Χαρακτηρισμός της απόδοσης του ανιχνευτή Micromegas για την αναβάθμιση New Small Wheel και ανάπτυξη και βελτίωση του συστήματος αυτομάτου ελέγχου των ανιχνευτών μιονίων στο πείραμα ATLAS

ΔΙΔΑΚΤΟΡΙΚΗ ΔΙΑΤΡΙΒΗ

Κωνσταντίνου Α. Ντέκα
Διπλωματούχου Φυσικού Εφαρμογών Ε.Μ.Π.

ΕΠΙΒΛΕΠΩΝ:
Θ. ΑΛΕΞΟΠΟΥΛΟΣ
Καθηγητής Ε.Μ.Π.

ΑΘΗΝΑ, Ιανουάριος 2016
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ΤΡΙΜΕΛΗΣ ΣΥΜΒΟΥΛΕΥΤΙΚΗ ΕΠΙΤΡΟΠΗ:
1. Θεόδωρος Αλεξάπουλος, Καθ. Ε.Μ.Π.
2. Ευάγγελος Γαζής, Καθ. Ε.Μ.Π.
3. Γεώργιος Τσιπολίτης, Καθ. Ε.Μ.Π.

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2. Ευάγγελος Γαζής, Καθ. Ε.Μ.Π.
3. Γεώργιος Τσιπολίτης, Καθ. Ε.Μ.Π.
4. Σ. Μαλτέζος, Αν. Καθ. Ε.Μ.Π.
5. Β. Πολυχρονάκος, Ερευνητής Β.Ν.Λ.
6. Θ. Γέραλης, Ερευνητής Α Δημόκριτος
7. Δ. Σαμψιώνίδης, Αν. Καθ. Α.Π.Θ.

ΑΘΗΝΑ, Ιανουάριος 2016
Κωνσταντίνος Α. Ντέκας

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Performance characterization of the Micromegas detector for the New Small Wheel upgrade and
Development and improvement of the Muon Spectrometer Detector Control System in the ATLAS experiment

A dissertation presented by
Konstantinos A. Ntekas
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Performance characterization of the Micromegas detector for the New Small Wheel upgrade and Development and improvement of the Muon Spectrometer Detector Control System in the ATLAS experiment

PhD THESIS

Konstantinos A. Ntekas

Advisor: Theodoros Alexopoulos
Professor, N.T.U.A.

Exam committee:

Theodoros Alexopoulos
Professor N.T.U.A.

Evangelos Gazis
Professor N.T.U.A.

Georgios Tsipolitis
Professor N.T.U.A.

Stavros Maltezos
Associate Professor N.T.U.A.

Venetios Polychronakos
Senior Researcher B.N.L.

Theodoros Geralis
Researcher A
N.C.S.R. Demokritos

Dimitrios Sampsonidis
Associate Professor A.U.TH.

Athens, (January 2016)
Στην οικογένειά μου
Αριστείδη, Κατερίνα, Αριστοτέλη

και στην αγαπημένη μου Φρανζέσκα
Περίληψη

Το πείραμα ATLAS (A Toroidal LHC ApparatuS) είναι ένα από τα δύο πειράματα υψηλής φωτεινότητας και γενικού σκοπού (μαζί με το πείραμα CMS) που κατασκευάστηκαν για τη μελέτη συγκρούσεων πρωτονιών-πρωτονιών και πρωτονιών-ιόντων ή ιόντων-ιόντων στον επιταχυντή LHC. Το φασματόμετρο μιονίων περικλείει τα υπόλοιπα υποανιγκευτικά συστήματα του ATLAS και κατά συνέπεια ορίζει τις εξωτερικές διαστάσεις του ανιγκευτή. Η αρχή λειτουργίας του βασίζεται στην απόκλιση των μιονικών τροχιών λόγω του μαγνητικού πεδίου, που δημιουργείται από ένα σύστημα υπεραγώγισμα τοροίδων μαγνητών, εξασφαλίζοντας μεγάλης ακρίβειας μέτρηση της ομήρη των μιονίων. Η αναβάθμιση του μιονικού συστήματος του πειράματος ATLAS είναι πρωταρχικά απαραίτητη λόγω της υψηλής ακτινοβολίας υποθάρυση που αναμένεται μετά την αναβάθμιση του LHC κατά την περίοδο Phase-1 (2021) και κυρίως στην φωτεινότητα \( L = 7 \times 10^{34} \text{ cm}^{-2} \text{s}^{-1} \) που αναμένεται στον αναβαθμισμένο HL-LHC (2026). Λόγος του παραπάνω, οι ανιγκευτές που καταλαμβάνουν την περιοχή του μιονικού συστήματος που βρίσκεται πιο κοντά στην σημεία αλληλεπίδρασης (IP), Small Wheel (SW), που είναι MDT, CSC & TGC, θα πρέπει να ανταπεξέλθουν σε περιβάλλον φωτεινότητας πολύ μεγαλύτερη από την τιμή για την οποία έχουν σχεδιαστεί. Παράλληλα ο ρυθμός του trigger των μιονίων θα ξεπεράσει τη διαθέσιμο εύρος ζώνης εξατμία των fake triggers (to 90% προέρχεται κυρίως από σωματίδια υποθάρυση χαμηλής ενέργειας). Το υπάρχον SW θα αντικατασταθεί με ένα νέο σύστημα (NSW) που θα αποτελείται από ανιγκευτές small-strip Thin Gap Chambers (sTGC) και resistive-strip Micromegas (MM) ώστε να διατηρήσει την εξαιρετική του απόδοση και μετα το Run-2. Η αναβάθμιση NSW απαιτεί και οι δύο τεχνολογίες ανιγκευτών του νέου συστήματος να μπορούν να παρέχουν ακρίβη ταυτοποίηση των μιονικών τροχιών καθώς και πληροφορίες που μπορούν να χρησιμοποιηθούν για το trigger. Το σύστημα του NSW θα συνεισφέρει με αυτό τον τρόπο στην ελαχιστοποίηση των fake triggers ανακατασκευάζοντας ακρίβη \( (\sigma_\theta \sim 1 \text{ mrad}) \) τιμήματα των μιονικών τροχιών που επεκτείνονται στο IP online. Ακόμη, η αποδοτική και ακρίβης ανακατασκευή των μιονικών τροχιών offline \( (\sigma_r \leq 100 \mu \text{m}) \), ακόμα και στο μέγιστο αναμενόμενο ρυθμό διερχόμενων σωματιδίων \((15 \text{ kHz}/\text{cm}^2)\) είναι προαιρετική. Μία σύντομη περιγραφή του πειράματος ATLAS και της αναβάθμισης NSW παρουσιάζονται στο Κεφ. 1.

Οι MM ανιγκευτές του NSW θα πρέπει να έχουν σταθερά υψηλή αποδοτικότητα ανεξάρτητα από το ρυθμό των διερχόμενων σωματιδίων και να μπορούν να τα αναγνωρίσουν με χαρακτηρική διακριτική ικανότητα καλύτερη από 100 μμ ανεξάρτητη της κλίσης της τροχιάς και του μαγνητικού πεδίου \((B \leq 0.3 \text{ T})\). Παράλληλα οι MM του NSW θα πρέπει να παρέχουν πληροφορίες για το trigger, συμπληρώνοντας αυτές των sTGC, και κατά συνέπεια θα πρέπει να χαρακτηρίζονται από καλή χρονική διακριτική ικανότητα. Προκειμένου να αποδειχθεί ότι οι ανιγκευτές MM ικανοποιούν απο το NSW μία σειρά από δοκιμές εκτελέστηκαν σε μικρούς \((10 \times 10 \text{ cm}^2)\) resistive-strip MM ανιγκευτές χρησιμοποιώντας μεσαίας \(10 \text{ GeV/c}\) και υψηλής \(150 \text{ GeV/c}\) ορμής.
πέρα από τη μελέτη και την βελτιστοποίηση της απόδοσης των ανιχνευτών MM, εξετάστηκε και η χρήση γεωμετρικών στοιχείων ανάγνωσης με διαφορετικά χαρακτηριστικά. Η εισήγηση αυτών των σχημάτων ανάγνωσης των MM μετόπεσε σημαντικά των αριθμό των επίπεδων ανίχνευσης και των ελεκτρονικών καναλιών, επιτρέποντας την χρήση των MM σε πειράματα μεγάλης κλίμακας (π.χ. NSW). Η χρήση ενός σχήματος με stereo strips, όπως προθέτεταν για τους MM του NSW, επιτρέπει την διαδιάσταση ανακατασκευής της θέσης ενός διερχομένου φορτισμένου σωματίδιου. Η μελέτη της αρχικός λειτουργίας του σχήματος των stereo strips έγινε χρησιμοποιώντας ένα μεσαίου μεγέθους ανίχνευτη MM με τέσσερα επίπεδα ανίχνευσης, στα πρότυπα του NSW. Επιπλέον, μελετήθηκε η πιθανότητα παλύπλεξης των strip του ανιχνευτή MM σε ένα μικρότερο αριθμό ελεκτρονικών καναλιών. Τα αποτελέσματα αποδεικνύουν ότι ένα σχήμα πολύπλεξης μπορεί να εφαρμοστεί στους MM, χωρίς να επιρρεάζονται τα εξαιρετικά εγγενή χαρακτηριστικά του ανιχνευτή. Τα αποτελέσματα των παραπάνω μελετών συνδεδεόμενα από την δοκιμή και τη μελέτη της πρώτης γενιάς των ελεκτρονικών ανάγνωσης VMM με ανιχνευτές MM παρουσιάζονται στο Κεφ. 7.

Παράλληλα με τις μελέτες έρευνας και ανάπτυξης του ανιχνευτή MM υλοποιήθηκαν συνεισφορές που διευρύνουν και βελτιώνουν τη λειτουργικότητα του συστήματος αυτόματου ελέγχου (DCS) των μικρούς ανιχνευτών στο περιβάλλον ATLAS. Τα δύο κύρια εργαλεία που αναπτύχθηκαν αφορούν την υλοποίηση ενός συστήματος για την βαθμονόμηση του κρίματος υποθέσεων στις κατακερματισμένες κατακερματιστικές της περιοχής ATLAS και την ανάπτυξη ενός ανεξάρτητου και ολοκληρωμένου DCS για την παρακολούθηση του συστήματος ευθυγράμμισης των ενδ-εαρ μικρού ανιχνευτών. Τα εργαλεία αυτά έχουν ενσωματωθεί στο κεντρικό DCS του ATLAS και χρησιμοποιούνται στην καθημερινή λειτουργία των πειραμάτων. Στο Κεφ. 2 παρατίθεται η εισαγωγή περιγραφή αυτών των εργαλείων μαζί με μία σύντομη εισαγωγή της δομής και της λειτουργίας του ATLAS DCS. Με τον χρήσιμο βαθμονόμησης του κρίματος υποθέσεων, με χρήση των δεδομένων φωτεινότητας, επικεκτέθηκε ούτως ώστε να αναπτυχθεί μία τεχνική για τον υπολογισμό της φωτεινότητας του ATLAS (Παράρτημα A).
Abstract

The ATLAS, an abbreviation for A Toroidal LHC ApparatuS, detector is one of the two general purpose high luminosity experiments (along with CMS) that have been built for probing p-p and Pb-Pb or p-Pb collisions in the LHC. The muon spectrometer encircles the rest of the ATLAS detector subsystems defining the ATLAS overall dimensions. Its principle of operation is based on the magnetic deflection of muon tracks by a system of superconducting air-core toroid magnets providing high resolution muon momentum measurement. The upgrade of the ATLAS muon spectrometer is primarily motivated by the high background radiation expected during Run-3 (2021) and ultimately at $\mathcal{L} = 7 \times 10^{34}$ cm$^{-2}$s$^{-1}$ in HL-LHC (2026). Owing to this the detectors that occupy the innermost muon station called Small Wheel (SW), MDT, CSC & TGC, will go beyond their design luminosity limit. In addition, the muon trigger rate will exceed the available bandwidth because of the fake endcap muon triggers (90% is coming from low energy particles, generated in the material located between the Small Wheel and the outer endcap muon station). The collaboration has decided to replace the SW with a NSW system combining sTGC & resistive MM detectors in order to maintain the excellent performance of the muon system beyond Run-2. Both detector technologies should provide tracking and triggering information for redundancy. The NSW will contribute to the suppression of fake triggers by reconstructing high quality ($\sigma_\theta \sim 1$ mrad) IP pointing segments online. Moreover, efficient & precise offline tracking ($\sigma_r \leq 100 \mu$m) even for the maximum expected rate of 15 kHz/cm$^2$ is required. A brief description of the ATLAS experiment along with the motivation and requirements for the NSW are described in Chap. 1.

The NSW requires fully efficient high-rate capable MM chambers with a single plane spatial resolution better than 100 $\mu$m independent of the track incidence angle and the magnetic field ($B \leq 0.3$ T). Along with the precise tracking the MM should be able to provide a trigger signal, complementary to the sTGC, thus a decent timing resolution is required. In order to demonstrate and prove that the MM satisfy the NSW requirements several tests have been performed on small ($10 \times 10 \text{ cm}^2$) resistive-strip MM chambers using medium (10 GeV/c) and high (150 GeV/c) momentum hadron beams at CERN and electron beam at DESY. The extensive studies presented in Chaps. 4,5 focus on the efficiency as well as hit and time reconstruction accuracy measured during these tests demonstrating the excellent characteristics of the MM. Exploiting the ability of the MM to work as a Time Projection Chamber a novel method, called the $\mu$TPC, has been developed for the case of inclined tracks, allowing for a precise segment reconstruction using a single detection plane. A detailed description of the method along with thorough studies towards refining the method’s performance are shown.
Moreover, owing to the moderate magnetic field expected in the NSW region (0.3 T), dedicated studies have been devoted in understanding the effect of the Lorentz force on the MM performance when operated inside a magnetic field. The effect of the field has been well understood using test beams, with chambers operated inside magnets, and in simulation. Owing to the quantitative agreement between simulation and test beam measurements the exact knowledge of the magnetic field value has become a prerequisite for a precise track reconstruction in the NSW Micromegas in order to correct for the field effect. Complementary to this, novel methods, for measuring the magnetic field using MM data, have been developed. The magnetic field studies are presented in Chap. 6.

Complementary to studying and optimising the MM performance, the use of readout geometries with different characteristics had been studied. The adoption of these schemes for the MM readout minimise the number of detection layers and electronic channels, decreasing the complexity, and make the application of Micromegas in large scale experiments feasible. The use of a stereo readout scheme, as foreseen for the NSW MM, allows for a two-dimensional hit position reconstruction with a decent accuracy. The validation of the stereo principle has been performed studying a medium size quadruplet prototype MM, following the NSW stereo readout scheme. Moreover, the possibility of multiplexing MM strips into a smaller number of electronic channels has been studied. The results demonstrate the feasibility of the multiplexing concept, proving that the excellent intrinsic characteristics of the detector remain unaffected by the multiplexing that significantly reduces the number of electronics channels. These studies accompanied by the testing and validation of the first version of VMM based readout electronics with MM chambers are discussed in Chap. 7.

In parallel to the R&D on the MM detector several contributions have been made in expanding and improving the efficiency and functionality of the ATLAS Muon Detector Control System (DCS). The two major developments that were realised concern the implementation of a calibration tool for the current offset of MDT high voltage channels using ATLAS luminosity data and a complete and independent DCS for the monitoring of the muon end-cap alignment system. Both developments are integrated into the ATLAS DCS and are used on the regular operation of the ATLAS detector. A detailed description of the above developments along with a brief presentation of the structure and functionality of the ATLAS DCS is given in Chap. 2. The initial idea of the current calibration tool, that uses the luminosity data, has been expanded towards developing a technique that can calculate the ATLAS luminosity using the MDT high voltage current data. The description of the method along with the accuracy that can be achieved with this method are the subject of the Appendix A.
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Chapter 1

The Large Hadron Collider and the ATLAS Experiment

1.1 The Large Hadron Collider

The Large Hadron Collider (LHC) [1] is the world’s largest and most powerful particle accelerator. It is a two-ring superconducting hadron accelerator and collider located in an underground tunnel at the European Organization for Nuclear Research (CERN), on the Franco-Swiss border near Geneva, Switzerland. The LHC is installed in the 26.7 km tunnel that was constructed between 1984 and 1989 for the purposes of the CERN LEP machine [2] which was in operation until the end of 2000. The first beam of the LHC was delivered in September 2008 and the first collisions were produced about a year later. The aim of the LHC is to reveal the physics beyond the Standard Model with center-of-mass proton-proton collision energies of up to 14 TeV.

1.1.1 Accelerator Complex and Experiments

An injector chain supplies the LHC with pre-accelerated protons. Initially, a simple bottle of hydrogen gas feeds the source chamber of a linear accelerator with hydrogen atoms. With the application of an electric field the hydrogen nuclei are stripped off their electrons and the protons proceed to the next stage of their acceleration route. The initial acceleration is performed by the LINear ACcelerator 2 (LINAC 2), which accelerates the protons at an energy of 50 MeV. The beam is then injected into the Proton Synchrotron Booster (PSB), where the proton energy is increased to 1.4 GeV, before they go through the Proton Synchrotron (PS) reaching the energy of 25 GeV. The last step before the LHC is the Super Proton Synchrotron (SPS), where the protons reach the energy of 450 GeV and the LHC then accelerates the particles at the design energy of 7 TeV. The accelerators of this chain were initially designed for their use in the LEP machine. They were later upgraded to meet the very stringent needs of the LHC [3] that require high intensity proton bunches with small transverse and well defined longitudinal emittances. The injector chain upgrade project [4] involved an increase of Linac 2 current, new RF systems in the PS Booster and the PS, raising the PS Booster energy from 1 to 1.4 GeV, two-batch filling scheme of the PS, and the installation of high-resolution beam profile measurement devices. A graphical representation of the complete injector-accelerator complex is shown in Fig. 1.1.

The LHC during Run-1 was mainly operated with a bunch splitting of 50 ns, with this spacing
resulting in \( \sim 1404 \) bunches\(^1\) per beam. The instantaneous LHC luminosity of proton-proton \((p - p)\) collisions \( \mathcal{L} \) is proportional to the rate \( R \) of the \( p - p \) process \( \mathcal{L} = R/\sigma \), where \( \sigma \) is the \( p - p \) cross section. The absolute luminosity depends only on the beam parameters and can be written in the form of Eq. (1.1) \([5]\) where \( f_r \) is the LHC revolution frequency, \( n_b \) the number of bunches colliding at the interaction point (IP), \( n_1 \) and \( n_2 \) are the number of particles in the two colliding bunches and \( \Sigma_x \) and \( \Sigma_y \) are the horizontal and vertical beam profiles respectively, assuming similar characteristics for both beams.

\[
\mathcal{L} = \frac{n_b f_r n_1 n_2}{2\pi \Sigma_x \Sigma_y} \tag{1.1}
\]

The luminosity in the LHC does not remain constant during a physics run, but decays due to the degradation of intensities and emittances of the circulating beams. The main cause of the luminosity decay during nominal LHC operation is the beam loss from collisions. Other contributions to beam losses come from Toucheck scattering \([6]\) and from particle losses due to a slow emittance blow-up. If these effects are taken into account a luminosity lifetime of \( \tau_{L} = 14.9 \) h can be estimated.

---

\(^1\) Each bunch contains \( \sim 1.5 \times 10^{11} \) protons at the start of a nominal fill.

---

**Figure 1.1:** A drawing of the LHC accelerator complex. The injector of chain along with the pre-accelerator rings that supply the 27 km ring with beam particles is shown. The beams collide at the 4 experimental insertion regions corresponding to the underground caverns of the experiments (ATLAS, CMS, ALICE, LHCb).

The LHC hosts two high luminosity experiments, ATLAS \([7]\) and CMS \([8]\), both aiming at a
peak luminosity of \( \mathcal{L} = 10^{34} \text{ cm}^{-2}\text{s}^{-1} \) for proton \((p - p)\) operation. There are also two experiments aiming at lower luminosity: LHCb [9] is dedicated to B-physics with a luminosity of \( \mathcal{L} = 10^{32} \text{ cm}^{-2}\text{s}^{-1} \), and TOTEM [10] for the detection of protons from elastic scattering at small angles at \( \mathcal{L} = 2 \times 10^{29} \text{ cm}^{-2}\text{s}^{-1} \). In addition to the proton beams, the LHC is also operated with ion beams, \((Pb - Pb)\) or \(p - Pb\) collisions, with one dedicated ion experiment, ALICE [11], \( \mathcal{L} = 2 \times 10^{27} \text{ cm}^{-2}\text{s}^{-1} \).

To deliver a luminosity of \( \mathcal{L} = 10^{34} \text{ cm}^{-2}\text{s}^{-1} \) to the experiments a very high beam intensity is required. This accounted for the choice of a particle-particle collider design for the LHC. In order to collide two counter-rotating proton/ion beams it is necessary to apply opposite magnetic dipole fields in the two rings. The LHC is therefore designed as a proton-proton collider with separate magnetic fields and vacuum chambers in the main arcs and with common sections only at the insertion regions where the experimental detectors are located. More than a thousand superconducting dipole, quadrupole, sextupole, octupole and decapole magnets bend and tighten the beams around the 27 km circumference of the LHC. At the nominal energy of 7 TeV per beam a magnetic field of around 8.4 T at a current of around 11.7 kA is required with the magnets having two apertures, one for each of the counter-rotating beams. This extremely high field can only be achieved with magnets made of superconducting Niobium-Titanium (NbTi) material and cooled at 1.9 K with super-fluid He. The cryogenic equipment needed to produce the 100 tons of superfluid helium is unprecedented in scale and complexity for the whole LHC ring. A photo of the LHC in the LEP tunnel along with a drawing of a the beam pipe cross-section are illustrated in Fig. 1.2.

![Figure 1.2: Left: The LHC installed inside the LEP tunnel. An open magnet interconnection can be seen. Right: Graphical representation of an LHC dipole magnet cross section.](image)

1.1.2 Towards the High Luminosity LHC

During Run-1 (2010-2012), the LHC was able to deliver a total of 28.26 fb\(^{-1}\) of \(p - p\) collision data leading to a major physics program and remarkable physics results from the experiments [12, 13]. The very successful first LHC run came to an end on December 2012 and was followed by the era of the Long Shutdown 1 (LS1). During the two-year shutdown period the accelerator complex, as well as the experiments, underwent a series of upgrade and maintenance activities.
in order to cope with the LHC schedule. During Run-2, that was initiated in early 2015, the LHC is expected to operate with almost double the center-of-mass energy (13 TeV) and a smaller bunch crossing (BC) of 25 ns that will lead to an increased luminosity of $\mathcal{L} \approx 10^{34} \text{cm}^{-2}\text{s}^{-1}$.

The current LHC schedule, shown in Fig. 1.3, foresees two additional long shutdown periods LS2 (2019) and LS3 (2024). The upgraded injector chain and LHC after LS2, will lead to a further increase in the luminosity that will go slightly beyond $\mathcal{L} = 2 \times 10^{34} \text{cm}^{-2}\text{s}^{-1}$. The transition from the LHC to the High Luminosity (HL) LHC will take place during LS3, with more than 3,000 fb$^{-1}$ of data expected to be delivered during Run-3. The harsh HL-LHC environment will be extremely challenging for the experiments with expected maximum peak luminosities of the order of $\mathcal{L} = 7 \times 10^{34} \text{cm}^{-2}\text{s}^{-1}$ for the ATLAS and the CMS experiments. In order to cope with the expected high particle rates, a series of upgrades has been planned for the LHC experiments that will allow them to retain their smooth and efficient operation also during the HL-LHC.

![Figure 1.3: The LHC baseline schedule as of 21.07.2015 [14].](image)

1.2 The ATLAS Experiment

The ATLAS, an abbreviation for A Toroidal LHC ApparatuS, experiment is one of the two general purpose detectors (along with CMS) that have been built for probing $p - p$ and $Pb - Pb$ or $p - Pb$ collisions in the LHC. The cylindrical structure of the ATLAS detector is 44 m long with a diameter of 25 m and it follows the slope of the LHC machine which is inclined by 1.23% with respect to the absolute horizontal plane and it is symmetric with respect to the IP.

The nominal IP defines the origin of the ATLAS coordinate system while the beam direction defines the z-axis and the transverse to it x-y plane. The positive x-axis is defined as pointing from the IP to the centre of the LHC ring and the perpendicular to it positive y-axis is defined as pointing upwards. The side-A of the detector is defined as that with positive z values while side-C is in the negative z region. The azimuthal angle $\phi$ is measured around the z-axis and the polar angle $\theta$ is the angle from the beam axis measured around the x-axis. The pseudorapidity is defined as $\eta = -\ln \tan (\theta/2)$. The transverse momentum $p_T$ of a particle is defined in the x-y plane unless stated otherwise. Using the notations of the ATLAS coordinate system, the distance $\Delta R$ in the pseudorapidity-azimuthal angle space is defined as $\Delta R = \sqrt{\Delta \eta^2 + \Delta \phi^2}$.

A graphical representation of the ATLAS experiment is shown in Fig. 1.4. The different parts of the detector are visible in the same figure with design of the detector mainly driven by the need to satisfy a set of general requirements for the LHC detectors:
1.2 The ATLAS Experiment

- Fine detector granularity complemented with fast, radiation-hard electronics and sensor elements to handle the particle fluxes and to reduce the influence of overlapping events.
- Large acceptance in pseudorapidity with almost full azimuthal angle coverage.
- Good charged-particle momentum resolution and reconstruction efficiency in the inner tracker.
- Very good electromagnetic (EM) calorimetry for electron/photon identification and measurements, complemented by full-coverage hadronic calorimetry.
- Good muon identification and momentum resolution over a wide range of momenta.
- Highly efficient triggering on low $p_T$ objects with sufficient background rejection to reduce the trigger rate to acceptable levels.

