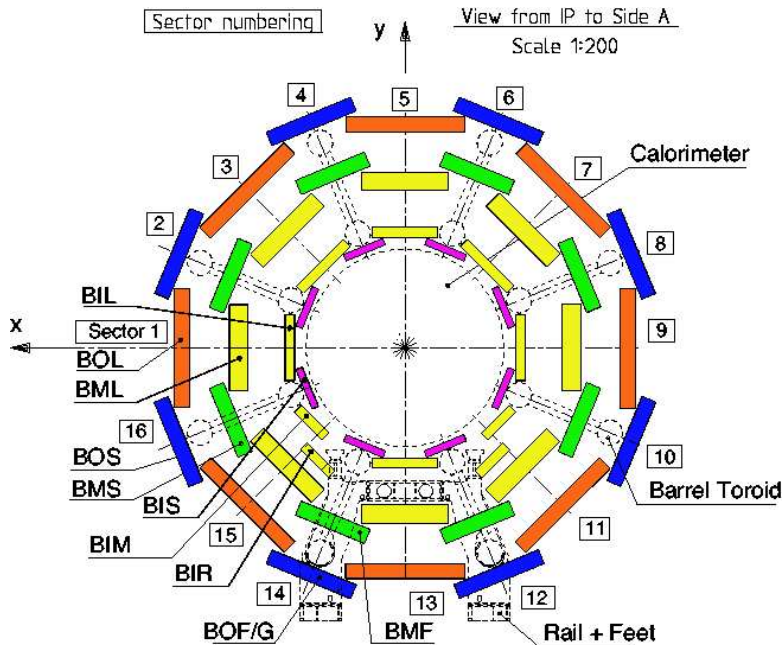


Figure 3.2: Cross-section of the barrel muon system perpendicular to the beam axis (non-bending plane) showing three concentric cylindrical layers of eight large and eight small chambers. The outer diameter is about 20 m. The global ATLAS coordinate system is indicated.

Parameter	Design value
Tube material	Aluminum
Outer tube diameter	29.970 mm
Tube wall thickness	0.4 mm
Wire material	gold plated W/Re (97/3)
Wire diameter	50 μm
Gas mixture	Ar/CO ₂ /H ₂ O (93/7/ $\leq 1000\text{ppm}$)
Gas pressure	3 bar (absolute)
Gas gain	2×10^4
Wire potential	3080 V
Maximum drift time	≈ 700 ns
Average resolution per tube	≈ 80 μm

Table 3.1: Parameters of the drift tubes in the ATLAS MDT chambers

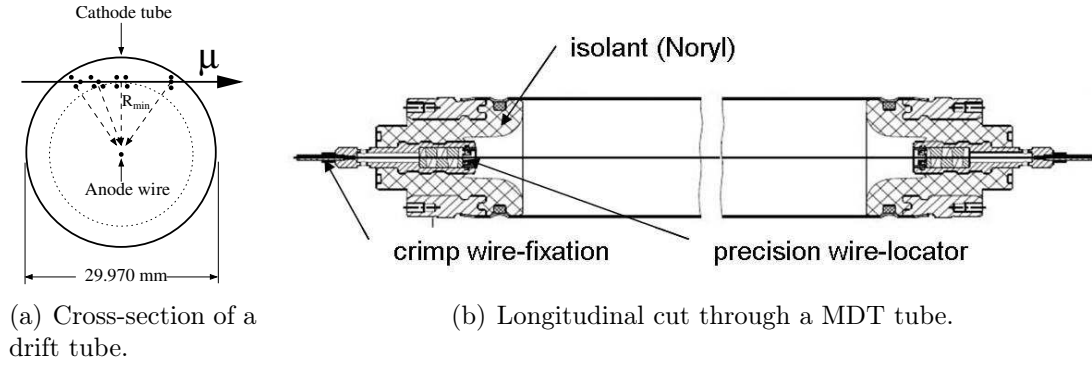


Figure 3.3: A MDT tube in different views.

temperature changes, respectively. There are also optical measurements between the different chambers to measure their relative movements.

Each chamber consist of 2 multilayers of drift tubes, each with 3 tube layers and 4 tube layers for the inner chambers, respectively. Design parameters of the drift tubes are shown in Table 3.1. The mechanical structure of a MDT chamber is shown in Figure 3.4.

All MDT chambers inside ATLAS have a unique name e.g. BOS5A04 (cp. Fig. 3.1 and Fig. 3.2). The name describes the position of the chamber and the type. The first letter indicates wether the chamber is in the barrel (B) or belongs the endcaps (E). The second letter stands for **I**nnner, **M**iddle or **O**uter and refers to the three layers of chambers around the interaction point. The next letter indicates if the chamber belongs to a **L**arge or a **S**mall sector. The coils of the toroid are in the 'small' sectors, leaving less space for the muon chambers. The first number stands for the η index of the chamber as shown in Figure 3.1. The last letter stands for the both sides of ATLAS, the **A** side (positive z axis) and the **C** side (negative z axis). The last number is the sector number. So our chamber is in the barrel, a small outer chamber in sector 4. It is located on the A side and has an η index of 5.

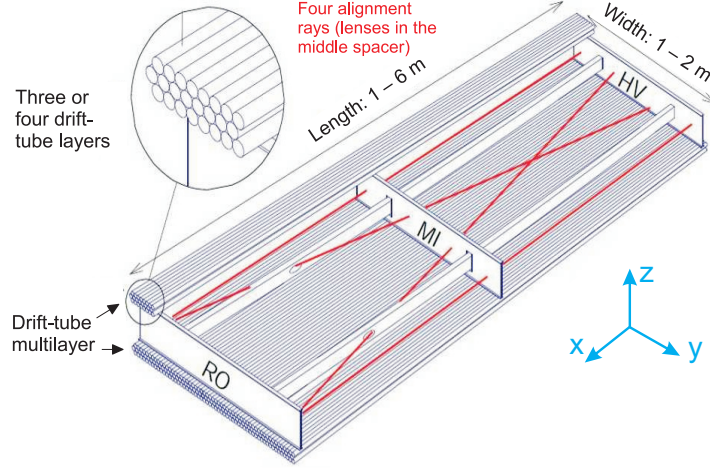


Figure 3.4: Mechanical structure of a MDT chamber. Three spacer bars connected by longitudinal beams form an aluminum space frame carrying two multilayers of three or four drift tube layers. Four optical alignment rays, two parallel and two diagonal, allow for monitoring of the internal geometry of the chamber. RO and HV designate the location of the readout electronics and high voltage supplies, respectively.

The local coordinate system of the chamber is given by the wires (x axis), the y axis perpendicular to the tubes and parallel to the tube layers and the z axis perpendicular to the tube layers.

3.2.1 Principle of Drift Tubes and MDT Chambers

When a charged particle is passing through the tube, the gas molecules along the path get ionised. Due to the high potential difference between the tube wall and the wire, the electrons drift to the anode wire in the centre of the tube, whereas the ions drift to the tube wall (cp. Fig. 3.3(a)). The drift velocity of the electrons depends on the local electric field. Due to the cylindrical geometry the field gets stronger closer to the wire. At a distance of about $150 \mu\text{m}$ from the wire, the field is strong enough that the energy gained by the electrons allows for the ionisation of the gas molecules. This leads to an avalanche of secondary electrons. Under normal ATLAS operating conditions, the gas amplification is about $2 \cdot 10^4$.

The readout electronics measures the time corrected for the muon flight time between the beam crossing signal and the charge pulse arriving on the wire plus an offset from the propagation of the signal along the wire. This gives the time the electrons needed to drift from the muon ionisation track to the wire. From the time measurement one can determine the minimal distance $R_{\min}$ between the muon track and the wire (see Fig. 3.3(a)). To determine the offset, the position information of the trigger chambers (RPC or TGC) in the second coordinate (local x) along the wire is used.

The drift time t is linked to the drift radius r by the so called space-to-drift relationship $r(t)$ or r - t relationship. This relationship depends on environmental parameters such as gas mixture and density, magnetic field and high voltage. To obtain a precise r - t relationship, each chamber has to be calibrated at regular time intervals of about one day (cp. [6]).

With this r - t calibration a resolution of a single tube of about $80 \mu\text{m}$ is achieved.

It is limited mostly by fluctuations of the ionisation clusters along the track and the diffusion of the electrons. Also, ionisation clusters from background radiation, such as thermal neutrons, have a negative influence on the resolution because of the induced fluctuations of the space charge and therefore of the local electric field in the tubes.

Combining the position measurements of the drift tubes in the 6 to 8 layers of a MDT chamber along the muon track, allows for a chamber position resolution of $40\text{ }\mu\text{m}$ provided the anode wire positions in a chamber are known with an accuracy of $20\text{ }\mu\text{m}$. This high mechanical accuracy of the MDT chambers is assured by the precise assembly of the chambers and by continuous optical monitoring of their deformations during operation.

3.2.2 MDT Chamber Monitoring

Each MDT chamber has its own internal optical monitoring system to measure mechanical deformations. As indicated in Figure 3.4, there are 4 optical alignment rays built into the frame of a chamber: two along the tubes and two diagonal. With this system, it is possible to monitor deformations with an accuracy of tens of micrometers [15]. This system was also used to adjust the tube sag to the wire sag of up to $500\text{ }\mu\text{m}$ due to gravity in order to centre the wires in the tubes.

The importance of the chamber deformations for the track reconstruction within a chamber is studied in Section 6.2.4.

3.2.3 MDT Chamber Electronics

Each chamber is served by a high voltage (HV) power supply for the drift tubes, a low voltage (LV) power supply for the readout electronics, a connection to the central trigger and readout system and a connection to the **Detector Control System (DCS)**.

High Voltage Supply

The high voltage for the drift tubes is distributed on the chamber via a HV splitter box to each of the tube layers. The two multilayers of the chambers are served by separate channels of the HV power supplies. Inside a multilayer, the tubes are connected serially via so-called HV hedgehog boards. Each board provides HV for a group of 24 tubes.

Readout of the Chambers

The central part of the MDT chamber readout electronics is the *Chamber Service Module (CSM)*. It has connections to the *mezzanine cards* (see below), the timing, trigger and control (TTC) system, an optical link to the readout system and a serial connection to the DCS box on the chamber. A schematic view of all electronic components on a chamber is given in Figure 3.5.

The mezzanine cards are mounted on read-out (RO) hedgehog boards. These boards are similar to the HV hedgehog boards, but their purpose is to decouple the signal from the HV and relay it to the ASD chips¹ on the mezzanine cards. Each

¹An ASD chip consists of 8 **A**mplifier, **S**haper and **D**iscriminator chains.

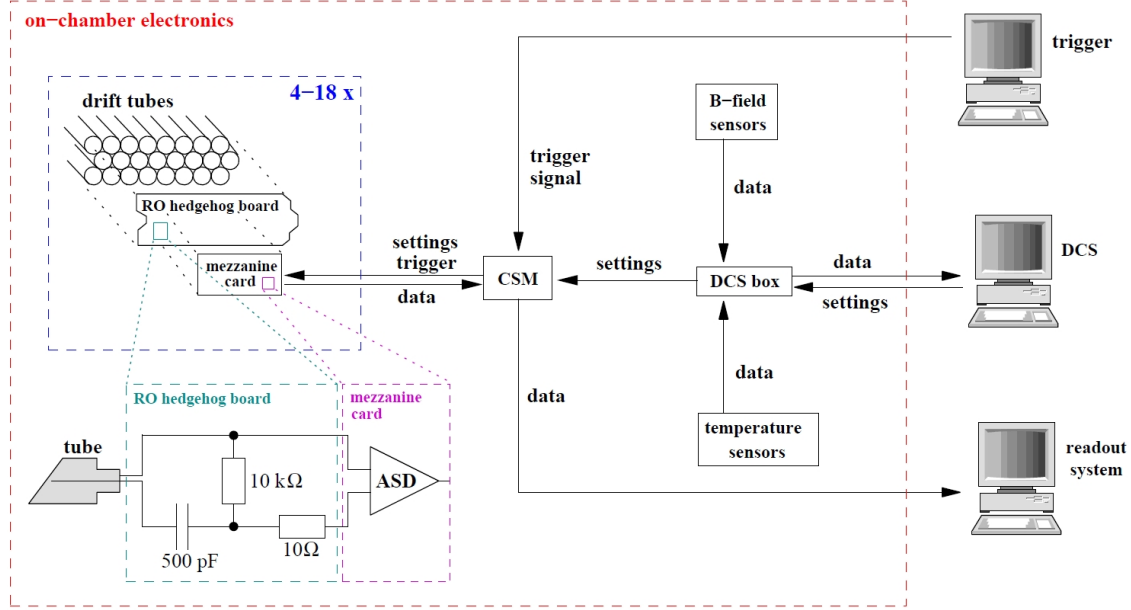


Figure 3.5: The readout electronics scheme of a MDT chamber. The Chamber Service Module (CSM) controls all components.

ASD chip has eight channels and there are three chips per mezzanine card. When the signal exceeds a programmed threshold which can be set separately for each ASD chip the ASDs send digital signals to a TDC² on the mezzanine card and analog signals to an ADC³.

The time measurement in the TDC is started by the bunch crossing signal of the LHC and stopped when the signal from the ASD chips arrives. With a time-of-flight correction, the start signal corresponds to the moment when the muon crosses the tube. Consequently, the time measured by the TDC is the drift time of the electrons in the tube plus the signal propagation time along the wire.

The ADC is measuring the charge of the pulse arriving during a certain time window after the threshold of the ASD is crossed (typically 20 ns). The information can be used to distinguish between real muon and noise hits, since muons have a higher signal. It is also possible to correct for time variations of the threshold crossing depending on the signal size.

The information from the TDC and the ADC are transferred to the CSM. If the module receives a trigger signal from the central ATLAS trigger, the data is sent via an optical fibre to the central DAQ⁴.

The DCS box on the chamber is connected to the CAN⁵ bus of ATLAS. Over this bus the electronics of the chambers can be programmed (e.g. different thresholds, new firmware versions) and initialized. Also the temperature and B-field sensors on the chambers are read out via this bus.

²TDC - **T**ime-to-**D**igital-**C**onverter.

³ADC - **A**nalog-to-**D**igital-**C**onverter.

⁴DAQ - **D**ata **A**cquisition.

⁵CAN - **C**ontroller **A**rea **N**etwork.

Chapter 4

Commissioning of the MDT Chambers in ATLAS

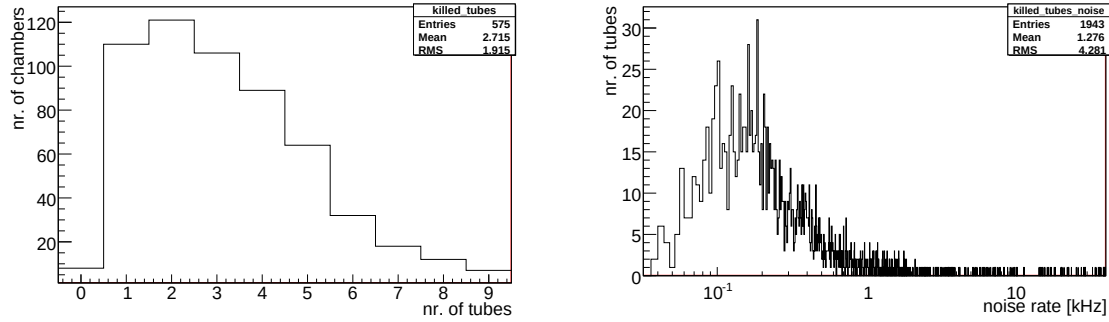
Once an MDT chamber is installed in the ATLAS detector, the access is very limited and repair is difficult. Therefore all chambers were tested several times—at the production sites, after transport to CERN [4, 7] and before installation—with preliminary power supplies and gas and read-out systems to ensure that only fully functional chambers are installed in the experiment. These tests included measurements of the gas leak rate, HV stability and noise rates. The complete chambers, including front-end-electronics and components of the optical alignment system, were certified with cosmic rays.

As soon as the chambers are installed in the detector, they should be connected to the final gas and power supplies and be included in the central trigger and readout chain. Unfortunately this was not always possible due to time limitations, interference from other installation tasks, and the limited availability of gas and electrical services. Chambers already installed in the detector and connected to the central services are continuously tested to discover new failures. The tests include taking cosmic and noise data with all available chambers and in combination with other subsystems of ATLAS [11].

The serial tests of the 88 MDT chambers built at MPI started in fall 2003 and continued until beginning of 2006 in Munich [8, 9]. The chambers were integrated with their trigger chambers and tested at CERN between November 2004 and April 2006 [16, 9]. They were installed in the experiment in 2005 and 2006 and subsequently commissioned [14, 12, 9].

Cosmic Ray Data Taking

For the so-called *milestone runs*, ATLAS was running with all available subdetector systems and recording muon events originating from cosmic radiation which is the only other radiation source besides the LHC which can illuminate the whole detector. The difference to normal data taking is the trigger setting as the muons are not originating from the primary vertex as during beam collisions and are arriving randomly in time. The purpose of these runs is the commissioning and optimization of the detector components and the debugging of hard- and software problems.



(a) Number of tubes per chamber with noise rate 3-RMS above average (see text for details).

(b) Noise rate distribution for tubes outside the 3-RMS window.

Figure 4.1: Frequency of drift tubes with high noise rates.

Noise Runs

The noise rate is determined with the same method as used in the pre-installation tests. A random trigger with a typical rate of 10 kHz was used. Accidental hits in the acceptance time window of the electronics can originate from discharges in the tubes, from pick-up on the cables and thermal noise in the electronics. To differentiate between discharges and electronics noise runs with and without HV applied were taken.

4.1 The Noise Rate of the MDT Chambers

The noise rate f_{noise} of a drift tube is determined by randomly triggering the MDT chamber readout electronics and dividing the fraction of hits per trigger by the active time window of the data acquisition:

$$f_{\text{noise}} = \frac{\text{events}}{\text{active time window} \cdot \text{total number of triggers}}. \quad (4.1)$$

Equation (4.1) is only valid for $1/f_{\text{noise}}$ much less than the active time window. The active time window is the time interval in which the electronics is accepting a trigger signal. For the MDT chambers it is set to $2.5 \mu\text{s}$ (3200 TDC counts a 25/32 ns). The noise rate of a drift tube during normal ATLAS operation is depending on the threshold settings on the ASD chip. The highest acceptable rate is 40 kHz per tube chosen such that the noise rate is negligible compared to the real hit rate [7].

To calculate the average noise rate, one determines the average rate over all tubes in the chamber. Tubes with zero hits are dropped. To minimize the effect of single noisy tubes, the RMS of the noise rate distribution is calculated and all tubes with a rate more than three times the RMS above the average values are excluded from the calculation of the new average is calculated. The numbers of excluded tubes and the noise rate spectrum are given in Figure 4.1.

For a reliable noise rate determination very high statistic is needed:

$$N = \frac{1}{0.01^2} = 10^4 \text{ events for } 1\% \text{ accuracy.}$$

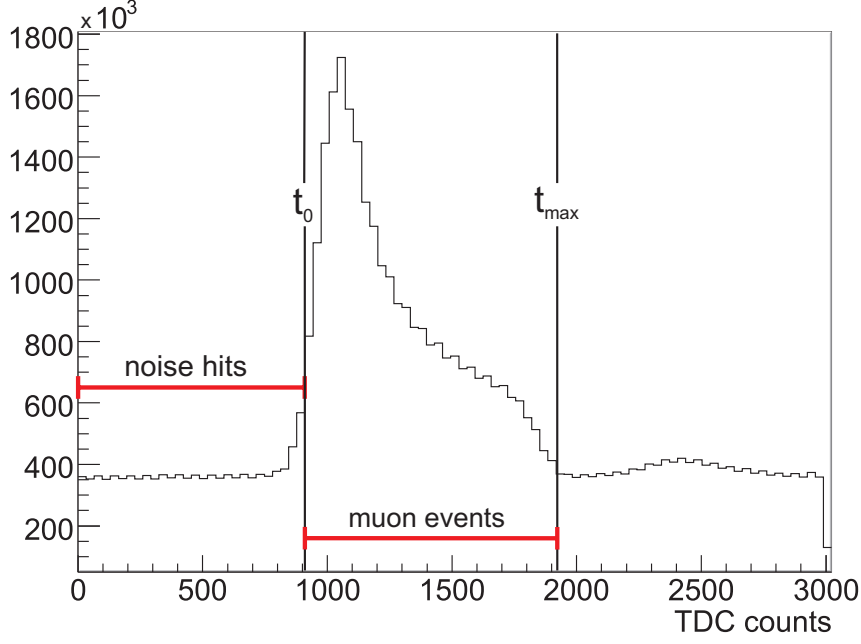


Figure 4.2: Example TDC spectrum. The drift time spectrum is clearly visible between $t_0 = 900$ and $t_{\max} = 1900$ TDC counts ($0.70 \mu\text{s}$ to $1.5 \mu\text{s}$). Every hit before 850 TDC counts is considered noise. For this specific run the active time window was set to 3000 TDC counts.