![Figure 1.4: A graphical representation of the ATLAS detector. The different parts of the detector are noted.](image)

### 1.2.1 Magnet System

In order to measure the momenta of the charged particles produced during the collisions a proper magnetic field distribution is required along the different detection layers of the ATLAS experiment. The ATLAS magnet system consists of superconducting magnets arranged in optimized positions around the IP that can be split in three main parts:

- A Central Solenoid [15] which is responsible for the magnetic field of the inner tracker.
- The air-core Barrel Toroid [16].
- Two air-cored End-cap Toroids [17] providing the necessary toroidal field configuration to the muon spectrometer.

The overall dimensions of the magnet system are determined by the Barrel Toroid structure that extends over a length of 26 m and an outer diameter of 20 m. The superconducting ATLAS magnet system is cooled by liquid helium at 4.8 K. In terms of power, the toroids are electrically connected in series and likewise operated at a current of 20 kA while the central solenoid operates at a lower nominal current of 7.6 kA. Photographs of the three different parts of the ATLAS magnet system are shown in Fig. 1.5.

![Figure 1.5: Photos of the different parts of the ATLAS magnet system during their assembly and installation in the ATLAS cavern. Left: In the top picture, the cylindrical solenoid magnet is being inserted into the liquid argon calorimeter on surface. A view of the eight barrel toroid coils installed in the ATLAS cavern is presented in the bottom picture. Right: One of the two end-cap toroid magnets in its final place surrounded by the barrel toroid coils.](image)

The solenoid provides a central field of ~ 2 T with a maximum field peak of 2.6 T on the windings superconductors. The magnetic field peaks on the toroidal superconductors are 3.9 T and 4.1 T for the barrel and the end-caps respectively. A graphical representation of the three components of the ATLAS magnet system can be seen in Fig. 1.6 (left). The resultant field intensity, summing up the different contributions, is not uniform along the detector volume. An example map of the field intensity as a function of the radial distance from the axis and along the z direction for a specific cross-section in $\phi$ ($\phi = \pi/8$) is presented in Fig. 1.6 (right). The maximum field intensity (~ 3 T) is observed in the area of the superconducting material of the magnet system that corresponds to the central solenoid and barrel/end-cap toroids.
1.2 The ATLAS Experiment

1.2.1 Magnet System

The central solenoid installed in the liquid argon calorimeter cavity (blue colour) encircled by the barrel (red colour) and the end-cap (green colour) toroid coils. Right: A magnetic field intensity map along different radial and $z$ positions at the cross-section $\phi = \pi/8$. The field intensity varies, depending on the region, from 0T to $\leq 1$T peaking in the region of the superconducting coils.

1.2.2 Inner Detector

The ATLAS Inner Detector [18] (ID) is composed of three different detector technologies namely the silicon Pixel detector (Pixel), the Semi-Conductor Tracker (SCT) and the Transition Radiation Tracker (TRT). The ID comprises high-resolution detectors at the inner radii with continuous tracking elements at outer radii, all encircled by the central solenoidal magnet. All the detectors provide precise measurement of charged particle trajectories in a multiple-track environment. The highest granularity is achieved around the vertex region using Pixel detectors followed by layers of the SCT microstrip detector. The Pixel system is mainly in charge of the accurate measurement of vertices whereas the SCT primary functionality is the precise measurement of the particle momenta with the two technologies providing at least three and four particle track reference points respectively. The TRT enhances the ID pattern recognition performance owing to the large number of precise tracking points (~36 per track) and contributes to the electron identification of the experiment via the detection of transition radiation photons in the straw tubes. The different parts of the ATLAS ID are presented in Fig. 1.7.

Hits recorded in the individual ID elements are combined to reconstruct the charged particle trajectories inside the tracker and ultimately to measure their kinematic parameters. The accuracy of the reconstruction is limited by a combination of uncertainty contributions including the finite resolutions of the detector elements, the knowledge of the magnetic field, the relative locations of the detector elements and finally the amount of material in the detector [19]. The intrinsic resolution of each Pixel detector element, with a size of $50 \times 400 \mu m^2$, can be as good as $10 \mu m$ in the measurement of the precision coordinate ($115 \mu m$ for the perpendicular to the precision one). The slightly coarser ($80 \mu m$) SCT elements limit the SCT hit reconstruction un-
certainty to 17 μm while the 4 mm diameter TRT straws provide a hit position measurement with a resolution of 130 μm. Misalignments or geometrical distortions of the active detector elements deteriorate the resolution of the reconstructed track and may lead to systematic biases on the reconstructed track parameters, thus several track-based alignment algorithms are employed to optimise the performance of the ID reconstruction [20].

Figure 1.7: A graphical representation of the different parts composing the ID of the ATLAS experiment. The relative distances between the various elements are also noted.

1.2.3 Calorimeters

The calorimeters of the ATLAS experiment are responsible for the accurate measurement of the energy and position/direction of electrons and photons or jets, evaluating also the missing $p_T$ of each event. Moreover, they are capable of particle identification and contribute in the muon momentum reconstruction [21]. Due to the large centre-of-mass energy provided by the LHC the calorimeters used in the experiments should be able to satisfy demanding performance requirements over an unprecedented energy range (extending from a few GeV up to the TeV scale). Moreover, at the LHC design luminosity ($10^{34}$ cm$^{-2}$s$^{-1}$), multiple collisions will be produced in every single BC (every 25 ns), giving rise to the so-called “pile-up” both in space and time. In order to cope with this situation, without sacrificing the physics performance, the calorimeters should be characterised by a fast detector response (better than 50 ns) and extra-fine granularity. The radiation tolerance is also a prerequisite, given the high particle fluxes expected over a period of operation of several years.

A graphical representation of the ATLAS calorimeters is presented in Fig. 1.8 where the different parts of the calorimeter ensemble are visible. The electromagnetic (EM) calorimeter covers the pseudorapidity region of $|\eta| < 3.2$. It is a liquid Argon (LAr) detector [22] with accordion-shaped Kapton electrodes and lead absorber plates over its full coverage divided into a barrel part and two end-caps. LAr is supplemented by a hadronic calorimeter realised with the iron scintillating tiles technique (Tile) [23], covering the barrel region $|\eta| < 1.7$ and the end-cap region $1.5 < |\eta| < 3.2$. Two additional forward LAr calorimeters in the range of $3.1 < |\eta| < 4.9$ complete the ATLAS calorimeter system.

---

2Pile-ups occur when the detector is not able to distinguish between two separate collision events, either in space or in time and thus considers them part of the same collision.
1.3 The ATLAS Muon Spectrometer

The ATLAS Muon Spectrometer \([24]\) defines the overall dimensions of the ATLAS detector. It is located on the outside of the calorimeter modules and covers the space between approximately 4.5 m and 11 m in radius and 7 m and 23 m longitudinally on both sides of the IP. Its principle of operation is based on the magnetic deflection of muon tracks by a system of three large superconducting air-core toroid magnets providing high resolution muon momentum measurement.

1.3.1 Detector Technologies & Layout

Destined to measure high-momentum final-state muons, the most promising signatures of physics at the Large Hadron Collider (LHC), the ATLAS Muon Spectrometer is instrumented with separate-function trigger and high-precision tracking chambers that belong to four different detector technologies:
• Cathode Strip Chambers (CSC)
• Monitored Drift Tubes (MDT)
• Resistive Plate Chambers (RPC)
• Thin Gap Chambers (TGC)

The different parts of the muon spectrometer are shown in Fig. 1.9. The CSC and MDT chambers are responsible for the precision tracking of the spectrometer. The MDTs span over the 99.5% of the total area covered by the precision detectors while the CSCs cover a small area in the most forward region where the maximum particle fluxes are observed. The precision chambers measure the track coordinates in the bending plane\(^3\) with high accuracy. For the MDTs no information on the non-bending coordinate and on the BC time is available in contrast to the CSCs which are able to provide additional measurements for these two quantities.

The trigger functionality is carried out by the RPCs in the barrel region and TGCs in the end-caps. These are fast detectors and contribute to the level-1 triggering and BC identification owing to their timing resolution of a few nanoseconds. Apart from the triggering, these detectors can also be used in pattern recognition reconstruction algorithm, characterized by a modest spatial resolution in the range 5 – 20 mm and they are also able to provide a measurement of the track along the second coordinate.

Figure 1.9: A graphical representation of the ATLAS Muon system. The different detector technologies of muon chambers along with the muon magnet system are noted.

The layout of the muon spectrometer is the result of an optimization process which takes into account different requirements driven mainly by the quest for the best detector performance:

\(^3\)The bending plane is parallel to the beam axis (\(z\)) and is called the \(\eta\) view (or precision coordinate). The plane perpendicular to the beam axis is the non-bending plane and is called the \(\phi\) view (or second coordinate).
1.3 The ATLAS Muon Spectrometer

- Efficient use of the bending power of the magnets for precision measurement and triggering.
- Coverage up to pseudorapidity $|\eta| < 2.7$ over the full azimuth.
- Use of a projective tower geometry for chamber alignment purposes [25].

The arrangement of the muon chambers is such that particles originating from the IP traverse three precision and three trigger detection layers. In the azimuthal direction a 16-fold segmentation is used following the geometry of the magnet system. The chambers are arranged in small and large sectors with the small ones matching the azimuthal positions of the barrel toroid coils and the large sectors covering the region in between them. Figure 1.10 shows a schematic representation of different cross-sections of the ATLAS muon spectrometer. The different layers of the four detector technologies composing the muon system are visible.

![Figure 1.10: Left: Schematic view of the muon spectrometer in the x-y projection of the barrel region. Inner, Middle and Outer chamber stations are denoted BI, BM, BO in the barrel (EI, EM, EO accordingly for the end-cap). Right: A cross section in z-y of one quarter of the ATLAS detector for $\phi = \pi/2$ matching the position of large muon sectors. The different types of muon chambers are shown with the different colours. End-cap MDT (blue), CSC (yellow), barrel MDT (green), RPC (white) and TGC (magenta). The regions corresponding to the Small Wheel and Big Wheel are also marked with different colours.](image)

Cathode Strip Chambers

The CSC are located in the two innermost end caps, the so called "Small Wheels (SW)", covering the largest rapidity region $2 \leq |\eta| \leq 2.7$ (~7 m from the IP) that is characterized by the highest particle flux among the muon spectrometer stations. They are arranged in two types of chambers, small and large, with each chamber combining four detection planes. The azimuthal segmentation of the CSC system follows the magnet system geometry with 16 sectors per wheel. The individual CSC chambers are tilted by $11.59^\circ$ with respect to the MDT/TGC x-y layer such that their planes are on average orthogonal to particles coming from the IP. They are operated with a gas mixture of Ar+20% CO$_2$ while the voltage is tuned individually per chamber layer (~1800 – 1900 V) in order to achieve uniform gain throughout the whole CSC system.
Figure 1.11 shows the internal structure of a CSC chamber. They are Multi-Wire Proportional Chambers with the wires serving as the detector anodes. The CSC host two cathode layers of readout strips measuring the precision and the perpendicular to it (second) coordinates. The precision coordinate is obtained by a charge interpolation on the segmented cathode, with strips running perpendicularly with respect to the anodes ($\sigma \approx 60 \mu m$ for perpendicular tracks). A second layer of readout strips, running parallelly to the wires, provide the second coordinate measurement. Apart from the precise tracking the CSC, due to the small gap, collect all the ionization electrons in less than $30 \text{ ns}$. This allows for efficient operation in the high background of the forward region of the muon spectrometer accounting for single layer timing resolution of $\sim 7 \text{ ns}$.

![Figure 1.11: Left: Graphical representation of a CSC chamber with four detection planes. The first layer is partly cut-out to reveal its internal structure including strips, wires and construction components. Right: Photograph of one of the CSC chambers of the ATLAS experiment (A side, sector 9) during the repair of a broken wire in March 2014. The third layer unsealed inside a clean room is visible.](image)

**Monitored Drift Tubes**

The MDT cover almost the full rapidity region of the ATLAS Muon Spectrometer $|\eta| < 2.7$ apart from the high rapidity region of the SW where CSC are used. The basic structure of an MDT chamber can be seen in Fig. 1.12 (left). It consists of two multi-layers of drift tubes separated by a support frame. Each multi-layer combines three layers of tubes with the exception of the inner stations of the muon spectrometer (small radius) where one additional layer of tubes is used in each multi-layer enhancing the pattern recognition performance in the high background rates of this region (Fig. 1.17). The shape and size of each chamber varies with its location (barrel, end-cap, inner, middle, outer, small, large etc.). A photo of an MDT chamber during the assembly and quality control procedure is shown in Fig.1.12 (right).

The elementary detection element of the ATLAS MDT chambers is a cylindrical aluminum drift tube, 30 mm in diameter, which serves as the cathode encompassing a W-Re central cathode wire of $50 \mu m$ diameter kept at a nominal potential of $3080 \text{ V}$. The tubes are flushed with a non-flammable gas mixture $\text{Ar} + 7\% \text{ CO}_2$ with a small amount of water vapor at a pressure of 3 bar. The above operating parameters ensure the optimum performance of the individual tube.
1.3 The ATLAS Muon Spectrometer

in the ATLAS environment fulfilling the following objectives:

- Relatively small drift time ($\leq 500$ ns) resulting in small occupation time.
- Lorentz angle because of the ATLAS magnet system $\theta_{\text{Lorentz}} \leq 20^\circ$.
- Gas gain of the order of $2 \times 10^4$ to delay the aging effect on the tubes.

Figure 1.12: Left: Schematic drawing of an MDT chamber of the barrel region consisting of two multi-layers with the three layers of tubes each. The internal spacer frame components are also shown consisting of the structural components (cross-plates and long-beams) and alignment parts. Right: Photograph of one MDT chamber during the construction procedure. One multi-layer combining three layers of tubes is visible.

The single tube spatial resolution after the calibration procedure and the correction for the effect of the magnetic field can be as good as 80 $\mu$m. By combining the drift time measurements of the ionization electrons in each drift tube, a single MDT chamber six-point segment can be reconstructed with high precision ($\sim 40 \mu$m).

Resistive Plate Chambers

In the muon barrel region ($|\eta| \leq 1.05$) the RPC system is responsible for providing the trigger signals. The RPC chamber is a gaseous parallel-plate detector able to provide a timing measurement with an accuracy of the order of 1 ns fulfilling the requirements of the ATLAS trigger system. Figure 1.13 (left) shows a drawing of the parallel plate structure an RPC chamber. They are operated with a multi-component gas mixture of $C_2H_2F_4 : 4.5\%i – C_4H_{10} : 0.3\%SF_6$. Moreover, being a fast detector technology the RPC are also characterized by BC identification capability. Additionally, their fast and coarse tracking can be used for identifying the hits of the precision chambers that are related to the detected muon track.

The RPC system layout, optimum for the barrel trigger performance, consists of three stations with each one comprising two detection layers. The two middle stations, installed with a lever arm of 50 cm in between are located near the centre of the magnetic field region and provide the low-$p_T$ muon trigger while the third station, at the outer radius of the magnet, allows for a more relaxed $p_T$ threshold, thus providing the high-$p_T$ muon trigger.
Thin Gap Chambers

The trigger information in the muon end-cap region is provided by the TGC. They are also able to provide a measurement of the azimuthal coordinate to complement the bending coordinate measured by the end-cap MDT chambers. The middle end-cap station of the MDT is complemented by seven layers of TGC, which provide both triggering and azimuthal coordinate measurement while the two layers of TGC in the inner muon end-cap (SW) measure the azimuthal coordinate.

The TGC are similar to the Multi-Wire Proportional Chambers with anode wires enclosed by two graphite cathode layers and two layers of readout strips running perpendicularly to the wires. A graphical representation of a TGC chamber cross-section is shown in Fig. 1.13 (right). They are operated with a highly quenching gas mixture of CO$_2 + 45\%$ n-C$_5$H$_{12}$ and a very intense electric field (3200 V) to satisfy the time, momentum, and azimuthal coordinate requirements while making the performance of large surface chambers insensitive to mechanical deformations. The very good timing resolution guarantees the BC identification capability of the TGC.

![Graphical representation of a TGC chamber cross-section.](image)

Figure 1.13: Left: Cross-section of an RPC chamber. Right: Schematic drawing of the TGC internal structure.

1.3.2 Alignment

In order to fully exploit the excellent spatial resolution of the muon precise trackers the relative position of each chamber with respect to the others should be known with an uncertainty smaller than the single hit position uncertainty. For this purpose a continuously running alignment monitoring system, based on optical/temperature sensors and on alignment bars, is used. The measured (slow) chamber displacements (hours scale) are then propagated to the offline track reconstruction allowing for the software correction of the misalignment between the precision chambers. Two independent systems are used for the alignment of the barrel and end-cap muon chambers respectively following approximately similar strategies. Here the muon end-cap alignment system structure and functionality are briefly described as input to section 2.4 where the Detector Control System developed for its monitoring is presented.

The alignment system measurements can be divided into two main categories, namely internal alignment and global alignment measurements. Individual chambers have internal alignment
1.3 The ATLAS Muon Spectrometer

The ATLAS Muon Spectrometer sensors that monitor individual distortions within a single chamber. On top of that there is a global alignment system that monitors the relative position difference between the chambers. Combining the two measurements the sensors are used to directly determine the locations of the muon chambers in space with respect to each other through an absolute alignment system approach. The layout of the muon end-cap alignment system is illustrated in Fig. 1.14 (left) while the internal alignment system of an MDT chamber is shown on the right of the same figure.

Figure 1.14: Left: The layout of the end-cap alignment (for the end-caps of one ATLAS side). The precision chambers are not visible and the numerous coloured lines represent the end-cap alignment sensor lines: polar BCAMs (green), azimuthal BCAMs (blue), RASNIK proximity sensors (orange), in-plane RASNIKs (red), chamber temperature sensors (yellow). Right: Schematic representation of the in-plane RASNIK layout for an MDT chamber installed in the internal spacer frame. It consists of two CCDs and two masks in the edges of the chamber and a setup of four lenses attached to the central cross-plate.

The basic principle of operation is common for all the different types of sensors. A source light, either a RASNIK (Red Alignment System of NIKHEF [26]) mask or a pair of BCAM (Brandeis CCD Angular Monitor [27]) laser diodes acting as point-like sources, is imaged through a system of lenses onto a Charge-Coupled Device (CCD) acting as a screen. When a camera views a light source, it observes the image of that source on its own CCD allowing the determination of the source position with a precision given by the uncertainty of the calibration constants of the camera. In the case of more than one sources the camera performs a measurement of the relative position between the sources. In addition to optical measurements, it is also vital to determine the thermal expansion of the monitored objects. The muon end-cap alignment devices are controlled, read out and analyzed via the Long Wire Data Acquisition (LWDAQ) system [28]. Then, a framework of processes reads the LWDAQ output and propagates it to the Detector Control System for monitoring sending also the sensor measurements to an Oracle database. The stored data are then read by the ARAMyS software [29] which reconstructs the alignment parameters of the full system and archives them in an additional Oracle database.
From there the alignment constants are read into the ATLAS detector model, which provides corrections to the nominal chamber locations and shapes in the track reconstruction packages.

1.4 The ATLAS New Small Wheel Upgrade Project

The LHC will be upgraded in several phases extending the reach of its physics program as discussed in Sec. 1.1.2. Already, after the end of the first long shutdown (LS1) during 2013-2014 the accelerator’s energy was increased at the design value of $7 \text{ TeV}$ per beam translating in a luminosity of the order of $L = 10^{34} \text{ cm}^{-2} \text{s}^{-1}$. With the intermediate upgrades that will follow in the next years the ATLAS foresees a luminosity increase by a (safe) factor 7 with respect to the design value. In order to maintain its current excellent performance and to cope with the corresponding increase in the particle rate that is expected, the ATLAS detector will be upgraded. The ATLAS upgrade will proceed in two steps: Phase-1 [30] in the LHC shutdown 2018/19 and Phase-2 [31] in 2023-25.

1.4.1 Motivation for the Small Wheel Upgrade

The largest of the ATLAS Phase-1 upgrades focuses on the inner end-cap region of the muon spectrometer, the so-called Small Wheel (SW) that is composed of CSC, MDT & TGC detectors. Figure 1.10 (right) shows a cross section of one quarter of the ATLAS detector in z-y plane. The area of interest, marked with a blue square, is located in the region $6 - 8 \text{ m}$ in $z$ and $1 - 5 \text{ m}$ in $y$. Photos of the current SW during the assembly and installation phases are shown in Fig. 1.15 and the three different detector technologies are visible. At the high luminosity foreseen after LS2 the following two points are of particular importance for the ATLAS muon system:

- The performance of the muon tracking chambers (MDT & CSC), efficiency and spatial resolution, significantly degrades with the expected increase of cavern background rate.

- The Level-1 muon trigger in the end-cap region, a significant part of which is background, is eight to nine times higher than that in the barrel region.

Figure 1.15: Left: The current muon SW during its assembly phase on surface. The three different detector technologies composing the inner muon end-cap are visible. Right: A photo taken during the lowering procedure of a SW fully assembled in the ATLAS cavern.
Both issues represent serious limitations on the ATLAS performance beyond the design luminosity as they will result in reduced acceptance of good muon tracking and in an unacceptable rate of high $p_T$ Level-1 muon triggers coming from the forward direction.

**End-cap Muon Trigger**

End-cap-Muon (EM) triggers are dominated by fake hits (> 90%) due to the background. Low energy particles, generated in the material located between the SW and the EM station, hit the EM at an angle similar to that of real high $p_T$ muons. This effect is illustrated in Fig. 1.16 where the $\eta$ distribution of ATLAS Level-1 muon trigger candidates is shown with the dashed histogram. The distribution of the trigger candidates that match offline reconstructed muon tracks is also shown before and after a selection cut of $p_T > 10 \text{ GeV}$. It is evident that more than 90% of the muon triggers are coming from the end-caps (for rapidities $|\eta| > 1.0$) with the vast majority of the end-cap muon candidates being non-reconstructable offline. Moreover, the preservation of low $p_T$ muon trigger threshold is considered essential for maximizing the physics acceptance [32].

![Figure 1.16: Number of Level-1 muon candidates as a function of the pseudorapidity $\eta$.](image)

**Tracking Performance & Efficiency**

In the SW region the luminosity increase will lead to a particle rate of up to 15 kHz/cm$^2$. The present SW detectors (MDT, CSC & TGC) will not be able to handle the increased rate efficiently. This can be seen for example in the dependence of the single MDT tube efficiency from the hit
rate illustrated in the left part of Fig. 1.17. The efficiency shows a rapidly decreasing trend anti-correlated with the increase of the hit rate, reaching already the levels of 70% for the hit rate value expected at the design luminosity of LHC (∼300 kHz/Tube). In the right plot of Fig. 1.17 the expected rate in the precision chambers of the current SW, for $\mathcal{L} = 3 \times 10^{34}$ cm$^{-2}$s$^{-1}$, is plotted as a function of the radial distance from the IP. The two curves represent the measured hit rates per radial distance unit, in the MDT ($r > 210$ cm) and the CSC ($r < 200$ cm) region respectively, extrapolated to the values expected at a luminosity of $3 \times 10^{34}$ cm$^{-2}$s$^{-1}$. Given the linear dependence of the hit rate with the luminosity, at the maximum Phase-2 luminosity of $7 \times 10^{34}$ cm$^{-2}$s$^{-1}$ (but already after Phase-1) a big fraction of the current Small Wheel MDT system will suffer from substantial single hit and segment inefficiency.

![Figure 1.17](image.png)

**Figure 1.17:** Left: MDT tube hit (solid line) and track segment efficiency (dashed line, referring to a MDT chamber with 2×4 tube layers) as a function of tube rate estimated with test-beam data at the design luminosity of $10^{34}$ cm$^{-2}$s$^{-1}$. The points on the plots are test beam measurements. Right: Extrapolated hit rate in the CSC and MDT regions for $\mathcal{L} = 3 \times 10^{34}$ cm$^{-2}$s$^{-1}$ as a function of the radial distance from the beam line. The tube hit rates (200 – 300 kHz) are also indicated. The plots are taken from [32].

### 1.4.2 Performance Requirements

For the reasons mentioned above, the ATLAS collaboration has decided to replace the current SW with New Small Wheels (NSW) during the LS2 shutdown. The NSW system will combine two detector technologies, small-strip Thin Gap Chambers (sTGC) and Micromegas (MM) detectors. The general coarse requirement for a detector that replaces the current one is that it should at least maintain the current performance at low luminosity in the high luminosity environment that is foreseen. It should, therefore, be able to measure the transverse momentum ($p_T$) of 1 TeV muons with a precision of 10% in the full $\eta$ coverage of the Small Wheel (up to $|\eta| = 2.7$). Moreover, in order to maintain the muon Level-1 trigger rate at sustainable levels, the NSW should be able to provide trigger information, suppressing the muon end-cap fake triggers. Along these lines the NSW should be able to meet the criteria summarized below.
### Triggering (Online)

- Online reconstruction of track segments for triggering with an angular resolution better than 1 mrad at high efficiency ($\geq 95\%$) in the full rapidity region ($1.3 \leq |\eta| \leq 2.5$). As illustrated in Fig. 1.18, by including the NSW trigger primitives in the Level-1 muon trigger the fake EM triggers will be suppressed and the expected rate will be reduced below 20 kHz.

- The online NSW segment reconstruction should be executed within a maximum latency of 1 $\mu$sec.

![Figure 1.18](image.png)

**Figure 1.18:** Left: After the enhancement of the EM trigger with the NSW primitives (currently based only on the BW) only the real muon track A, which is confirmed by both the BW and the NSW, will be accepted suppressing the fake triggers B, C. Right: Estimation of ATLAS muon level-1 trigger rate extrapolated for pp collisions at $\sqrt{s} = 14$ TeV with instantaneous luminosity of $L = 3 \times 10^{34}$ cm$^{-2}$s$^{-1}$ is shown as a function of $p_T$ threshold for three different EM trigger configurations. The trigger rate expectations, assuming the current trigger configuration, are shown with the black curve, while the blue curve illustrates the reduced trigger rate expected with an updated trigger scheme combining information from E14-TGC chambers with Tile Calorimeter in the region $1 \leq |\eta| \leq 1.3$. The red curve represents the expected trigger rate after including also the NSW in the EM trigger illustrating a significant reduction reaching a rate of $\sim 15$ kHz for a $p_T$ threshold of 20 GeV. The plot is taken from [33].

### Tracking (Offline)

- Offline reconstruction of track segments with a position resolution in the precision coordinate better than 50 $\mu$m ($\leq 100\mu$m resolution per plane for a 4-layer detector) accompanied by a segment finding efficiency better than 97% for muons with $p_T$ greater than 10 GeV.

- Measurement of the second coordinate, perpendicular to the precision one, with a coarse resolution of $\sim 2 - 3$ mm to facilitate good linking between the MS and the ID track for the combined muon reconstruction [34].
Moreover, following the philosophy of the current muon system, the NSW should be composed of multiple detection planes to enhance the pattern recognition performance of the track reconstruction rejecting the multiple background hits that are expected in the SW environment. A redundant number of detection planes will also ensure the efficient operation of the detector tolerating any possible single plane failures.

1.4.3 Detector Technologies

Small-strip Thin Gap Chambers

The sTGC will be the primary trigger detector featuring BC identification capability and angular resolution for online reconstructed segments better than 1 mrad [32]. Figure 1.19 (right) shows the distributions of the measured drift times in an sTGC with 95% of the experimental and simulated data being inside the 25 ns time window (equivalent to the beam BC frequency). The detector is also characterized by good spatial resolution for the offline tracking using the precision coordinate (readout strips) owing to the smaller, compared to the current TGC, strip pitch (3.2 mm). It is based on the proven TGC technology with additional cathode pads that for muon track identification and readout region definition [35].

The internal sTGC structure consists of a grid of 50 µm gold-plated tungsten wires placed every 1.8 mm enclosed between two cathode planes that are kept at a distance of 1.4 mm from the wire plane. The cathode planes are made of a graphite-epoxy mixture with a typical surface resistivity of 100 kΩ/□ sprayed on a 100 µm thick G-10 plane. Behind the resistive protection layer there are on one side copper strips (oriented perpendicularly to the wires) and on the other side copper pads (covering large rectangular surfaces) acting as readout electrodes. A cross-section of the sTGC is graphically represented in Fig. 1.19 (left).

Figure 1.19: Left: Graphical representation of the sTGC internal structure. The signal due to the drifting of the ionization charges and their multiplication is induced on the anode wires, readout pads and strips sitting behind the cathode planes. Right: Due to the thin gap and the very intense electric field applied ~ 95% of the measured drift times are confined within a 25 ns time window proving the BC identification capability of the sTGC detector.

\[ ^4 \text{The cathode plane specifications mentioned correspond to the inner chambers while the outer layers will have } 200 \text{kΩ/□ surface resistivity and } 200 \mu \text{m G-10 thickness.} \]
1.4 The ATLAS New Small Wheel Upgrade Project

Micromegas

The resistive-strip MM detector will be the primary precision tracker characterised by excellent spatial resolution ($\sigma \leq 100 \mu m$) independently of the track incident angle [36] and good track separation due to the fine readout granularity (strips). Moreover, with the MM being sensitive to a single primary ionization cluster, a very good timing resolution can be achieved (less than 10 ns as reported in Chap. 4). For the NSW MM chambers, the earliest arrival time recorded in every BC will be used as a trigger primitive. The novel resistive MM technology is characterized by excellent high rate capability [37] due to the thin amplification gap and the small space charge effects. The MM detector is the main subject of this thesis and the main characteristics of the technology will be discussed in detail in the next chapters.

1.4.4 Design & Layout

The sTGC detectors will primarily serve as the triggering detectors of the NSW, because of the excellent timing resolution and bunch crossing identification capability contributing also with precise offline muon tracking. The MM chambers, given their excellent spatial resolution independently of the track incidence angle, comfortably fit in the tracking requirements for the NSW primary tracking detector ($\sigma \leq 100 \mu m$) while in parallel their good timing resolution accounts for their ability to provide triggering primitives. The fact that each of the two detector technologies is also expected to complement the primary function of the other ensures the system’s redundancy and robustness over the full NSW rapidity region.

Figure 1.20: Graphical representation of an assembled NSW. Two MM sectors, one small and one large, are also shown. In reality, the MM will not be visible sitting in between the two sTGC quadruplets.
One NSW will consist of sixteen sectors, eight large and eight small as shown in the drawing of Fig. 1.20. Four wedges will be arranged along $z$ in each sector following the sTGC-MM-MM-sTGC configuration. The arrangement of the different technology wedges is chosen such that the largest possible lever arm between the triggering wedges (sTGC) is achieved, ensuring precise reconstruction of online track segments. Each wedge, is basically a stack of chambers, combining four detection layers of the same technology. In the case of the sTGC wedges, four identical layers are stacked together while the MM wedge combines three different types of detection layers with respect to the readout geometry. There is also a radial segmentation of each wedge in modules of different sizes and shapes. For the MM wedges four types of MM quadruplets are distributed along $r$ and in small/large sectors while each sTGC sector is composed of three different quadruplet types:

### MM
- **LM1**, lower radius of the large sectors
- **LM2**, larger radius of the large sectors
- **SM1**, lower radius of the small sectors
- **SM2**, larger radius of the small sectors

### sTGC
- **QL1**, lower radius of the large sectors
- **QL2**, medium radius of the large sectors
- **QL3**, larger radius of the large sectors
- **QS1**, lower radius of the small sectors
- **QS2**, medium radius of the small sectors
- **QS3**, larger radius of the small sectors

A graphical representation of the NSW small sector components can be seen in Fig. 1.21. Two similar MM small wedges, made of SM1 and SM2 modules, are mounted on the two sides of an internal spacer frame that defines the MM lever-arm (~ 40 mm). The two MM wedges are then framed by two sTGC quadruplets to complete the NSW small sector.

**Figure 1.21:** Graphical representation of the different sTGC and MM detector modules composing a small sector of the NSW. A similar configuration is foreseen for the large sectors as well.
1.4.5 Mechanical Precision Requirements

The performance criteria for the NSW detectors place very stringent precision requirements for the construction of the large detector modules. In order to maintain the momentum resolution of 10% for muons up to 1 TeV the precise alignment of the NSW detectors with the rest of the muon system is essential. This implies that for every detector plane the position of each readout element measuring the precision coordinate should be known with an RMS error of less than 30 \( \mu m \). For the readout elements measuring the coordinate perpendicular to the precision one their relative position should be known with an RMS error of less than 80 \( \mu m \). The adherence to these requirements is challenging for the construction and assembly of the large-size MM and sTGC modules and the possible mechanical deformations should be well under control.

1.4.6 Schedule

Since the NSW will be essential already for Run-3 of the LHC the time-plan of the project spans till the end of LS2 with the last two years 2018-2019 dedicated to the commissioning and installation of the new detector sub-system. A pictorial perspective of the NSW schedule is presented in Fig. 1.22 with the collaboration, after the formal approval of the project and the release of the TDR, focusing in the production, qualification and testing of the detector modules and the readout electronic components.

![Figure 1.22: The NSW schedule as was envisaged at the end of 2014. During 2015 a small delay has been introduced in the Module-0 construction that will be ready in the first months of 2016.](image-url)
Bibliography


Developments in the ATLAS Detector Control System

ATLAS is the largest experiment at LHC composed of 12 individual detector subsystems. The constant control and monitoring of all the systems along with the common experimental infrastructure is carried out by the ATLAS Detector Control System (DCS). The general purpose along with the basic architecture and functionality of the ATLAS DCS will be described in this chapter. More extensive insight will be given in the MDT and CSC DCS subsystems going through the main developments and improvements that have been carried out under the scope of this thesis.

2.1 The ATLAS Detector Control System

The DCS of the ATLAS detector, is a homogeneous interface responsible for the coherent and safe control and monitoring of all the individual subsystems and the common infrastructure. It handles the transition between the possible operational states of the detector while in parallel ensures the constant monitoring and archiving of the system's operational parameters. Any abnormal behavior of even the smallest detector element triggers a signal to the relevant user through automated procedures. Moreover, it provides the synchronisation of the detector state with the physics data acquisition system, through a bi-directional communication interface, ensuring the effective operation of the detector. Finally, the DCS handles the communication with other systems which are controlled independently, such as the LHC accelerator, the CERN technical services, the ATLAS magnets and the Detector Safety System (DSS).

The ATLAS DCS was designed and implemented within the framework of the Joint COntrols Project (JCOP) [1]. a collaboration of the CERN controls group and DCS teams of the LHC experiments. The JCOP combines common standards for the use of the DCS hardware based on the Siemens WinCC Open Architecture SCADA system [2] (formerly known as PVSS) that serves as the basis for all DCS applications. Figure 2.1 shows the DCS architecture which can be split in Front-End (FE) equipment and a Back-End (BE) system. The FE encompasses the DCS hardware, including custom electronics and/or associated services such as power supplies and cooling circuits. The BE uses the WinCC software, incorporating front-end controls within the JCOP framework components to facilitate the integration of standard hardware devices and the implementation of homogeneous control applications. The two ends of the DCS architec-
tecture communicate mainly via the industrial field-bus CAN [3], while the standard OPC [4] is used among others as the software protocol for communications. The BE part is organized hierarchically in three layers:

- The Local Control Stations (LCS), that represent the local back-end which are responsible for the connection and readout of the subsystem front end.

- The Sub-detector Control Stations (SCS) perform the high-level control of a sub-detector allowing its standalone operation.

- The Global Control Stations (GCS) combines all the subsystems into a common ATLAS DCS and offers a high-level supervision of the full tree through service applications and operator interfaces.

In total, the BE consists of more than a hundred stations (PCs) connected into a distributed system. The communication between the system sub-nodes is handled by WinCC via the local area network. The complete BE hierarchy from the operator interface down to the level of individual devices is represented by a distributed Finite State Machine (FSM). The FSM unifies more than 10 M data elements into a single tree structure ensuring the coherent operation and efficient error handling in each functional layer. The cornerstone of this highly distributed system is the datapoint (DP) structure that plays the role of global system variable network. Each element of this structure has a unique name and configurable functionality. A DP holds the online value of any type of information with supplementary configuration for alarm and archive handling. In those DCS systems that are directly linked with the hardware, like the MDT Power Supply and Electronics described in Secs. 2.2.1, 2.2.2, dedicated DPs are used to store the online readings of the hardware components that are updated by the OPC server-client communication interface.

**Figure 2.1:** Graphical representation of the ATLAS DCS architecture split into three layers: GCS, SCS (BE) and LCS (FE).
2.1 The ATLAS Detector Control System

2.1.1 The Finite State Machine

A simple and efficient way to describe control systems of complex large-scale systems is through a Finite State Machine (FSM) that represents a formal model for sequential behaviour control. In this way multi-element systems are broken down into small and simple objects that can be controlled and monitored not only individually but also in an hierarchically unified way. The JCOP FSM framework provides a generic, platform-independent, and object-oriented implementation of a state machine toolkit for a highly distributed environment, interfaced to a WinCC control application with the attributes of an FSM object instance linked to the associated WinCC application database. In this way the FSM functionality is integrated into the WinCC user interfaces allowing also the archiving of the FSM states and transitions. The ATLAS DCS FSMs are created and modified via the JCOP FSM toolkit that expands its predecessor SMI/SMI++ framework\(^1\) (State Manager Interface). The SMI++ is based on the original State Manager concept employing the SML language [6] for defining the object model along with states, actions and associated conditions.

Each FSM node has a unique name based on the subsystem name and its functionality following the ATLAS DCS conventions and its state and status is defined by a corresponding internal DP. The FSM object type, that defines the basic functionality of the node and its sub-elements, depends on the element’s functional purpose and position in the DCS architecture hierarchy. Three different object categories can be defined through the JCOP FSM toolkit:

- The Device Units (DU) are the lowest-level interfaces with the hardware and reflect its actual state and status. The state/status transitions are based solely on direct hardware readings.
- The Logical Units (LU) occupy a higher hierarchy level integrating several DUs (children) and their states/statuses are calculated on the base of their children via combination of boolean expressions.
- The Control Units (CU) can be envisaged as slightly more complex LUs that are able to control one or several LUs or DUs. On top of this, the CUs functionality is governed by a control script that runs on the background and implements more complex state determination decisions on top of the boolean expressions based on their sub-elements.

The complete DCS BE, shown in Fig. 2.1, is hierarchically distributed along FSM elements. State changes are propagated from the lower levels to their parents while the commands are issued downwards. This allows for the operation and control of the complete ATLAS detector by means of a "single FSM node". The tree FSM structure is enhanced by a fixed state model that reflects each subsystem’s conditions: (physics data taking) READY, NOT READY and SHUTDOWN. A special STANDBY state is reserved for detectors with an intermediate stage for unstable beam conditions (MDT and CSC chambers). An undefined state (UNKNOWN) has been also reserved in the case where the actual condition cannot be verified while there is also an intermediate state (TRANSITION). The actual state of these logical objects is determined by the states of the associated lower level objects (children) via boolean condition state rules. The lower level objects may follow a more subsystem-specific state model for which guidelines exist. A view of the ATLAS DCS FSM as it can be seen in the PCs of the ATLAS control room is shown in Fig. 2.2.

\(^1\)SMI was developed for designing and implementing distributed control systems by the DELPHI experiment in collaboration with the DD/OC group of CERN [5].
The top FSM node that reflects the state and status of the whole detector can be seen on the top left part of the figure. In order to ensure the coherent and safe operation of the detector in the most efficient way all the sub-detector nodes of the ATLAS DCS follow the same state/status conventions scheme with the unified approach being two-fold justified:

- The same set of commands and states/statuses are used for all the sub-detectors making the shifters and the experts life easier in controlling and monitoring very large systems.
- The status of each single element and/or the whole detector are determined via simplified boolean equations.

Figure 2.2: The main graphical user interface of the ATLAS DCS with all the subsystems unified in an hierarchical FSM structure.

2.1.2 The Alarm Screen

The alarm screen, an instance of which is shown in Fig. 2.3, displays in real time a list of active alarms within the selected ATLAS DCS system. The alarms are raised upon the occurrence of one or several hardware or software component malfunctions and are categorised according to their severity to WARNING, ERROR and FATAL. The appearance of an alarm is also reflected in the status of the corresponding FSM node as i.e. can be seen in the PIX node in Fig. 2.2.
The alarm scheme allows for rapid detection from the shifters and efficient follow-up by the experts of possible problems that may come up during normal operation. The Alarm Screen user interface allows for filtering on different alarm attributes such as corresponding system, description, severity and time. Moreover, it implements the ability to query the alarm history of a specific system with all the above features proving the importance of this tool for the safe and efficient operation of the ATLAS detector.

![Image](image.png)

**Figure 2.3:** The alarm screen of the ATLAS DCS. Some errors coming from the MDT End-cap Alignment DCS monitoring, that is described in Sec. 2.4, are shown.

## 2.2 Developments in the MDT DCS

With more than 1000 MDT chambers the MDT DCS is one of the largest and most complicated systems in the ATLAS experiment. It follows the baseline design and structure of the ATLAS DCS with tailor made modifications. Several small scale developments have been implemented towards improving the existing system on the scope of this thesis. A brief overview of the system architecture and functionality will be presented with some more insight given on the subsystems of interest.

### 2.2.1 MDT power supply system DCS

One of the most neuralgic infrastructure systems of the MDT chambers, that requires constant control and monitoring, is the Power Supply (PS) system. For the High and Low Voltage (HV/LV) powering needs of the MDT the commercial CAEN modules A3540P [7] (HV), A3025B [8] (LV) and A3016B [9] (LV) are used. These modules are hosted in CAEN EASY 3000S [10] 20-slot crates, inside the ATLAS experimental cavern (UX15). All the components installed in the experimental cavern are magnetic field and radiation tolerant. Up to six crates can be connected in series and are controlled by a single CAEN A1676 branch controller [11] and the power for the EASY 3000S is provided by the 400 V AC - 48V DC converter CAEN A3485 [12]. There are 14 branch controllers, for the whole MDT system, that are installed in two CAEN SY4527 mainframes [13] located outside the experimental cavern in the USA15 services room while the 48 V generators are installed in the US15 services room. In total 2865 channels are needed for the whole MDT system, distributed in 337 HV/LV modules and 64 EASY crates.

The MDT PS has its own FSM tree some instances of which are depicted in Fig. 2.4. The FSM nodes are arranged according to the MDT chamber’s naming scheme depending on their “relative position” in the detector reference frame. They are therefore categorised in A/C side,
Barrel/End-cap region, INNER/MIDDLE/OUTER layer, radial position within a layer and SECTION (1-16). The PS chamber level FSM node is then split into three parts each of which corresponds to an actual hardware HV/LV channel

- Multilayer 1 HV
- Multilayer 2 HV
- LV - Power for the on-chamber front-end electronics

The bottom left part of Fig. 2.4 shows the main graphical user interface that is associated with the chamber FSM node for the MDT chamber B1L1A01 where information for the three power supply channels associated with the chamber is available to the user. The single channel settings can be configured from this level while there is a constant monitoring of the online values that are read from the hardware. A similar FSM structure is employed for the monitoring and configuration of the MDT readout electronics with the main panel displayed on the chamber level shown on the bottom right of the same figure.

**Figure 2.4:** The different layers of the MDT FSM the Power Supply and the Jtag subsystems. The same tree structure and hierarchy is followed in both systems and the main graphical user interfaces displayed on the chamber level are presented.
2.2 Developments in the MDT DCS

2.2.2 DCS for the MDT front-end electronics monitoring

A set of mezzanine cards is employed to read out one MDT chamber. A single card can acquire data from up to 24 tubes and 18 of these cards are connected to one Chamber Service Module (CSM). The CSM multiplexes data from the mezzanine cards handling also the transmission via an optical fiber to the off-chamber readout electronics. Each of the 1173 MDT chambers\(^2\) of the ATLAS Muon system, is equipped with on CSM card and the 14300 mezzanines in total are readout by six control machines\(^3\).

The monitoring of the CSM and its associated mezzanine cards is implemented through the DCS via the dedicated MDT Front-end Electronics project [14]. The slow control communication is established via the CAN interface [15] of an "Embedded Local Monitor Board" (ELMB) [16] that is mounted on a custom module hosting all the necessary I/O connectors. Every single MDT chamber is equipped with one custom-made box called "MDT DCS Module" (MDM) [17]. The MDMs are connected to the control systems (PCs) via the SYSTEC CAN-USB interface[18] while the CANopen [3] has been implemented as high-level communication protocol for establishing the link with the DCS. The reference voltage and temperature parameters of each CSM and mezzanine card are read out and monitored by the control systems in cycles of 30 sec. An instance of the user interface that publishes the monitored values of one CSM and the corresponding mezzanines is illustrated in Fig. 2.5.

The MDT Front-end Electronics (ELTX) DCS runs on a separate control machine that is connected via ethernet to the control machines reading the CAN data from the MDMs. In order to efficiently monitor the ~ 70000 parameters of the MDMs, an advanced copying mechanism reads and writes the MDM data into custom-made DP structures with reading-cycle frequency smaller than 30 sec. Moreover, a discrete alarm configuration scheme has been implemented that allows the timely and robust detection of an abnormal condition.

During LS1 a deep re-organization of the MDT Front-end Electronics DCS has been performed in order to keep the level of consistency with the rest of the MDT DCS systems at the highest level possible. The FSM of the system has been re-designed in order to introduce the "Layer" chamber level in the tree hierarchy such that MDT PS, JTAG and ELTX share a similar FSM structure. The new main panel of the top node is shown on the left part of Fig. 2.6 that gives an intuitive view of the whole system’s status with the possibility of a single-click navigation to an MDT sector level. In addition to the FSM modification, 10 additional MDT chambers that have been installed during the same period have been integrated in all the parts of the ELTX DCS including DP structure and the alarm configuration. An example of the integrated chambers can be seen in the right part of Fig. 2.6 with the new chambers of the A side barrel region depicted with the black arrows.

\(^2\)The number 1173 corresponds to the initial number of MDT chambers foreseen in the TDR of the ATLAS Muon system but not all of them have been installed during the start of Run-1. During LS1 ten additional chambers have been installed (called BME/BMR/BOE/BOR) with the installation of twelve more (called BMG) pending for the MDT puzzle to be completed.

\(^3\)During Run-1 eight control machines have been used for the CSM readout which was adopted to a six-machine scheme during LS1.
Figure 2.5: The main graphical user interface of the MDT ELTX FSM at the chamber level node. The monitored CSM and mezzanine voltage and temperature parameters are displayed.

Figure 2.6: Left: The main panel of the MDT ELTX DCS FSM that has been re-designed during LS1 implementing also the updated FSM structure. Right: The main panel of the Barrel A-side FSM node that shows an example of the new MDT chambers that have been integrated into the existing system during LS1.
2.3 MDT Current Offset Calibration

As already mentioned in Sec. 2.2.1, the MDT HV is provided by the commercial, 12 channel, A3540 CAEN power supply modules. The voltage and current operational parameters of each channel are constantly monitored via the DCS. The product specifications dictate that the output current is measured with 0.1 μA resolution. However, the operation and experience of the MDT HV distribution system over the years has shown that each HV channel has a unique current offset that can be as high as a few μA. In order to have an accurate measurement of the output current, comparable between different channels, the current offset per channel needs to be measured. For this reason a graphical user interface has been developed that allows for offset calculation of one or more channels at a time. The offset per channel can be estimated using two different algorithms, direct or luminosity extrapolated method, that are described in the following sections. In both cases the correlation of the output current with the particle rate is presupposed. The panel is illustrated in Fig. 2.9 and is divided in three parts from left to right:

- Single or multiple HV channel filtering and selection of calibration method.
- Configuration and control of the Direct Measurement method.
- Configuration and control of the Luminosity Extrapolated method.

The channels of interest can be selected by filtering the corresponding chamber names in the leftmost table of the panel and are then supplied to the preferred calibration method to be processed.

2.3.1 Direct offset measurement

The current offset can be directly calculated by measuring the actual output current of each channel when the chamber connected to it is not sensitive to incoming particles. If the chamber is inefficient, the online measurement of the current should be equal to the offset with an uncertainty equal to the current measurement resolution. Along these lines an algorithm based on the online current measurement has been designed and implemented inside the dedicated current offset calibration panel.

The calibration procedure begins by setting the channels that are selected for calibration to a voltage much lower than the nominal one. Then, the output current is measured at fixed time intervals over a period of few minutes. The current offset of a single channel is determined from the average of the current measurements over this period. Exploiting the full functionality of the panel the user is able to compare the calculated current offsets with the values the are saved in the database. The new offsets may then be saved, overwriting the old values or discarded.

2.3.2 Luminosity extrapolated offset measurement

By studying in detail the direct measurement method it has been noticed that in several channels the calculated offset is exactly zero. This fact has given rise to the suspicion that there can also be negative current offsets that cannot be directly measured by the HV boards since the output current values are restricted to be positive. In order to overcome this important limitation of the direct measurement method a more sophisticated algorithm has been proposed that exploits the linear correlation of the output current with the incoming particle rate in a fully
The time unit in which ATLAS luminosity data are recorded is called Luminosity Block (LB). Within this time interval (~ 2 min) the luminosity is supposed to remain constant. For online luminosity measurements ATLAS uses six types of detectors\(^4\), with each one publishing luminosity measurements using different algorithms. The Online Luminosity Calculator [19] (OLC) processes the raw luminosity data from the detectors and archives the values in a database [20] (COOL). Thus, the luminosity information can be easily retrieved and combined with the output current data, that are also archived in the same database, for the needs of the offset calibration scheme. Out of the 16 luminosity values that are published from the different detectors the value of a "preferred algorithm" from one "preferred detector" is then used as the "official" ATLAS luminosity\(^5\). The luminosity measurement that is used for the current offset estimation is the averaged luminosity per LB integrated over the total number of bunches in the LHC ring (LBAv).

An example of the archived data, for both luminosity and current, as a function of time during a physics fill is presented in Fig. 2.7. The red distribution represents the measured average instantaneous luminosity during a 12-hour fill of June 2012. The shape, with the luminosity decreasing with time is an effect of the accelerator and has been discussed in Sec. 1.1.1 and the maximum achieved luminosity is \( \mathcal{L} = 6.5 \times 10^{33} \text{cm}^{-2}\text{s}^{-1} \). The current data for two MDT chambers of the innermost muon station (EI) are shown with the blue colour. From the similar distribution trends it is evident that the output current and the luminosity are significantly correlated for both chambers. It is also worth mentioning here that EIL1A09 chamber shows much higher current values than EIL4A09 because of the enhanced particle rate that it is exposed to compared to the other chamber [21].

\[\text{Figure 2.7:} \text{ The red distribution shows the average instantaneous luminosity of the ATLAS experiment as a function of time for a 12-hour physics fill during 16-17 of June 2012. The measured output current for two MDT chambers of the EI region is also plotted for the same period with the blue distributions. Note the different scales in the y-axes of the three histograms.}\]

One complication that arises when trying to compare the two different data sets (e.g. current and luminosity) is the asynchronous archiving between them. The luminosity measurements are archived at regular time intervals defined by the LB duration while the current data have

\(^{4}\text{The ATLAS sub-detectors that provide online luminosity measurements are: LUCID, FCAL, ZDC, BCM, MBTS, HLT.}\)

\(^{5}\text{The choice of the preferred algorithm and sub-detector depends on the performance of each sub-detector, and can change with the actual running conditions.}\)
a different smoothing configuration which depends also on the comparison between the new and old measurement. In order to synchronise the two streams, fixed time intervals of 25 min are selected and the average of all the measurements within this interval is then used for both quantities. The correlation plot between the average current and luminosity, for the same June physics run presented in Fig. 2.7, is shown in Fig. 2.8 for the MDT chamber BIL4A09. The almost perfect linear correlation between current and luminosity is profound. The data-points are fitted with a first-order polynomial function to disentangle the current-luminosity relationship and by extrapolating the fitted line to the zero luminosity value the current offset of the HV channel is extracted. As illustrated in Fig. 2.8, in the specific case of BIL4A09 a negative current offset is extracted. The offset that has been calculated with the direct measurement method described in Sec. 2.3.1 was zero.