The time measurement always shows an offset between the trigger time $t = 0$ and the arrival time of the signal. All events *before* the start of the drift time spectrum must be noise hits (cp. Fig. 4.2). The noise rate during cosmic data taking is given by:

$$f_{\text{noise, cosmic}} = \frac{\text{events before } t_0}{t_0 \cdot \text{total number of triggers}} . \quad (4.2)$$

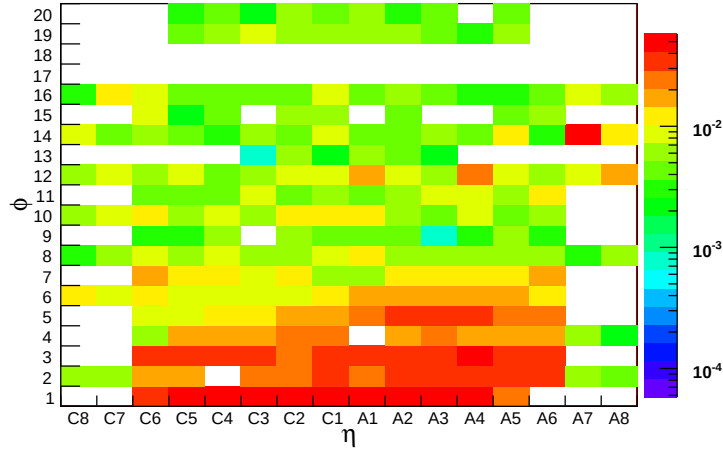
To achieve an accuracy of 1% in the noise rate measurement one needs 10^4 events per tube, because not all are in the noise window. One needs about

$$10^4 \cdot \frac{\text{active time window}}{t_0} \approx 60 \cdot 10^3$$

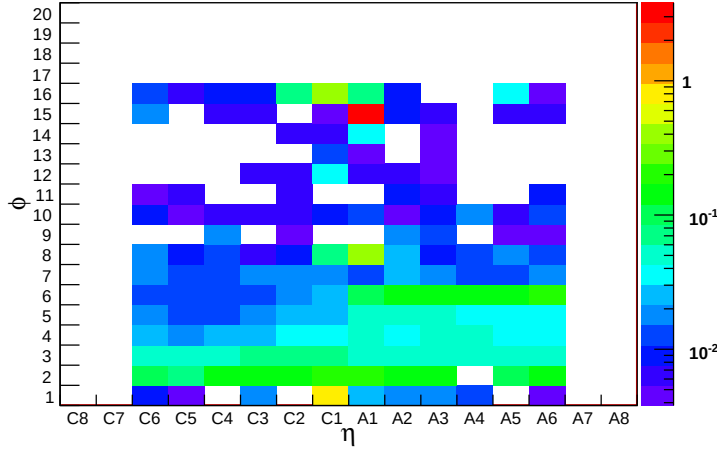
events.

An overview of the measured noise rates for the barrel MDT chambers is given in Figure 4.3. The noise rate is not uniform for all chambers in the barrel. The highest noise rates are observed in azimuthal sectors 1 to 6. This is especially obvious for the inner layer. Also the noise rate of chambers on the A side are slightly higher than on side C. A possible explanation for this pattern is that most of the cables for the inner detector are routed through these sectors.

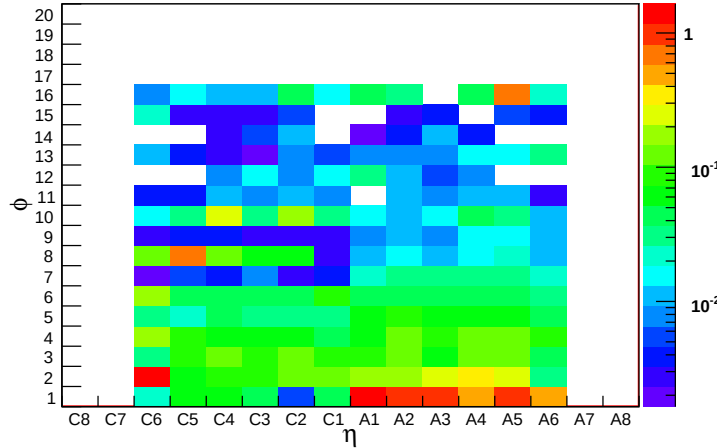
With very few exceptions the noise rates are below the maximum tolerable value (e.g. BML1A15). The BML1A15 chamber has one layer with very high noise rate which is most probably related to a broken HV cable between the splitter box and the tube layer.



(a) Noise of the inner layer chambers in kHz.



(b) Noise of the middle layer chambers in kHz.



(c) Noise of the outer layer chambers in kHz.

Figure 4.3: Average noise rates of the barrel MDT chambers identified by their code names as function of η and ϕ (cp. Sec. 3.2). Note the different scales. Chambers with less than 100 hits per layer are left blank. The BIR chambers in ϕ -sector 11 and 15 are moved to the (virtual) sectors 19 and 20, respectively, since the bins are already occupied by the BIM.

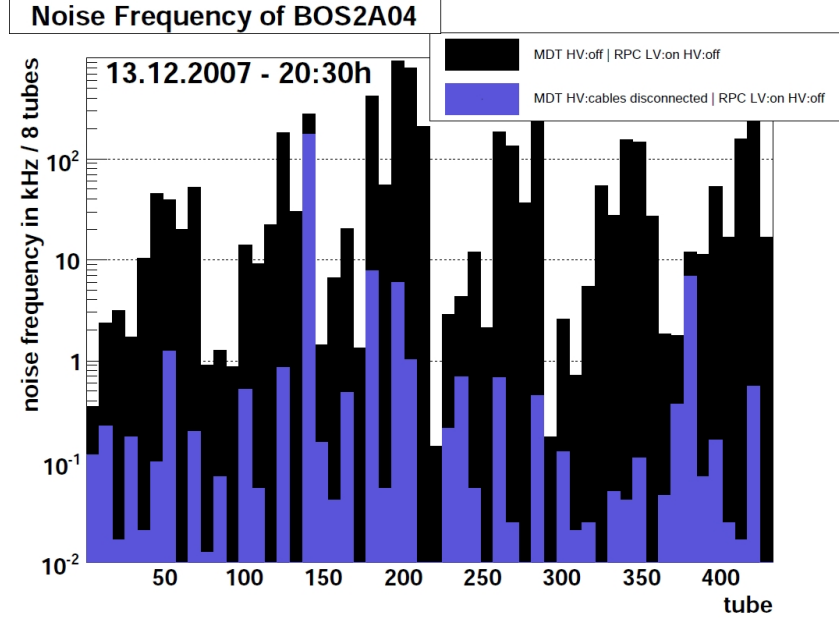


Figure 4.4: Noise rates of the 432 drift tubes of a BOS MDT chamber in ATLAS with (black) and without (blue) HV cables connected to the chamber.

4.1.1 Noise Rate of BOS chambers

During the noise runs in summer 2008, a significantly higher noise rate compared to other chambers and to the tests before the chamber installation in the ATLAS detector was found on several of the BOS MDT chambers built at the MPI. The pattern is visible in Figure 4.3(c). All even ϕ -sectors (BOS MDT chambers) on side C have a higher average noise rate than the neighboring BOL chambers in the odd sectors. The effect is also visible on side A, but not to as pronounced.

Further investigation revealed that the noise is equally distributed over all mezzanine cards on the chambers and therefore a problem in the electronic components is very unlikely. One explanation is pick-up on the HV cables. To verify this assumption, noise runs with different settings were taken: HV cables not connected, HV cables only connected to the chamber and not to the power supply, HV cables connected to the chamber and the power supply. Also the routing of the HV cables was changed. The tests revealed a clear pick-up on the HV cables with the noise rates dropping by a factor 10 to 100 when disconnecting the cables (cp. Fig. 4.4).

Closer investigation, including measurements of signals induced on the cables, revealed no explicit sources for the pick-up on the chamber, only a small influence of the RPC electronics mounted on the muon stations was discovered. Since the source of the noise could not be located and eliminated, an alternative approach was followed: installing additional low-pass filters between the HV cables and the tube layers to dampen pick-up signals with high frequencies. Two possible locations for the filters were considered:

- inside the splitter box (cp. Fig. 4.6(a)),
- between the splitter box and the single layers (cp. Fig. 4.6(b), 4.7(a)).

After several tests, the best results were achieved by installing filters between the original splitterbox and the tube layers as close as possible to the connectors leading

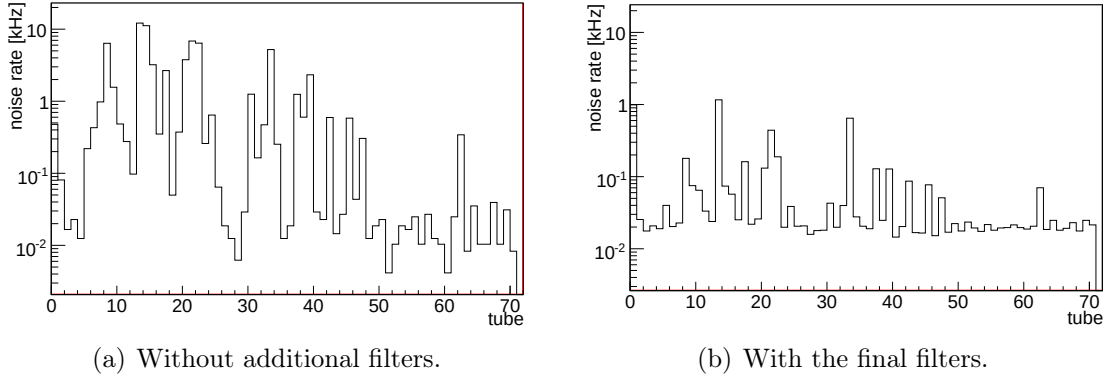


Figure 4.5: Effect of the noise filters: a significant decrease of the noise rates is clearly visible.

into the Faraday cage of the readout electronics. Since the 15th of August 2008 all 88 MDT chambers constructed in Munich are equipped with the final noise filters and are now well below the 40 kHz noise limit per tube (see next section).

4.1.2 The Noise Filters

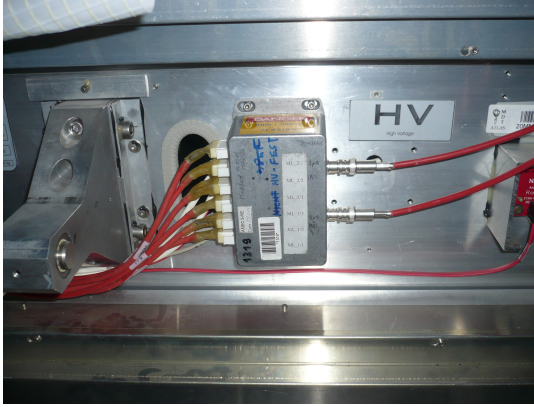
The splitter boxes installed on the MDT chambers already have a low-pass filter with a cut-off frequency of $f_C \approx 160$ kHz included. To further reduce the noise, filters with lower cut-off frequency are needed. f_C is defined as the frequency above which the amplitude of an incoming signal is damped to less than half of the initial value. For a simple R - C filter it is given by

$$f_C = \frac{1}{2\pi \cdot R_{\text{total}} \cdot C_{\text{total}}} . \quad (4.3)$$

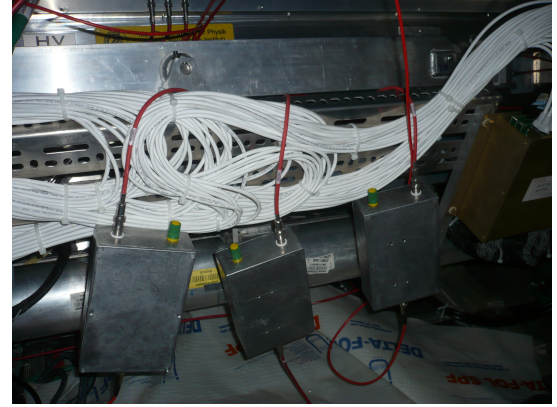
The cut-off frequency can be lowered by either increasing the resistance or the capacitance of the R - C circuit. For the first prototypes the original splitter box was modified. The capacitance was increased by a factor of 20 (from 500 pF to 10 nF) while the resistor in the shielding was removed to reduce potential differences between the ground and the chamber resulting in $f_{C,\text{new}} \approx 16$ kHz. This modification led to a decrease of the noise rate by a factor of 10 to 100 (cp. Fig. 4.5).

Placing the filter before the original splitter boxes did not change the noise rate, leading to the conclusion that there is also pick-up on the HV distribution cables on the chambers. Therefore it is preferable to have a filter close to each tube layer minimizing the length of cable between filter and tubes.

First prototypes with a cut-off frequency of less than 100 Hz have been tested with very good results, resulting in the decision to install such filters on all chambers. The final design of the filters with a cutoff frequency of $f_C \approx 725$ Hz is shown in Figure 4.7.

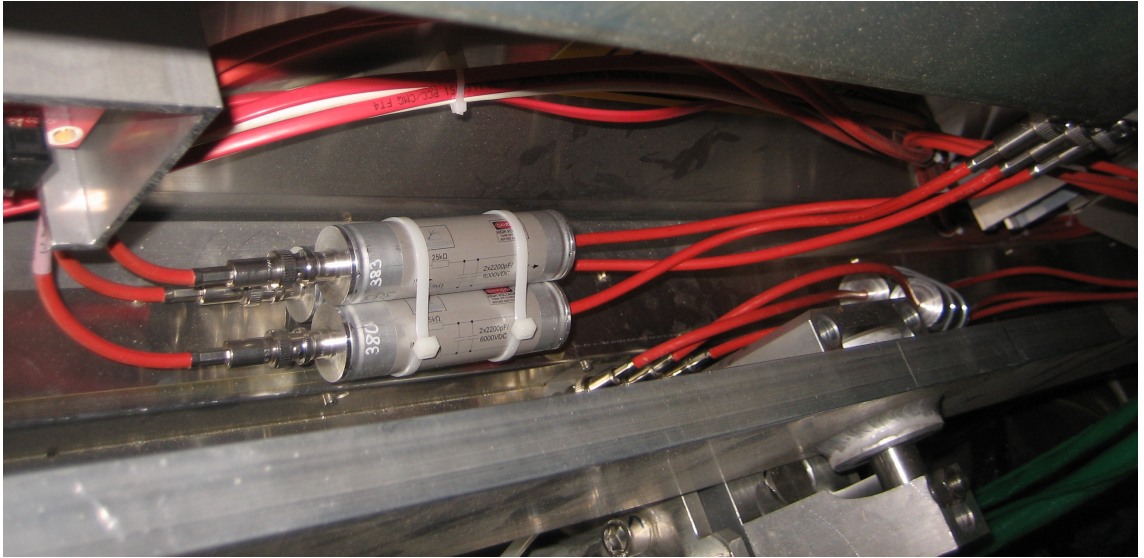


(a) Included in a splitter box

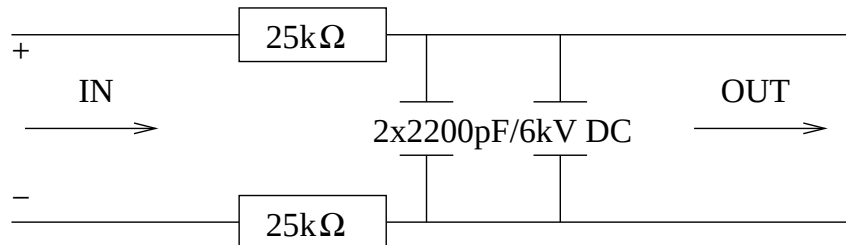


(b) Separately for each layer

Figure 4.6: First prototypes of the noise filters.



(a) Final Design of the noise filters.



(b) Circuit diagram of the final noise filters.

Figure 4.7: The final design of the noise filters with a cut-off frequency of $f_c = 732.4$ Hz.

4.2 Commissioning of the MDT Chambers in ATLAS

The cosmic and noise runs are also an opportunity to identify chambers with hard- or software problems. Errors can occur at different stages in the data taking process, in particular during

1. powering of the chambers with LV and HV controlled by the DCS¹,
2. initialisation of the on-chamber electronics (e.g. programming of the CSMs and mezzanine cards with the individual thresholds),
3. the actual data taking.

Problems occurring during the powering up are easy to locate: either the chamber is not yet connected to the power supplies (no current drawn) or there is a short circuit in the HV cable (e.g. badly isolated connectors) or on the chamber (e.g. a broken wire in a tube). A short circuit is obvious if the current reaches the limit of $10\text{ }\mu\text{A}$. During cosmic ray data taking, a chamber is expected to draw less than $1\text{ }\mu\text{A}$ of current.

To check if the short circuit is on the chamber or on the HV cable, the chamber is disconnected from the HV cables and the power supply is ramped up. If the nominal voltage of 3080 V is reached without current flow, the problem has to be on the chamber itself. Now each tube layer is tested separately, then the individual tubes in the layer. A broken wire is disconnected from the HV distribution by removing the corresponding resistor on the hedgehog card.

If the on-chamber electronic fails to be initialised there are several possible reasons:

- the chamber has no connection to the CAN bus (e.g. damaged CAN distribution box),
- a hardware problem occurred on the CSM or a mezzanine card,
- the CSM has the wrong firmware version installed,
- the CSM has no connection to the TTC fibre (e.g. due to a broken or dirty fibre).

The nature of the problem can be seen from the error messages in the DCS.

When starting a new run, it is possible that chambers stop sending data after some time. If this happens right at the beginning of the run, it indicates a problem with the readout fibre. Chambers that stop sending data after some time of normal running, usually have lost their electronics initialisation and have to be reinitialized.

The recorded data can also reveal problems. From special runs with HV applied to only one multilayer it is possible to tell if the HV channels are correctly connected.

An overview of the problems solved during the MDT chamber commissioning in spring 2008 is given in Table 4.1.

¹DCS – **D**etector **C**ontrol **S**ystem.

Problem	#
readout fibre problems	7
TTC fibre problems	13
old firmware on the CSM	23
broken CSM	3
broken mezzanine card	5
no LV connection	32
no HV connection	42
trips of the LV	1
trips of the HV	5
wrong HV mapping	6

Table 4.1: Problems of installed ATLAS MDT chambers solved during the commissioning in spring 2008.

4.3 Overview of the Commissioning Status of the Muon Spectrometer

At the time of writing, all barrel chambers and almost all endcap chambers have been installed and connected to gas and electrical services. A very high percentage of the chambers is working as expected[10]:

- 1088 of 1150 MDT chambers are installed (the only exception are the except staged EE chambers in the endcaps).
- 99.8% of the installed MDT chambers are included in the readout, only 2 presently not accessible endcap chambers are not properly connected (cp. Fig. 4.9(a)).
- 98.5% of the chambers in the readout are operational with HV.
- 98.3% of the 339640 readout channels (drift tubes) are working.

During the first beam injections in the LHC on 10. September. 2008, ATLAS was able to record events from interactions of the proton beam with residual gas molecules in the vacuum beam pipe. An example of a beam halo event is shown in Figure 4.8.

The ATLAS muon spectrometer is now ready to take data. The remaining problems are already located (see Fig. 4.9(b)) and are scheduled for repair during the winter 2008/2009 shutdown of the accelerator.

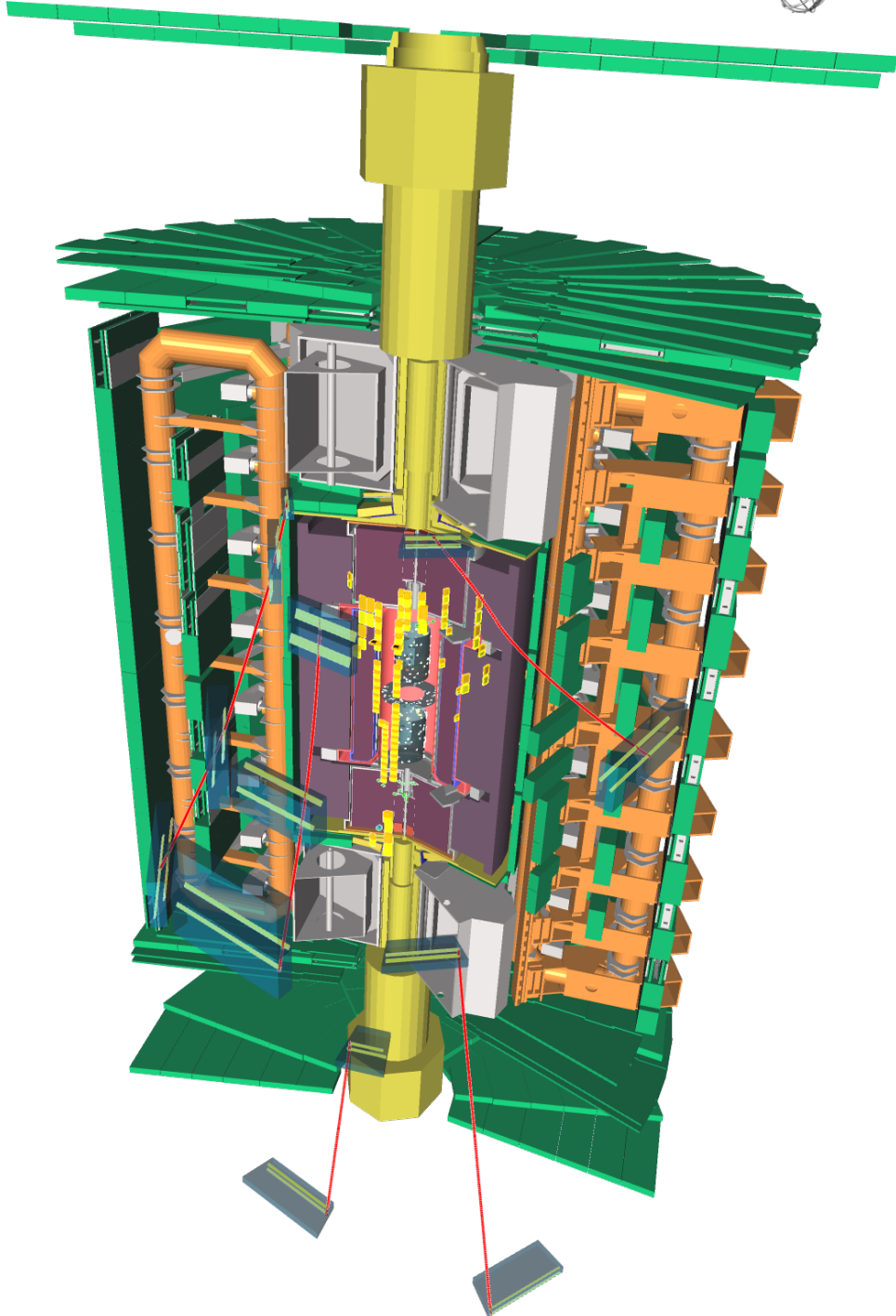
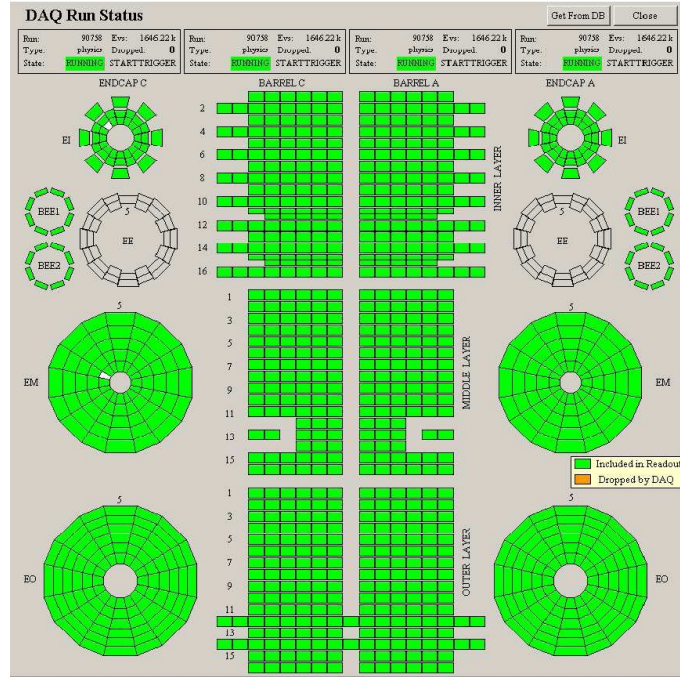
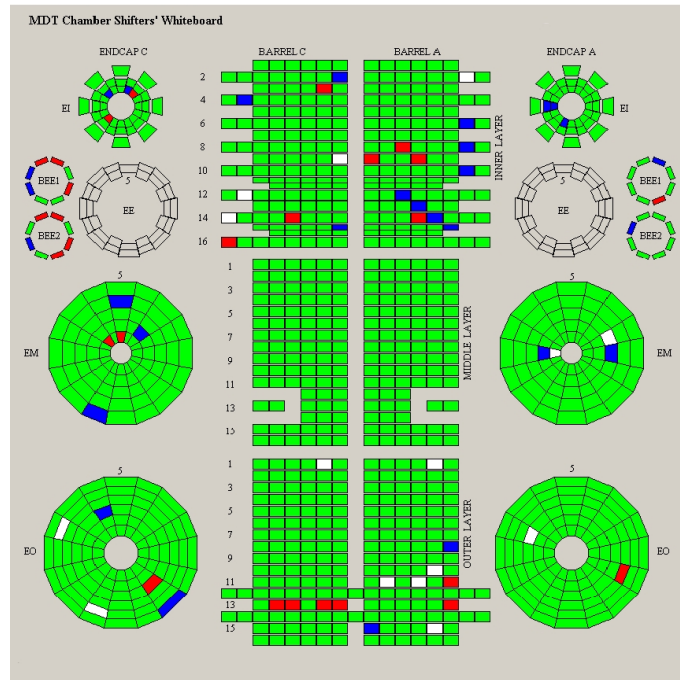


Figure 4.8: First beam halo events reconstructed by ATLAS in September 2008. The red lines indicate reconstructed muon tracks.



(a) MDT chambers included in the readout. Only two presently not accessible chambers in the endcap C (white) are not connected.



■ OK
 ■ readout problem
 ■ gas problem
 ■ HV problem

(b) Open problems in the ATLAS MDT system. Chambers with gas problems are not connected to the central service because of leaks.

Figure 4.9: Status of the MDT chambers end of October 2008. Chambers are sorted by their position along the beam pipe. Starting on the left with the endcap chambers on side C, then the barrel chambers and finally the endcap A chambers. From top to bottom are the different layers of the spectrometer: inner chambers at the top, middle chambers in the middle, and outer chambers at the bottom.

Part III

The Alignment of the ATLAS Muon Spectrometer

Chapter 5

Alignment Concepts

5.1 Why Is Alignment of the MDT Chambers Needed?

The design goal for the ATLAS muon spectrometer is a momentum resolution of better than 10% for 1 TeV/c muon transverse momentum. This requires a precise alignment of the muon chambers; the momentum resolution degrades from 9% for perfectly aligned chambers to 11% for a relative positioning uncertainty of only $30\text{ }\mu\text{m}$ which is the goal for the ATLAS muon spectrometer (cp. Fig. 5.1). It is also important to know the chamber positions with respect to the toroid coils and the magnetic field because of the relatively high non-uniformity of the magnetic field inside the muon spectrometer.

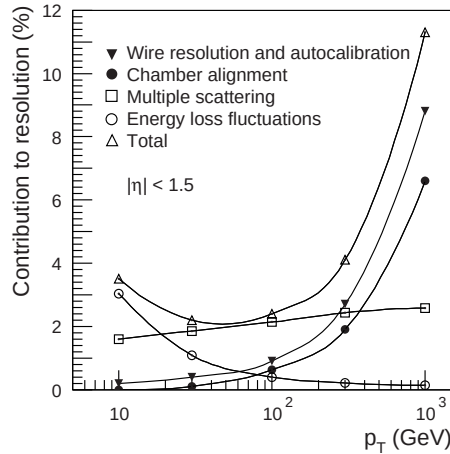


Figure 5.1: Contributions to the fractional muon momentum resolution. The alignment contribution assumes $30\text{ }\mu\text{m}$ alignment accuracy in the track bending coordinate in the magnetic field. The alignment becomes very important for highly energetic muons with $p_T > 500\text{ GeV}$ [3].

A system of 12,000 optical alignment sensors is installed in the muon spectrometer to monitor relative chamber movements with $10\text{ }\mu\text{m}$ accuracy[15]. The optical alignment system and its limitations are discussed in more detail in Section 5.4.

In order to determine the relative chamber positions in addition to chamber movements, the optical alignment monitoring system needs to be calibrated by measuring the initial positions of the chambers by means of straight muon tracks with magnetic field switched off (see Chapter 7). Curved muon tracks will be used for

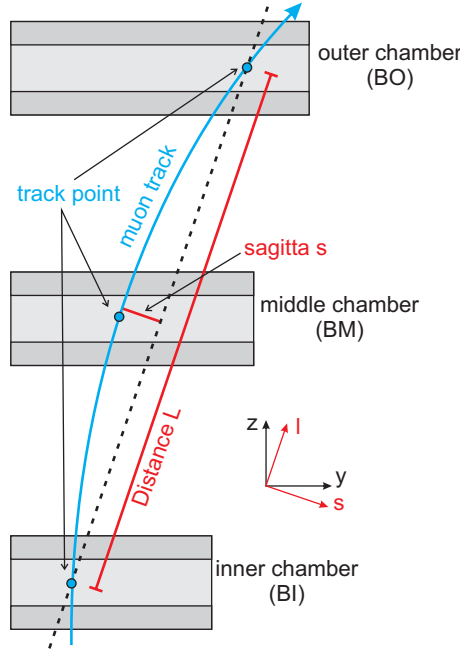


Figure 5.2: Illustration of the track sagitta measurement in the (barrel) muon spectrometer (precision or bending plane in which the precision track point measurements are performed). The z - y coordinate system is parallel to the local chamber coordinate system. The auxiliary coordinate system for a muon track (l - s) is determined by the direction of the line connecting the track points in the BO and BI chambers and the direction of the track sagitta s perpendicular to l .

chambers not connected to the optical alignment system (small chamber sectors in the barrel, see Sec. 3.1) and to monitor the optical alignment. Curved tracks are recorded during the normal ATLAS operation when the magnets are switched on. The alignment with curved tracks (see Chapter 8) requires independent knowledge of the momentum of the particle and is therefore more complicated compared to the alignment with straight tracks.

5.2 Momentum Determination with the Sagitta Method

To understand how misalignment of the chambers influences the momentum measurement, one must have a closer look at the momentum reconstruction. Muon momenta are measured via the track sagitta which is defined as the maximum deviation of the curved track from the straight interconnection of the hits in the inner and outer chambers. As depicted in Figure 5.2, we use a coordinate system in which the l axis is parallel to the straight interconnection of the inner and outer chamber hits. The s axis is orthogonal to the l axis in the precision plane (cp. Fig. 5.2). S_i is the s coordinate of the i^{th} track point (i = inner, middle, outer). The sagitta s is given by

$$s = \left| \frac{1}{2} (S_{\text{inner}} - 2S_{\text{middle}} + S_{\text{outer}}) \right|. \quad (5.1)$$

For an auxiliary coordinate system with origin at the inner track point, S_{inner} and S_{outer} are zero by definition. In the approximation of a uniform magnetic field B ,

the momentum is related to the sagitta s by:

$$p = \frac{0.3 \cdot B \cdot L^2}{8 \cdot S} \quad \text{for } [B] = \text{T}, [L, S] = \text{m}, [p] = \text{GeV}/c. \quad (5.2)$$

5.3 Impact of Misalignment on the Sagitta Measurement

The muon chambers are mounted in the muon spectrometer with 1 mm position and 1 mrad orientation accuracy. These limitations in the mounting precision have an influence on the measured sagitta. The impact of misalignment in each coordinate dimension of the auxiliary coordinate system is the following:

x axis: Although not shown in Figure 5.2 the axis along the tubes is the third degree of freedom for chamber displacements. A displacement in this direction does not affect the sagitta such that misalignment in x direction can be neglected.

l axis: A displacement in l direction has also no impact on the sagitta. But the distance between the hits in the outer and inner chambers is important for the momentum calculation (cp. Eq. (5.2)). Since L enters quadratically in equation (5.2), the momentum uncertainty for position uncertainty ΔL in this axis is

$$\frac{\Delta p}{p} = 2 \cdot \frac{\Delta L}{L}. \quad (5.3)$$

The minimum distance L in ATLAS is about 5 m (for a track close to $\eta = 0$). From the installation accuracy ΔL is less than 2 cm resulting in a maximum momentum error contribution of 0.8%.

Thus displacements in l direction do not contribute significantly to the error on the momentum and no high alignment accuracy in this direction is required.

s axis: Shifts along this axis obviously have a direct influence on the sagitta. To achieve the aim of a misalignment uncertainty of only 30 μm on the sagitta, the chamber alignment in this direction must fulfill the same requirement.

5.3.1 Misalignment in the Local Chamber Coordinate System

The auxiliary l - s coordinate system is different for each track. It is not useful to work with it when combining the results of several events. The global ATLAS coordinate system is used for all calculations involving more than one chamber.

The alignment parameters, on the other hand, are given in the local chamber reference system. The definition of the local chamber coordinate system is given in Figure 5.3. The sagitta measurement is only influenced by shifts and rotations in the precision plane (see Fig. 5.2), a displacement along the tubes has only a small effect via the determination of the magnetic field along the track.

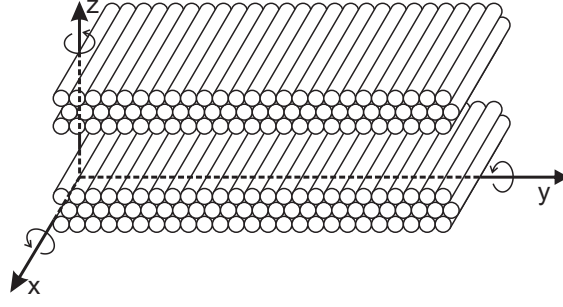


Figure 5.3: Definition of the local chamber coordinate system. The origin is on the wire of the first tube in the innermost tube layer in the middle of the tube. The rotation angles α , β and γ are defined around the x , y and z axes, respectively.

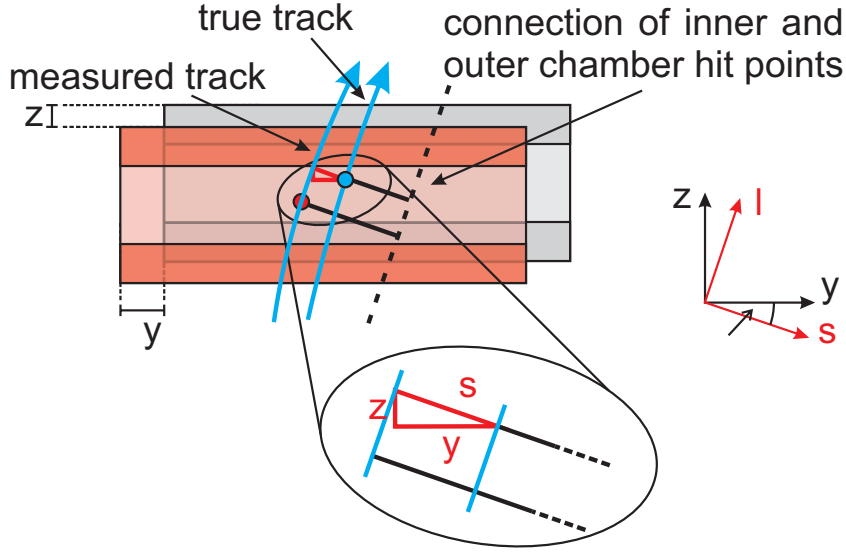


Figure 5.4: Impact on the measured $\Delta s = S' - s$ sagitta by shifts in y and z of the middle chamber (cp. Fig. 5.2).

Translations

Displacements Δs are combinations of shifts in y and z of the middle chamber with respect to the inner and outer chambers on a muon track (cp. Fig. 5.4). The contribution of each of the shifts depends on the local track angle ϑ defined in Figure 5.4:

$$\Delta s = \Delta y \cos \vartheta + \Delta z \sin \vartheta . \quad (5.4)$$

Rotations

The relevant rotation is a displacement the precision plane, i.e. around the x axis. It results mainly in an z shift of the measured track point. The additional shift in y is negligible for expected chamber rotations. For a rotation $\Delta\alpha$ shifts of the track point depend on the track distance a from the rotation axis x (cp. Fig. 5.5).

$$\Delta y = c \cdot \sin \frac{\Delta\alpha}{2} = 2a \cdot \sin^2 \frac{\Delta\alpha}{2} \approx 0 , \quad \Delta z = c \cdot \cos \frac{\Delta\alpha}{2} = 2a \cdot \cos \frac{\Delta\alpha}{2} \cdot \sin \frac{\Delta\alpha}{2} \approx a \cdot \Delta\alpha . \quad (5.5)$$

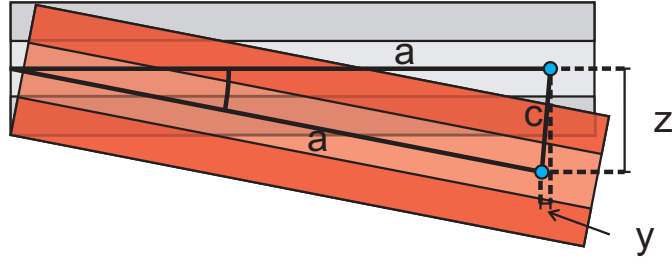


Figure 5.5: Impact on the measured trackpoint from a chamber rotation around the x axis (cp. Fig. 5.2).

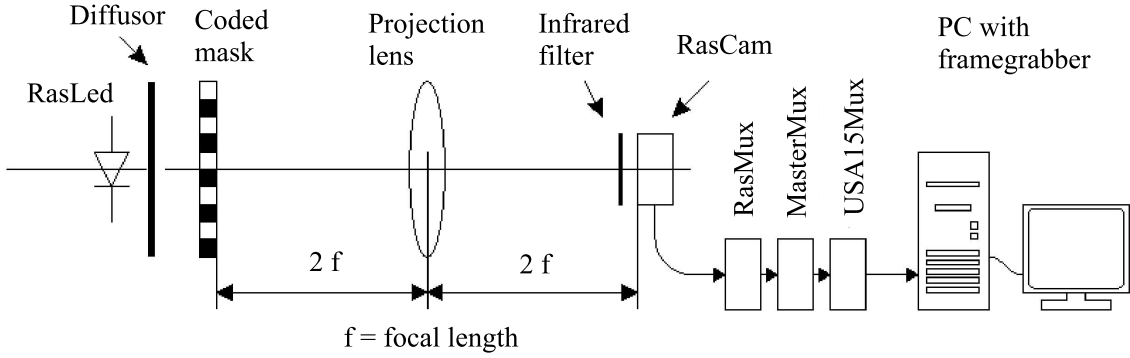


Figure 5.6: The **Red** alignment system of **NIKHEF** (RasNIK). The image sensor (RasCam) is a CMOS pixel sensor in the barrel and a CCD sensor in the endcaps. An infrared filter is placed in front of the sensor to avoid stray light. A RasMux multiplexer is installed on each chamber reading out up to eight RasCam sensors. A MasterMux can multiplex up to 16 RasMux, sending the data to a computer for processing.

Other rotations do not have a significant impact on the sagitta.

5.4 The ATLAS Optical Alignment System

An optical alignment system is used to monitor the relative positions of the MDT chambers[5]. The optical alignment sensors work as follows: an infrared LED projects via a lens an encoded chess-board mask on an optical position sensor(cp. Fig. 5.6 for details). Relative movements of the mask, the lens, and the camera translate into a movement of the recorded chess board image. The image analysis permits the measurement of these relative movements with an accuracy of about $1\text{ }\mu\text{m}$. The sensors are mounted on the MDT chambers, on the toroid magnet coils in the barrel and on special alignment reference bars in the endcaps. With the knowledge of the positions of the sensors an absolute alignment of the relative MDT chamber positions is possible.

An overview of the optical alignment system in the barrel is shown in Figure 5.7.