The almost perfect linear correlation between current and luminosity is profound. The data-points are fitted with a first-order polynomial function to disentangle the current-luminosity relationship and by extrapolating the fitted line to the zero luminosity value the current offset of the HV channel is extracted. As illustrated in Fig. 2.8, in the specific case of BIL4A09 a negative current offset is extracted. The offset that has been calculated with the direct measurement method described in Sec. 2.3.1 was zero.

![Current vs Luminosity for BIL4A09](image)

**Figure 2.8:** The HV current is plotted as a function of the LB averaged instantaneous luminosity for the BIL4A09 MDT chamber. The two quantities are averaged in fixed time intervals of 25 min. By fitting the scatter plot with a first order polynomial function the current offset that corresponds to the zero luminosity environment can be extracted.

The same procedure can be applied for all the MDT HV channels. In order to allow for a mass current offset calibration of the full MDT system the data processing procedure described above has been implemented inside a graphical user interface that is shown in Fig. 2.9. The panel, can be used through the MDT DCS and allows for querying the current and luminosity data from the online DCS database for the selected MDT chambers over a selectable time-period\(^6\). The current offset is then calculated and can be compared to the previous value and/or saved in the dedicated DPs that have been created for this purpose. The calculated offsets for all MDT HV channels, using the data of 16-17 June 2012, are illustrated in the colour map user interface of the MDT DCS that is shown in Fig. 2.12 (left). In addition, the direct offset measurement method is also implemented in the same panel allowing for a comparison with the luminosity extrapolated values. A good agreement has been observed in the offset values calculated with the two methods for the case of positive current offsets.

\(^6\)A proper calibration period should correspond to a long ATLAS physics run in order to have enough statistics to perform the offset measurement.
Figure 2.9: The graphical user interface that was developed for the current offset calibration of the MDT HV channels. The user is able to select the chambers that will be calibrated from the left most part of the panel. Then the selected chambers can be calibrated either using the direct measurement method or with the method that uses the luminosity information. For the direct measurement, the user must define the test (non-nominal) voltage value on the chambers of interest. In the case of the luminosity extrapolated method a proper calibration period must be defined from the top right part of the panel before the offset calculation takes place. In both cases the calculated offsets can be saved or discarded.

The perfect linear correlation between the HV current and the luminosity should account for estimating the ATLAS luminosity using only the MDT current measurements. The implementation of this idea along with detailed studies on the accuracy that can be achieved with this method are presented in Appendix A.
2.4 Development of DCS for the MDT End-cap Alignment

2.4.1 The End-cap Alignment readout chain and the LWDAQ

The muon End-cap Alignment devices are controlled and readout via the Long Wire Data Acquisition (LWDAQ) system [22]. It consists of the devices, which are the various Rasniks/BCAMs/sensors that are installed on chamber and bars inside the ATLAS cavern, the drivers, installed in VME crates inside the USA15 service room, and the connection elements between the two ends combining cables multiplexers and repeaters. The "Long Wire" phrase stands for the category-5 cables that connect the LWDAQ devices and may reach the 130 m length. A single device is connected to the driver through a multiplexer, hosting multiple devices. The single cables connecting the drivers to the multiplexers are custom-designed solid-conductor cables referred to as "root cables" and are able to provide power, to the multiplexers and all the children-devices and two-way transfer of signals between the elements of the chain. The limitation is that only one device element at a time can send information to the driver while all the elements can be controlled either simultaneously or sequentially. A graphical representation of the different devices and their intermediate connectivity is presented in Fig. 2.10 (left).

The readings that are retrieved from the driver boards via low level acquisifier LWDAQ scripts go through a series of processes that take care of the redirection of the information towards the different destinations. The LTX program handles the communication with the low level scripts through a two-way link allowing for the reception of the LWDAQ readings and control of the acquisifier state in parallel. The information is then propagated to the next process in chain, the cycleLogic, that is the main interface between the user/expert and the readout chain. The cycleLogic can be controlled via a command center parsing the user input and propagating them through predefined commands to the LTX. Moreover, the cycleLogic distributes the received readings to an independent database (DB) writing process that saves the readings for offline analysis. The various processes along with their intermediate communication roots are illustrated in the block diagram of Fig. 2.10 (right).

**Figure 2.10:** Left: Graphical representation of the LWDAQ system cabling scheme. A single LWDAQ device may be connected directly to the driver via a root cable or alternatively multiple devices can be connected through branch cables to the multiplexers. Figure is taken from [23]. Right: A block diagram representing the flow of the End-cap Alignment data through the various processes and the DCS [24].
2.4.2 The End-cap Alignment DCS

The constant monitoring of the End-cap Alignment system is essential in order to ensure the efficient and coherent operation of the full chain allowing also the immediate detection of possible errors. For this purpose a dedicated DCS has been developed following the rules and conventions of the ATLAS DCS.

Communication protocol

The need for communication with the End-cap Alignment system requires the establishment of a TCP/IP connection between the DCS PC and the End-cap Alignment system. This type of communication is implemented using the Distributed Information Management system (DIM) [25]. It is a communication system for distributed environments, that provides a network transparent inter-process communication layer based on a server/client paradigm. The DIM is built on the basis concept of named services (sets of data categorized by a name). A DIM server implements services for the client to subscribe to. The subscription to each service is done at the start-up of the client and the data are automatically updated by the server either at regular time intervals or depending on change of conditions.

For the DCS needs a dedicated DIM server has been set-up in the End-cap Alignment system. The corresponding client, configured in the DCS system, is subscribed to a number of DIM services (15 in total) that have been configured and named according to the system needs and MDT DCS conventions. Each service submits a string message from the server to the client with a frequency determined by the processes of the server system. The DIM client configuration requires the connection of each subscribed service with a local DP for the temporal saving of the service's messages. Thus, a DP network has been created for hosting the DIM messages and transmitting them to the processing phase.

DIM message parsing

Depending on the service, the DIM message may contain information that would require coarse or a more intermediate handling. The message may consist of date/time information, state flags or device readings. Upon the receipt of a new message in the client, the DIM service datapoint is updated and the string is automatically parsed by a dedicated background script that implements also the distribution of the parsed information to the corresponding datapoint elements. For this purpose a dedicated control manager has been introduced in the DCS project that parses the received DIM messages.

Datapoint structure

Apart from the DPs that are needed to hold the DIM messages of the subscribed services (one for each service) a tree of several DP structures has also been created tailor-made to fit the needs of an efficient DCS system. There are different DP types for the End-cap Alignment services monitored, that are expanded to multiple sub-elements according to the characteristics of each process. In total ~ 100 DPs are used in the final version of the End-cap Alignment DCS system. Moreover, in order to maximise the performance and efficiency of the system a connection between different DP elements via statistical functions has been implemented exploiting the WinCC functionality.
2.4 Development of DCS for the MDT End-cap Alignment

Process heartbeat monitoring

The monitoring of the process status is based on the heartbeat DIM message sent from inside the process. Upon the receipt of a new message WinCC is able to tag the time-stamp of the update allowing for measurement of the time frequency of the updates. In our case the time interval between two updates is known and defined inside the End-cap Alignment processes that sit behind the DIM servers. Thus, exploiting the WinCC features an independent statistical function is applied on each process heartbeat datapoint that determines whether the update rate is healthy or not. The processes heartbeats that are constantly monitored by the End-cap Alignment DCS are

- Process checker
- LTX
- CycleLogic
- DB Reading

Process checker monitoring

The process checker is a supporting background program running on the End-cap Alignment system which sends information via DIM on the running/not running state of the main processes (cycleLogic, LTX, Java, tclsh). In order to ensure the normal state of the processes the information from the process checker and from the process heartbeats are combined allowing for fast detection of possible problems.

cycleLogic monitoring

The cycleLogic process, acting as intermediate server between the LTX, the user, the DCS, and database is the program that controls the reading cycle of the End-cap Alignment devices and transmits the data from the LTX to the database. During this course it also publishes the number of devices which are read along with the number of errors to the DCS via DIM services. There are two streams of data, the live readings that update each time the reading procedure from a single driver board is completed and the final readings which are determined at the end of a full cycle. The cycle length depends on a time duration parameter tuned according to the needs of the alignment system. The number of readings per device type is not only used for display purposes from the DCS, but there is also an automatic check at the end of the cycle for the integrity of the readings comparing them with the expected values.

Database monitoring

Another independent End-cap Alignment process accesses the online database and recovers the last entry written concerning the statistics of a full reading cycle. This information is then propagated to the DCS using a DIM service. Exploiting this information, the internal DCS scripts perform an additional sanity check on the database entries comparing them with the statistics of the last complete cycle. The database readings are compared to the expected values as well, as an additional redundant check of the data integrity.
Crate communication monitoring

As mentioned in Sec. 2.4.1 the End-cap Alignment processes communicate with the crates via the LWDAQ readout chain. Apart from acquiring the device readings it is also necessary to ensure the quality of the measurements and the readiness of the hardware to deliver meaningful data. An internal mechanism is implemented within the LTX process that constantly checks the communication and the state of each crate by pinging \(^7\) at fixed time intervals. The determined state of the crate pinging is sent to the DCS via a dedicated DIM service and the internal background DCS processes decide whether the communication with the crate is healthy or not. There is a general requirement that number of failed pings should be less than 5% over a sample of several pings that is statistically large enough. The percentage of failed pings, for each crate, is determined inside a “moving window” of a fixed size that ends at the last ping received from the crate of interest. The statistical calculation of the failed pings percentage is performed upon the receipt of a new ping and the parameters of the bad pings tolerance as well as the size of the sample used are tunable.

Automatic crate-off watchdog

The End-cap Alignment devices are powered from the driver boards sitting in the VME crates. As it has been described before, the readout of the devices is done sequentially. During the reading cycle, the processes power on one driver board at a time. The devices that are connected to the specific board are read out sequentially and as soon as they are all read out the board and consequently the devices are powered off. This power cycling of the board chain serves also safety purposes since the devices and the driver boards must not remain powered on for a long time to avoid hardware failures \(^8\). In rare occasions it may happen that the readout is stopped unexpectedly due to network communication problems. In this case single alignment devices and driver boards may remain on and the risk of a fatal hardware failure is high.

In order to protect the End-cap Alignment devices, a watchdog mechanism has been developed inside the End-cap Alignment DCS system. This mechanism, based on the information and the status of the End-cap Alignment DCS nodes, decides whether the system status is such that it may risk leaving the devices powered on in an uncontrollable manner. The criteria that are translated in abnormal conditions are:

- cycleLogic, LTX or process checker individual heartbeats not updating
- cycleLogic or LTX process status provided by the process checker is not running
- at least one unhealthy communication with a crate (failed pings requirement)
- the DIM and/or the Ctrl manager of the DCS project are not running

In all the above cases the monitoring and control of the End-cap Alignment crates is not reliable and upon indication of an abnormal condition the crates are automatically turned off via the independent CAN communication path.

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\(^7\) Sending Internet Control Message Protocol (ICMP) echo request packets to the target host (crate) and waiting for an ICMP echo reply measuring also the round-trip time from transmission to reception and reporting errors and packet loss.

\(^8\) It had been observed that the RASNIK devices may fail due to overheating when they are powered on for several hours.
2.4 Development of DCS for the MDT End-cap Alignment

Alarms and expert notifications

Because of the complexity of the End-cap Alignment DCS system an extended alarm/notification scheme has been developed and adopted to the ATLAS DCS requirements. This includes automatic email/sms notifications to experts as well as logging of important information in local log files. This mechanism is transparent to the muon DCS and is intended for expert use only. However, in the case where the watchdog script issues the automatic crate-off command, the alarm handling scheme of the ATLAS DCS is automatically notifying the relevant users. A list of the alarms that are triggered when the automatic crate-off action is executed are shown in Fig. 2.3.

The FSM and the Main Panel

Apart from the DCS architecture, processes and communication mechanisms, graphical user interface tools have also been developed enhancing the system functionality and making the interaction between the user and the system more efficient.

A dedicated End-cap Alignment FSM tree has been created using the ATLAS DCS conventions under the "Infrastructure" node of the MDT FSM. The main node is then populated with sub-nodes corresponding to the main End-cap Alignment processes (Process Checker, CycleLogic, LTX, DB reading) as can be seen in the top left part of Fig. 2.11. The status and state of each node is determined as described in the corresponding subsections and is then propagated to the main FSM node of the End-cap Alignment and consequently along the ATLAS FSM. In this way, an abnormal state of a single process will be immediately tracked by the ATLAS DCS FSM user and actions can be taken instantly.

The second and most sophisticated part of the End-cap Alignment DCS graphical tools is the main panel that is assigned to the main FSM node of the system and is shown in the right part of Fig. 2.11. It can be divided in eight parts that are arranged in different frames over the panel surface and it follows the colour code scheme of the ATLAS DCS (green colours indicate a healthy state).

Section 1 is composed of the indicators showing the state of the Control and the DIM manager respectively that should be always running. Section 2 displays the process checker information with a state/status text indication flanked by indications for the individual statuses of the processes that the checker reports. The LTX process state and status is reported in the section 3. Section 4 is dedicated to the display of the End-cap Alignment crates status. There is a main text state indicator reporting the general state of the crates on the top left while the power state of each crates is reported in the leftmost table of the frame. The second row of this table shows the number of bad pings for each crate while the current pinging sample size and failed pings tolerance are displayed on the second table of the frame. On the right part of the crate section the user can check and configure the status of the automatic crate-off functionality (enable/disable) that is used by the watchdog script.

The cycLogic status and statistics are displayed in section 5. Apart from the state of the process itself (reading/stopped/paused), the user is provided with information about the current cycle (cycle number, time started and pause time remaining). It is worth mentioning that the paused state is a normal part of the cycle reading procedure and is dictated by the End-cap Alignment processes that define also the duration of the pause. The table displays the real-time readings
of the different types of devices in the first row that increment at each reading step. At the end of a full cycle the total number of the different devices that have been read along with the number of possible errors are displayed in the second row of the table. The statistics of a full cycle, before these are saved in the online Oracle database, are automatically compared to the expected values that are displayed in section 7. These values are also retrieved from the database, section 6, where they are stored at the end of the cycle and are compared to the expected values and with the full cycle readings for possible discrepancies. In the case of disagreement there is a colour indication on the table and an automatic notification is sent to the experts. The expected values for the readings of a full cycle are also provided by a DIM service, so that they can be tuned by the experts, and are populated in the table of section 7.

The lowest part of the panel, section 8, displays the errors messages that are received from a specific DIM service in a table. There are also a couple of check boxes allowing the user to enable/disable the automatic email and logging functionality. In all the different sections of the panel the time stamp of the last DIM update that has been received for the corresponding process is displayed along with flashing indicators that visualize the processes heartbeats.

**Figure 2.11:** The FSM and the main monitoring panel of the MDT DCS End-cap Alignment.
End-cap Alignment Temperature Readings

Apart from the MDT temperature sensors that are read out through the ELMB [17] chain there are also additional temperature sensors which are part of the End-cap Alignment devices. For some MDT chambers, mostly in the EI region, only the sensors that are readout via the LWDAQ provide temperature information. These data follow the same route going from the End-cap Alignment processes to the DCS via DIM services and are then processed and stored in the dedicated DPs. The temperature values that are retrieved are then propagated to the MDT DCS and the users can have an insight of the temperature variation along the different areas of the MDT system. A visual representation of the MDT temperatures can be seen in the right plot of Fig. 2.12 (right) where the different MDT segments are shown in a colour map correlated with the temperature level along the MDT system. By depicting one chamber (e.g. EIL1A09) the individual temperature sensor values, that are acquired via the LWDAQ, are listed.

Figure 2.12: Left: The MDT DCS colour map for the current offset calculated with the luminosity correlation measurement. The offsets for the HV channels that supply the second multilayer of all the chambers are shown and the colour scale is shown on at the bottom of the panel. Several cases with negative offsets are visible. Right: A different instance of the colour map panel is used for the visual representation of the MDT chambers temperatures. By clicking on a single chamber (rectangle selection) the readings from all the temperatures sensors associated with the selected chamber are shown.

2.5 Developments in the CSC DCS

A smaller in scale DCS in terms of number of elements, but with similar complexity as the MDT system, controls and monitors the CSC chambers of the ATLAS detector. The system architecture follows the common conventions and hierarchy of the muon systems concerning HV, LV and infrastructure with some CSC specific alterations. Enhancements and improvements in the CSC front-end electronics temperature monitoring mechanisms as well as FSM, graphical tools and system architecture developments that have been applied in the existing system will be discussed.
2.5.1 The FSM of the CSC DCS

The FSM structure of the CSC DCS matches the MDT scheme with the power supply tree segmented into nodes according to the topology of the chambers. Each CSC PS chamber node combines five device units that correspond to the hardware power supply channels with one HV channel for each of the four detection layers and one LV channel supplying the power to the chamber front-end electronics. Apart from the PS nodes the CSC system employs an additional, with respect to the MDT, FSM node dedicated to the front-end electronics temperature for each side. The temperature FSM is segmented into sectors, matching the one of the PS system, and each sector combines three sensors.

All the services and hardware components that are essential for the optimal operation of the CSC system are represented with individual “Infrastructure” FSM sub-nodes. The “Cooling”, “Gas”, “ATCA”, “Racks” and “Systems” constitute the CSC “Infrastructure” node which references independent FSM trees built and operated in different DCS projects external to the CSC core project. The higher layer structure of the CSC FSM can be seen in the top left part of Fig. 2.13 where the side A and Infrastructure nodes are expanded. On the right part of the same figure the main panel of the CSC FSM top node is included providing a graphical representation of the CSC PS/Temp sector statuses.

![Figure 2.13: The FSM of the ATLAS muon CSC DCS. The organisation of the sub-nodes follows the MDT architecture with one secondary node per side and one infrastructure node. In the right part of the figure the main panel displaying the states and statuses of the 32 CSC sectors is shown. The CSC DCS uses the same colour conventions as the ATLAS DCS.](image-url)
2.5 Developments in the CSC DCS

2.5.2 HV/LV Power scheme

The HV power supply chain of the CSC chambers uses the same standards with the MDT in terms of hardware and communication that have been described in sec 2.2.1. The LV supply chain however is completely different due to the large current needs of the CSC front-end electronics. To cope with the LV power requirements of the CSC the Wiener Maraton\(^9\) power supplies [26] have been employed. In total six water-cooled MARATON supplies, with twelve independent channels each, are used to provide power to the thirty-two front-end electronics chains of the ATLAS CSC chambers. The 385 V payload power of the MARATONs is supplied by six Power Factor Correction (PFC) units that occupy a single primary rectifier slot in one of the US15 racks. In order to achieve the required \(~ 40\) A current per CSC chamber, two MARATON output channels are coupled together into a single LV input thus there are in total thirty-six LV channels available for the CSC system (thirty-two connected and four serving as spares). The output voltage, current limit and over-voltage protection level are adjustable for each MARATON channel. In order to ensure the proper cooling of the energy consuming MARATON equipment the temperature of the output cooling water is monitored through the DCS in addition to the cooling channel flow and pressure parameters.

The remote control and monitoring of the LV channels status, voltage and current is realised using the Remote Controller Module (RCM) designed by WIENER specifically for the MARATON. Each RCM is composed of twelve channels that can be connected to one or more MARATONs via two input DSUB37 front panel connectors. In the CSC case, three RCM units are installed in a WIENER VME crate in USA15 and each RCM controls two MARATONs. The communication between the RCMs and the DCS PC is implemented using the OPC server-client protocol via ethernet. Apart from monitoring the LV channel parameters and status, the on/off powering of each channel can be carried out via the DCS. A schematic representation of the CSC DCS LV power scheme is presented in Fig.2.14.

The CSC system features 160 HV/LV channels that can be controlled individually. However, in the daily operation of the detector the need for changing the power state of more than one channel may arise. For this reason a graphical tool has been developed and integrated in the CSC DCS that allows to control the power of multiple HV/LV channels with a single user action. The panel is shown on the right part of Fig. 2.15. It allows the user to select HV/LV CSC PS channels based on a pattern match with the detector name and change their power state with a single click making the group operation of the CSC PS channels more effective.

2.5.3 Front-end electronics temperature control and monitoring

In contrast to the MDT, the CSC front-end electronics, owing to their very high current consumption, require the use of external cooling system in order to maintain their temperature at tolerable levels. For this purpose the CSC use the ATLAS water cooling loops that are controlled and monitored via the dedicated DCS of the ATLAS cooling system [27]. Two loops are employed for the cooling of each side, each one serving eight sectors. The loops are arranged in top and bottom according to the sector numbers they are connected to.

For the purposes of temperature monitoring in the front-end region, temperature sensors are

\(^9\)MA\(g\)netism and RA\(d\)iation TO\(ler\)ant New power supplies that have been specifically designed to meet the CERN LHC experiments need for medium-high range currents distributed in a controlled mode over large distances to low-noise electronics.
installed on the cooling plate surface that serves as the medium between the cooling water and electronic cards. These sensors are readout via an instance of the LWDAQ system that has been described in Sec. 2.4.1. In the CSC case, the sensors are multiplexed before they reach the LWDAQ readout driver A2071 device [28] which then transmits the data to the CSC DCS machine via DIM client-server communication. The CSC temperature reading is completely decoupled and independent from the PS DCS of the CSC but the temperature information is combined with the PS data inside the DCS software resulting in a complete monitoring scheme of the CSC system.

To ensure the longevity of the CSC front-end electronics it is essential that their temperature is constantly monitored. The monitoring is moreover enhanced with an alarm configuration based on the comparison of the reading value with the predefined limits. If the temperature is much higher than the warning pre-alarm limit, the LV of the whole sector is turned off automatically to ensure that any damage to the electronics is avoided. The dedicated temperature FSM of the CSC DCS assists the rapid detection of possible cooling or electronics problems with the different states and statuses coupled to the user-defined limits. In order to make the change of the alarm limits for individual sensors easy, the existing temperature monitoring panel per sector has been expanded with an alarm limits configuration section that can be seen in the left part of Fig. 2.15. In addition, the temperature FSM state transitions have been re-configured.
2.5 Developments in the CSC DCS

Figure 2.15: Some of the graphical tools developed for the CSC DCS. Left: The main panel of the CSC temperature FSM chamber node has been expanded to allow the configuration of the alarm limits individually for each temperature sensor. Right: The group operations panel for the CSC PS system. Multiple HV/LV channels can be selected, using a pattern search option, and switched on or off with a single action.

such that they depend on the exact same parameters with which the alarm limits are configured.

During LS1 several interventions have been carried out in the CSC chambers that involved disconnection of most of the services, including the cooling lines. Before the start of LHC Run-2 and after the re-commissioning of the CSC, the cooling system needed to be regulated to ensure a laminar water flow along the cooling lines and stable temperature. For this reason the input/output pressure for all the 32 cooling lines was measured and reconfigured such that it is everywhere below atmospheric pressure ensuring a proper water flow. Moreover, in several cases the cooling flow was stressed out for a short time period to unblock the cooling lines from trapped air that was hampering the water flow producing temperature readings oscillating with time. A map of the cooling pressure measurements made for the chambers of side C is shown in Fig. 2.16. The plot that is shown in the same figure reports the temperature reading of a single sensor from one CSC sector with the evident spikes indicating air trapped inside the line tubes. In most of the cases the temperatures stay below 30°C in normal operation and are automatically switched off when the temperature exceeds a predefined safety limit (~ 35°C).

2.5.4 DCS integration of the ATCA based CSC readout system

The commercial ATCA is becoming increasingly popular in high energy physics featuring high speed backplane, hot swappable board elements and the Intelligent Platform Management Interface (IPMI) based shelf management infrastructure. The ATLAS CSC back-end readout system has been upgraded during the LHC 2013-2014 shutdown to be able to handle the increased Level-1 trigger rate (100 kHz) and the higher occupancy expected during Run-2. The readout design [29] is based on the Reconfiguration Cluster Element (RCE) concept for high bandwidth generic DAQ implemented on an Advanced Telecommunication Computing Architecture (ATCA) platform [30]. The new system, built on the ASIS 6-slot ATCA chassis [31], replaced the Run-1
As a consequence of the readout upgrade the CSC DCS needed also to be adjusted so that the new ATCA hardware is properly monitored and controlled. The communication between the CSC DCS machine and the ATCA shelf manager is realized using the Simple Network Management Protocol (SNMP) that is interfaced in the CSC DCS project via a dedicated SNMP manager. For the CSC needs a separate WinCC project is used for the ATCA DCS monitoring that is then referenced by the core CSC DCS project. The DP architecture along with the alarm/archive configuration, FSM and graphical tools are provided by the fwAtca framework\(^34\) developed by the CSC and Tile DCS communities with the guidance of the ATLAS Central DCS. An example of the ATCA DCS FSM and graphical user interfaces is presented in the left part of Fig. 2.17. Information on the state and status of the several components that are installed in the ATCA shelf along with constant monitoring of their operational parameters are provided. The actual ATCA shelf that is installed in USA15 is shown in the photos of Fig. 2.17 (six COBs\(^{10}\) are visible. The integration of the ATCA shelf monitoring in the CSC DCS has been the first instance of an ATCA DCS implementation and is operational since the beginning of Run-2.