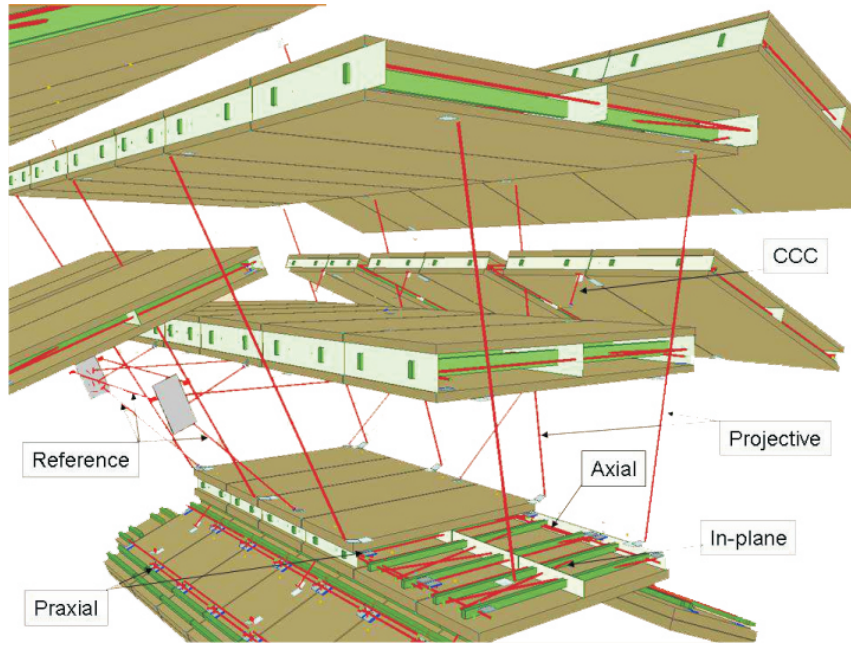


Figure 5.7: Layout of the optical alignment rays (red) for three adjacent barrel sectors (see Sec. 3.1). The Chamber-to-Chamber Connection sensors (CCC) measure the positions of chambers in a small sector relative to those in adjacent large sectors which are internally aligned with projective light rays.

5.4.1 The In-plane Alignment System

Optical *in-plane alignment systems* are integrated into the MDT chambers as has already been discussed in Section 3.2.2. Their purpose is to monitor chamber deformations induced by thermal expansion, gravity etc. with an accuracy of better than $10\ \mu\text{m}$.

5.4.2 The PrAxial Chamber-to-Chamber Alignment System

The *praxial alignment system* is monitoring the shifts and rotations between neighboring chambers in the same layer. The name derives from the two sensor types used: *proximity* and *axial* sensors. The set-up of the two sensors types is shown in Figure 5.8.

The combination of both systems is used to determine the relative positions and orientations of chambers within a layer with accuracies of about $10\ \mu\text{m}$ and $30\ \mu\text{rad}$, respectively.

5.4.3 The Projective Alignment System

To assure precise alignment of the three chambers on a track one needs measurements linking the three layers of the spectrometer. This central part of the optical alignment system is called *projective alignment system* because the light rays are pointing in the direction of straight tracks originating from the interaction point. For each large sector and each barrel hemisphere there are eight projective optical lines interconnecting the inner, middle and outer layer (cp. Fig. 5.7).

The small sectors do not have projective optical lines because of space reasons.

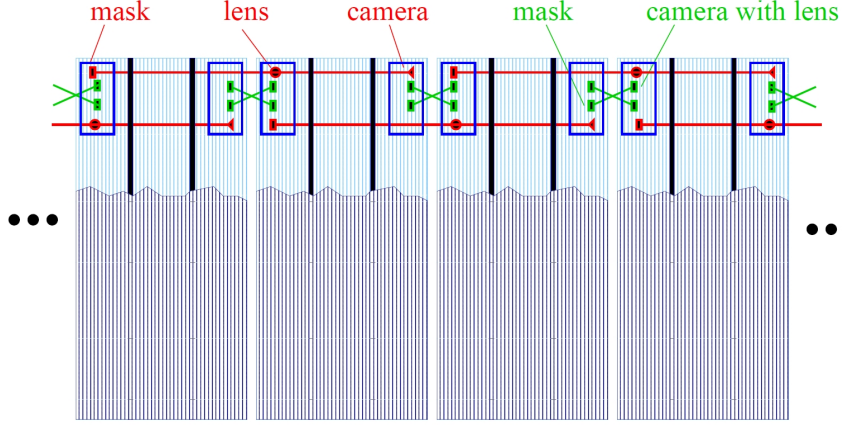


Figure 5.8: The layout of the praxial alignment sensors on a layer of MDT chambers. The sensors are mounted relative to a reference sense wire on each chamber with a precision of $20\ \mu\text{m}$. The proximity sensors are indicated in green, the axial sensors in red.

They are aligned by means of the chamber-to-chamber connection sensors (CCC) and using muon tracks passing through overlap regions between small and optically aligned large chambers.

5.5 Alignment Using Muon Tracks

The barrel chambers mounted on the toroid coils, special chambers installed on the cryostat of the endcap toroid magnets in the transition region between the barrel and the endcaps are not monitored by projective optical sensors. There is also no optical connection between the barrel and the endcap chambers. All these chambers have to be aligned using muon tracks during the operation of the ATLAS detector. The momenta of the muon tracks are measured in the optically aligned chambers. The muon trajectories are then extrapolated to the chambers without optical projective alignment sensors and compared with the measurements of the same tracks there.

Alignment with Straight Tracks

Since the required positioning accuracy of the sensors on the chambers of $20\ \mu\text{m}$ could not be achieved for all chambers it is necessary to calibrate the optical system before it can reach its design accuracy. This process is already ongoing with cosmic muons and will be continued with first collisions data during special runs with the toroidal magnetic field turned off. An algorithm for the alignment with straight muon tracks is discussed in Chapter 7.

Alignment of the Small Chambers

In order to align the small chamber sectors it is necessary to relate their positions to the optically monitored large sectors. Tracks passing through overlap regions between large and a small chambers are used. If the large chambers are correctly aligned the momentum of muons can be precisely determined. Requiring the same

momentum measured in the small and the large chambers determines the relative alignment corrections.

Alignment with Curved Tracks

To provide additional monitoring of the chamber alignment besides the optical system during data taking an algorithm using curved tracks has been developed which is the main part of this thesis. First studies of this method have been performed by J. Schmalzer in 2007[14]. Details and performance of the method are discussed in Chapter 8 concentrating on the barrel part of the muon spectrometer.

Chapter 6

Segment Reconstruction Within a MDT Chamber

The alignment of the muon spectrometer with muon tracks requires precise reconstruction of track segments in the muon chambers. The reconstruction for the segment reconstruction and its accuracy are discussed in this chapter.

6.1 Segment Reconstruction for Curved Tracks

For each track traversing a MDT chamber there is a certain number of hits in the drift tubes. For each hit we know the position of the wire with an accuracy of about $20\ \mu\text{m}$ and the drift time. The muon trajectory within a MDT chamber is well described by a parabola.

$$y(z) = a \cdot z^2 + b \cdot z + c . \quad (6.1)$$

First we perform a quality evaluation of the track. Hits with unphysical drift time are eliminated. The next step is to assure that there is at least one hit in each of the two multilayers. One needs at least three points to fit a parabola. In practice there are usually three hits per multilayer. The drift time measurements do not provide single space points, but only the minimal distances (drift radii) of the track to the wires without information about the orientation of the tracks in each tube.

To find the parameters of the parabola (6.1) we perform a fit to the individual hits of a track using the MINUIT 2[1] algorithm implemented in ROOT[2]. Starting parameters are taken from a straight-line fit to all hits in a chamber. This first straight-line fit selects hits belonging to a track, rejecting for example noise hits.

The fit minimizes the χ^2 function

$$\chi^2 = \sum_{\text{hits}} \frac{(d_{\text{hit}}^2 - r_{\text{hit}}(t))^2}{\sigma^2(r_{\text{hit}}(t))} , \quad (6.2)$$

where d_{hit} is the distance of the parabola from the anode wire, r_{hit} the measured drift radius and $\sigma(r_{\text{hit}}(t))$ the error on the drift radius.

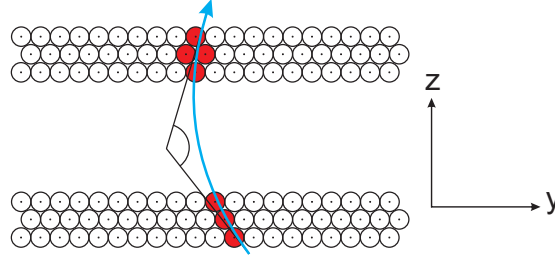


Figure 6.1: Reconstructed track segment in a MDT chamber with the definition of the deflection is δ . Tubes with hits are indicated in red.

6.1.1 Momentum Reconstruction with Curved Track Segments

For low muon momenta ($p_T \lesssim 10 \text{ GeV}/c$) the high spatial resolution of the MDT chambers is sufficient to resolve the curvature of the muon track over the short distance within a chamber. The curvature of the muon track is a measure of the muon momentum. The deflection angle δ which is defined as the angle between the muon flight direction at the entrance of the chamber and the flight direction at the exit (see Fig 6.1) can be used to determine the muon momentum analytically based on the relation

$$\Delta \vec{p} = q \cdot \int_{\mathcal{P}} d\vec{l} \times \vec{B} \quad \Delta \vec{p} = \vec{p}_{\text{outgoing}} - \vec{p}_{\text{incoming}} . \quad (6.3)$$

To calculate the bendingpower $\int_{\mathcal{P}} d\vec{s} \times \vec{B}$ along the path the parabola is segmented into 1 mm steps. Since the parabola is defined in the y - z plane, we have to add additional information about the x coordinate along the path. The magnetic field is in first approximation parallel to the x -axis, such that a deflection in x -direction is negligible. The path in the x -direction is therefore approximated by a straight line defined by the x positions of the first and last hit in the chamber. Since MDT chambers do not measure the x coordinates, data from the RPC chambers are used. For the middle chamber stations which have two RPCs the track can be reconstructed in the x - z -plane. The outer chambers are only equipped with one RPC. Here we use the x -coordinate from the RPC measurement for all MDT hits assuming only small movement of the muon in x direction within the station. The inner stations are not equipped with RPC chambers at all. One has to extrapolate the muon trajectory in the x - z plane from the middle to the inner station to get the x coordinates of the hits in the inner layer, however with lower accuracy.

The position of the hit closest to the interaction point is defined as the entrance point of the chamber and is used as starting point of the integral in Equation (6.3). The slope of the parabola and the assumed path in x determine the direction to the next point on the track using a Runge-Kutta algorithm of second order.

With the deflection angle calculated from the slopes of the fit parabola at the first and the last hit position, the absolute value of the momentum p can be calculated. Assuming a constant magnetic field B and constant momentum p the deflection angle δ is linked to Δp :

$$\Delta p = \delta \cdot p = q \cdot \int_{\mathcal{P}} B dl \quad \Rightarrow \quad p = \frac{q}{\delta} \cdot \int_{\mathcal{P}} B dl . \quad (6.4)$$

A detailed description of the formulae used is given in Appendix A.

Set number	p_T [GeV/c]	Events [10^3]
MC1	6	389
MC2	10	246
MC3	20	234
MC4	mixture	432

Table 6.1: Monte-Carlo datasets used for testing of the track segment reconstruction algorithm. They only contain the information from the muon spectrometer, no hits in the calorimeter or ID are stored. After the propagation through the calorimeters the muons loose about 3 GeV/c of momentum. The direction of the muons at the interaction point was limited to the chamber tower closest to $\eta = 0$ to ensure high statistics of tracks per chamber.

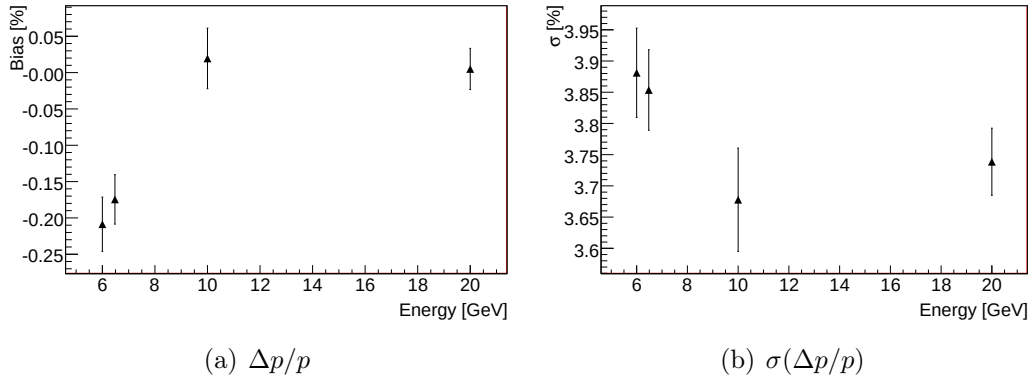


Figure 6.2: Momentum bias Δp (a) and resolution σ (b) from the track segment reconstruction algorithm. The MC4 data set is placed at its average energy of 6.5 GeV. Perfect muon spectrometer geometry was assumed.

6.2 Tests of the Segment Reconstruction Algorithm

Several factors influence the accuracy of the reconstructed track segment: the accuracy of the r - t relationship, the spatial resolution of the tubes, and the accuracy of the knowledge of the wire positions in the chamber. All these effects can be investigated very accurately with simulated data.

Four different data sets were used for the tests. They are listed in Table 6.1. Set MC4 is a mixture of events from sets MC1 to MC3 in the ratio

$$\text{MC1} : \text{MC2} : \text{MC3} = 100 : 10 : 1 ,$$

as expected in proton-proton collisions at 14 TeV.

6.2.1 Perfect Geometry and True Drift Radii

To test the algorithm, the track reconstruction and momentum calculation is performed with using generated instead of reconstructed hits.

The test clearly shows that the track segment reconstruction is working correctly. The differences between the track and the true drift radii are less than $5\mu\text{m}$. Also the determination of the momentum is working correctly. The bias with respect to the true momentum at the entrance of the muon spectrometer is always below 0.25%

and the resolution, which is limited by multiple scattering, is better then 3.9% (see Fig. 6.2).

Now we have to investigate how the performance changes when we take into account the limited single-tube resolution, uncertainties in the determination of the r - t relationship and imperfections of the chamber geometry (wire positions and chamber deformations).

6.2.2 Impact of a Limited Spatial Resolution

The drift tubes have an average spatial resolution of $80\ \mu\text{m}$. The impact of limited spatial resolution of the tubes on the accuracy of the reconstructed segments was studied by smearing the Monte-Carlo generated hit radii with random numbers generated according to Gaussian distributions with different widths σ . The simulation was done for σ values of $1\ \mu\text{m}$, $10\ \mu\text{m}$, $80\ \mu\text{m}$ and $100\ \mu\text{m}$ and then compared to the results without smearing.

To understand the influence of the resolution on the segment reconstruction, two fits are performed: one for the generated hits and one for the smeared hits. Then the results for the slope m_{entrance} and the y coordinate y_{entrance} of the track entrance point in the chamber, as well as the momentum (as in the previous section) are compared. With z_{entrance} being the local z position of the lowest anode wire on the track, m_{entrance} and y_{entrance} are defined as:

$$\begin{aligned} m_{\text{entrance}} &= y'(z_{\text{entrance}}) = a \cdot z_{\text{entrance}} + b , \\ y_{\text{entrance}} &= a \cdot z_{\text{entrance}}^2 + b \cdot z_{\text{entrance}} + c . \end{aligned} \tag{6.5}$$

The results are show in Fig. 6.3. The influence of tube resolutions better than $100\ \mu\text{m}$ on the local momentum reconstruction is small (Bias $< 0.2\%$, $\sigma < 15\%$). For a single tube resolution of $100\ \mu\text{m}$ or lesser it becomes impossible to resolve the deflection angle for muon momenta $> 10\ \text{GeV}/c$ (sets MC2 and MC3). Since those energies are relatively rare in the muon spectrum at LHC, the MC4 data set still shows a quite good resolution and small bias. For the further tests the momentum reconstruction for the MC2 and MC3 sets were performed, but since they have a big bias and poor resolution they are not included in all plots so that is still possible to see the effects on the interesting MC4 set.

No matter what resolution was assumed, an influence on the entrance point (less than $1\ \mu\text{m}$) or the slope of the track are barely noticeable. The only bigger deviation arises for a resolution of $100\ \mu\text{m}$ for the momentum measurement with a bias of about $(1 \pm 0.5)\%$. This is large compared to the less then 0.2% we get for the other values.

At the expected resolution for a single tube of $80\ \mu\text{m}$ all bias and resolutions for the whole chamber are well within the requirements necessary for the alignment algorithms developed in [14].

For all following tests with Monte-Carlo data a single tube resolution of $80\ \mu\text{m}$ was assumed.

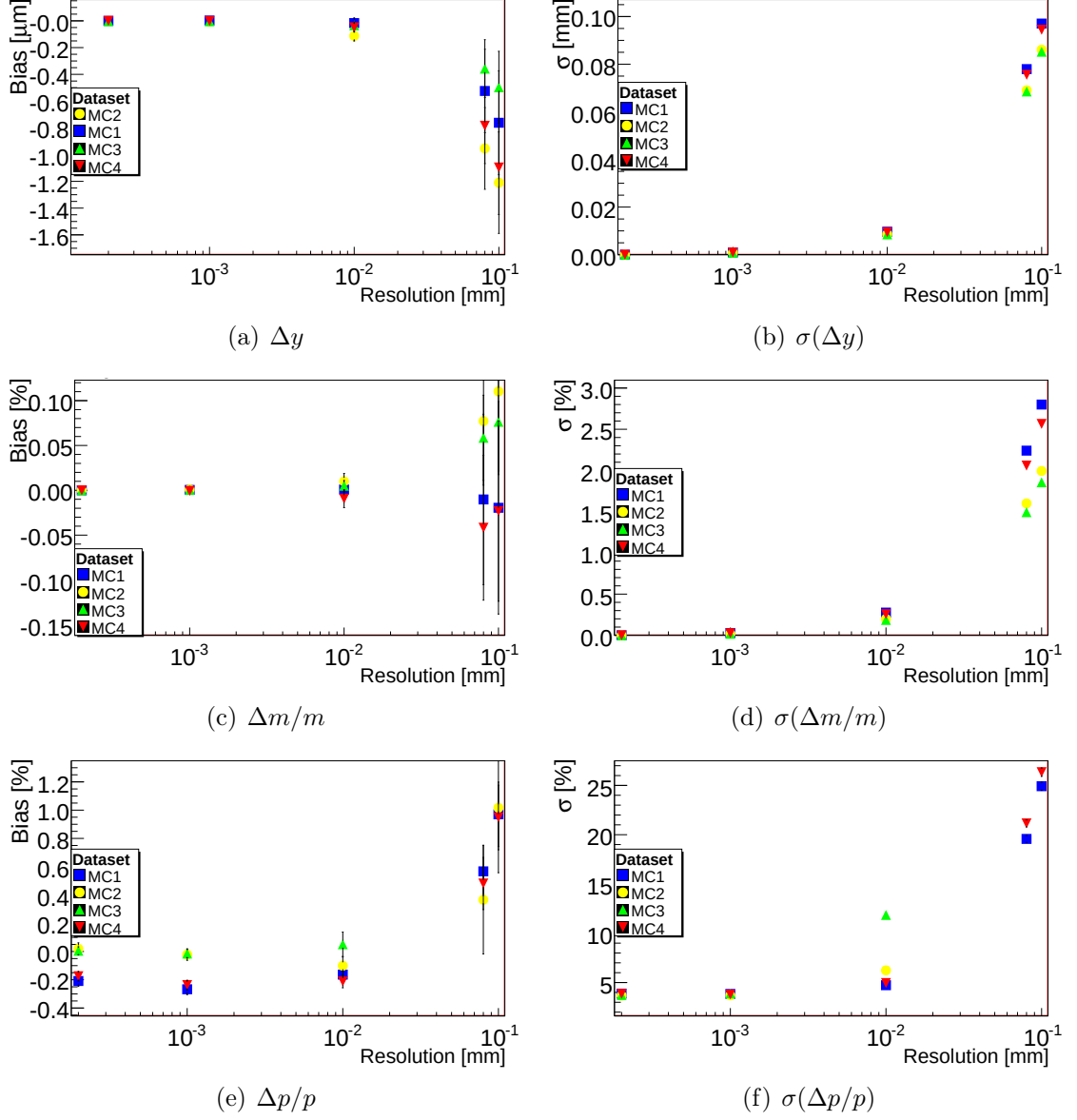


Figure 6.3: Influence of the single tube resolution on the bias (mean (left) and width (right)) of the parameters of the reconstructed track segment: track y -position, slope m at the chamber entrance and momentum value p . Resolutions of $1\ \mu\text{m}$, $10\ \mu\text{m}$, $80\ \mu\text{m}$, $100\ \mu\text{m}$ and just the true hits were used. As shown in Table 3.1 $80\ \mu\text{m}$ is the expected resolution of a single drift tube.

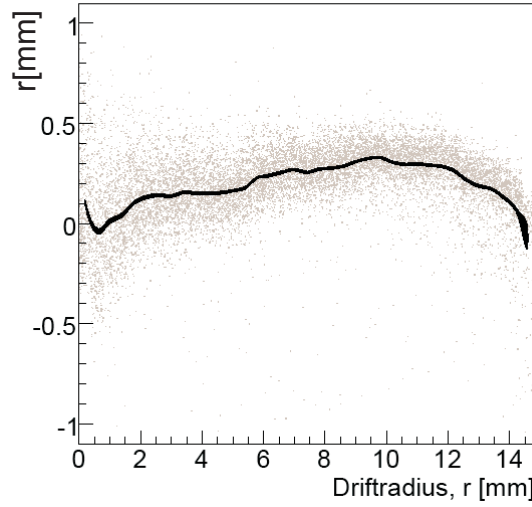


Figure 6.4: Difference Δr between the true r - t relationship and an initial r - t calibrated relationship.

6.2.3 Impact of a Non Perfect r - t Relationship

The r - t relationship will be calibrated for each chamber using muon tracks during data taking. with a typical accuracy of $20 \mu\text{m}$. The calibrated r - t relationship can deviate from the true r - t relationship with this uncertainty (cp. Fig. 6.4). Studies of the calibration procedure show that one can model the final deviations of the measured r - t relationship by a parabola as a function r [16]. At the wire and at the tube wall the correction is set to zero, the maximum deviation is in the middle between the tube wall and the center of the tube.

The impact of an incorrect r - t relationship on the segment reconstruction is studied for four values of the maximum deviation: $20 \mu\text{m}$, $50 \mu\text{m}$, $100 \mu\text{m}$ and $200 \mu\text{m}$. The effect from the single tube resolution is also included at a level of $80 \mu\text{m}$. The results are show in Fig. 6.5.

Even small parabolic distortions have large effects. The impact is largest for the momentum measurement. The impact on the entrance point measurement is also quite strong. For the expected uncertainties in the r - t relationship accuracy of $20 \mu\text{m}$, the mean bias on the entry point is about $30 \mu\text{m}$ and on the momentum measurement -3% . This is sufficient to get the desired alignment accuracy of better than $50 \mu\text{m}$ as required in the muon TDR[3]. On the other hand, the initial determination of the r - t relationship with an accuracy of about $100 \mu\text{m}$ is only sufficient for an alignment uncertainty of $150 \mu\text{m}$.

For the slope the effect strongly depends on the muon energy. For 10 GeV and 20 GeV muons the bias is at an acceptable level for all studied points. But for 6 GeV muons and the mixed dataset the bias is much larger.

6.2.4 Impact of Limited Geometrical Precision of the Chambers

The MDT chambers have been built with a wire positioning accuracy of $20 \mu\text{m}$. Still it is possible that in particular the two multilayers are not perfectly aligned.

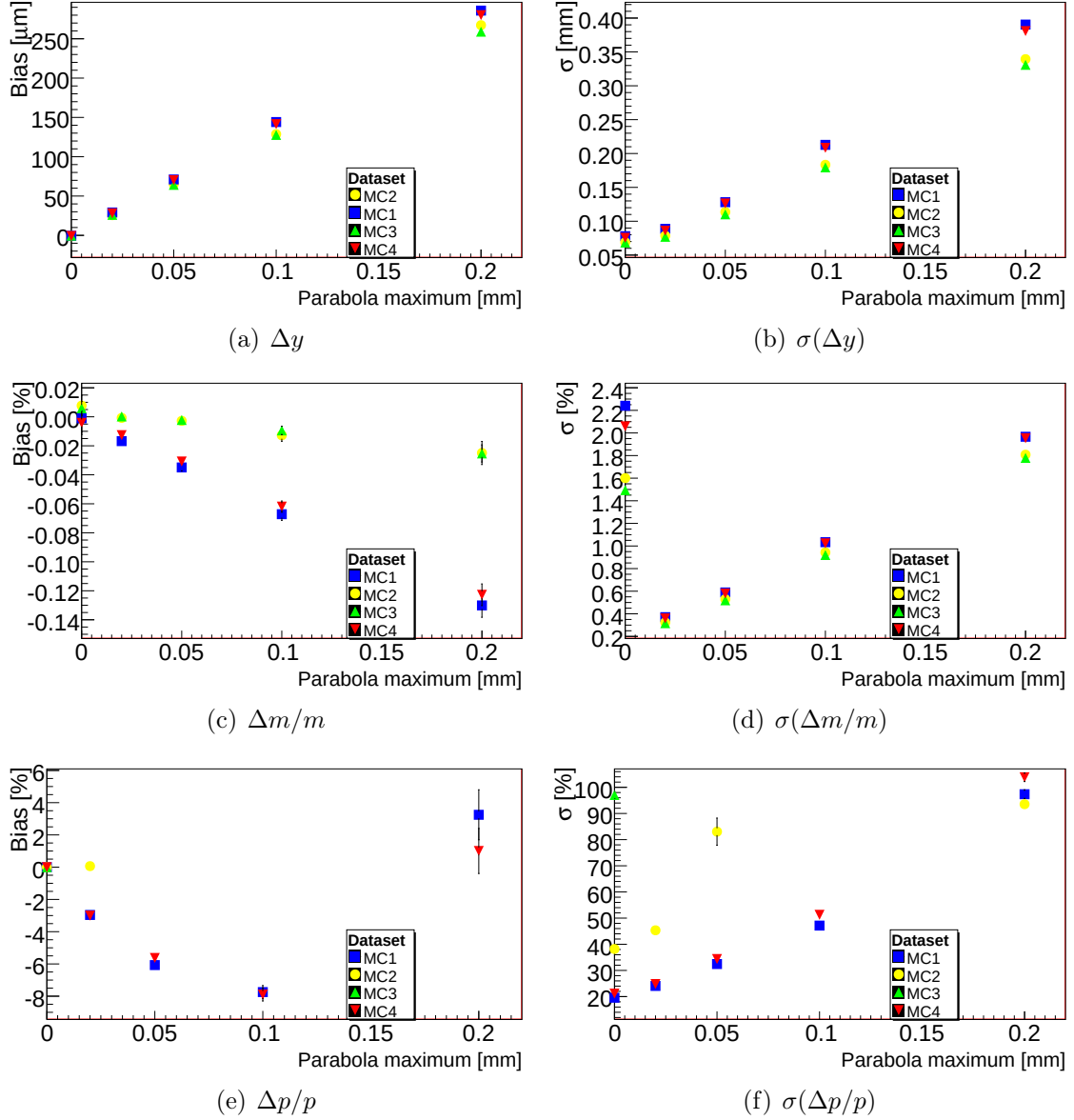
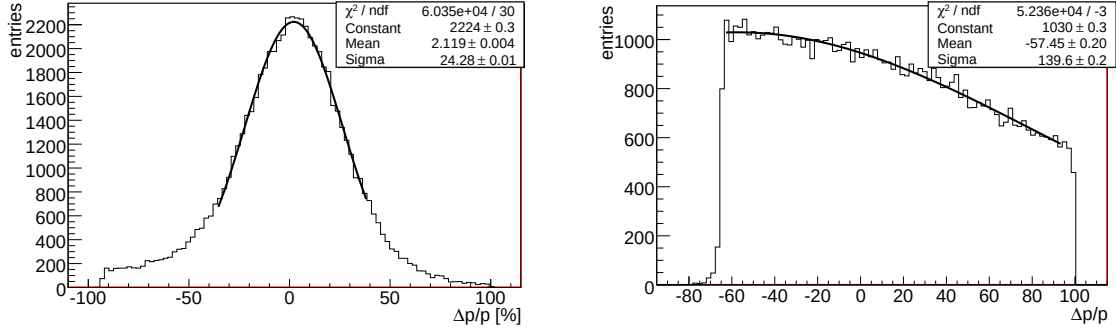


Figure 6.5: Influence of deviations (parabola maximum) from the true r - t relationship on the bias (mean (left) and width (right)) of the parameters of the reconstructed track segment: track y -position, slope m at the chamber entrance and momentum value p . The results for the momentum calculation have to be taken with caution because the distribution of $\Delta p/p$ is very wide and not a Gaussian function (cp. Fig. 6.6).



(a) $\Delta p/p$ for 6 GeV muons for r - t relationship accuracy of 20 μm

(b) $\Delta p/p$ for 20 GeV muons for r - t relationship accuracy of 20 μm

Figure 6.6: Reconstructed momentum for the MC1 and MC3 data sets within a chamber with a r - t relationship accuracy of 20 μm . For the 6 GeV muons the momentum reconstruction works correctly, for the 20 GeV muons no mean value can be found.

For the track segment and momentum reconstruction displacements that influence the local y coordinate measurement have the biggest effect: displacements in y or rotations around the x axis by an angle $\Delta\alpha$ (see Fig. 5.3).

To explore the impact of imperfections of the chamber geometry on the segment reconstruction three displacements and three rotations of second multilayer with respect to the first one were simulated. The displacements were 20 μm , 50 μm and 100 μm in the local y direction and the rotation angles are 0.02 mrad, 0.05 mrad and 0.1 mrad.

The study was performed assuming the nominal single tube resolution of 80 μm . The results are shown in Fig. 6.7.

The bias on the momentum measurement does not depend on the distortions of the chamber geometry. The noticeable effects are on the slope of the track and the entrance point in the chamber. For the investigated rotations and displacements, the track is displaced by at most 7 μm , and the slope is biased by less than 0.2% for an average slope of 0.1.

So far only the upper multilayer has been displaced such that the lower multilayer hits still guarantee a track close to the true one. If the lower multilayer is displaced as well a bigger bias on the entry point is expected. But for the track inclination and the momentum measurement the results are not expected to change.

The effects of displacements are stronger than those of expected rotations. The typical MDT chamber construction accuracy is about 20 μm for the relative wire positions in both multilayers with a relative rotations between the multilayers around the x axis of less than 0.1 mrad. Only very few chambers have displacements as big as 100 μm .

6.3 Conclusions

The reconstruction algorithm for the track segments in a chambers is working correctly. There is no bias introduced by the limited spatial resolution of the drift tubes. Tests with non-perfect chamber geometry show that the bias and resolution for track momentum, position and slope are within the limits required for the

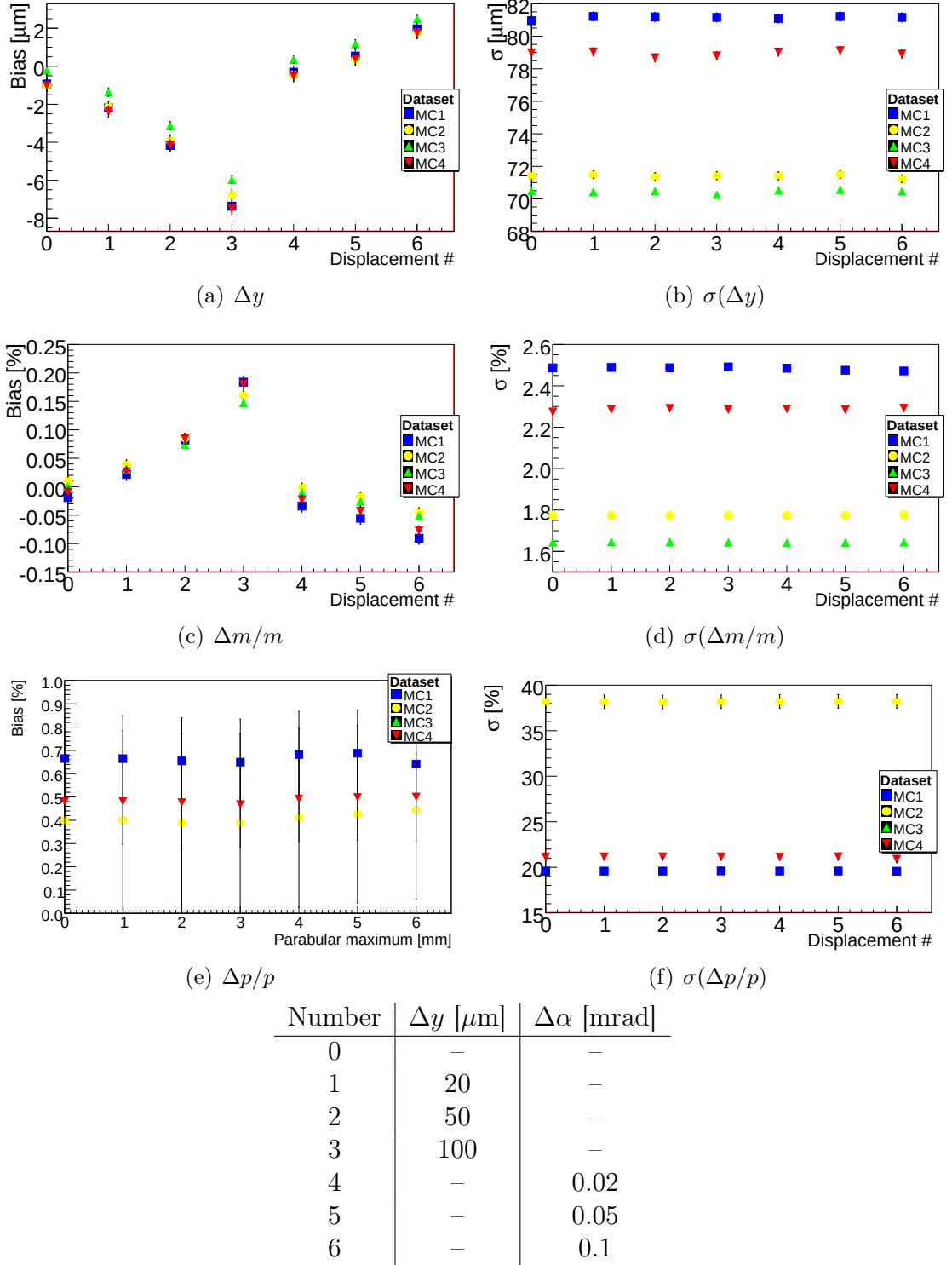


Figure 6.7: Influence of relative displacements and rotations between the two multi-layers in a MDT chamber on the bias (mean (left) and width (right)) of the parameters of the reconstructed track segment: track y -position, slope m at the chamber entrance and momentum value p . The numbers on the horizontal axis correspond to different simulated displacements (see Table above).

attempted alignment accuracy of $30\text{ }\mu\text{m}$.

However, the bias on the reconstructed momentum of $\Delta p/p = 3\%$ caused by the limited accuracy in the determination of the r - t relationship of $20\text{ }\mu\text{m}$ is too large for the attempted alignment accuracy.

Chapter 7

Alignment with Straight Tracks

The alignment monitoring system of the barrel muon spectrometer must be calibrated by means of straight muon tracks. For this task, a χ^2 minimisation algorithm with free track and misalignment parameters is used providing excellent results[13]. Unfortunately, this method does not provide histograms to visualize the results other than a successful minimisation. The purpose of this chapter is to provide control histograms to validate the results of the χ^2 minimisation method with a complementary approach, even though resulting in lower accuracy and speed.

7.1 Alignment with Straight Tracks Using χ^2 Minimisation

Here the χ^2 minimisation algorithm is described as reference for the new method developed.

As illustrated in Figure 5.2, we use the chamber-internal coordinate system to describe the track. The muon trajectory can be parametrized by straight lines in the xy and yz planes:

$$x = m_x y + b_x , \quad (7.1)$$

$$z = m_z y + b_z . \quad (7.2)$$

The MDT chambers measure the trajectory in the yz plane. The trajectory in the xy plane is measured by the RPC trigger chambers.

m_x and b_x are determined by minimizing

$$\chi_{\text{RPC,track}}^2 = \sum_{h=1}^H \frac{[x_h - (m_x y_h + b_x)]^2}{\sigma_h^2} \quad (7.3)$$

where H denotes the number of hits in the RPC chambers, x_h and y_h are the x and y coordinates of the h th hit. While the RPCs measure the hit position the MDT chambers only measure the distances $r(t_k)$ of the track to the wires (cp. Sec. 3.2.1). One therefore has to minimize

$$\chi_{\text{MDT,track}}^2 = \sum_{k=1}^K \frac{[r(t_k) - d_k(m_x, b_x, m_z, b_z)]^2}{\sigma(r(t_k))^2} \quad (7.4)$$

with $d_k(m_x, b_x, m_y, b_y)$ being the distance of the track to the anode wire of the k^{th} hit tube and K being the number of hit tubes. Let w_{y_k} and w_{z_k} be the wire coordinates of the k^{th} hit and w_{x_k} the reconstructed hit position along the wire. Then $d_k(m_x, b_x, m_z, b_z)$ is given by

$$\begin{aligned} d_k(m_x, b_x, m_z, b_z) &= \frac{|m_z w_{y_k} + b_z - w_{z_k}|}{\sqrt{1 + m_z^2}} \\ &= \text{sgn}(m_z w_{y_k} + b_z - w_{z_k}) \cdot \frac{m_z w_{y_k} + b_z - w_{z_k}}{\sqrt{1 + m_z^2}}. \end{aligned} \quad (7.5)$$

Let $C(k)$ denote the chamber to which the k^{th} hit belongs. If the MDT chamber C is displaced from its nominal position by δ_{y_C} in y direction and δ_{z_C} in z direction and rotated by small angles ϕ_{x_C} , ϕ_{y_C} , and ϕ_{z_C} around the x , y , and z axes, w_{y_k} and w_{z_k} in Equation (7.5) have to be replaced by

$$w'_{y_k} := w_{y_k} + \delta_{y_{C(k)}} - w_{z_k} \phi_{x_{C(k)}} + w_{x_k} \phi_{z_{C(k)}}, \quad (7.6)$$

$$w'_{z_k} := w_{z_k} + \delta_{z_{C(k)}} + w_{y_k} \phi_{x_{C(k)}} - w_{x_k} \phi_{y_{C(k)}}. \quad (7.7)$$

d_k is neither linear in the track parameters (slopes $m_{x,z}$ and offsets $b_{x,z}$) nor in the alignment parameters (the rotation angles $\phi_{x,y,z}$ and displacements $\delta_{y,z}$). It can be linearized without loss of precision in the following way. Firstly, as the geometry of the chambers is known, the restriction of the track fit to each chamber provides us with the sgn term. Secondly, as the inner and outer muon chambers are 5 m apart, the slope is reconstructed with permille accuracy even for the limited chamber mounting accuracy on the order of a millimeter. Let s_k denote the term $\text{sgn}(m_z w_{y_k} + b_z - w_{z_k})$ as obtained from the restricted track fit and $\bar{m}_z$ be the slope reconstructed in a first-pass track fit before alignment corrections have been applied. Then

$$\begin{aligned} d_k(m_x, b_x, m_z, b_z) &\approx \frac{s_k}{\sqrt{1 + \bar{m}_z^2}} [\bar{m}_z w'_{y_k} + b_z - w'_{z_k}] = \frac{s_k}{\sqrt{1 + \bar{m}_z^2}} [m_z w_{y_k} + b_z - w_{z_k}] + \\ &+ \frac{s_k}{\sqrt{1 + \bar{m}_z^2}} \left[\delta_{y_{C(k)}} \bar{m}_z - \delta_{z_{C(k)}} - \phi_{x_{C(k)}} (w_{y_k} + \bar{m}_z w_{z_k}) + \phi_{y_{C(k)}} w_{x_k} + \phi_{z_{C(k)}} \bar{m}_z w_{x_k} \right] \\ &=: \bar{d}_k(m_x, b_x, m_z, b_z) \end{aligned} \quad (7.8)$$

to good approximation which is linear in the alignment parameters. We replace d_k by $\bar{d}_k$ in Equation (7.4). In order to determine the alignment parameters, we minimize the sum of the $\chi_{\text{MDT,track}}^2$ over all collected tracks in one hemisphere of a barrel sector within the track and alignment parameter as free parameters. For the fit we impose the boundary condition on the alignment parameters that the centre-of-gravity of the sector is unaltered, only relative movements of the chambers in a sector are relevant. Due to the linearisation of d_k , the minimisation problem can be solved analytically.