\(^{10}\)Cluster-On-Board (COB) card that hosts up to 8 processing RCEs on 4 Data Processing Modules (DPM) and one control RCE on Data Transfer Module (DTM)\(^{35}\).
2.5 Developments in the CSC DCS

Figure 2.17: Left: The main panel of the CSC ATCA DCS hooked up to the top node of the ATCA FSM that sits under the CSC Infrastructure FSM. Right: A photo of the actual ATCA shelf (front and back view) of the CSC readout installed in the ATLAS services room (USA15) [33].
Bibliography


Evolution of the MicroPattern Gaseous Detectors -
The Micromegas detector for the ATLAS New Small Wheels

The gaseous detectors have, over the last century, become an invaluable tool for particle physics research. A brief overview of the interaction and propagation mechanisms that govern the passage of particles through the detector active material will be given, preseeding the discussion on the gaseous detectors principle of operation and evolution towards the Micropattern gaseous detectors. This latest generation of avalanche gaseous detectors are nowadays at a blooming stage, due to their excellent characteristics and simplicity of construction and are adopted by several small/large scale and low/high energy experiments across the world. More extensive insight will be given on the design and operational parameters of the resistive-strip Micromegas technology that is the main research topic of this thesis.

3.1 Interaction of charged particles with matter

The operation principle of any particle detector is based on the interaction between the incoming particles and the molecules/atoms of the detection medium that result in a detectable signal. The interaction process depends primarily on the incident particle’s characteristics and secondary on the detector’s active material. The basic interaction principles of charged particles with the detector medium are described, along with the mechanisms that govern the propagation of the interaction products in the detector medium from their creation up to their detection.

The interaction of charged particles with matter is governed by electromagnetic processes. Upon entering any absorbing medium a charged particle interacts simultaneously with many atomic electrons occupying the area in the vicinity of the charged trajectory. Depending on the energy of the particle and the proximity of each particle-electron encounter the electron can be promoted to an energetically higher atomic shell (excitation) or completely released by the atom’s binding force (ionisation). During each interaction the particle looses only a small fraction of its initial energy, thus many interactions are required for the particle to stop. The ionisation products, ions and electrons, are used as the basis of the detector response.
The number of ionizing collisions is purely random and the mean free flight path between two ionizing encounters $\lambda$ is given by Eq. (3.1) where $\sigma_1$ is the ionisation cross-section per electron and N the electron density. The number of primary ion pairs per unit length will then be equal to $1/\lambda$ and depends on the type of charged particle, its velocity and the gas mixture.

$$\lambda = \frac{1}{N\sigma_1}$$  \hspace{1cm} (3.1)

The probability of having $k$ ionisation interactions over a given distance $L$ follows the Poisson distribution of Eq. (3.2). The number of primary clusters per unit length $N_p$ and the space distribution of the primary ionisation clusters depend on the nature and energy of the radiation. The created electrons may have sufficient energy to ionise further creating secondary electron-ion pairs, thus the total number of electron-ion pairs may be slightly higher than $N_p$.

$$P(L/\lambda, k) = \frac{(L/\lambda)^k}{k!} e^{-L/\lambda}$$  \hspace{1cm} (3.2)

The energy loss rate (measured in g/cm$^2$), often referred to as linear stopping power, for heavy relativistic charged particles ($m_0 \gg m_i$) in a given absorber is given by the classic Bethe-Bloch Eq. (3.3) [1]. In this equation the particle’s velocity is $\beta = u/c$, $I$ denotes the mean excitation energy, $K = 4\pi N_A r_e^2 m_e c^2$, $\gamma = E/Mc^2$, $z$ is the charge of the incident particle, $Z$ and $A$ the atomic number and atomic mass of the absorber respectively, $m_e$ the electron mass, $r_e$ the classical electron radius, $N_A$ Avogadro number and $\delta(\beta)$ is the density effect term discussed below.

$$-\left(\frac{dE}{dx}\right) = Kz^2 \frac{Z}{A} \beta^2 \left(\frac{1}{2} \ln \frac{2m_e c^2 \gamma^2 \beta^2}{I} - \beta^2 - \delta(\beta)\right)$$  \hspace{1cm} (3.3)

From Eq. (3.3) it can be derived that the energy loss decreases rapidly with $1/\beta^2$ for small values of $\beta \gamma$ reaching a wide global minimum value. Most relativistic particles have mean energy loss rates in the minimum area and are thus often referred to as Minimum Ionising Particles (MIPs) [2]. The MIPs ionisation losses, for almost all materials, range between 1 and 2 MeV/(g/cm$^2$) slightly increasing with $Z$. When however $\beta \gamma$ exceeds a certain level, the energy loss becomes subject to a relativistic rise (logarithmic term in Eq. 3.3) with the slope of the rise depending on the mean excitation energy $I$. A correction term that depends on the absorber material has been added to Eq. 3.3 representing the density effect [3] of the surrounding polarised particles that shield the field of the moving particle. This extra term controls the otherwise unlimited increase of the relativistic rise term. This additional term $\delta(\beta)$ confines the increase of the energy loss with the particle’s momentum to a much smaller rate and in the MIPs region is zero.

The case of electrons is different, compared to heavy charged particles since, in addition to the ionisation, they also lose energy by radiation (e.g. Bremsstrahlung). Owing to the similar characteristics with the absorber’s target electrons, the electron energy loss rate is lower compared to heavier particles and they follow a twisting path through the medium. The energy dependence of the energy loss is not identical for each of the two processes. An electron looses energy by Bremsstrahlung at a rate nearly proportional to its energy, while the ionisation loss rate varies only logarithmically with the electron energy. The critical energy $E_c$ is sometimes defined as the energy at which the two loss rates are equal \(^1\). The modified Bethe-Bloch formula

\(^1\)Approximations that can be found in bibliography estimate $E_c \approx (800 \text{MeV})/(Z + 1.2)$. However this relation slightly varies between solid, air and liquid matter.
for electrons is illustrated in Eq. 3.4 where $\tau = \gamma - 1$ is the kinetic energy of the electron divided by $m_e c^2$ and $C(I,\beta)/Z$ represents the so-called inner shell corrections due to screening effects. Radiative processes exist for other charged particles as well with the critical energy for muons and pions in iron occurring in several hundred GeV.

$$-\left(\frac{dE}{dx}\right) = K_z^2 Z \frac{1}{A \beta^2} \left( \ln \frac{\tau \sqrt{\tau + 2}}{\sqrt{2(I/(m_e c^2))}} - \frac{F(\tau)}{2} - \frac{\delta(\beta)}{2} - \frac{C(I,\beta)}{Z} \right), \quad F(\tau) = 1 - \beta^2 + \frac{\tau^2}{2} - (2\tau + 1) \ln 2 \frac{1}{(\tau + 1)^2}$$

(3.4)

Electrons with energy higher than 100 MeV loose their energy almost exclusively by Bremsstrahlung. The produced photons in each interaction with the medium’s atoms either disappear or undergo a dramatic change in their energy. The possible processes of photon interaction with matter are:

- **Photoelectric absorption**
  Absorption of a photon by an atom and ejection of a photoelectron from one of the atom’s bound states. The electron vacancy in the resulting ion is rapidly filled through the absorption of a free electron or by the re-arrangement of the atom electrons and the emission of an x-ray photon that is most probably reabsorbed very close to its generation point.

- **Compton scattering**
  Inelastic scattering of the photon by quasi-free atomic electrons and ejection of a recoil electron with the scattering probability per absorber atom increasing linearly with the material atomic number $Z$.

- **Pair production**
  If the photon’s energy is significantly larger than twice the rest-mass energy of an electron the photon disappears and is replaced by an electron-positron pair.

In the sub-MeV region the photoelectric effect dominates with the probability decreasing with the increase of the photon’s energy. The Compton scattering process is important for energy values of a few MeV while for values larger than 10 MeV the photons interact with matter most probably via pair-production. All these processes lead to the partial or total transfer of the photon’s energy to the atomic electron, significantly altering the state of the photon that is either hardly scattered or vanished.

The total energy loss expressions for heavy charged particles and electrons, Eqs. 3.3, 3.4, include all the kinematically possible energy-transfer interactions that do not necessarily contribute to the detection of a charged particle’s track in a detector (i.e. a gaseous chamber). Moreover, the recoil ionisation electron may have sufficient energy to ionise the detector’s medium as a virtual incoming charged particle with a path that can possibly extend to large distances (δ electron). To take these effects into account Eq. (3.3) is parametrised with the maximum energy transfer possible $E_{\text{max}}$ as in Eq. (3.5) which is valid for $\gamma^2 \gg E_{\text{max}}/m_e c^2$ and is applicable also for the electrons [4].

$$-\left(\frac{dE}{dx}\right) = K_z^2 Z \frac{1}{A \beta^2} \left( \frac{1}{2} \ln \frac{2 m_e c^2 \gamma^2 \beta^2 E_{\text{max}}}{I^2} - \beta^2 - \delta(\beta) \right)$$

(3.5)

The differential energy loss provided by the Bethe-Bloch formulation give an estimate of the average energy loss only. In the (gaseous) detector reality however, the process is dominated by
event per event fluctuations, depending on the particle’s energy and the absorbing medium [5]. The low probability for \( \delta \) electrons production in combination with their large ionisation yield result in asymmetric energy loss distribution (Landau) with a characteristic large tail in the high values. Values of the relevant ionisation parameters for various noble and molecular gases can be found in [2].

### 3.2 Drifting and diffusing ions and electrons inside gas

The operation principle of gaseous detectors is based on the electron/ion products of the incoming particle’s interaction with the gas and their motion until they reach the detection plane. The thermal motion of electrons and ions along with their drifting and interaction with the gas atoms/molecules under the influence of an electric field are discussed.

#### 3.2.1 Ion mobility

Because of their relatively large mass, compared to electrons, the ions drift much slower than the electrons loosing significant part of their energy upon each interaction with the gas molecules/atoms.

**Drift velocity**

With the application of an electric field in the gas volume a net movement of the positive ions along the field direction is observed. In the case of gaseous detectors the ion’s mean kinetic energy is usually comparable to the thermal velocity of the gas atoms. The mean drift velocity of the ion motion is linearly proportional to the applied electric field, following Eq. (3.6) for an ion of mass \( m \) interacting with the gas molecules, each of mass \( M \). The quantity \( \mu \) is called the ion mobility in a gas and \( \sigma \) the scattering cross-section of ions by gas molecules, \( k \) is the Boltzmann’s constant, \( T \) is the temperature and \( N \) is the density number.

\[
\mu_d^{\text{ion}} = \left( \frac{1}{m + M} \right)^{1/2} \left( \frac{1}{3kT} \right)^{1/2} \left( \frac{eE}{N\sigma} \right) = \mu E
\]  
(3.6)

The value of the mobility is characteristic of a specific ion moving in a given gas and in the case of stable environmental parameters (temperature and pressure) it can be considered constant. This is a direct consequence of the fact that, even for very intensive electric fields, the net energy of the ions remains unchanged. In the more realistic case of gas mixtures however, the fact that one type of ion with mass \( m \) interacts with atoms and molecules of different compounds should be taken into account [4].

**Diffusion**

In the absence of electric field, a localised distribution of ions thermally diffuses in a symmetric way via multiple collisions with the medium components. Their distribution in space follows a Gaussian law, as shown in Eq. (3.7), where \( dN/N \) is the fraction of the charge which is found in the element \( dx \) at a distance \( x \) after a time \( t \) while \( D \) denotes the diffusion coefficient. The standard deviation of Eq. (3.7) gives an estimate of the ion diffusion yielding \( \sigma_x^{\text{ion}} = \sqrt{2Dt} \) in
3.2 Drifting and diffusing ions and electrons inside gas

The case of linear and $\sigma_{x}^{\text{ion}} = \sqrt{6D\tau}$ for the volume diffusion respectively.

$$\frac{dN}{N} (x, t) = \left( \frac{1}{\sqrt{4\pi D\tau}} \right) \exp \left( -\frac{x^2}{2\left( \sqrt{2D\tau} \right)^2} \right) dx$$  \hspace{1cm} (3.7)

Under the influence of an electric field the ions move along the field direction with an average drift velocity $u_d$. In this case the diffusion coefficient $D$ is directly related to the ion mobility $\mu$ via the Einstein relation of Eq. (3.8).

$$\frac{D}{\mu} = \frac{kT}{e}$$  \hspace{1cm} (3.8)

By substituting the diffusion coefficient from the relation of Eq. (3.8) the linear standard deviation at a distance $x$ becomes

$$\sigma_{x}^{\text{ion}} = \sqrt{\frac{2kT x}{eE}}$$  \hspace{1cm} (3.9)

### 3.2.2 Electron mobility

In the case of the electrons the situation is completely different. Due to their smaller mass compared to the ions, the electrons transfer only a small fraction of their energy (almost two orders of magnitude smaller compared to the ions) to the surrounding gas atoms and molecules during their interactions.

**Drift velocity**

In the case of no electric field, a free electron in a gas has a thermal kinetic energy equal to $(3/2) k_B T$. Once the electric field is present, the electron starts to collide with the gas molecules. If the mean free time between two such collisions is $\Delta t$ then the drift velocity can be expressed with the Townsend formulation

$$u_d' = k \frac{eE}{m}$$  \hspace{1cm} (3.10)

where $\tau$ which is the mean free time between two collisions and $k$ is a constant, between 0.75 and 1, depending on the energy distribution of the electrons. The dependence of the velocity on the electric field is much more complicated compared to the ion case since $\tau$ also depends on the gas and the electric field.

The problem of the electron drifting inside a gas medium can also be approached classically. The equation of motion for one electron with mass $m$ moving inside a gas under the presence of magnetic field $B$ and electric field $E$ has been enriched by Langevin [6] with an additional term, equivalent to a friction force. This takes also into account the slow down effect of the electrons coming from their interactions with the gas atoms/molecules as shown in the form

$$m \frac{dv_d}{dt} = e \left( E + v_d^{\text{e}} \times B \right) - \frac{m}{\tau} v_d^{\text{e}}$$  \hspace{1cm} (3.11)

where $-(m/\tau) v_d$ stands for the friction force and $\tau$, the average time between two interactions. Assuming that an electron drifts under constant velocity and in a uniform electric field the drift
velocity for the case of zero magnetic field is simplified in the form of Eq. (3.12) as described in Appendix D. This is in good agreement with Eq. (3.10) assuming again that the mean free time between two collisions \( \tau \) depends on the electric field for the electrons case and that \( k = 1 \).

\[
|e_d^e| = \frac{eE}{m} \tau \tag{3.12}
\]

**Diffusion**

Ionisation electrons rapidly reach thermal equilibrium with the gas molecules in the absence of an electric field. The same diffusion laws described for the ions hold also for the electrons in this case with the electrons diffusing with a correspondingly larger diffusion coefficient because of their smaller mass. With the introduction of an electric field however, except for the case of very small field values, the mobility of the electrons significantly varies with the electric field intensity since their kinetic energy can be substantially increased between collision with the gas atoms/molecules and the standard deviation \( \sigma_x^e \) starts to deviate from the \( 1/\sqrt{E} \) behaviour that has been observed for the ions. The extent of diffusion now depends on the gas as well as on the electric field. This dependence can be included in Eq. (3.8) for the case of the electrons by replacing the thermal energy term with an empirical factor \( \epsilon_k \) called characteristic energy as in Eq. (3.13).

\[
\frac{D}{\mu} = \frac{\epsilon_k}{e} \tag{3.13}
\]

The linear space diffusion for the case of the electrons in high electric field will then be written in the form of Eq. (3.14) where \( \epsilon_k \) depends on the gas and the electric field. In addition and in contrast with the classical consideration, it has been observed that for several gases (i.e. Ar) the electron diffusion coefficient is not uniform in all directions at high electric fields. In these cases, two diffusion coefficients, one along the drift direction and one along the direction transverse to it, must be considered.

\[
\sigma_x^e = \sqrt{\frac{2\epsilon_k}{eE}} \tag{3.14}
\]

### 3.2.3 Electron attachment and ion recombination

While drifting and interacting with the gas atoms under the influence of the applied electric field, the ionisation electrons can also be "captured" by neutral gas molecules forming negative ions \cite{7}. However, the probability of the electron attachment is significant for specific electro-negative gas species, like Oxygen, while hydrocarbon and noble gases are characterised by relatively low electron attachment coefficients.

In addition to the electron attachment effect, collisions between positive ions and free electrons or negative ions may result in their neutralisation \cite{8}. The positive ion can possibly capture the free electron or the extra electron of the negative ion becomes neutralised (recombination). The recombination cross-section is normally orders of magnitude larger between positive and negative ions compared to the one between positive ions and electrons. In either recombination instance, unlike the electron attachment case, the charge represented by the original electron-ion pair is lost. In order to minimise the recombination effect, the ionisation charge separation and collection should be as rapid as possible thus high electric fields help towards this direction.
3.3 Avalanche and signal formation

Under the influence of a strong electric force, the ionisation electrons can gain sufficient kinetic energy to further ionise neutral gas molecules resulting in secondary ionisations. The secondary electrons are also subject to the same process and higher-order ionisations with the multiplication process taking the form of a cascade which is known as the Townsend avalanche [9]. Since the electrons drift significantly faster compared to the positive ions a drop-like shaped avalanche is formed where electrons occupy the head of the drop, facing the anode, with a slow ion tail.

The number of secondary ion pairs produced per unit length of drift is equivalent to a multiplication factor which is called the first Townsend coefficient \( \alpha = 1/\lambda \), where \( \lambda \) is the mean free path of the ionisation electron as defined in Eq. (3.1). In reality however, the electric field is not uniform, thus \( \alpha = \alpha(x) \). An initial population of electrons \( n_e \) will be multiplied after a path of distance \( dx \) into \( dn_e \) electrons and the multiplied number of electrons for a given path \( x_1 \to x_2 \) is given by Eq. (3.15) where \( n_0 \) is the number of electrons at \( x = 0 \) and \( n \) is the total number of secondary electron-ion pairs produced within the detector volume. The multiplication factor (gain) is then given by the ratio between the final and the initial electron population, \( G = n/n_0 \).

\[
\frac{dn_e}{n_e} = n_e \alpha dx \Rightarrow n_e = n_0 \exp \left( \int_{x_1}^{x_2} \alpha (x) dx \right) \tag{3.15}
\]

These considerations hold only for the expression of the average avalanche development. The electron-atom interactions are dominated by statistical fluctuations and as a result the avalanche size should follow a probability distribution. Depending only on the Townsend coefficient and the electric field the probability of having \( n \) electrons after a path \( x \) for an avalanche initiated by one electron can be expressed by the Furry’s law expressed in Eq. (3.16) where the probability decreases exponentially for increasing \( n \) having the maximum at \( n = 1 \). Moreover, it has been observed experimentally that the electrons, under the influence of very intense electric field, use a significant fraction of their path to reach the energy state that can produce ionisations, thus the exponential (3.16) evolves into a peaked distribution known as Polya [10].

\[
P(n, x) = \frac{\exp(-n/\bar{n})}{\bar{n}} \quad \bar{n} = \exp(-\alpha x) \text{ is the average avalanche size} \tag{3.16}
\]

Apart from the direct secondary ionisations, provoked by the primary electrons, additional effects can contribute to the multiplication process. Depending on the gas mixture the energy excess of an excited state of a molecule or atom may be sufficient to satisfy the ionisation potential of a neutral gas molecule. The interaction between the two results in the ionisation of the molecule yielding an ion, an electron, and a neutral gas molecule (Penning effect [11]). In addition to this, during the multiplication process there can be gas molecules left in an excited state from their interaction with the ionisation electrons. These decay to their ground state through the emission of visible or ultra-violet photons which consequently provoke secondary ionisations. All these second or higher-order processes result in spreading the charge over the avalanche area. The temporary space-charge distributions formed in the avalanche region locally distort the electric field. In case of large ionisation charges the enhanced field distortions along the avalanche result in a forward and backward propagation of secondary ionisation charges evolving it into a streamer [5]. If not mitigated by a lower electric field or by the detector geometry the streamer continues to prolong reaching the detector’s electrodes and consequently
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leading to a discharge\(^2\) (spark). Raether [12] has calculated a phenomenological limit for the total avalanche size \(\sim 10^8\) above which the proportional multiplication of the ionisation charge results in a breakdown. However, the gain fluctuations that can be observed in gaseous proportional counters result in an effective multiplication limit of \(\sim 10^6\) before the discharges occur.

In order to control the secondary ionisations coming from the excitation photons, so that the multiplication factor stays safely below the Raether limit, a small amount of poly-atomic gas is added in the gas mixture. The atoms of the so-called quencher, absorb the photons suppressing the photon-induced secondary ionisations.

The motion of the avalanche products gives rise to electrical signals on the detector electrodes. Electrons and positive ions drift towards opposite directions with different speeds and as a consequence, they induce signals with very different characteristics. Depending on the detector and the electric field configuration, the secondary electrons reach the anode within a few nanoseconds (in most cases less than \(\sim 1\) ns) resulting in a very fast signal pulses. On the other hand, the positive ions drift with a velocity hundreds of times smaller in magnitude compared to the electrons and the resulting signal has a long tail with several hundred nanoseconds duration. In theory, the move of an electron/ion induces signals on all the electrode elements with the signal characteristics depending on the electric field lines and the relative position of the moving charge with respect to the electrode element. In a simplified scheme with a point charge moving in the vicinity of grounded electrodes, the induced current in each electrode will be given by Shockley-Ramo’s [13, 14] theorem

\[
I_n(t) = -\frac{q}{V_w}E_n[x(t)] \cdot u(t)
\]

where \(E_n[x(t)] = -\nabla \psi_n[x(t)]\) is the weighting field, \(\psi_n[x(t)]\) the weighting potential of electrode \(n\) and \(u(t)\) is the drift velocity of the point charge. Applications of the generic theorem in specific detector geometries are discussed in [15].

3.4 Gaseous Detectors

The gaseous detectors have been employed and operated in various applications and experiments with very successful results over the last century. Despite the great diversity in the designs they are all based on the same principle of operation:

*The incoming particle’s interaction with the gas molecules liberates electron-ion pairs that are multiplied, with the application of an electric field and are then transformed into measurable signal.*

The differences between various types of gas counters with respect to their operation voltage are illustrated in Fig. 3.1. The number of ion pairs, equivalent to the detected pulse amplitude, is plotted as a function of the electric field for two different types of radiation.

\(^2\)The discharges pose a significant rate limitation for the gaseous detectors and they may harm the detector structure and/or the readout electronics. As will be discussed in Sec. 3.4 the tolerability to sparks is prerequisite for the development of novel gaseous detectors for use in high particle rate environments.
In the region of weak fields (I), the recombination of the ionisation products dominates as the applied voltage is not sufficient to drift electrons and ions away from their point of creation before their reattachment takes place. The recombination is suppressed by increasing the applied voltage and most of the ionisation charge can be detected. This region (II) is the normal operation mode for the ionisation chambers. By further increasing the applied field intensity the ionisation electrons are able to gain significant energy to produce secondary ionisations and multiplication starts to occur increasing the number of ions detected by raising the applied voltage. This is the operation region (III) suitable for proportional counters, that will be described in the next sections (MWPC, MSGC, MicroMeGas) and are based on the internal amplification of the ionisation signal. By increasing the electric field further the linear proportionality between collected charge and electric field intensity is lost owing to the large number of ions that are produced during the multiplication phase. If the ion concentration is sufficiently high they form a space charge and the electric field is locally distorted introducing nonlinearities. At a very intense electric field, the positive ion space charge becomes completely dominant and the induced pulse is of the same amplitude independently of the voltage value. This (IV) is called the Geiger-Müller region of operation. By increasing the field further (V) the discharges dominate the gas detector operation.

**Figure 3.1:** The ionisation charge (equivalent to the pulse amplitude) as a function of the applied high voltage for two different types of radiation (different amounts of released energy within the gas). The different operating regions of gaseous detectors are noted (I,II,III,IV,V).
3.4.1 Multi-Wire Proportional Chamber

In 1968 the invention of the Multi-Wire Proportional Chamber (MWPC) [16] revolutionised the field of gaseous detectors and served as a base design for the drift and TPC chambers that have been employed by several experiments over the past decades. It consists of a set of parallel, evenly spaced wires made of stainless steel that are stretched and enclosed in the middle between two cathode planes. A graphical representation of the MWPC structure is given in Fig. 3.2 (left). By applying a potential difference between the anode wires and the cathodes an almost uniform electric field is formed along the full volume of the detector. In the vicinity of the wires the density of the field lines increases and these areas can serve as multiplication regions. Fig. 3.2 illustrates the equipotential and field lines for a region extending up to ~2 mm away from the wires. The ionisation electrons, liberated by the passage of a charged particle through the detector, drift along the field lines approaching the high field region, close to the anode wires, where avalanche multiplication occurs within a fraction of a ns. A large pulse of negative-polarity is induced on the anode from which the avalanche is collected, while the neighbouring wires develop smaller positive pulses.