7.1.1 Application to Cosmic Muon Data

During the past year, ATLAS recorded several millions of cosmic muon events. These data can be used to align the top and bottom sectors of the barrel muon

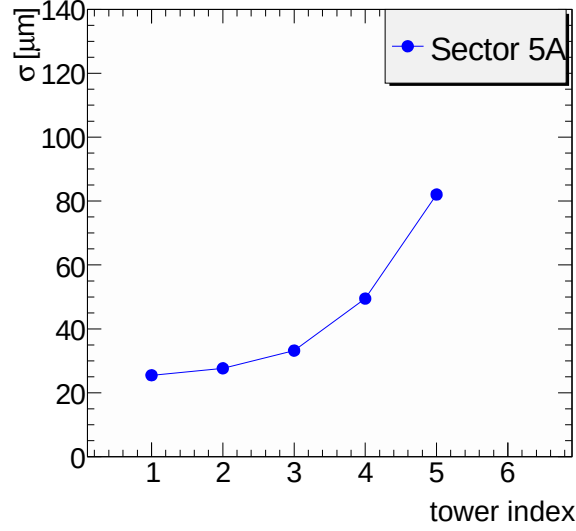


Figure 7.1: Accuracy of the track sagitta correction after the alignment with 400,000 straight cosmic muon tracks in the sector 5, A side, of the barrel muon spectrometer. The tower index counts the chamber triplets (towers) in a sector with increasing η value.

spectrometer. For the vertically mounted chambers there are not enough tracks because of the angular distribution of the cosmic muons. The algorithm was applied to 400,000 muon tracks traversing the sector 5 at the top of the spectrometer (cp. Fig. 3.2).

As shown in Figure 7.1, it was possible to align the three inner towers of the sector with $30 \mu\text{m}$ resolution and the outer towers with a resolution still better than $80 \mu\text{m}$. We excluded the outermost tower from the alignment fit because of lack of statistics of muons connecting the outermost chambers with the rest of the chambers of the sector.

The measured distances between the chambers of the inner and outer layer of the top sector were compared with a measurement of the chamber distances using a feeler gauge. Figure 7.2 shows a clear correlation between the distances measured with the track alignment procedure and the mechanical measurements. The distance measurements of the outer chambers agree within $85 \mu\text{m}$, but an average shift of $190 \mu\text{m}$ is observed between the track alignment and the mechanical measurements for the inner chambers. The difference in accuracy can be explained by the fact that the mechanical chamber distance measurements were performed between the cross plates of the inner chambers while they were performed between the tubes for adjacent outer chambers which are much more precisely positioned with respect to the sense wire than the cross plates. New measurements of the distances of adjacent tubes of the inner chambers are planned to verify the explanation and to improve the precision of the comparison.

7.2 Simplified Alignment Method

The basic idea of the alignment with straight tracks is a comparison of reconstructed tracks extrapolated to a chamber with the track segments measured in the traversed chamber. Interesting parameters are the track direction and position in the chamber.

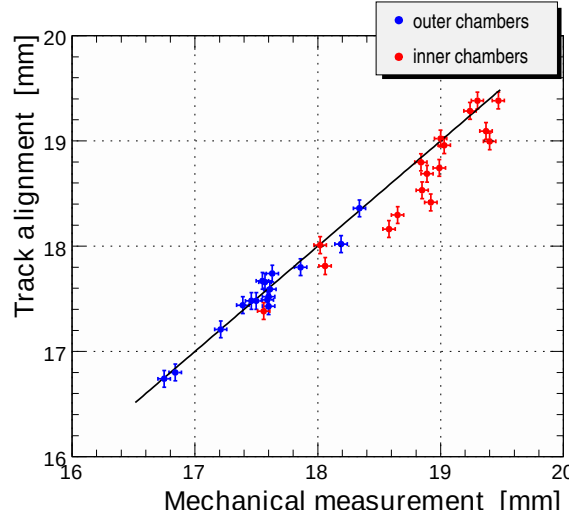


Figure 7.2: Comparison of the distances between the inner and outer chambers of sector 5, A side, as measured with cosmic rays using the track alignment algorithm and with a feeler gauge (mechanical measurement).

Since the track is measured in all three (possibly misaligned) chambers of a tower, we use the middle chamber as a reference and align the other chambers with respect to it.

The track segments in the middle chamber are extrapolated to the outer and inner chambers. Choosing the middle chamber as reference has two advantages:

- With the two RPCs attached to it the BM chambers have the best resolution in the local x direction. The outer stations have only one RPC which is only sufficient for a good position (but not direction) resolution and the BI chambers do not have any RPC at all.
- The extrapolation distance to the other chambers in the tower and the associated extrapolation errors are smallest.

Comparing the extrapolated tracks to the measured segment position and slope in the BI or BO chambers gives residuals which allow for the determination of displacements and rotations. The influence of a displacement in y direction on the track residual is shown in figure 7.3.

For both the reconstruction of displacements and rotations, one has to account for multiple scattering and therefore average over many tracks. The alignment parameters can be extracted from the distributions of the residuals of displacements and rotations. It is important to determine the relative rotations before the displacements are calculated. Otherwise the estimated displacements are biased because all track segments have the wrong direction (cp. Fig. 7.4).

There is also a precise way to determine a rotation angle γ . A rotation around the z axis will result in residuals $\Delta y_{\text{rot},z}$ depending on the x position of the track (cp. Fig. 7.5). If one plots the residuals against the x position and fits a straight line $\Delta y_{\text{rot},z}(x) = a \cdot x + b$ to the data points, the slope of the line equals $\tan \gamma$. Since the angles are small ($\gamma < 0.1$ rad), it is justified to approximate $\gamma \approx \tan \gamma$, i.e.

$$\gamma \approx \tan \gamma = \frac{d}{dx} \Delta y_{\text{rot},z}(x) = a . \quad (7.9)$$

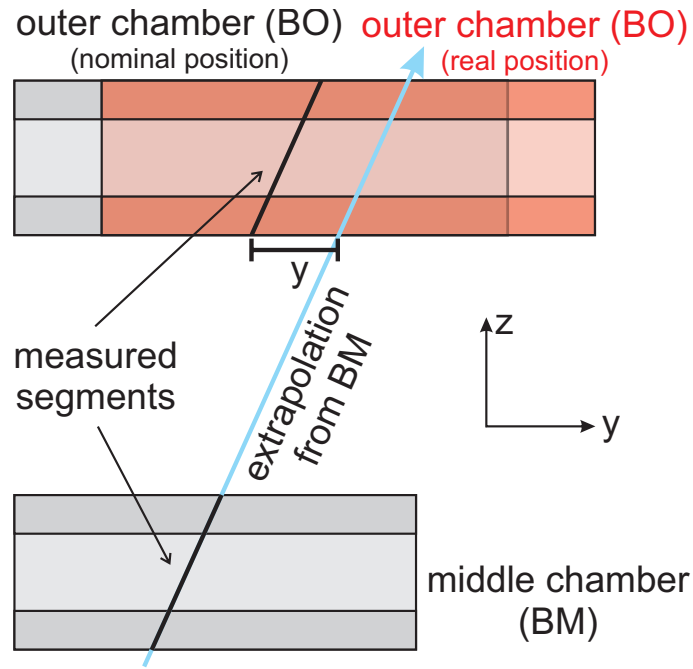


Figure 7.3: Displacement Δy of a BO chamber (relative to a BM chamber) in the y direction.

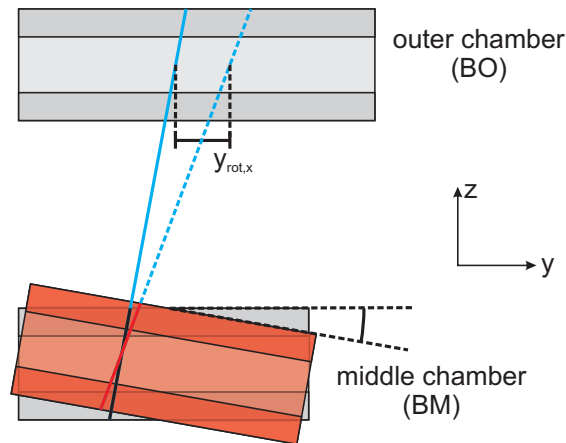


Figure 7.4: If the chamber rotation is not corrected before the displacement is calculated, the displacement residual is biased by $\Delta y_{rot,x}$.

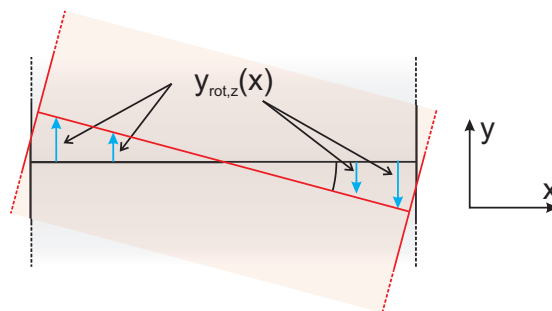


Figure 7.5: Determination of a rotation around the z axis by the angle $\Delta\gamma$.

7.2.1 Application to Cosmic Muon Data

The alignment procedure was applied to the same cosmic ray data set as the global χ^2 method. With ATLAS being located about 100 m below ground, most of the muons have to pass through a large amount of rock and a large fraction is absorbed. Only the two big shafts for lowering detector parts provide good luminosity of cosmic muons.

The data set used was recorded in October 2007 containing about 750.000 muon events. At this time, only the upper part of the spectrometer was operational and thus the data set only contains data from sector 5 and 6 (cp. Fig. 3.2). The advantage of this set is that in the mean time a very good calibration is available and DAQ software bugs have been resolved.

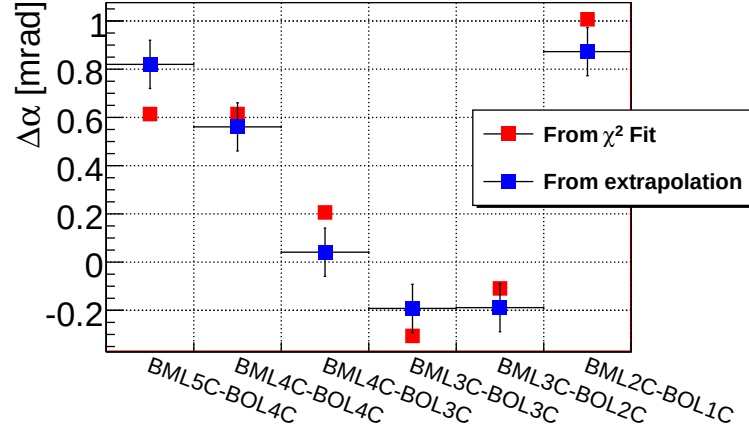
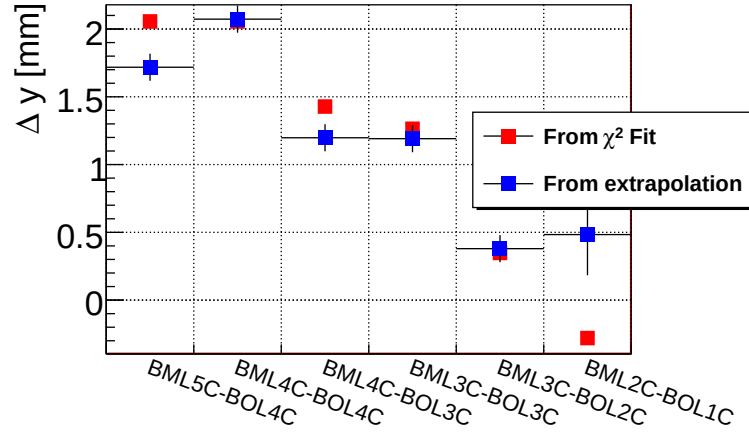
To verify that the algorithm is delivering the correct alignment corrections, the results are compared to the ones of the χ^2 minimisation method¹. Figure 7.6 shows the correlations between the results of the two algorithms for chamber stations on side C of ATLAS. All chamber pairs with more than 10,000 recorded tracks are considered to ensure a good resolution. Except for one chamber pair the agreement is within less than 400 μm , for the rotations the difference is not bigger than 0.2 mrad for all pairs.

Figure 7.7 shows the residual distribution for rotations and displacements for the chamber pair BML3C5 - BOL2C5, as an example. The resolution is good and the misalignment effects are obvious.

7.3 Conclusions

The results of the simple method for straight track alignment reproduce the results of the more powerful χ^2 minimisation method with sufficient accuracy to be used as a monitoring tool for the chamber alignment performance.

¹The χ^2 minimisation results are in very good agreement with mechanical measurements and therefore taken as reference.

(a) Rotations around the x axis of chambers on side C of sector 5

(b) Displacements of chambers on side C of sector 5

Figure 7.6: Comparison between the results of the χ^2 minimisation and of the simplified method for relative chamber displacements and rotations. The results are shown for all middle-outer chamber pairs with a sufficient number of tracks in sector 5 on the C side of ATLAS.

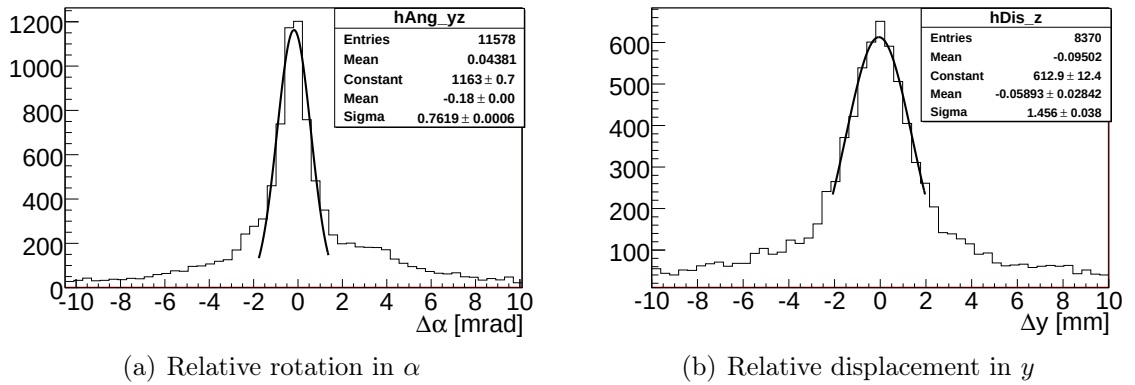


Figure 7.7: Plots for the relative rotation and displacement for the chamber pair BML3C5 - BOL2C5.

Chapter 8

Alignment with Curved Tracks, Method I

The alignment method with straight tracks can only be used when the magnet is off. When the magnets are turned on, the muons follow a curved trajectory. The extrapolation of the muon trajectory from one to another chamber then requires the knowledge of the muon momentum.

As discussed earlier, the momentum reconstruction is affected by the misalignment of the muon chambers. An alignment procedure using curved muon tracks therefore must exploit independent information about the muon momentum. Two momentum measurements complementary to the sagitta measurement are discussed in this chapter.

8.1 Momentum Measurement in the Middle Chamber

As shown in Section 6.1, the curvature of muons with $p_T \leq 6$ GeV can be resolved within the middle muon chamber. The momentum derived from the curvature of the muon trajectory within this chamber is independent of misalignment between chambers. It therefore provides an unbiased momentum measurement albeit with relatively low resolution. Unfortunately, the presently achievable accuracy in the calibration of the r - t relationship leads to a bias in this momentum measurement which is quite large and cannot provide the necessary accuracy for the alignment of the muon spectrometer (cp. Sec. 6.3 and [14]).

8.2 Momentum Measurement from Angular Deflection

Due to the deflection of the muon trajectory in the magnetic field of the muon spectrometer, the direction-of-flight of the muon at the exit of the spectrometer differs from the direction-of-flight at the entrance. The deflection angle is a measure of the momentum which is complementary to the sagitta measurement. The deflection angle can be measured by comparing the directions of the track segments in the inner and outer muon chambers. The calculation of the momentum from the deflection

angle requires the knowledge of the magnetic field integral $\int_{\mathcal{P}} B ds$ along the muon path $\mathcal{P}$ (cp. Ch. 6.1.1 and Appendix A). Since the field is non-uniform, the track cannot be approximated by a parabola. Rather the trajectory must be determined by an iterative procedure based on the equation of motion for a charged particle in a magnetic field:

$$F = q (\vec{v} \times \vec{B}) \quad \Rightarrow \quad \Delta \vec{p} = q (\Delta \vec{s} \times \vec{B}) \quad (8.1)$$

The deflection angle $\propto \frac{\Delta \vec{s}}{L}$ depends on the muon momentum p . A first estimate of p can be obtained by connecting the hits in the three chambers of a tower by straight lines and using this polygon for the approximate calculation of the field integral and then of the muon momentum. The muon momentum obtained this way can be used to calculate an improved trajectory in a second iteration. After a few further iteration steps one converges to the right muon momentum. This procedure is repeated until the momentum does not change by more than 0.01% which in almost all cases is reached with less than 2 iterations.

Relative rotations between the inner and outer chamber are biasing the algorithm and have to be corrected before this procedure can be used. In the original study [14] it was proposed to use the momentum measured in the middle chamber for low momentum muons to determine the rotation angle between the inner and outer chamber. The studies of this thesis (see Section 6) show that the r - t relationship cannot be calibrated with sufficient precision to provide an unbiased momentum measurement in the middle chamber. We shall therefore present another approach in Chapter 9 which is independent of the momentum measurement of the middle chamber. In this chapter we shall investigate the impact of systematic uncertainties on the alignment with curved tracks based on the assumption that the angle between the inner and outer chambers is known.

8.3 Influence of the Calibration

To find the influences of the r - t relation on the overall momentum calculation and the reconstruction accuracy the same tests as in Section 6.2.3 were performed for the whole spectrometer. Again, the different drift time relations were simulated with an accuracy of 20 μm , 50 μm , 100 μm and 200 μm . To exclude effects from a shift or rotation of some chambers the ideal geometry was used.

The effects on the overall momentum are much smaller (less than $8.3 \cdot 10^{-4}$ in the *worst* case for a 20 μm distortion on the r - t relationship, cp. Fig. 8.1) than the ones on the measurement inside a single chamber (about $3 \cdot 10^{-2}$ in the *best* case for a 20 μm distortion on the r - t relationship).

8.4 Track Reconstruction Accuracy

To test the reconstruction accuracy the residuals in the inner and outer chamber are studied for different r - t relation accuracies. The residuals in the middle chamber are zero by definition, because we start the propagation there. The displacement of a chamber is determined by fitting a Gaussian function to all single track residuals. The mean values of the fit function represents the residual, the width σ the

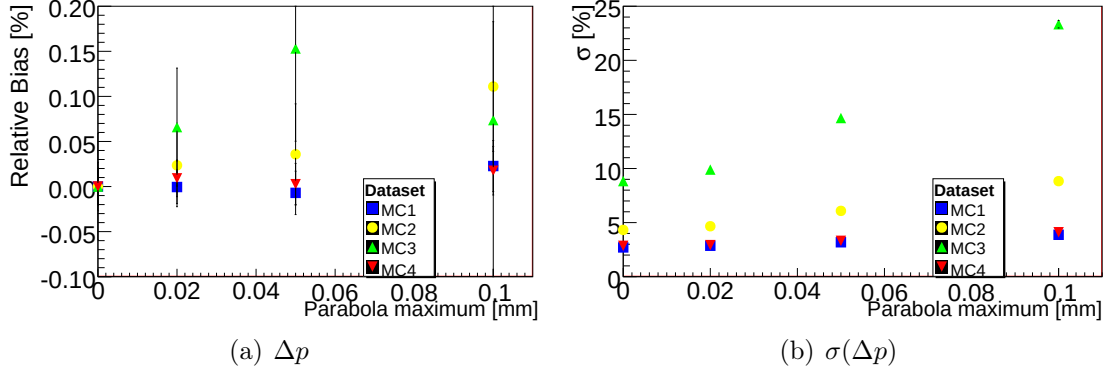


Figure 8.1: Influence of different r - t relations on the momentum measurement for all three chambers. Again, the bias and resolutions for MC2 and MC3 data sets are worse than for the MC1 and MC4 sets.

resolution.

As one can see in Figures 8.2(a) to 8.2(d) the residuals are quite small. The bias on the residuals is getting bigger with the maximum deviation in the r - t relation because the slope measurement in the middle chamber is biased depending on the drift time relation (cp. Fig. 6.5(c)). This also explains why the sign of the residuals is changing from the inner to the outer chamber.

For the outer chamber the residuals are at a level of less than 400 μm for all data sets. For the high energetic sets MC2 and MC3 the residuals are below 100 μm , for MC1 and MC4 the residuals are larger. These values hold for both the perfect r - t relation as well as for a r - t relation one can obtain from an optimal calibration.

The resolution is not dependent on the peak position and here the similarities are also evident. This supports also the assumption that the propagation works with the same precision for both directions. With this algorithm a resolution of 12 mm is realistic for an optimal calibration. The deviation of the residuals from zero in particular at low momenta indicates the limited accuracy of the numerically determined trajectory. The accuracy of the trajectory has to be improved in the future. The present quality, however, is sufficient to study the impact of misalignment and miscalibration of the spectrometer.

The residuals are also dependent on the charge of the muon. Due to the geometry of the studied part of the muon spectrometer and the curvature of the tracks the ratio of μ^- to μ^+ depends on the energy of the muons. For the MC3 data set the ratio is very close to one, for the MC1 data set the ratio is at

$$\frac{N(\mu^-)}{N(\mu^+)} \approx 1.5 .$$

Thus the overall residual is shifted towards the residual of the negatively charged muons for the low energetic sets. The origin of this charge dependent bias has not yet been fully understood. One possibility is a small discrepancy in the magnetic field map used for simulation and reconstruction.

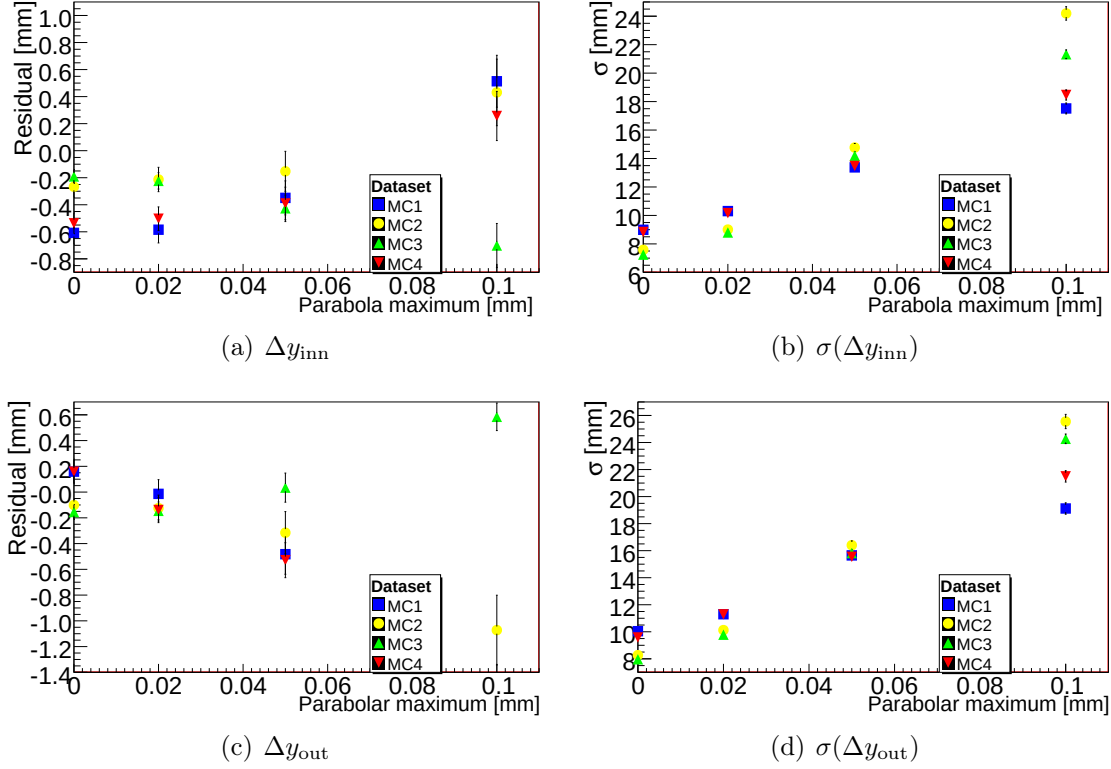


Figure 8.2: Influence of the r - t relation on the residuals and the resolution in the BI and BO chambers.

8.5 Chamber Shift Reconstruction

To test the alignment performance of the method, the algorithm was tested on some artificially misaligned geometries. The way of simulating the wrong chamber positions is the same as described in Section 6.2.4, this time applied to a whole chamber and not only to a multilayer. Plot 8.3 shows the different residuals for a y displacement of the BO chamber relative to the BM chamber. There was no rotation applied, since the rotation reconstruction has some problems (see Sec. 8.6). These tests have been performed assuming a perfect r - t relation and a single tube resolution of $80\ \mu\text{m}$.

A fit to the different residuals of the MC4 data set shows that within errors the reconstruction is very linear in the initial displacement for the tested scenarios. The slope of the line is -1.09 ± 0.02 with an offset of $2 \pm 4\ \mu\text{m}$ (cp. fig. 8.3(a)). The slope is negative because it gives the direction the chamber has to be shifted in order to get to an optimal alignment, the opposite of what it was displaced before.

Also for the residuals at smaller shifts ($|\Delta y| < 50\ \mu\text{m}$) the mean value of the residual is where one would expect it. But due to the errors of $\pm 50\ \mu\text{m}$ for the MC1 and MC4 data sets it is not possible to find an absolute alignment at this level of displacement. For the MC2 and MC3 sets the error is below $\pm 30\ \mu\text{m}$, although these sets have less statistics.

The initial offset for the unshifted chamber (cp. Fig. 8.2(c)) has been subtracted on all points. It would have no effect on the slope or the errors, but only results in an additional offset of approximately $150\ \mu\text{m}$.

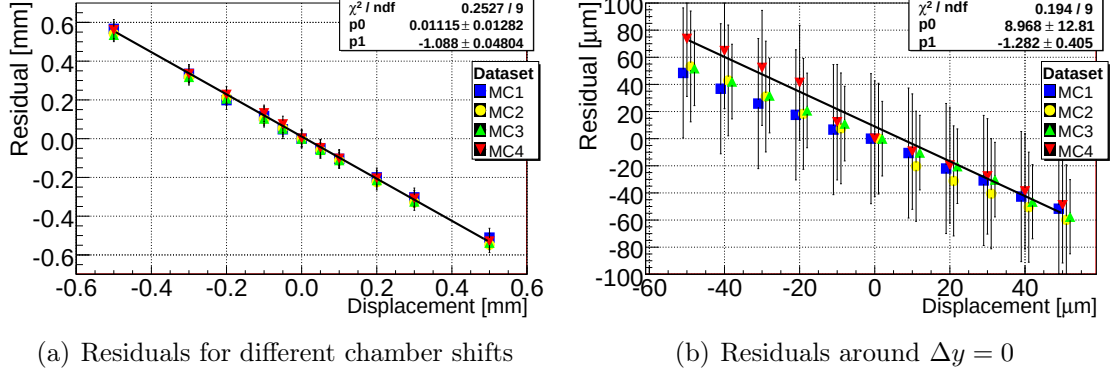


Figure 8.3: Reconstruction of an artificial introduced displacement an the outer chamber. Here a prefect r - t relation was assumed. Fits have been done on the MC4 data set because this gives the best representation of the muon spectrum in ATLAS. The data points of the MC1 to MC3 sets in Fig. 8.3(b) are shifted a little bit on the x axis to allow a better distinction of the sets.

8.6 Conclusions

The original idea of aligning the muon spectrometer with curved muon tracks had two main ingredients:

- The muon momentum is determined from the deflection angle.
- The rotation angle between the inner and outer chambers is measured by means of the momentum measurement in the middle chamber, since the momentum measurement of the deflection angle is biased due to rotations between the inner and outer muon chambers.

The studies in this thesis show that the deflection angle is measured with sufficient precision for realistic r - t calibration accuracy and distortions of the chamber geometry. They also show that the r - t accuracy is not sufficient to provide an unbiased measurement of the muon momentum in the middle chamber. It is therefore necessary to follow another approach which only uses the complementarity of the sagitta and deflection angle measurements. A feasibility study is presented in the next chapter.

Chapter 9

Alignment with Curved Tracks, Method II

The original method for the alignment with curved tracks developed by J. Schmaler in his thesis [14] turns out to require a higher accuracy in the calibration of the r - t relationship of the MDT chambers than presently achievable as was discussed in Chapters 6 and 8. It is therefore necessary to explore alternative methods. An obvious option is to use the complementarity of the sagitta-based and deflection angle-based momentum measurements. A feasibility study of this approach is presented in this chapter.

9.1 Alternative Alignment Method

We modify the original method for the alignment with curved tracks described in the previous chapter as follows:

- The muon momentum is determined from the deflection angle.
- The muon trajectory is extrapolated from the middle chamber to the inner and outer chambers using the momentum determined from the deflection angle and compared with the segments reconstructed in the inner and outer chambers.

As the exact value of the rotation angle between the inner and outer chambers is not known, the measured residual has two contributions, one from the displacement of the inner or outer chamber with respect to the middle chamber and one from the extrapolation error caused by the potential bias in the momentum estimate.

The observed residual δy from track extrapolation for a relative rotation $\Delta\alpha$ of the inner or outer chamber with respect to the middle chamber can be described

$$\delta y(\vartheta + \Delta\alpha) = \delta y(\vartheta) + \frac{\partial \delta y(\vartheta_{\text{ob}})}{\partial \Delta\alpha} \cdot \Delta\alpha , \quad (9.1)$$

with $\vartheta_{\text{ob}} = \vartheta + \Delta\alpha$ being the observed and ϑ the actual deflection angle. The derivative $\frac{\partial}{\partial \Delta\alpha} \delta y(\vartheta_{\text{ob}})$ has to be calculated numerically. Assuming a linear dependence of $\delta y(\vartheta)$ around the actual deflection angle and only small chamber rotations, the slope of the dependence can be determined by calculating the residual δy_{ob} for different deflection angles:

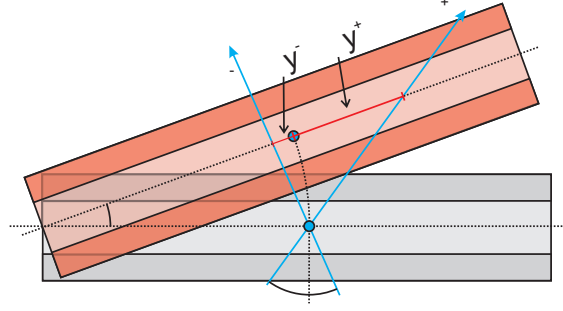


Figure 9.1: Track residuals caused by relative rotation of the inner and outer chambers with respect to the middle one for curved muon tracks with opposite charge.

$$\frac{\partial \delta y(\vartheta_{\text{ob}})}{\partial \Delta \alpha} \approx \frac{\delta y(\vartheta_{\text{ob}} + \epsilon) - \delta y(\vartheta_{\text{ob}} - \epsilon)}{2 \cdot \epsilon} . \quad (9.2)$$

ϵ is set to 1 mrad, which is about the same magnitude as the expected misalignment effects from rotations. If the residuals $\delta y_i(\vartheta_{i,\text{ob}})$ and slopes $\frac{\partial}{\partial \Delta \alpha} \delta y_i(\vartheta_{i,\text{ob}})$ are determined for a large number N of tracks, it is possible to perform a χ^2 minimisation and determine the displacement Δy and the rotation $\Delta \alpha$ simultaneously. The χ^2 function is:

$$\chi^2 = \sum_{\text{tracks } i=1}^N \frac{(\delta y_i(\vartheta_{i,\text{ob}}) - \Delta y)^2}{\sigma_i^2} = \sum_{\text{tracks } i=1}^N \frac{(\delta y_i(\vartheta_{i,\text{ob}}) + \frac{\partial}{\partial \Delta \alpha} \delta y_i(\vartheta_{i,\text{ob}}) \cdot \Delta \alpha - \Delta y)^2}{\sigma_i^2} . \quad (9.3)$$

The errors σ_i for all tracks are assumed to be equal and $\sigma_i = 1$.

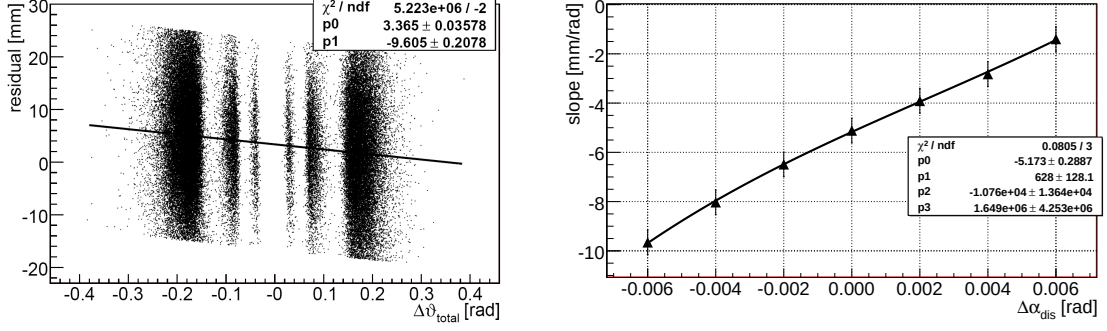
The fit turns out to be very sensitive to tails and small bias in the residual distributions depending on the charge of the muons. Cuts on the measured residuals improve the robustness, but could not completely solve the problem. In order to improve the robustness of the fits an independent method for determining the rotation angle $\Delta \alpha$ was developed which is described in the next section.

9.2 Rotation Determination

A relative rotation of the chambers results in a bias in the momentum measurement and in a bias $\Delta y^\pm$ in the residuals depending on the charge (cp. Fig. 9.1). If one plots the total deflection angle $\Delta \vartheta$ (which is proportional to $1/p_T$) against the residuals from track extrapolation this dependence is visible (cp. Fig. 9.2(a)). The slope of a linear fit to the data points is proportional to the relative rotation of the chambers.

The exact relationship between the fitted slope and the relative rotation of the inner and outer chambers is determined by means of Monte-Carlo data in this feasibility study.

The linear fit is applied to data from chamber pairs with known relative rotation (e.g. after alignment with straight tracks). Once the slope of the linear fit is known for different relative chamber rotations they can be plotted against each other and third degree polynomial fitted the points (cp. Fig. 9.2(b)). The inverse of the fit function is used to determine the rotation of a chamber.



(a) Example fit of a fit to the dependence of the residuals on the total deflection angle $\Delta\vartheta_{\text{total}}$ for a rotation of 6 mrad. The three bands corresponding to the different muon energies of the Monte-Carlo data sets are clearly visible, as well as the splitting between μ^+ and μ^- (pos. and neg. $\Delta\vartheta_{\text{total}}$)

(b) The dependence of the slope of the fitted line in (a) on the relative chamber rotation angle $\Delta\alpha$ is fitted with a third order polynomial.

Figure 9.2: Calibration from the individual fits

Since the momentum measurement was biased by the initially unknown chamber rotations, the residuals are also biased and one does not obtain the correct rotation angle $\Delta\alpha$ directly. Iterations are required.

In a second iteration step, the geometry of the spectrometer is corrected by the rotation angle determined in the first iteration step. The rotation angle $\Delta\alpha$ obtained in the second iteration step was found to agree with its true value in the Monte-Carlo simulation and further iterations are not needed. The bias in the momentum measurement using the deflection angle is removed. The relative displacements can now be obtained as described in the previous chapter.

9.3 Performance Tests with Monte-Carlo Data

To test the performance of the algorithm it was applied to the MC4 data set. 13 different relative rotations between -6 mrad and +6 mrad were simulated (cp. Sec. 6.2.4 and Sec. 8.5). This covers the range of the maximal expected rotations of about 5 mrad in ATLAS (5 mm displacement per 1 m for a chamber). For the calibration only even rotations were used so that the odd rotations can provide a control sample for the reconstruction performance.

The results are shown in Figure 9.3 for the reconstructed rotations (Fig. 9.3(a)) and the difference between the reconstructed and the input rotation (Fig. 9.3(b)), respectively. The 13 different rotations were also simulated with an additional displacement of $\Delta y = \pm 50 \mu\text{m}$ to investigate the influence of a misalignment. The rotation reconstruction is accurate to less than 0.2 mrad for all three misalignment values.

The whole algorithm is again applied to the data with an artificial antirotation on the chamber determined from the calibration. Then a simple fit as described in the previous chapter is done on the residuals to determine the displacement. The results are shown in Figure 9.4. Even with an rotation error of 0.2 mrad there is still a bias of about $100 \mu\text{m}$ on the displacement depending on the rotation.

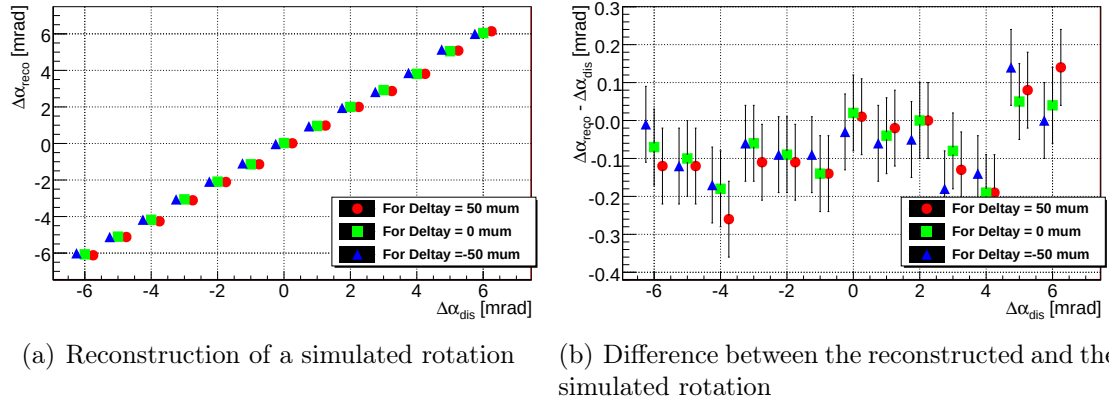


Figure 9.3: Reconstruction of a chamber rotation using the calibration (cp. Fig. 9.2(b)). The performance was tested for three different displacements: $+50\mu\text{m}$, $0\mu\text{m}$ and $-50\mu\text{m}$.

The data points for the missaligned geometry are shifted in x to allow a better differentiation.

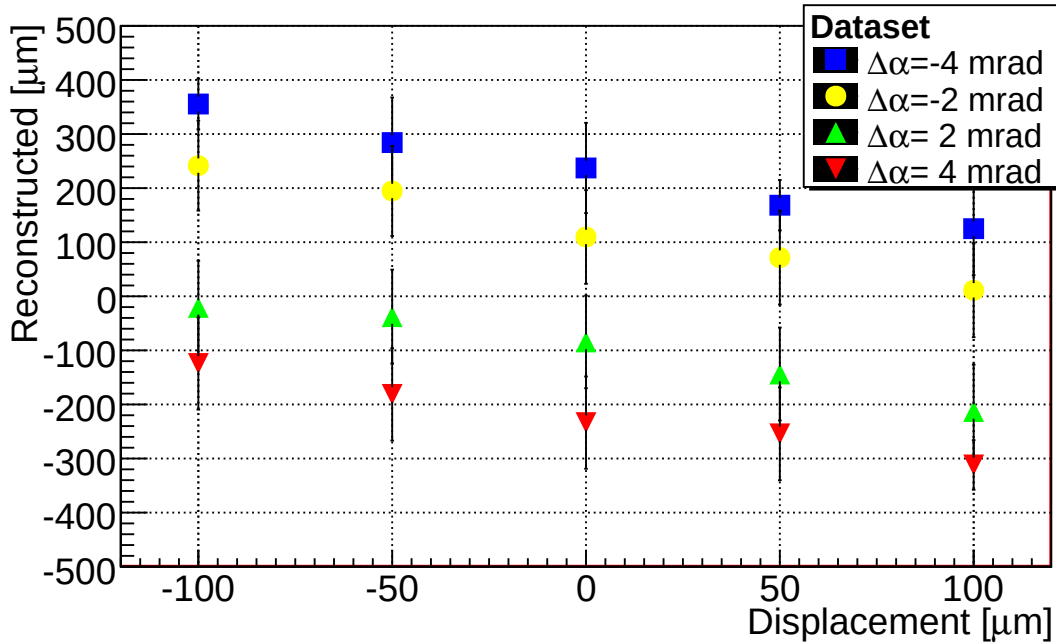


Figure 9.4: Displacements derived from a gaussian fit to the residuals after an rotation correction with an assumed error of 0.2 mrad from the calibration.

However, within errors the bias is consistent with zero. An accuracy of $100\ \mu\text{m}$ for the displacement reconstruction is reachable, with an accuracy of the rotation reconstruction of $0.2\ \text{mrad}$.