The accuracy of an ionisation event localisation, using a digital readout of the anodes, is mainly dependent on the wire spacing which is typically in the mm scale. The cathode planes can also be fabricated in the form of isolated readout elements (strips). By using the positive charge signals of the fine-segmented cathodes and performing a charge interpolation, a position reconstruction accuracy of ~50 µm can be achieved for tracks perpendicular to the wire plane. Moreover, depending on the orientation of the cathode strips a two dimensional localisation of the ionisation event is possible.

The slow drift of the positive ions that are produced during the multiplication procedure result in a (particle) rate-dependent accumulation of positive space-charge in the detector volume. The distortion of the electric field results in a reduction of the effective detector gain and degrades the detector’s performance (spatial resolution, efficiency). As illustrated in Fig. 3.3 the gain of an MWPC starts to decrease at particle rates above $10^3 \text{mm}^{-2}\text{s}^{-1}$ because of the space-charge formation. The rate capability of the MWPC appears to be orders of magnitude inferior to two other micro-pattern detector technologies and this fact along with the constraint imposed by the technical difficulty to produce MWPCs with sub-mm wire spacing were the key factors that led to the rise of the next generation gaseous detectors that are described in the following sections.
3.5 Micro-Pattern Gas Detectors

In spite of their popularity, the operation capability and performance of the classical gaseous detectors are limited from the coarse readout granularity and space-charge effects that provoke non-uniformities of the gain inside the chamber’s active volume.

The advances in the photolithographic technology have led to the rise of the novel Micro-Pattern species of the gaseous detectors. Revolutionary microelectronic fabrication procedures, that have been widely used for the production of semi-conductor (silicon) detectors since 1980’s [19], can be also employed for the realisation of extra fine-segmented gas amplification structures. As a result, the readout granularity is improved by almost an order of magnitude providing excellent spatial resolution (< 100 µm) and intrinsic high-rate capability (up to 100 kHz/cm²). In addition, the thickness of the multiplication region can be scaled down to tens of microns, allowing the use of significantly lower voltage, compared to the classical gaseous chambers, while the timing resolution reaches the ns range.

A brief overview of the MPGD detector technology will be given in this section focusing mainly on the Micromegas detector that is the main subject of this thesis. The basic structural and operational parameters of the Micromegas will be described leading to the specifications of the Micromegas modules for the ATLAS New Small Wheel project.

**Figure 3.3:** Comparison of the normalised gain (with a fixed multiplication factor of $10^5$) as a function of the particle rate between the MWPC and two detectors of the MPGD family that are described in Sec. 3.5. The plot is taken from [18].
3.5.1 The Micro-Strip Gas Chamber

The first prototype of the MPGD concept has been the Micro-strip Gas Chamber (MSGC) invented in 1985 \[\text{[20]}\]. A set of consecutive parallel metal strips is formed on top of a thin insulating substrate exploiting the modern photolithography technology. The strips, that can be scalped to be extremely fine (order of $10 \, \mu m$), can all serve as the detector anodes with separate continuous cathodes developed on the substrate or can be alternately connected to the voltage supply as anodes and cathodes. The rear side, opposite to the drift electrode, can also be equipped with an electrode (usually referred to as the “back-plane”) which can be either continuous or segmented to perform two-dimensional localisation. Figure 3.4 (left) shows the equipotential and electric field lines in the vicinity of the strips for the alternate configuration using also the back-plane electrode. By keeping the anodes and the back-plane at equal potentials all the field lines from the drift volume terminate on the anode allowing for the full collection of the ionisation electrons.

![Figure 3.4](image)

**Figure 3.4:** Left: The electric field lines of a MSGC. The back-plane is kept at the same voltage as the cathodes, alternating with the anode strips, ensuring full efficiency in the collection of ionisation electrons \[\text{[21]}\]. Right: In the high fields and narrow gaps, typical of MSGC, discharges occur that damage the fragile readout structure. Strips damaged by sparks are shown in the top photo \[\text{[22]}\]. Optical investigation of MSGC elements, using a microscope, are shown in the bottom photos. The long-term irradiation (total accumulated charge of $2 \, \text{mC/cm}$ using a proton beam) revealed the deposition of a Carbon layer, $80 \, \text{nm}$ thick, on the anodes of the irradiated area \[\text{[23]}\].

Despite their promising performance, the medium and long-term stability of the MSGC detectors when it comes to large multiplication settings and high particle rates cannot be guaranteed. Owing to the fragile strip structure the detector turned out to be extremely sensitive to sparks by heavily ionizing particles that can damage the readout layer in an irreversible way \[\text{[23]}\]. Moreover, the MSGC is prone to operational instabilities introduced by the charging-up of the resistive substrate and polymerisation (aging) at long-term irradiation \[\text{[24]}\]. Examples of damage caused by discharges and aging observations are illustrated in Fig. 3.4 (right). These limitations have given rise to quests for more reliable and high rate tolerant devices that could exploit the promising performance characteristics of the early MPGD designs.
3.5.2 The Gas Electron Multiplier

In 1997 the Gas Electron Multiplier (GEM) was added in the MPGD family [25]. It consists of a thin (typically 50 µm) polymer (Kapton) foil metal-coated on both sides that is perforated with chemical etching or other photolithographic processes to acquire a high density of holes. The hole diameter is typically between 25 µm and 150 µm and the distance between the holes varies from 50 µm up to 200 µm. The GEM foil is enclosed between a drift and a collection electrode. By applying a suitable scheme of electrode voltages, the ionisation electrons are forced to drift through the GEM holes. A voltage difference is also applied between the two metallic surfaces of the foil creating an intense electric field (typically ~ 50 kV/cm) within each of the holes. A graphical representation of the electric field and equipotential lines in a GEM hole is illustrated in Fig. 3.5 (left). The very high electric field inside the GEM openings transforms them into amplification regions, as can be seen in the simulation result of Fig. 3.5 (right). Most of the electrons are transferred to the gap below the foil inducing current (pulse) on the readout elements of the completely decoupled anode electrode.

![Figure 3.5: Left: Equipotentials and electric field lines in the holes of the GEM foil [21]. Right: Simulation (with Garfield [26] and Magboltz [27]) of the multiplication electrons/ions drifting paths for two primary ionisation electrons that arrive in the GEM hole. Electron paths are shown with light yellow lines, ion paths as dark red lines and the green spots mark places where ionisation processes have occurred [28].](image)

The diameter and shape with which the holes are shaped on the foil have a direct impact on the performance and long-term stability and operation of a detector. To ensure high gains, it has been found that the optimum hole diameter should be comparable to the foil thickness [29]. An image of a GEM foil acquired with an electron microscope is shown in Fig. 3.6 (left). Moreover, in order to achieve gains suitable for efficient detection of minimum ionizing particles, several GEM amplification stages can be cascaded in a single detector. This allows for the operation of the detector with much lower voltages over each GEM foil achieving the equivalent gains with a standard single GEM. In addition the multi-stage amplification reduces the probability of a gas discharge in presence of heavily ionizing radiation by orders of magnitude. A sketch of a triple GEM with a two-dimensional readout is shown in Fig. 3.6 (right). Such detectors are employed for tracking in the COMPASS experiment [30, 31] at CERN and served also as reference chambers in the test beam data analysis that will be discussed in Sec. 7.3.
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Figure 3.6: Left: An electron microscope photo of a GEM foil [21]. The foil 70 µm diameter holes are formed with a pitch of 140 µm. Right: Graphical representation of a triple GEM detector with a two-dimensional readout based on strips [32]. For the COMPASS GEMs a conversion gap of 3 mm and gaps between GEM foils and the readout anode of 2 mm are used.

3.5.3 The MICROMEsh GAseous Structure

The Micromegas detector, an abbreviation for MICRO MEsh GAseous Structure (MM), was introduced in the middle of the 1990’s [33]. The MM is an MPGD characterised mainly by its two very asymmetric regions. Standard MM detectors consist of a planar (drift) electrode, a gas gap of a few millimeters thickness acting as conversion and drift region, and a thin metallic mesh at typically 100 – 150 µm distance from the readout electrode, creating the amplification region. A structure of cylindrical spacers (pillars), made of insulating material and placed with a pitch of a few mm, defines the height of the amplification region. The typical internal structure and operational parameters of a MM are shown in Figure 3.7. The electric field in the drift region is defined by the high voltage that is applied on the drift electrode and the mesh while the HV potentials are chosen such that the electric field in the drift region is a few hundred V/cm and 40–50 kV/cm in the amplification region achieving gas gain values of the order of $10^4$.

Charged particles traversing the drift space ionise the gas and the electrons, liberated by the ionisation process, drift towards the mesh (in tens of nanoseconds). With an electric field in the amplification region 50 – 100 times stronger than the drift field, the mesh is transparent to more than 95 % of the electrons. The electron avalanche takes place in the thin amplification region in about a nanosecond, resulting in a fast pulse on the readout strip. The ions that are produced in the avalanche process move towards the mesh with velocities about 200 times slower than the electrons. The drifting of the electrons and the avalanche formation in the amplification region for perpendicular and inclined, with respect to the chamber plane, tracks is illustrated in Fig. 3.7.

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$^3$Initially designed as a metallic (copper or Nickel) foil with holes of $\sim$ 50 µm diameter

$^4$The electron transparency of the mesh highly depends on the mesh characteristics and the ratio of the drift and amplification electric fields.
Figure 3.7: Graphical representation of a standard MM cross-section illustrating the different parts of the MM internal structure and its principle of operation.

Because of the very thin amplification region, even with the application of reasonable voltage, very large amplification (order of $10^4$) can be achieved. Moreover, the vast majority of the slow positive ions created in the amplification region are rapidly collected by the mesh allowing for rapid recovery from space charge effects and making the detector tolerant to high particle fluxes with a rate capability exceeding by far its predecessors (Fig. 3.3). As far as the performance is concerned, the MM is characterised by good energy resolution provided by the uniform and high gain in the amplification region. Depending on the granularity of the readout elements and the electronics that are employed for the signal acquisition and processing, superb spatial resolution can be reached [34].

The bulk MM

A novel technique to manufacture the MM structure called "bulk" has been introduced in 2006 [35]. This simple and low cost industrial fabrication process based on the Printed Circuit Board (PCB), an FR4 plane with printed copper anode strips, is employed to produce the entire sensitive detector from the readout layer up to the micromesh. The main pros of the bulk technique are low cost, robustness of the electrode materials and possibility to extend it for large area MM detectors.

A photo-resistive film (e.g. DuPont™ Vacrel®8100) is laminated on the top of the PCB. A pre-stretched woven micromesh made of stainless steel along with an additional photo-resistive film are then put on top of the anode structure and are laminated together forming a single object. The cylindrical spacers (pillars), defining the height of the amplification region, are etched by photolithography. The PCB readout pattern along with the dimensions and separation distances of the mesh wires and the pillars are tunable parameters depending on the detector needs. A photo of a bulk MM acquired during the detector5 assembly procedure is illustrated in Fig. 3.8. The $10 \times 10 \text{cm}^2$ active area of the detector covers a square region in the middle part of the PCB.

5The detector is property of the National Technical University of Athens HEP group [36] and has been fabricated in the CERN PCB workshop [37]. It is actually a bulk MM built with the resistive strip technology that is described in Sec. 3.5.3.
The stainless steel mesh (with a density of 403 lpi\textsuperscript{6}) is embedded inside the pill structure that for this specific case were patterned with a diameter of 0.5 mm and a pitch of 5 mm. A close photo in the region of a pillar, taken with a microscope, is also shown in the same figure where the almost perfect circular profile of the pillar is revealed. The woven micro-structure of the mesh can also be distinguished from the microscope photo even in the pillar region where the wires are embedded inside the transparent photo-resistive film.

The last part of the MM structure is the drift electrode. It is made of stainless steel woven mesh, similar to the micromesh, that is attached to an FR4 frame of 2.5 mm thickness defining the minimum drift gap. It is then installed on top of the bulk structure with additional spacers on the edges employed to extend the drift region to the desirable thickness. Photos of the drift plane and the drift mesh structure are illustrated in Fig. 3.9. A small residue of the drift mesh wire sticking out of the FR4 frame is visible on the right picture taken using a microscope.

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\textsuperscript{6}Density unit corresponding to lines (wires) per inch.
MM with resistive strips

In spite of the excellent characteristics of the MM technology and the promising industrial bulk fabrication procedure, the very thin amplification region along with the finely sculpted readout structure makes them particularly vulnerable to discharges (sparks). As has already been discussed in Sec. 3.3 sparks occur when the electron avalanche population goes beyond $\sim 10^6$. Since, high detection efficiency for MIPs (e.g. muons) requires gas amplification factors of the order of $10^4$, ionisation processes producing more than a few thousand electrons over very short distances imply the risk of sparking for the MM detectors.

In 2008 an R&D activity, called Muon ATLAS MicroMegas Activity (MAMMA) [38], was initiated to explore the potential of the MM technology for its use in LHC detectors and in particular for the NSW project of the ATLAS muon spectrometer (Sec.1.4). In the NSW region of the ATLAS muon system during the LHC Run-2 and beyond, particle rates of the order of $15\text{kHz/cm}^2$ are expected, with more than 70% coming from hadron (protons and neutrons) and photon interactions that lead to large energy depositions. This radiation harsh environment increases the risk of sparking for the MM operated at high gas multiplication values. Sparks may damage the detector elements and the readout electronics, leading to large dead times as a result of the high voltage breakdown. The chosen spark protection scheme for the MMs employs a layer of resistive strips above the readout strips making the detectors spark resistant while maintaining their ability to measure MIPs with excellent precision in high-rate environments. The concept of the resistive strip MM [39] is schematically described in Fig. 3.10. The signals from the electron-ion movement are now induced on the resistive strips and are then capacitively coupled to the readout strips.

![Figure 3.10: Graphical representation of a resistive MM cross-section illustrating the different parts of the MM internal structure and its principle of operation.](image)

A thin (50 – 70 $\mu$m thick) layer of insulator (photo-resistive coverlay or Kapton) with strips of resistive paste with a resistivity of a few M$\Omega$/cm to a few tens of M$\Omega$/cm is created. The development of the resistive strip pattern can be realised either with the conventional screen printing technique, or via the novel carbon-sputtering method [41]. Geometrically, the $\sim$
30–60 µm thick resistive strips pattern matches the geometry of the readout strips. They are connected at one end through a 15–50 MΩ resistor to the detector ground or high voltage and are electrically isolated from the readout strips. A schematic representation of the resistive strip concept is illustrated in Fig. 3.11 (left). The fabrication process of the resistive strip MM is described in Fig. 3.11 (right) that shows the extra steps added to the bulk procedure for integrating the resistive strip foil in the bulk structure.

**Figure 3.11:** Left: Sketch of the resistive-strip MM principle illustrating the resistive protection scheme from the view orthogonal to the strip direction (taken from [39]). Right: The different steps of the fabrication procedure for the resistive strip MM (taken from [42]).

In the event of a spark the resistive strip charges up and the discharge current flows through the resistive strip to ground. Typical spark signals, directly measured through 50 Ω on the readout strips, are shown in Fig. 3.12 for a standard (non-resistive) on the left and a resistive (45 MΩ resistor and 5 MΩ/cm strip resistance) MM on the right. The spark amplitudes in the resistive MM are reduced by an order of magnitude compared to the MM without resistive-strip protection. Moreover, the discharge is recovered much faster (~1 µs) in the resistive MM and the dead time caused by the spark is greatly reduced by the resistive-strip protection scheme. The choice of a segmented resistive protection instead of a continuous layer has several advantages:

- The segmentation keeps the area affected from the discharge as small as possible and doesn’t permit the charge spreading across several readout strips maintaining the high rate capability of the detector.

- With the use of narrow resistive strips, with a relatively low surface resistive in the order of 100 kΩ/Ω, a high local resistivity of several MΩ/cm is achieved.

they are characterised by excellent precision and uniform resistivity however the production cost is significantly higher compared to the screen-printing [40].
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Figure 3.12: Spark signals, as recorded with an oscilloscope terminated with a 50Ω resistor, for a non-resistive [43] (left) and a resistive [39] (right) MM. The different colours correspond to different spark signals plotted on top of each other. Note that the axes in the two plots have different scales.

A comparison between a resistive MM (15 MΩ resistor and 2 MΩ/cm strip resistance) and a standard MM chamber was also done by exposing them to a beam of 5.5 MeV neutrons with a flux of $10^6$ Hz/cm². The chambers were operated with the same electronics and the same Ar+15%CO₂ gas mixtures. The high voltage and the current readings, that were constantly monitored and recorded, over a period of 1.5 h are shown in Fig. 3.13. The steps in the voltage value correspond to changes in the amplification field (voltage applied to the mesh) that were applied simultaneously for the two chambers. Although the two chambers are not characterised by the same gain (20 – 25 V higher field needed for the resistive MM to reach the same gain as the standard MM) the difference in the voltage drop and the current amplitudes illustrate the tolerability of the resistive MM to sparks. During the same test, gas mixes with different ratios of Ar and CO₂ have been compared with the 93:7 concentration showing a spark rate reduced by a factor five compared to the 85:15 mixture with largest amount of quenching gas. The detailed results on the neutron test are discussed in [44].

Figure 3.13: The monitored mesh high voltage and current as a function of time for a non-resistive (left) and a resistive (right) MM that were operated in a neutron beam with a flux of $10^6$ Hz/cm² [44].
High rate capability and aging properties

The initial tests of the resistive-strip protection scheme have demonstrated the tolerability of the resistive MM detectors to sparks extending their excellent performance and functionality even for the extremely high rates expected in the ATLAS NSW region. However, in order to fully qualify the protection scheme for the NSW MM chambers extensive high rate and aging tests of small $10 \times 10 \text{ cm}^2$ resistive-strip MMs have been performed in the ATLAS cavern and at CEA Saclay/CERN respectively.

In order to test resistive-strip MM detectors under realistic LHC conditions five small chambers were installed in the ATLAS detector and operated parasitically for one year (2012-2013). The chambers were triggered and read out standalone and the high voltage and current values were constantly monitored. From the reconstructed hits that were recorded, the particle hit could be extracted, which for the case of the MM that was installed in front of the ATLAS electromagnetic end-cap calorimeter (referred to as MBT), was about $70 \text{ kHz/cm}^2$ for an ATLAS luminosity of $5 \times 10^{33} \text{ cm}^{-2}\text{s}^{-1}$ \cite{45}. By analysing the high voltage/current data a strong linear correlation between the ATLAS luminosity and the current drawn by the MM detectors has been observed. Correlation plots between the measured current of the MBT chamber and the ATLAS luminosity for one day of data taking are presented in Fig. 3.14. This leads to the conclusion that it could even be possible to use the micromegas detectors to monitor the LHC luminosity in the ATLAS cavern with a very good accuracy \cite{46}. The measurement also proves that the resistive-strip MM chamber show no evidence of aging as there is a linear relationship between the current drawn and the ATLAS luminosity even for the highest luminosity values. The total accumulated charge\textsuperscript{9} by the MBT chamber during the whole data taking adds up to about $1.2 \text{ C}$ or $0.03 \text{ C/cm}^2$ with no sign of degradation observed in the chamber’s performance.

\textbf{Figure 3.14:} Left: The MBT current (red points) and the ATLAS luminosity (black line) as a function of time for one day of data taking. Left: Correlation plot of the MBT current versus the ATLAS luminosity. The blue line is a linear fit to the data. The plots are taken from \cite{46}

\textsuperscript{9}This charge is equivalent to six years of operating the MM in the NSW at a luminosity of $\mathcal{L} = 5 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$.

In parallel to the tests in the ATLAS cavern, another small resistive-strip MM (referred to as R17a) was put into extensive irradiation tests at CEA Saclay during 2012 \cite{47}. The chamber...
was accordingly exposed to 8 keV X-rays, thermal neutrons, gamma rays of 1 MeV and alpha particles. The total accumulated charge during each of these exposure periods along with its equivalency in years of operation with the maximum particle rate expected in the NSW during HL-LHC (for an expected luminosity of $\mathcal{L} = 5 \times 10^{34}$ cm$^{-2}$s$^{-1}$) is listed in Table 3.1. The chamber was then tested in a pion beam at CERN along with a second twin MM (referred to as R17b) that has not been irradiated to serve as a reference. Figure 3.15 shows the measured efficiency and spatial resolution of the two chambers as a function of the gas gain and the amplification voltage respectively. An almost similar performance is measured for both chambers, irradiated (R17a) and non-irradiated one (R17b) with no sign of degradation due to aging observed.

### Table 3.1: Total accumulated charge and HL-LHC equivalent time during aging tests of a small resistive-strip MM detector. The table is taken from [48].

<table>
<thead>
<tr>
<th>Source</th>
<th>Accumulated Charge (mC/cm$^2$)</th>
<th>HL-LHC/Spark Equivalent</th>
</tr>
</thead>
<tbody>
<tr>
<td>X-Ray</td>
<td>225</td>
<td>5 years</td>
</tr>
<tr>
<td>X-Neutron</td>
<td>0.5</td>
<td>10 years</td>
</tr>
<tr>
<td>Gamma</td>
<td>14.84</td>
<td>10 years</td>
</tr>
<tr>
<td>Alpha</td>
<td>2.4</td>
<td>$5 \times 10^8$ sparks</td>
</tr>
</tbody>
</table>

**Figure 3.15:** Measured efficiency and spatial resolution as a function of the absolute gain and amplification voltage for the irradiated (R17a) and non-irradiated (R17b) resistive-strip MM. The plots are taken from [47].

**Resistive MM detectors with multidimensional readout**

The resistive strips concept can also be expanded to MM chambers with multiple readout layers. An example of a resistive MM featuring a two-dimensional readout is shown in Fig. 3.16. A second layer (called Y layer) of readout strips is built on top of a conventional MM readout PCB (copper strips 150 µm wide printed with a pitch of 250 µm called X layer) with the two layers separated by 70 µm of insulating FR4 material. The strips of the upper layer are orientated perpendicularly to the ones of the bottom layer enabling a two-dimensional hit identification using a single MM chamber. Since the signal is capacitively coupled from the resistive to the readout strips a smaller, compared to the X, width of 80 µm is used for the Y layer strips to compensate for the smaller capacitance (larger distance) between X readout and resistive strips.
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Figure 3.16: Cross section of a resistive MM with two-dimensional readout. An additional layer of copper readout strips is intersected between the parallel readout and resistive strips layers with elements oriented perpendicularly with respect to the other two.

A comparison of the signal characteristics between the two readout layers is described in [49]. The multiple readout concept can be expanded to more than two readout layers with some prototype resistive-strip MMs with three-dimensional readout presented in [50]. Performance studies of resistive-strip MM chambers with two-dimensional readout are presented in Chaps. 5 and 7. Although a good two-dimensional reconstruction is required from the NSW MM detectors the multidimensional readout concept has been rejected since it significantly complicates the construction procedure along with the readout of the chambers. A scheme with separate detection layers slightly rotated by a small stereo angle will be implemented.

3.6 The MM modules for the ATLAS NSW

The ATLAS collaboration has decided to equip the new innermost end-cap muon stations with MM detectors under the scope of the NSW project as discussed already in Sec. 1.4. The choice of resistive-strip type of MM is definite since the selected detectors should be capable of tolerating the high rate ($\sim 15 \text{ kHz/cm}^2$) environment of the NSW while in parallel preserving their excellent performance characteristics. However, owing to the functions the NSW MM detectors are expected to carry out and their large area, several custom-made modifications are foreseen on the conventional readout and detector layout. The detailed specifications of the NSW MM detectors are discussed in the next sessions.

3.6.1 NSW MM detector parameters

The different dimensions of the different MM modules (SM1, SM2, LM1, LM2) that have to be built are illustrated in Fig. 3.17 (left) covering a total active area of $\sim 1200 \text{ m}^2$. Depending on the type (large/small sector and radial position) each trapezoidal module consists of several PCBs precisely glued together.

The readout PCB will consist of $0.5 \pm 0.05 \text{ mm}$ thick PCB base material$^{10}$ with thick copper strips

$^{10}$Flame-retardant rated UL 94V-0 laminate halogen-free glass fibre epoxy conforming to L94 according
of $17 \mu m$ height etched via photolithography. The strip width will be $300 \pm 20 \mu m$ for all the modules with a pitch of $425 \pm 20 \mu m$ and $450 \pm 20 \mu m$ for small and large modules respectively. The absolute accuracy of the copper pattern, with respect to the design, must be better than $\pm 30 \mu m$ in the direction perpendicular to the strip length and $\pm 100 \mu m$ along the strip. The layout of the readout PCB boards is illustrated in Fig. 3.17 (right). Each PCB comprises 1023 readout strips with half of them read out on one side and the other half on the opposite side. This anti-symmetric configuration equalises the heat and weight load of the on-detector readout boards on the two sides of the detector while it also leaves some extra space for the placement of supplementary electronics and services. There will be three different types of readout PCBs in each MM module depending on the orientation of the strips. Two will have the strips running perpendicularly to the radial direction (precision strips or $\eta$) while the other two will have the strips tilted by a small stereo angle ($+1.5^\circ$ and $-1.5^\circ$ stereo strips respectively) to allow for the reconstruction of the second coordinate ($\phi$). Drawings of the different types of PCBs along with their relative placement along the beam direction are shown in Fig. 3.17 (right). More details along with validation studies of the stereo readout scheme using a MM quadruplet prototype are presented in Sec. 7.1. The intermediate gap between adjacent PCBs, along the radial direction, will be $400 \mu m$.

![Figure 3.17](image-url)

Figure 3.17: Left: Dimensions of the small and large NSW MM wedges. As the maximum MM PCB width is limited, each MM module layer consists of eight PCBs, three for the outer and five for the inner radius module respectively, precisely stuck together. The figure is taken from [51]. Right: Drawings of the four different readout PCBs that make up one MM module (one PCB per module layer is considered) [52].

For the integration of the resistive layer a procedure similar to the bulk MM fabrication is foreseen. The resistive foils will be composed of a $50 \pm 5 \mu m$ thick DuPont™ Kapton®200EN foil with screen-printed resistive strips, $8 \mu m$ thick, matching the readout strips pattern. The resistive layer will then be glued on the readout PCB using a layer of $25 \mu m$ thick Krempel™ Akaflex®CDF25 glue. The resistive strips are split in two in the middle so that each side has a
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Due to the size limitations in the bulk process production a new construction scheme has been adopted for the NSW MM detectors in which the amplification mesh is no longer integrated in the anode PCB, but it is incorporated in the drift panel. Regarding the mesh material specifications, stainless steel (special corrosion resistant type 304/316) had been selected with 30 ± 2 µm wire diameter and 70 µm wide openings (this is equivalent to 250 ± 3 lpi or to 100 µm wire pitch). The mesh is initially stretched (nominal tension 8N/cm) and glued on an aluminum frame which is then precisely attached to the drift panel. When the readout and the drift panels are assembled together, the mesh is only pressed on the pillars of the readout board in contrast to its lamination in the bulk procedure. This assembly technique is usually referred to as "mechanically floating mesh" and has the obvious advantage that keeps the amplification region accessible in case cleaning or some other after-production intervention is needed. Moreover, the mesh can stretch over several PCBs without creating the dead areas that would be unavoidable if the case of individual bulk PCBs. A graphical representation of the "floating mesh" assembly procedure is shown in Fig. 3.18. It should be noted that this modification results in a larger amplification gap compared to the bulk MM since the embedding of the mesh in the pillars in the bulk results in slightly thinner than 128 µm gap (~100 µm). As a consequence higher amplification voltage is required to achieve equivalent gas gain values.

Figure 3.18: Graphical representation of the "mechanically floating mesh" assembly procedure taken from [53]. In contrast to the "bulk" MM the micro-mesh is integrated in the cathode structure. The mesh is initially stretched and glued on a precise aluminum frame that is then attached to the drift part of the detector. By joining the two parts together the mesh is osculated on the pillars of the readout structure.
3.6 The MM modules for the ATLAS NSW

### 3.6.2 NSW MM multiplet parameters

Each MM module will combine four detection layers (equivalent to four MM gaps). A schematic view of a Micromegas quadruplet is shown in Fig. 3.19 (right) consisting of three drift panels and two readout panels. Readout or cathode PCBs occupy the external faces of intermediate panels, consisting of aluminum honeycomb and aluminum reinforcement bars glued together. The outer layers of one MM quadruplet are two identical one-sided drift panels that carry the drift cathode structure and the integrated micro-mesh on their inward side. One additional double-sided drift panel carries drift cathode and micro-mesh on both sides occupying the middle of the quadruplet. In between the drift panels two double-sided readout panels carry the readout PCB on both sides. One of the two readout panels features two parallel eta-strip readout PCBs while the second one has PCBs with stereo strips tilted by \( \pm 1.5^\circ \), with respect to the eta strips, on each side.

In order to satisfy the ATLAS muon spectrometer performance requirements (10% momentum resolution for 1 TeV muons) the NSW MM multiplets should be capable of measuring the overall muon track position with an accuracy of 30 \( \mu \)m in the radial and 80 \( \mu \)m in the beam direction. In order to satisfy these strict requirements the relative alignment of the two readout panels should be better than 18 \( \mu \)m. During assembly, the five panels will be screwed together using precisely drilled holes and alignment pins. A cutout of a MM quadruplet is shown in the schematic of Fig. 3.19 (left). The foreseen precisely drilled hole, that will guide the alignment pin through the different panels is visible. In the same figure the outer part of the quadruplet’s side can be seen. The space of the extended readout panels will be used for the routing of the service cables and the cooling of the on-chamber electronics that will be placed on the readout PCB surface. In the NSW MM detectors the connection between the readout board and the readout strips will be realised via shoulder-less Zebra [54] connectors. To ensure a good contact between the front-end and the strips a suppression bar, installed on the outer part of the drift panel, will push the readout board (MMFE8 [55]) on the strip pattern.

![Figure 3.19](image)

**Figure 3.19:** Cross-section of a NSW MM module showing the main parts of the quadruplet structure. Left: 3-D drawing of the quadruplet edge showing the guide for the alignment pin and the electronics and services placement on the readout PCB surplus part. Right: The quadruplet internal sequence of readout/drift panels and active volumes with their approximate dimensions along the z direction [51].

In addition to the precise relative alignment and positioning of the various sub-elements in
a single quadruplet, the surface planarity of the readout and drift panels is required also to be controlled with a maximum deviation of 110 µm. One of the main factors contributing to the mechanical deformation of large detector planar surfaces is the effect of the gas pressure. During 2012 a large (1 m²) MM functional prototype has been built and tested at CERN within the Muon Atlas Micromegas Activity [38]. A photo of the L1 chamber installed inside the test beam area at CERN is shown in Fig. 3.20 (left). The chamber has been integrated in the standard MM experimental setup described in Appendix B and was flushed with Ar+7%CO₂ gas at 4 mbar overpressure.¹¹ One of the studies performed during the test beam included a position scan of the L1 chamber, in the direction along the strips, in three different areas with respect to the strip numbering to examine the uniformity of various parameters along the full length of the detector. The measurement of the mean arrival time for the strip¹² with the maximum charge within a cluster as a function of the position along the strip is shown in Fig. 3.20 (right). A clear parabolic effect can be observed for the strips running through the middle area of the detector (black points) with the mean drift time increasing in the middle of the chamber. The same effect cannot be observed for the other two strip regions examined that run close to the chamber edges. This effect is attributed to a mechanical deformation as an effect of the gas overpressure increasing the size of the drift gap in the middle of the chamber. A maximum time difference of ~ 14 ns has been measured which, if translated into distance using the electron drift velocity value (assumed 47 µm/μs for the applied electric field and gas mixture that was used), corresponds to 658 µm maximum deformation. However, this number is overestimated since the increase of the drift gap thickness reduces the local electric field and thus the drift velocity so the actual size of the deformation should be smaller. Some more details regarding the chamber and additional studies can be found in [56].

Figure 3.20: Left: The large MM prototype L1 chamber installed in the test beam area at CERN in 2012. Right: Measurement of the arrival time of the primary cluster with the maximum charge in different positions along a single strip (horizontal scan). The different colours correspond to different groups of strips: black for the strips in the middle of the chamber, green and red for strips in the edges of the chamber.

¹¹A slightly higher gas flow has been used in this test beam to ensure uniform gas concentration in the L1 chamber. The normal operating condition for the NSW MM modules is expected to be ~ 2 mbar.

¹²The estimation of the primary cluster's arrival time for each strips using the APV25 front-end hybrids for the readout is described in Sec. 4.1.
The measured deformation, although slightly exaggerated, far exceeds the planarity deformation tolerance of $110\,\mu\text{m}$. To mitigate this issue a scheme with interconnections between the five panels has been envisaged. The exact positions and numbers of the interconnections is being defined through mechanical simulations as can be seen in Fig. 3.21 (left) while in parallel mechanical prototypes, like the one shown in Fig. 3.21 (right), are being manufactured and tested in order to find the optimal solution.

**Figure 3.21:** The interconnection scheme foreseen for the NSW MM quadruplets to mitigate the mechanical deformations caused by the gas overpressure with screws penetrating the five panels of each quadruplet. Left: A solution scheme with eight interconnections distributed along the surface of a LM1 MM module is studied in simulation of $2\,\text{mbar}$ gas overpressure. Figure taken from [57]. Right: Mechanical prototype of an interconnection screw.


Characterisation of the Micromegas timing performance

Independently of the gaseous detector type (e.g. MPGD) the intrinsic performance characteristics of the detector are primarily determined by the gas mixture and the gap size that are used for the detection of charged particles. The uncertainty in the timing measurement of a MPGD is determined by statistical fluctuations of the induced signal and depends on the arrival time of the earliest primary cluster within a strip. The multiplication factor (gain) also plays a role, since a certain gas amplification level is required for the detector to be sensitive to a single primary cluster. Apart from the ionisation and multiplication statistics the actual measured time depends also on the front-end electronics with the shaping time of the amplifier and the timing resolution of the chip defining the accuracy of the measurement.

Using the standard MM experimental setup in a test beam, as described in Appendix B, the timing performance of small resistive-strip MM chambers has been studied. The chambers were operated with Ar+7%CO₂ gas mixture and read out using APV25 [1] front-end hybrid cards via the SRS [2] system. Studies on the timing information, that can be extracted from a MM chamber, will be discussed primarily focusing on the timing resolution of a single MM detection plane. Similar measurements have been performed using fast gas mixtures and regular gas gains with a GEM detector reporting a timing resolution of the order of 10 ns [3].

4.1 Drift Time Measurement with APV25

A typical distribution of the integrated charge, for a single electronic channel, sampled per time slice over the full sampling phase of the APV25 is shown in Fig. 4.1. Each time sample is 25 ns wide and the duration of the sampling phase is adjustable [4]. For the example that is presented in Fig. 4.1, and for the results that are discussed later in this chapter, the APV25 was configured to run with a range of 18 samples. The y-axis in the same plot corresponds to ADC counts. A measurement of the APV25 gain using the SRS system described in [5] estimates ~ 230 electrons per ADC unit. The analogue-like charge information per electronic channel (strip) can be used for estimating the drift time\(^1\) of the primary cluster, that is created on top of the avalanche formation. As discussed in Sec. 3.5.3 the avalanche formation in a MM with 128 µm thick amplification gap happens within ~ 1 ns while the drifting of the primary electrons towards the mesh takes several

\(^1\)Actually, the measured time is the sum of the drift time and the time needed for the avalanche formation. As discussed in Sec. 3.5.3 the avalanche formation in a MM with 128 µm thick amplification gap happens within ~ 1 ns while the drifting of the primary electrons towards the mesh takes several
the corresponding strip (Fig. 3.7).

![Figure 4.1](image)

**Figure 4.1:** Typical shape of the total integrated charge from one MM strip read out with the APV25 hybrid cards configured to run with 18 time samples. A fit with a Fermi-Dirac function is performed to extract the strip time measurement \( t_{FD} \), which is defined as the inflection point of the fitted function.

For the extraction of the drift time, the integrated charge distribution of each channel is fitted with a Fermi-Dirac function (Eq. 4.1) in its rising part. The different parameters of the function are noted in Fig. 4.1 and the \( \tau \) parameter is proportional to the Fermi-Dirac slope (indicative of the signal’s rise time) measured in units of 25 ns. The Fermi-Dirac inflection point, parameter \( t_{FD} \), is considered equivalent to the drift time measured by the specific channel. Different functions have been also used to describe the integrated charge distribution (i.e. Landau function convoluted with a Gaussian) but the Fermi-Dirac fit appeared to be more robust and insensitive to the saturation\(^2\) of the peak charge value that may occur in the case of a large charge deposition that is amplified by a high gas gain. It is worth mentioning that the pedestal subtraction is done online by the data acquisition software \([6]\). The pedestal charge is calculated per electronic channel (strip) and is then subtracted from the sampled value of each time slice. This allows for negative values of the pedestal subtracted integrated charge distribution.

\[
q(t) = q_{base} + \frac{q_{max}}{1 + e^{-(t-t_{FD})/\tau}}
\]  

(4.1)

Regarding the quality of the time measurement, the Fermi-Dirac fit allows to overcome the sampling uncertainty (25 ns) of the chip\(^3\). However, the time that is extracted from the procedure described above is very much dependent on the fit quality. Not only the fit may fail, in which case the measurement is discarded, but there are also cases where the result is not trustworthy. One such occasion which can be often observed is the case of integrated charge distributions tens of ns.

\(^2\)The dynamic range of the charge measurement per time sample is limited to \( \sim 2000 \) ADC.

\(^3\)The APV25 has not been designed for precise timing measurement and an offline procedure is required to estimate the time from the integrated charge distribution.
with very steep rising edge expanding in three time samples or less. In these cases the fit is not able to follow the sharp rising edge of the distribution resulting in a bad quality ($\chi^2$) fit with a $t_{FD}$ parameter highly dominated by the time discretisation of the time sampling.

An example of a channel charge distribution with a very steep rising is illustrated in the left plot of Fig. 4.2. In order to catch these instances the fit parameter $\tau$ is used which in the case of steep pulses has a very small value. The distribution of the Fermi-Dirac $\tau$ parameter, multiplied by 25 ns, calculated for all the channels of a single MM chamber, inclined by 30° with respect to the beam, over 20000 events of a test beam run is presented in the right plot of Fig.4.2. The main part of the distribution, peaking at $\tau$ value around 13 ns, is spoiled by a few peaks at very small slope values ($\leq 5$).

Another indication of the problematic fits in the cases described above comes directly from the calculated $t_{FD}$ time per channel. The inclusive time distribution ($t_{FD} \times 25 \text{ ns}$) for all the events of one test beam run and all the strips of a single MM chamber is shown in the left plot of Fig. 4.3 with the blue line. The spikes that appear at fixed time intervals of 25 ns, on top of an almost uniform distribution, are an effect of the very steep charge distributions that the fit fails to describe. This is proven in the right contour plot of Fig.4.3 where the times are plotted as a function of the corresponding $\tau$ values. The discretization in the calculated $t_{FD}$ times, corresponding to the spikes of the left distribution, is coming from small $\tau$ values and can be eliminated using a quality selection cut. The resulting inclusive time distribution is superimposed, with the red line, in Fig.4.3 (left).

The dynamic range of the charge measurement in the APV25 corresponds to $\sim 2000$ ADC. Since the MM chambers are operated at high gain (order of $10^4$), in the case of very energetic primary cluster of electrons, the induced charge on the readout strip will saturate the chip's amplifier measurement. The left plot of Fig. 4.4 shows an example of a saturated integrated charge for one APV25 channel. In this case the time sample with the maximum charge has almost the same amplitude as its neighbouring samples resulting in $\sim 3$ time samples with equal charge measurement.
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Characterisation of the Micromegas timing performance

Figure 4.3: Left: The inclusive distribution of the $t_{FD}$ times, for $30^\circ$ track angles, is shown in the left plot with the blue line. Right: The $t_{FD}$ times plotted as a function of the $\tau$ values. The red distribution of the left plot shows the inclusive time distribution after applying a quality cut $\tau > 3$ ns.

The Fermi-Dirac fit is not able to reconstruct the lost charge information and thus the $t_{FD}$ measurement is inaccurate in these cases. Moreover, despite the pedestal subtraction, an additional suppression of noise (low charges) is needed. The vast majority of the channels with very low charge is coming from noise and thus a very loose cut on the channel’s maximum charge is applied to clean our data. An example of a channel’s integrated charge coming from noise and finally discarded from further analysis can be seen in the right plot of Fig. 4.4.

Figure 4.4: Examples of total integrated charge distributions for the case of signals with very large charge amplitude that is saturated (left) and very low charge probably coming from noise (right). The negative charge values are caused by the pedestal subtraction.

The cut on the low-charge signals, except for the noise, discards also good small signals. However, the $t_{FD}$ time that is extracted from the channel’s charge distribution is characterised by a larger fit error and thus contributes to the uncertainty of the timing measurement that will be performed. The distribution of the $t_{FD}$ errors is illustrated in the left plot of Fig. 4.5 showing a peak at values smaller than 1 ns followed by a very large tail. If the $t_{FD}$ errors are plotted as a function of the maximum time bin charge, shown on Fig. 4.5 (right), the tail towards the large error values is significantly anti-correlated (following a simple rational function) with the charge value. Thus, by excluding the strips with very low charges ($q_{max} < 60$ ADC) the $t_{FD}$ values that
4.2 Strip Time Distributions

have a large error are excluded from the consequence processing.

The inclusive time distribution shown in Fig. 4.6, gives an estimate of the maximum and minimum measured arrival time within a MM gas gap. The distribution can be described using Eq. (4.2) which is basically the sum of two Fermi-Dirac functions. The minimum arrival time is given by the fit parameter $p_3$ and the maximum time from $p_5$. The time difference between the maximum and minimum times, extracted from the double Fermi-Dirac fit, are indicative of the MM chamber’s drift gap and the drift velocity of the gas that is used.

\[ F(t) = \frac{p_0}{1 + e^{-t/p_4}} + \frac{p_1}{1 + e^{-(p_5-t)/p_6}} + p_2 \]  

(4.2)

4.2 Strip Time Distributions

Upon the interaction of the charged particle with the gas atoms one or more ionization electrons may be liberated at each encounter depending on the deposited energy. The number of the primary electrons along with their initial position and energy are subject to fluctuations as has been discussed in Sec. 3.1. The ensemble of the ionization electrons per interaction form a primary cluster with each electron drifting individually towards the mesh. Simulation studies
of the Ar+7%CO$_2$ gas mixture yield a mean value of $\sim 17$ primary clusters and a mean value of $\sim 50$ total electrons for 5 mm track length within the gas volume [7].

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure4.6.png}
\caption{The inclusive $t_{FD}$ time distribution fitted with the function of Eq. (4.2). The fit parameters are noted. The MM chamber (T type) was inclined by 37° with respect to the beam axis.}
\end{figure}

Because of the interaction of each ionization electron with the gas atoms the drifting path that it follows is characterised by a certain diffusion uncertainty depending on the gas mixture and the drift electric field that are employed. The resulting signal, that is formed in each readout strip after the multiplication process, is a convolution of the contributions from the drifting of all the primary electrons towards the specific strip. A simplified sketch illustrating the formation and drifting of primary clusters towards the strip anodes is presented in Fig. 4.7.

Depending on the detector’s readout granularity and the distribution of the ionisation collisions along the particle’s trajectory, it may be possible to discriminate consecutive primary clusters. Figure 4.8 shows the distribution of the distance between consecutive primary clusters along the readout direction ($\delta x$) and along the drift gap ($\delta y$) for a simulated 100 GeV/c pion track traversing the chamber under an angle of 10°. Using the mean values of the distributions, $\overline{\delta x} = 64 \mu m$ and $\overline{\delta y} = 358 \mu m$ (equivalent to 6.4 ns), it is evident that the 400 $\mu m$ strip pitch MM detector, read out with the 25 ns sampling of the APV25, is not sensitive to a single primary cluster for the case of 10° track inclination angle.
Figure 4.7: Graphical representation of the primary cluster formation along a charged particle track inside the chamber’s gas volume (not to scale).

Figure 4.8: Distributions of the distance between consecutive primary clusters along the read-out (left) and along the drift gap (right). The plots are produced from the Garfield [8] simulation framework developed for the studies presented in [7].

The same measurement is repeated for 0°, 20° and 30° track angles as well and the evolution of the $\delta x$ and $\delta y$ values with the track angle is illustrated in Fig. 4.9. As expected, the $\delta x$ separation increases for larger track angles, reaching a maximum value of 180 $\mu$m which is still inferior to the strip granularity of the MM chamber under study. On the other hand, the separation along the drift gap direction slightly decreases, with the ratio between the two components being proportional to the track inclination angle $\delta x/\delta y = \tan \theta$. 
The superposition of several primary cluster signals within a single readout strip, along with the primary ionisation fluctuations and the diffusion, pose an intrinsic limit to the single MM timing resolution that is also dependent on the track angle. As described in Sec. 4.1 the drift time extraction using the APV25 front-end electronics is determined by fitting the rising edge of the integrated charge distribution. Thus, in the case where the signal on the readout strip is a convolution of more than one primary cluster or electrons, it is the earliest signal that defines the drift time measurement.

Figure 4.9: Mean distance between consecutive primary clusters for simulated track angles 0°, 10°, 20° and 30°. The blue line represents the mean distance along the readout while the red line stands for the distance along the drift gap. The simulated distributions for 10° tracks are shown in Fig. 4.8.

When a particle traverses the MM active volume, the products of its ionising encounters with the gas molecules induce signals in several strips. These strips are more or less consecutive forming a cluster of strips (not to be confused with the primary ionisation cluster). Using test beam data, for 10° track angles, the distribution of the time measurements as a function of the strip's position within each cluster is reconstructed. The strip numbering inside a cluster, is done such that the first strip is the edge of the cluster in the earliest time region. The strip time distributions for two identical chambers are shown in the two plots of Fig. 4.10. The time measurements are distributed along the x-axis while the z-axis, with values in the range (0 – 10), shows the cluster strip number. Only events with one cluster (single track) of three or more strips are included in the analysis. The individual strip time distributions are Gaussian-like with tails towards smaller or larger time values depending on their position within the cluster. As expected, the peak value moves towards higher times with increasing the strip identification number.

*The ionisation fluctuations and the diffusion combined with the electronic channel thresholds and noise may introduce gaps within the cluster of strips.*
4.2 Strip Time Distributions

**Figure 4.10:** Drift time distributions as a function of the strip’s position within the cluster for two T type MM chambers inclined by $10^\circ$ with respect to the beam axis.

The width of the time distribution of the first cluster strip reveals the fact that the last ionization may occur at different heights within few hundreds of $\mu$m. Moreover, except for the strips in the geometrical middle of the cluster, the distributions are asymmetric. The earliest strips show tails towards larger times while the distributions for the later strips of the cluster have tails towards the earlier time values. These correspond to drift time measurements of primary electrons that their initial position is geometrically attributed to the neighboring strip but due to its motion, which is also affected by the diffusion, induces signal to the strip of interest as well. In addition to this, because of the fine strip pitch, there is a non-negligible charge sharing between neighbouring strips. In the case of strips with capacitively coupled only signal from their neighbours, the time measurement is equivalent to the adjoining strip time. These two effects explain also the tails asymmetry between the earliest and latest edges towards the center of the of the cluster while the timing distribution is much more symmetric for the strips in the middle.

**Figure 4.11:** Drift time distributions as a function of the strip’s position within the cluster for two T type MM chambers inclined by $30^\circ$ with respect to the beam axis.

When the same study is repeated for an inclination angle of $30^\circ$ the contribution of the effects described above in the single strip timing measurement are significantly suppressed. It is evident in Fig. 4.11 that the width of the distributions is much smaller, compared to the $10^\circ$ case, with the cluster size increasing as expected. The tails are also less pronounced for
the larger inclination angle case simply due to the fact that the primary clusters are better distinguishable by the MM readout elements owing to the larger $\Delta x$ distance (Fig. 4.9).

### 4.3 Micromegas Timing Resolution

The timing information that can be extracted from the MM detectors allow for a precise track reconstruction using a single chamber gap as is described in Sec. 5.3, but it can also be employed as trigger primitive according to the application needs. In either case the uncertainty that governs the timing measurement is of primary importance and a series of studies has been devoted in the timing resolution that can be achieved with the current combination of MM chambers and APV25 front-end electronics. For this study a single time measurement in one chamber needs to be compared to a reference time in an event-per-event basis. During a beam test period four identical MM chambers have been employed for the needs of this study thus the single MM timing resolution could be estimated by comparing the measured timing performance in two chambers. Two definitions of the time measurement per chamber are used and compared according to their performance:

- The earliest time in each chamber per event.
- The average time of all the strips in each chamber per event.

All the selection criteria that have been discussed in the previous sections are also used in this study and only single-track events, with at least three strips, are taken into account. The distributions of the earliest and average time measurements, of a single MM chamber, for $10^\circ$ and $30^\circ$ track inclination angles, are shown in Fig.4.12.

**Figure 4.12:** Distributions of the earliest (blue line) and average (red line) time measurements in a MM chamber for $10^\circ$ and $30^\circ$ track inclination angles.

In both cases the earliest time distribution (blue) is much more asymmetric compared to the average one (red). This is justified by the discussion in Sec. 4.2 since the result of the average
time depends on the individual timing measurements of all the strips within the cluster and the asymmetry that is observed at the per-strip distribution is smeared away. On the other hand, the earliest time distribution, for both track angles, looks very similar to the distributions for the first cluster strip that are presented in Figs. 4.10,4.11 respectively proving that in the vast majority of the cases the earliest time recorded is coming from the edge strip of the cluster. It is also evident that the width of both the earliest and the average time distributions becomes smaller with increasing the track angle. A similar effect has also been observed in the comparison between Fig. 4.10 and Fig. 4.11.

For the estimation of the single gap timing resolution the time difference between two MM chambers is measured. The width of the time difference distribution over all the events of a single test beam run will be indicative of the uncertainty included in the time measurement with the current experimental setup. The same technique is applied for both time definitions, earliest (Sec. 4.3.1) and average (Sec. 4.3.2) and the measurement is repeated for different chamber inclination angles (10°, 20°, 30°, 37°) to reveal the dependence of the resolution from the angle of the incoming tracks.