9.4 Conclusions

The feasibility study of an alignment algorithm for curved tracks shows that it is possible to align barrel chamber towers of the ATLAS muon spectrometer with an accuracy of at least $100\ \mu\text{m}$ with the presently achievable accuracy in the calibration of the r - t relationship of the drift tubes. A Monte-Carlo simulation based determination of the relationship between the track residual and the deflection angle was used. The dependence on this Monte-Carlo input has to be removed in the final implementation of the alignment algorithm. The global χ^2 minimisation approach as used for the alignment of barrel sectors with straight tracks does not require Monte-Carlo input. One can expect the global χ^2 minimisation (see Ch. 7) to work also for alignment with alignment constants with curved tracks.

Part IV

Conclusions

Chapter 10

Summary

ATLAS, one of the multipurpose detectors at the LHC, will be used to study proton-proton collisions to understand the mechanism of electroweak symmetry breaking and to explore physics beyond the standard model. An important part of the ATLAS detector is the muon spectrometer. It permits the efficient measurement of muon momenta with an accuracy better than 10% up to muon energies of 1 TeV/c². Muon detection with high efficiency and high precision momentum measurement are based on two requirements:

- All muon chambers are fully operational including power supplies, gas supply, read out and control system, and record data with high signal-to-noise ratio.
- The goal of 10% traverse momentum resolution at 1 TeV/c² muon energy requires the knowledge of the relative positions of the muon chambers with 30 μm accuracy.

The work in this thesis contributes to the achievement of both requirements.

The author was involved in the commissioning of the precision muon drift tube chambers after installation in ATLAS. During this year more than 200 chambers have been connected to the final power supplies and readout system and problems detected on more than 100 chambers have been resolved.

The chambers have also been tested with muons originating from cosmic radiation. With these data it is possible to measure the signal-to-noise ratio of the muon chambers. Chambers with a relatively high noise rate, compared to neighboring chambers or the maximal acceptable rate of 40 kHz, were identified and their noise rates decreased by a factor 10 by installing additional low-pass filters in the HV distribution of these chambers.

The second requirement, the precise alignment of the muon chambers, is ensured by the combination of a very precise optical alignment system and additional information from a muon track reconstruction. Both components have been tested extensively and proven to perform as expected.

The chamber alignment with straight tracks has been tested with data from cosmic muons. The desired alignment accuracy of 30 μm was confirmed by Monte-Carlo studies and the comparison with mechanical measurements of the chamber distances.

Since straight tracks are only available when the magnets of the muon spectrometer are switched off, the alignment of the chambers must be monitored with curved tracks during normal operation of ATLAS. A proposal for such an algorithm was developed in a former thesis. Systematic studies of this algorithm were the main part of this thesis. Two aspects had to be studied in detail: the track segment reconstruction in combination with a momentum measurement within individual muon chambers and the overall alignment algorithm.

The track segment reconstruction within a chamber was shown not to be biased due to the limited drift tube resolution or imperfections of the chamber geometry, and no resolution decrease was observed. But it was found that the accuracy of the calibration of the space-to-drifttime relationship of the muon drift of $20\text{ }\mu\text{m}$ is not sufficient for a local momentum measurement within a chamber with a resolution required for the originally proposed alignment algorithm.

An alternative method with much lower sensitivity to the calibration of the muon chambers was developed. The tests of the new method with Monte-Carlo data show that an alignment with an accuracy of $100\text{ }\mu\text{m}$ is achievable with curved muon tracks. The method can be used to monitor the alignment accuracy of the muon spectrometer with curved tracks.

Part V

Appendix

Appendix A

Momentum Calculation Using the Track Deflection Angle

In [14] a method is derived to calculate the momentum of a particle from the track deflection angle using the knowledge of the bending power of the magnetic field along the track. This method is shortly described.

The movement of a charged particle with the momentum $\vec{p}$ in a magnetic field under the Lorentz force is described by the equation

$$\vec{F} = \frac{d\vec{p}}{dt} = q \cdot \vec{v} \times \vec{B} , \quad (\text{A.1})$$

with q being the charge and $\vec{v}$ the velocity of the particle. The change of the particle momentum when moving along the trajectory $\mathcal{P}$ can be determined by integrating Equation (A.1):

$$\Delta\vec{p} = q \cdot \int_{\mathcal{P}} d\vec{s} \times \vec{B} , \quad (\text{A.2})$$

with $d\vec{s}$ being a path element along the trajectory. The Lorentz force is always perpendicular to the momentum. Thus only the direction of the particle changes while the magnitude p of the momentum remains the same.

With $\vec{p}_{\text{initial}}$ being the initial momentum of the particle, the momentum $\vec{p}_{\text{final}}$ at the end of the trajectory will be

$$\vec{p}_{\text{final}} = \vec{p}_{\text{initial}} + \Delta\vec{p} . \quad (\text{A.3})$$

Now we take a closer look to the situation in ATLAS. The MDT chambers can only determine the deflection angle in the precision plane perpendicular to the beam. Let $(\vec{p}_{\text{final}})^{\text{PP}}$ and $(\vec{p}_{\text{initial}})^{\text{PP}}$ be the projections of $\vec{p}_{\text{final}}$ and $\vec{p}_{\text{initial}}$ into this plane, then the deflection angle $\Delta\alpha$ is given by the scalar product

$$(\vec{p}_{\text{initial}})^{\text{PP}} \circ (\vec{p}_{\text{final}})^{\text{PP}} = |(\vec{p}_{\text{initial}})^{\text{PP}}| \cdot |(\vec{p}_{\text{final}})^{\text{PP}}| \cdot \cos \Delta\alpha . \quad (\text{A.4})$$

With the unit vectors $\hat{d}_{\text{initial}} = \vec{p}_{\text{initial}}/p$ and $\hat{d}_{\text{final}} = \vec{p}_{\text{final}}/p$ the left hand side of Equation (A.4) can be rewritten using (A.3):

$$\begin{aligned}
(\vec{p}_{\text{initial}})^{\text{PP}} \circ (\vec{p}_{\text{final}})^{\text{PP}} &= (\vec{p}_{\text{initial}})^{\text{PP}} \circ (\vec{p}_{\text{initial}})^{\text{PP}} + (\vec{p}_{\text{initial}})^{\text{PP}} \circ (\Delta\vec{p})^{\text{PP}} \\
&= p^2 \cdot \left| (\hat{d}_{\text{initial}})^{\text{PP}} \right|^2 + p \cdot (\hat{d}_{\text{initial}})^{\text{PP}} \circ (\Delta\vec{p})^{\text{PP}} . \quad (\text{A.5})
\end{aligned}$$

The precision plane can be described by two unit vectors $\hat{n}$ and $\hat{z}$. $\hat{n}$ is normal to the local chamber plane whereas $\hat{z}$ is parallel to the beam axis (the global z direction). Now one can rewrite the two projections on the right hand side of (A.4) resulting in

$$|(\vec{p}_{\text{initial}})^{\text{PP}}| = \left| p \cdot \left[(\hat{d}_{\text{initial}} \circ \hat{n}) \cdot \hat{n} + (\hat{d}_{\text{initial}} \circ \hat{z}) \cdot \hat{z} \right] \right| \equiv p \cdot \left| (\hat{d}_{\text{initial}})^{\text{PP}} \right| \quad (\text{A.6})$$

and

$$\begin{aligned}
|(\vec{p}_{\text{final}})^{\text{PP}}| &= |(\vec{p}_{\text{initial}})^{\text{PP}} + (\Delta\vec{p})^{\text{PP}}| \\
&= \left| p \cdot (\hat{d}_{\text{initial}} \circ \hat{n}) \cdot \hat{n} + p \cdot (\hat{d}_{\text{initial}} \circ \hat{z}) \cdot \hat{z} + (\Delta\vec{p} \circ \hat{n}) \cdot \hat{n} + (\Delta\vec{p} \circ \hat{z}) \cdot \hat{z} \right| \\
&= \sqrt{\left[(p \cdot \hat{d}_{\text{initial}} + \Delta\vec{p}) \circ \hat{n} \right]^2 + \left[(p \cdot \hat{d}_{\text{initial}} + \Delta\vec{p}) \circ \hat{z} \right]^2} . \quad (\text{A.7})
\end{aligned}$$

Squaring (A.4) and using (A.5) to (A.7) leads to an equation for the momentum:

$$\begin{aligned}
p^4 |(\hat{d}_{\text{initial}})^{\text{PP}}|^4 + 2p^3 |(\hat{d}_{\text{initial}})^{\text{PP}}|^2 \cdot \left[(\hat{d}_{\text{initial}})^{\text{PP}} \circ (\Delta\vec{p})^{\text{PP}} \right] + p^2 \cdot \left[(\hat{d}_{\text{initial}})^{\text{PP}} \circ (\Delta\vec{p})^{\text{PP}} \right] &= \\
\cos^2 \Delta\alpha \cdot p^2 |(\hat{d}_{\text{initial}})^{\text{PP}}|^2 \cdot \left\{ \left[(p \cdot \hat{d}_{\text{initial}} + \Delta\vec{p}) \circ \hat{n} \right]^2 + \left[(p \cdot \hat{d}_{\text{initial}} + \Delta\vec{p}) \circ \hat{z} \right]^2 \right\} . \quad (\text{A.8})
\end{aligned}$$

Assuming $p \neq 0$ one can divide (A.8) by p^2 . The result is the quadratic equation

$$A \cdot p^2 + B \cdot p + C = 0 \quad (\text{A.9})$$

with the coefficients:

$$\begin{aligned}
A &= |(\hat{d}_{\text{initial}})^{\text{PP}}|^4 - \cos^2 \Delta\alpha \cdot |(\hat{d}_{\text{initial}})^{\text{PP}}|^2 \cdot [(\hat{d}_{\text{initial}} \circ \hat{n})^2 + (\hat{d}_{\text{initial}} \circ \hat{z})^2] \\
&= |(\hat{d}_{\text{initial}})^{\text{PP}}|^4 (1 - \cos^2 \Delta\alpha) = |(\hat{d}_{\text{initial}})^{\text{PP}}|^4 \sin^2 \Delta\alpha \quad (\text{A.10})
\end{aligned}$$

$$\begin{aligned}
B &= 2 |(\hat{d}_{\text{initial}})^{\text{PP}}|^2 \cdot \left\{ \left[(\hat{d}_{\text{initial}})^{\text{PP}} \circ (\Delta\vec{p})^{\text{PP}} \right] - \right. \\
&\quad \left. - \cos^2 \Delta\alpha \cdot \left[(\hat{d}_{\text{initial}} \circ \hat{n})(\Delta\vec{p} \circ \hat{n}) + (\hat{d}_{\text{initial}} \circ \hat{z})(\Delta\vec{p} \circ \hat{z}) \right] \right\} \quad (\text{A.11})
\end{aligned}$$

$$\begin{aligned}
C &= \left[(\hat{d}_{\text{initial}})^{\text{PP}} \circ (\Delta\vec{p})^{\text{PP}} \right]^2 - \cos^2 \Delta\alpha \cdot |(\hat{d}_{\text{initial}})^{\text{PP}}|^2 \cdot [(\Delta\vec{p} \circ \hat{n})^2 + (\Delta\vec{p} \circ \hat{z})^2] . \quad (\text{A.12})
\end{aligned}$$

Equation (A.9) has the solutions

$$p_{1,2} = \frac{-B \pm \sqrt{B^2 - 4AC}}{2A} \quad (\text{A.13})$$

where p has to be positive by definition which is only true for one of the solutions.

Bibliography

- [1] MINUIT 2, a new object-oriented implementation, written in C++, of the popular MINUIT minimization package. Website: http://root.cern.ch/root/html/MATH_MINUIT2_Index.html.
- [2] ROOT, An Object-Orientated Analysis Framework. Website: <http://root.cern.ch/>.
- [3] ATLAS Muon Spectrometer Technical Design Report. Technical report, 2002. Website: <http://atlas.web.cern.ch/Atlas/GROUPS/MUON/TDR/Web/TDR.html>.
- [4] Aielli, G. and others. Assembly and Certification of ATLAS Muon Stations for the Middle and Outer Barrel at CERN. Technical Report ATL-MUON-PUB-2007-001. ATL-COM-MUON-2006-021, CERN, Geneva, Oct 2006.
- [5] Amelung, C. and others. The ATLAS muon alignment system. *1st LHC Detector Alignment Workshop*, page 11 p, 2007. Website: <http://documents.cern.ch/cgi-bin/setlink?base=yellowarticle&categ=2007-004&id=p159>.
- [6] Bagnaia, P. and others. Calibration model for the MDT chambers of the ATLAS Muon Spectrometer. Technical Report ATL-MUON-PUB-2008-004. ATL-COM-MUON-2008-006, CERN, Geneva, Feb 2008. Backup paper for Atlas Detector paper.
- [7] Beretta, M. and others. MDT Commissioning Procedures Guidelines for Certifying RFI Chambers. Technical Report ATL-MUON-2004-022. CERN-ATL-MUON-2004-022. ATL-COM-MUON-2004-018. CERN-ATL-COM-MUON-2004-018, CERN, Geneva, 2004.
- [8] Biebel, O. and others. A cosmic ray measurement facility for ATLAS muon chambers. *arXiv*, physics/0307147, 2003.
- [9] Biebel, O. and others. Test and calibration of large drift tube chambers with cosmic rays. *IEEE Trans. Nucl. Sci.*, 52:2998–3004, 2005.
- [10] Dubbert, J. MDT Chamber Status and Shutdown Activities. In *ATLAS Muon Week*, October 2008. Website: <http://indico.cern.ch/conferenceDisplay.py?confId=43957>.
- [11] Dubbert, J. and others. First experience with the ATLAS muon spectrometer. *Nucl. Instrum. Meth.*, A581:507–510, 2007.

- [12] Dubbert, J. and others. Integration, commissioning and installation of monitored drift tube chambers for the ATLAS barrel muon spectrometer. *Nucl. Instrum. Meth.*, A572:53–56, 2007.
- [13] Potrap, I. and Kortner, O. and Kotov, S. and Kroha, H. Alignment of the ATLAS Muon Spectrometer with straight tracks using MILLEPEDE method. Technical Report ATL-COM-MUON-2007-017, CERN, Geneva, Dec 2007.
- [14] Schmalzer, J. Test and Alignment of the ATLAS Precision Muon Chambers. Diplomarbeit, TU München & MPI für Physik, 2007.
- [15] The ATLAS Collaboration and G Aad *et al.* The ATLAS Experiment at the CERN Large Hadron Collider. *Journal of Instrumentation*, 3(08):S08003, 2008. Website: <http://stacks.iop.org/1748-0221/3/S08003>.
- [16] von Loeben, J. Test und Kalibrierung der Präzisionsdriftrohrkammern des ATLAS-Myonspektrometers. Diplomarbeit, TU München & MPI für Physik, 2007.

List of Figures

1.1	The Large Hadron Collider and its four large detectors: ALICE (A L arge I on C ollider E xperiment), ATLAS (A T oroidal L H C A pparatu S), CMS (C ompact M uon S olenoid) and LHCb (L arge H adron C ollider b eauty experiment).	4
2.1	Cut-away view of the ATLAS detector	6
2.2	Magnetic Coils in ATLAS	9
3.1	Schematic view of the Muonsystem	14
3.2	Cross-section of the barrel muon system perpendicular to the beam axis	14
3.3	A MDT tube in different views	15
3.4	Mechanical structure of a MDT chamber	16
3.5	The electronic components of a MDT chamber	18
4.1	Frequency of drift tubes with high noise rates.	20
4.2	Example TDC spectrum. The drift time spectrum is clearly visible between $t_0 = 900$ and $t_{\max} = 1900$ TDC counts ($0.70 \mu\text{s}$ to $1.5 \mu\text{s}$). Every hit before 850 TDC counts is considered noise. For this specific run the active time window was set to 3000 TDC counts.	21
4.3	Average noise rates of the barrel MDT chambers identified by their code names as function of η and ϕ (cp. Sec. 3.2). Note the different scales. Chambers with less than 100 hits per layer are left blank. The BIR chambers in ϕ -sector 11 and 15 are moved to the (virtual) sectors 19 and 20, respectively, since the bins are already occupied by the BIM.	22
4.4	Noise rates of the 432 drift tubes of a BOS MDT chamber in ATLAS with (black) and without (blue) HV cables connected to the chamber.	23
4.5	Effect of the noise filters: a significant decrease of the noise rates is clearly visible.	24
4.6	First prototypes of the noise filters.	25
4.7	The final design of the noise filters with a cut-off frequency of $f_c = 732.4 \text{ Hz}$	25
4.8	First beam halo events reconstructed by ATLAS in September 2008. The red lines indicate reconstructed muon tracks.	28

4.9	Status of the MDT chambers end of October 2008. Chambers are sorted by their position along the beam pipe. Starting on the left with the endcap chambers on side C, then the barrel chambers and finally the endcap A chambers. From top to bottom are the different layers of the spectrometer: inner chambers at the top, middle chambers in the middle, and outer chambers at the bottom.	29
5.1	Contributions to the muon momentum resolution	33
5.2	Definition of the track sagitta	34
5.3	Definition of the Local Chamber Coordinate System	36
5.4	Impact on the measured $\Delta s = S' - s$ sagitta by shifts in y and z of the middle chamber (cp. Fig. 5.2).	36
5.5	Impact on the measured trackpoint from a chamber rotation around the x axis (cp. Fig. 5.2).	37
5.6	Principle of the Optical Alignment System	37
5.7	Scheme of the Optical Alignment System	38
5.8	The PrAxial Alignment System Layout	39
6.1	Reconstructed track segment in a MDT chamber	42
6.2	Bias and σ for a reconstruction on the true hits	43
6.3	Influence of the single tube resolution on the segment reconstruction	45
6.4	Difference Δr between the true r - t relationship and an initial r - t calibrated relationship.	46
6.5	Influence of deviations from the true r - t relationship	47
6.6	Reconstructed momentum for the MC1 and MC3 data sets within a chamber with a r - t relationship accuracy of $20 \mu\text{m}$. For the 6 GeV muons the momentum reconstruction works correctly, for the 20 GeV muons no mean value can be found.	48
6.7	Influence of displacements and rotations	49
7.1	Accuracy of the track sagitta correction after the alignment with 400,000 straight cosmic muon tracks in the sector 5, A side, of the barrel muon spectrometer. The tower index counts the chamber triplets (towers) in a sector with increasing η value.	53
7.2	Comparison of the distances between the inner and outer chambers of sector 5, A side, as measured with cosmic rays using the track alignment algorithm and with a feeler gauge (mechanical measurement).	54
7.3	Displacement of a BO chamber	55
7.4	Bias from a rotated chamber on the residual	55
7.5	Determination of a γ rotation	55
7.6	Comparison of the χ^2 minimisation results and the simple method	57
7.7	Relative misalignments for a sample chamber pair	57
8.1	Influence of the r - t relation on the momentum measurement	61
8.2	Influence of the r - t relation	62
8.3	Reconstruction of an artificial displacement	63

9.1	Track residuals caused by relative rotation of the inner and outer chambers with respect to the middle one for curved muon tracks with opposite charge.	66
9.2	Calibration from the individual fits	67
9.3	Reconstruction from the fit	68
9.4	Residuals after angle correction	68

List of Tables

3.1	Parameters of the drift tubes in the ATLAS MDT chambers	15
4.1	Problems of installed ATLAS MDT chambers solved during the commissioning in spring 2008.	27
6.1	Monte-Carlo datasets used for testing	43

Acknowledgment

During the last year I had a very nice time working at the institute. Special tanks to PD Dr. Hubert Kroha for giving me the option to be part of the ATLAS group, all help during my time here the very fast an elaborate corrections of my work during the last few weeks.

I also would like to tank Dr. Oliver Kortner for all the time he spend discussing new ideas and solutions to all parts of my work. During my time at CERN, and of course also afterwards when i had any questions regarding the ATLAS detector hardware or commissioning, Dr. Jörg Dubbert and Jörg v. Loeben never got tired explaining the fine details of the hardware or other parts down in the pit.

Last but definitely not least, I want to thank all members of the MDT ATLAS group at the MPP for the nice workin atmosphere. Another valuable source of information and always willing to help.

Erklärung

des Diplomanden

Bernhard Korbinian Bittner

Mit der Abgabe der Diplomarbeit versichere ich, dass ich die Arbeit selbständig verfasst und keine anderen als die angegebenen Quellen und Hilfsmittel benutzt habe.

.....
(Ort, Datum)

.....
(Unterschrift)