4.3.1 Resolution of the Earliest Time

The distributions of the earliest time difference between two MM chambers divided by \( \sqrt{2} \) are shown in Fig. 4.13 for 10°, 20°, 30° and 37° track angles. The distributions are fitted with double Gaussian functions in order to describe the tails. The \( \sigma \) of the core Gaussian gives an estimate of the intrinsic detector resolution while the tails of the distribution, described by the wider Gaussian, are attributed to additional uncertainty contributions coming from the APV25 chip and the time extraction procedure described in Sec. 4.1. For completeness, in all the cases the \( \sigma \) of the core Gaussian along with the weighted average \( \sigma \) of the two Gaussian functions are quoted. The weighting of the contributions from the two Gaussian functions is based on their integral and is given by Eq. 4.3.

\[
\sigma_{\text{weight}}^2 = f_{\text{core}}\sigma_{\text{core}}^2 + f_{\text{tails}}\sigma_{\text{tails}}^2 \quad f_{\text{core,tails}} = p_{\text{core,tails}}\sigma_{\text{core,tails}}/(p_{\text{core}}\sigma_{\text{core}} + p_{\text{tails}}\sigma_{\text{tails}})
\]

From top to bottom and from left to right each distribution of Fig. 4.13 corresponds to 10°, 20°, 30° and 37° inclination angle respectively. It is evident that the accuracy of the timing measurement is improved at larger track angles with the improvement in the resolution evident not only for the core Gaussian but for the tails as well. The effect of the increasing timing uncertainty for smaller track angles can be attributed to the geometrical effect of overlapping consecutive primary clusters that was described in Sec. 4.1. The distance, along the drift path direction, between two consecutive primary clusters, depends on the track angle as illustrated in Fig. 4.9. Building on that, it can be anticipated that by increasing the angle of the track, the projection of the inter-cluster distance on the readout layer becomes larger while the size of the projection on the perpendicular to the readout axis decreases. This means that there is a higher probability of having consecutive primary clusters separated in different strips at large angles with their distance in time slightly decreasing. In the case of small track angles (e.g. 10°) the number of primary clusters that are created is significantly larger compared to the number of readout strips that populate the footprint of the track and so, the induced signal in one strip is the

---

5 The division by \( \sqrt{2} \) is justified by the assumption that the timing resolution of both chambers that are compared is identical.
combination of several primary cluster signals. The superposition of signals originating from different primary cluster along with the increased distance in time between them account for larger uncertainty in the single strip time measurement and a worse timing resolution.

![Figure 4.13: Distributions of the earliest time difference between two T type MM chambers divided by \( \sqrt{2} \) for track angles 10\(^\circ\), 20\(^\circ\), 30\(^\circ\) and 37\(^\circ\). The distributions are fitted a with a double Gaussian function, also taking into account the tails, and the \( \sigma \) of the core Gaussian as well as the weighted average one are noted.](image)

Figure 4.14 shows the measured timing resolution as a function of the track incident angle for the four different (identical) chamber pairs. The different colours correspond to the different definitions of the resolution depending on the fit parameter that is used (core, weighted, RMS). As expected, the best results in all the cases are obtained from the \( \sigma \) of the core Gaussian function that are represented by the black lines and points. The other two lines that are superimposed on each of the four plots are the weighted \( \sigma \) of the fit and the RMS value of the time difference distribution, that are shown with red and blue colour respectively. The
almost perfect agreement between the RMS and the weighted \( \sigma \) indicates that almost all the time difference histogram entries are within the limits of the fit function and that the weighted \( \sigma \) does not include any bias in the time uncertainty measurement. Moreover, Fig. 4.14 confirms that all the chambers compared are identical and thus the method of extracting the timing uncertainty per plane using two chambers is valid independently of the uncertainty measure that is used (\( \sigma_{\text{core}} \), \( \sigma_{\text{weighted}} \), RMS). It also gives a first evidence that the uncertainty measured with the time difference method does not depend on the distance between the chamber planes compared.

**Figure 4.14:** The measured timing resolution, using the earliest time per detector plane, plotted as a function of the track incident angle for the four possible different chamber pairs. The different colours correspond to different definitions of the timing uncertainty extracted from the \( \sigma \) of the core Gaussian, the weighted \( \sigma \) of the two Gaussian functions and the RMS. These are shown with black, red and blue colour respectively.
4.3.2 Resolution of the Average Time

Instead of the earliest arrival time per event the average time can also be used as the timing merit. In this case the ensemble of points that belong to a reconstructed particle track inside the chamber’s gas gap is used. We have already seen in Fig.4.12 that the cumulative distribution of the weighted time has a smaller RMS value than the one of the earliest time thus a better timing uncertainty is anticipated by combining the timing information of several strips. This improvement is naively expected since the use of multiple time measurements per event decreases the sensitivity of the method to single time measurement fluctuations.

![Comparison of time definitions](image)

**Figure 4.15:** Comparison of the time difference distributions, for a track inclination angle of 20°, calculated using two different time definitions: the earliest time (left) and the average time (right). The σ parameters of the two Gaussian functions as well as the RMS of the histogram indicate the improvement in the timing measurement uncertainty that is achieved by using the average time per chamber plane in the time difference calculation.

The average time difference distribution for the case of 20° inclination angle is shown on the right plot of Fig.4.16. This distribution can be directly compared with the left plot of the same figure which represents the earliest time differences for the same inclination angle. The σ parameter of both Gaussian functions is smaller for the average time case compared to the earliest time resulting also in a smaller weighted σ value.

The comparison of the measured performance between the earliest and the average time as a function of the track incident angle is presented in Fig.4.16. The red lines correspond to the earliest time measurements while the results with the average time are shown with blue colour. For the weighted σ of the double Gaussian fit, that is shown with the full lines, the average time gives a consistently better timing resolution along the different inclination angles reaching values better that 10 ns for the case of 37° inclination. Moreover, the comparison of the core Gaussian width for the two time definitions shows an improvement of the timing resolution when the average time is used. However, the difference between the two dotted lines fades away as the inclination angle increases with almost the same timing resolution measured for the 30° and 37° cases. This indicates that the most significant improvement when using the average time per detector plane is the reduction in the width or the weight of the wide Gaussian.
4.4 Timing from combining multiple MM planes

In all the studies described above the subject has been the timing performance of a single MM detector plane. In a system of multiple detection layers however, the timing information of several layers can be combined to provide a single trigger primitive for the whole system. The effect that the combination of several detection layers has on the earliest time distributions shown in Fig. 4.12 can be predicted theoretically assuming that the earliest (or average) times of a single chamber follow a Gaussian distribution like Eq. (4.4).

\[ f(t) = \frac{1}{\sqrt{2\pi\sigma}} e^{-(t-\mu)^2/2\sigma^2} \]  (4.4)

The cumulative distribution function (cdf) of \( x \) will be given by Eq. (4.5) were \( \text{erf} \) is the error function (also known as the Gauss error function). The cdf of the minimum will then be \( G(x) = 1 - [1 - F(x)]^n \) and the distribution of the combination of \( n \) random values of \( x \), each one following Eq. (4.4), will be described by Eq. (4.6).

\[ F(x) = \int_0^x f(t)dt = \cdots = \frac{1}{2} \left[ \text{erf}\left( \frac{x-\mu}{\sqrt{2\sigma}} \right) + \text{erf}\left( \frac{\mu}{\sqrt{2\sigma}} \right) \right] \]  (4.5)

\[ g(x) = \frac{dG(x)}{dx} = \cdots = \frac{n}{\sqrt{2\pi\sigma}} \left[ 1 - \frac{1}{2} \left( \text{erf} \left( \frac{x-\mu}{\sqrt{2\sigma}} \right) + \text{erf} \left( \frac{\mu}{\sqrt{2\sigma}} \right) \right) \right]^{n-1} e^{-(x-\mu)^2/2\sigma^2} \]  (4.6)

By using Eq. (4.6) the theoretical distribution of the earliest time of all \( n \) stations is reconstructed. The \( \mu \) and \( \sigma \) values are calculated by fitting the earliest time distribution of Fig. 4.12.
(right) with a Gaussian function. The theoretical distributions for different values of \( n = 1, \ldots, 8 \) are shown with different colours in Fig. 4.17. For all the distributions the same \( \mu \) and \( \sigma \) values are used. It can be observed that with increasing the \( n \) value the width of the distribution becomes smaller while its mean value moves towards earlier times.

![Theoretical time distributions](image)

**Figure 4.17:** The theoretically predicted time distributions from Eq. (4.6) for different numbers of detection layers \( n \). The \( \mu \) and \( \sigma \) values are calculated from the earliest time distribution reconstructed from the test beam data for 30° track angles (Fig. 4.12 (right)).

The same exercise is performed using the earliest time distribution of Fig. 4.12 (right) for each of the \( n \) hypothetical detection planes. An ensemble of \( n \) random numbers are extracted from the \( n \) time distributions and the reconstructed distributions of their mean value and their earliest time are illustrated in the left and right plot of Fig. 4.18 respectively. For both combined time definitions the width of the resulting distribution becomes smaller as the number of detection layers \( n \) increases. However, the mean time histograms (left) are much closer to Gaussian distributions compared to the earliest time ones (right). Moreover, while in the earliest time distributions the mean value moves towards smaller times for increasing \( n \), similarly to the theoretical curves of Fig. 4.17, the mean time distributions remain almost perfectly centered along the different \( n \) values.

The theoretical (Fig. 4.17) and experimental (Fig. 4.18) earliest time distributions, for the different \( n \) values are fitted with a Gaussian function. The extracted \( \mu \) and \( \sigma \) values of the fit, for both theory and data, are plotted as a function of the number of detection planes \( n \) in Fig. 4.19. The decreasing trend for both fit parameters, as the \( n \) value increases, is evident in both plots with a good agreement observed between the data measurements and the theoretical model expectations.
Figure 4.18: The time distribution extracted by combining different numbers of detection layers $n$. Left: The average of the $n$ earliest times per event. Right: The earliest of the $n$ earliest times per event.

Figure 4.19: The $\mu$ (left) and $\sigma$ (right) values extracted by fitting the theoretical (Fig. 4.17) and the experimental (Fig. 4.18 (right)) earliest time distributions plotted as a function of the number of detection layers $n$.

The time distributions of Fig. 4.18, reconstructed using the test beam data, can also be used to examine the percentage of the time measurements that lie within the same time window of 25 ns (equivalent to an LHC BC). For both mean (left) and earliest (right) time distributions, the percentage of events that correspond to a 25 ns wide time window centered at each distribution’s mean value is calculated. The result, plotted as a function of the number of planes $n$, is shown in Fig. 4.20 for the mean and earliest time distributions. It can be noticed that eight layers are
needed for the earliest time distribution to have ~ 95% of the measurements within the same BC whereas by using the mean time, the ~ 95% value can be achieved with even $n = 5$ detection layers.

Figure 4.20: The percentage of time measurements that are within a time window of 25 ns (equivalent to the LHC BC) centered in the mean value of the distributions shown in Fig. 4.18 (test beam data for 30° track angles) plotted as a function of the number of detection layers $n$. The different markers correspond to the earliest (full circles) and average (open circles) of the $n$ time measurements per event.
Bibliography


Hit & Track reconstruction with Micromegas chambers

The MM will be primarily employed as the precise muon tracker of the NSW system. In order to fulfill the ATLAS Muon Spectrometer requirements the MM should be able to provide a hit reconstruction with accuracy better than $100\,\mu\text{m}$ per detection plane along the full range of muon track angles that is expected in the NSW region\(^1\). The hit and track reconstruction techniques that have been developed for the MM chambers will be described in the following sections followed by extensive performance studies using test beam data. Moreover, the geometrical efficiency of small resistive MM chambers has been studied in detail along with possible effects that may affect the MM hit reconstruction accuracy. The results of these studies are discussed in this chapter.

5.1 Methods used for reconstruction

As described in Appendix B, the APV25-based \([1]\) SRS system \([2]\) is employed for the chamber readout during the test beam periods of the NSW MM collaboration. This readout system provides the total integrated charge, sampled every $25\,\text{ns}$, for each electronic channel (strip). Using this information the channel charge is defined as the maximum charge sample. Moreover, the drift time of the ionisation electron clusters arriving in each strip is estimated by fitting the evolution of the integrated charge of each strip. The processing of the APV25 raw data are described in Sec. 4.1. Using the charge and time information per channel, different methods for hit and segment reconstruction, using a single MM plane, can be employed.

The Centroid method

When the chamber readout plane is oriented perpendicularly to the beam axis the Centroid method has been proven to provide a very accurate hit reconstruction in the absence of a magnetic field. Each incoming charged particle induces signal in only a few strips per event. A simple clusterisation algorithm is used to merge the adjacent strips, with a signal above threshold, into a single cluster. The cluster (hit) position is calculated by weighting the position of each strip with its signal amplitude and taking the average. In the case of inclined tracks

\(^1\)The NSW detectors will face muon track angles in the range $8^\circ - 30^\circ$.\)
the primary ionisation clusters are distributed along several readout strips and consequently
the single strip signal amplitude becomes sensitive to the primary cluster charge fluctuations.
As a result, the accuracy of the charge Centroid method deteriorates with increasing track
inclination angles and it cannot be used for non-perpendicular tracks.

The $\mu$TPC method

For perpendicular tracks, the timing information is not really accurate since the charge of each
strip is the superposition of several primary clusters (Sec. 4.2). This is illustrated in Fig. 5.2
(top right) where all the strips of the same cluster measure effectively the same drift time.

However, when the tracks are inclined, there is a higher possibility that the signal of each
strip is induced more likely by the drifting of a single primary cluster allowing for an accurate
measurement of its drift time. This information along with the strip address allow for a two-
dimensional reconstruction of the primary cluster’s initial position inside the chamber’s drift
gap. For the translation of the measured time into distance the precise knowledge of the drift
velocity value is presupposed. The ensemble of the two-dimensional points per event provides
the particle’s track in the chamber that is called the $\mu$TPC track. This can then be used either
for determining a single position in the gap, by extrapolating it to a reference point, or as a
single detector segment.

Combination of the $\mu$TPC and Centroid methods

The hit positions reconstructed with the Centroid and $\mu$TPC methods can also be integrated in
a combined hit per gap [3]. The combination algorithm weights the contribution of each of the
two reconstructed hits ($x_{\text{Centroid}}$ and $x_{\mu\text{TPC}}$) with the size of the track footprint using Eq. (5.1).
In the case of large clusters the $\mu$TPC method contributes more, while in clusters with a size
smaller than four strips (Fig. 5.1) the combined hit is mostly defined by the Centroid method.
The $n_{\text{cut}}$ parameter is set equal to four, which is the most probable cluster size expected for
track angles smaller than 10° (Fig. 5.1). It will be shown in Sec. 5.4 that by using the combined
hit a very good spatial resolution ($\leq 100\,\mu\text{m}$) can be achieved independently of the track angle.

$$x_{\text{comb}} = \frac{\left(\frac{n_{\text{strips}}}{n_{\text{cut}}}\right)^2 x_{\mu\text{TPC}} + \left(\frac{n_{\text{cut}}}{n_{\text{strips}}}\right)^2 x_{\text{Centroid}}}{\left(\frac{n_{\text{strips}}}{n_{\text{cut}}}\right)^2 + \left(\frac{n_{\text{cut}}}{n_{\text{strips}}}\right)^2}, \quad n_{\text{cut}} = 4, \quad n_{\text{strips}} = \text{cluster size} \quad (5.1)$$

The need to develop and optimise the different reconstruction techniques described above can
be emphasised further by checking the evolution of the track footprint size on a single MM
readout for different track inclination angles. Figure 5.1 shows the mean cluster size, defined as
$|\text{strip}_\text{first} - \text{strip}_\text{last}| + 1$, as a function of the track angle for a resistive MM chamber of T-type
(Appendix B). As soon as the track angle becomes larger than 2 – 3° the Gaussian distribution
of the ionisation charge among the cluster strips is lost and the Centroid method cannot be
used to provide accurate hit reconstruction.
5.2 Performance studies of the Centroid method

The charge interpolation method is a well established hit reconstruction technique for strip detectors. Owing to the spreading of the ionisation charge along several strips it is possible to overcome the naive performance limitation dictated by the granularity of the readout elements [4]. In the case of gaseous detectors, for a charged particle traversing perpendicularly the detector’s active volume the ionisation charge is shared among several readout strips due to different phenomena:

- The movement (drifting) of the ionisation electrons (ions) towards the anode (cathode).
- The diffusion of the ionisation electrons and ions governed by the gas mixture properties and the drift electric field.
- The charge sharing between capacitively coupled neighbouring readout strips.

The Centroid method has been used in the analysis of the ATLAS NSW MM test beam data to characterise the performance of MM detectors with different characteristics. In the case of the resistive-strip MM the hit position reconstruction uncertainty is not only determined by the fine segmentation of the readout but it is also significantly affected by the material (resistivity) and the geometry of the resistive strip layer. These parameters vary the total induced charge on the readout per charged particle and the number of strips with signal above threshold.

Figure 5.2 shows the charge and time shape for a cluster of strips reconstructed in a two-dimensional readout chamber of Tmm type (B). On the left column histograms, the strip charge is plotted as a function of the strip address for X and Y readouts (top and bottom row respectively). The difference in the cluster shape between the two layers is evident with the Y readout having a larger number of strips per cluster compared to the X. This difference represents the effect of the relative orientation of the resistive with respect to the readout strips. In the case of the Tmm chamber, the resistive strips are oriented parallelly to the X readout.
strips and orthogonally to the Y readout strips. Thus, in the Y readout layer, the propagation of
the charge along one resistive strips induces signal on several readout strips through capacitive
coupling.

\[\text{Figure 5.2: Display of a cluster of strips, corresponding to the same particle, reconstructed in}
\]
the two readout layers, X (top row) and Y (bottom row), of a Tmm type MM. Left: Strip charge
as function of its address. Right: Strip time as function of its address

In the right column of Fig. 5.2 the drift time measurement per strip is shown. In the case of the
X readout, all strips measure the same drift time, as expected, as a result of the overlapping
different primary clusters spread along five strips. For the Y readout the situation is different
owing to the propagation of the signal along the resistive strip, as the peak amplitude is
measured at different times that are proportional to the propagation speed of the signal on the
resistive strip. This results in the v-shaped scatter-plot shown in the bottom right of Fig. 5.2.
The earliest drift times correspond to the central strips of the cluster and the measured time
increases when going towards the edges of the cluster. It can also be seen that the time mea-
surements for the central Y strips, are in good agreement with the average time measured in
the X readout (~ 100 ns). The extra tails on the Y readout clusters, provoked by the spreading
of the signal along the resistive strips, do not spoil the charge symmetry of the cluster which
maintains its Gaussian shape for the Y readout as well.

Some initial performance studies on the Tmm type MM chambers are described in [5]. As the
X readout strips are placed below the Y readout strips the largest fraction of the resistive strip
signal is capacitively coupled to Y readout and the charge ratio between two layers X:Y has been
measured to be 1:1.4. The spatial resolution of the two layers has been studied using 120 GeV/c
pions. The distribution of the hit position difference between two Tmm chambers divided\(^2\) by

\(^2\)The division by \(\sqrt{2}\) is justified by the assumption that the spatial resolution of the two identical
\(\sqrt{2}\) is presented in Fig. 5.3. The chambers were positioned with their readout plane vertical with respect to the beam and with an intermediate distance of 2 cm. The left plot of Fig. 5.3 shows the position difference distribution for the X readout and the one for the Y readout is shown on the right plot. Each distribution is fitted with a double Gaussian function to take into account also the tails. The \(\sigma\) of the core Gaussian along with the weighted \(\sigma\) of the two Gaussian fits, extracted from Eq. (4.3), are quoted. The signal induction from a single resistive strip along several Y readout strips does not degrade the accuracy of the hit position reconstruction and a spatial resolution of \(\sim 55 \mu m\) is measured for both layers.

![Figure 5.3: Distributions of the hit position difference divided by \(\sqrt{2}\) between two Tmm chambers. The left distribution corresponds to the X readout while the distribution of the Y readout is shown on the right plot. The mean value of the left distribution shows the misalignment offset between the two MM that are compared while on the right plot the chambers are aligned offline.](image)

The intrinsic spatial resolution of the MM detectors should primarily depend on the readout segmentation assuming constant operational parameters of the chamber (drift and amplification gap size, mesh, resistivity, HV, gas mixture and beam conditions). To visualise the dependence of the spatial resolution on the readout strip pitch the same study is repeated for two small T type MM chambers with a single layer of readout strips matching the resistive strip geometry. The performance of the chambers was studied in the same test beam period as the Tmm and the distance between the chambers compared was 2 cm. The distribution of the hit position differences divided by \(\sqrt{2}\) is shown in Fig. 5.4. A single plane spatial resolution of 68 \(\mu m\) is measured and the difference of 12 \(\mu m\) compared to the Tmm case is attributed purely on the coarser segmentation of the T chamber’s readout (400 \(\mu m\) for the T and 250 \(\mu m\) for the Tmm).

Detailed specifications of the MM chambers that have been studied in test beams are listed in Table B.1 of the Appendix B.

chambers that are compared is the same.
5.3 The $\mu$TPC method

In the case of tracks inclined with respect to the readout strips, the charge weighting method is not able to provide a precise hit position reconstruction as discussed in Sec. 5.1. However, because of the distribution of the primary ionisation clusters along several strips, the single strip drift time measurement becomes more accurate with increasing the inclination angle. To exploit the timing information per strip the $\mu$TPC reconstruction method has been developed that is able to provide a very precise track segment in a single detector gap. The analysis and the results that will be discussed in the following sections are specific for the APV25 front-end hybrid cards. However, the method has been successfully applied to data acquired with MM chambers using the VMM1 readout electronics providing similar results [6].

The first step of the $\mu$TPC reconstruction is related to the time extraction from the integrated charge distribution per strip\(^3\). The procedure for calculating the single strip drift time is described in Sec. 4.1. The quality cut criteria that are described in the same section are also applied on the $\mu$TPC method. The very steep rise times and very small or saturated signal shapes are discarded, to exclude the biased timing measurements which may affect the method’s accuracy. After the pre-processing of the raw data information the qualified strips enter the cluster reconstruction stage.

The clustering algorithm distinguishes multiple tracks and/or hits due to noise or delta rays. In the case of inclined tracks, the topological clustering applied in the Centroid method is not ideal. As a consequence of the increased sensitivity in single primary clusters and the primary cluster charge fluctuations, there is a high possibility of having single strip or larger gaps that

---

\(^3\)This holds only for the APV25 readout electronics.
contaminate the continuity of a topologically defined cluster. The topological clustering algo-
rithm may be refined to take into account also the possibility of having holes between adjacent
strips of the same cluster but it is not possible to make it transparent to the track inclination
angle. For this reason, a very robust two-dimensional clustering algorithm has been developed.
The algorithm takes into account the strip address and time information and by employing
pattern recognition techniques, it identifies the strips that are associated to the same charged
particle track.

The two-dimensional clustering relies on the Hough transform \[^{[7]}\]. Each Cartesian point in two
dimensions \((x,y)\) reconstructed in a single gas gap\[^{[4]}\] is transformed, using polar coordinates \((\rho,\theta)\),
to the Hough space according to Eq. (5.2). Thus, each point in the Cartesian space corresponds
to a curve in the Hough space. Figure 5.5 shows a double track event, with signal induced on
several strips by the incoming charged particles in the Cartesian (left) and in the Hough (right)
space respectively. The accumulation point is found by dividing the Hough space into a two-
dimensional matrix and locating the cell with the maximum concentration. The coordinates
of the accumulation point correspond to the slope and the intercept of the estimated straight
track pattern that satisfies the majority of the two-dimensional Cartesian points.

\[
\rho = x \cos \theta + y \sin \theta
\]  

\[^{[4]}\] Where \(x\) stands for the strip address and \(y\) is the \(t_{FD}\) time transformed into distance using the drift
velocity.
The maximum deviation value depends on the readout strip pitch and the 1 mm is valid only for the case of T type MMs that are used for the analysis described in the next sections. The points that survive the filtering step are then used for the $\mu$TPC track reconstruction as shown in Fig. 5.6 (right). In the same plot it can be observed that each point used in the $\mu$TPC track reconstruction is assigned errors along both x and y coordinates. Not the same errors are used for all the points of a single track but the error values are calculated using Eq. (5.3). The error in the parallel to the readout direction $\sigma_x$, is governed by the readout strip pitch uncertainty ($\text{pitch}/\sqrt{12}$) with an additional term related to the strip charge. The error in the drift gap direction $\sigma_y$, is calculated from the time measurement error. The error in the time measurement, given by the Fermi-Dirac fit function on the integrated charge distribution of the strip, is anti-correlated with the strip maximum charge as shown in Fig. 4.5 (right). Thus, strips with smaller signal amplitudes are assigned larger errors in both x and y directions.

\[
x = \text{pitch} \sqrt{12} \left(1 + \frac{q_{\text{cl}}}{\text{size}_{\text{cl}} q_{\text{st}}} \right), \quad y = v_d t_{\text{err}}
\] (5.3)

After the two-dimensional clustering and the error assignment in the cluster points a linear fit is performed to extract the $\mu$TPC track using a single MM detector. Since the single point errors are calculated individually per event, using semi-empirical formulas, several quality checks on the reconstructed track are performed to ensure the proper error assignment. One of the most effective checks is the shape of the $\chi^2$ probability distribution. An unbiased error assignment is translated in a flat $p(\chi^2)$ distribution as can be seen in Fig. 5.7 (left). The distribution is perfectly flat except for a steep peak in the very small $p(\chi^2)$ region that corresponds to bad quality fits. The tracks that occupy this region are discarded from the analysis. The $\mu$TPC track may be used as a segment but it may also be used to calculate a single impact point per charged particle in one detector plane. The interpolation of the $\mu$TPC track in the middle of
the chamber’s drift gap represents the reconstructed hit position in a single MM, the so-called \( x_{\text{half}} \) point. Figure 5.7 (right) shows the correlation between the reconstructed \( x_{\text{half}} \) points for two T type MM chambers. The MMs were inclined by an angle of 30° with respect to the beam separated by a distance of \( \sim 2 \) cm.

![Figure 5.7: Track fit quality checks. Left: Check of the \( \mu \)TPC fit quality. A flat \( \chi^2 \) distribution ensures the unbiased distribution of errors along the cluster points. Right: Correlation between the reconstructed \( x_{\text{half}} \) points for two T type MM chambers (namely T1 and T3).]

### 5.3.1 Early performance results

The \( \mu \)TPC recipe has been tested and optimised through the analysis of test beam data acquired with small MM chambers inclined at different angles with respect to the beam axis during the summer of 2012. The early results, presented in Fig. 5.8 (left), have proven that the MM technology satisfies the NSW requirements in terms of precision tracking with spatial resolution of the order of \( \sim 100 \) µm independently of the track incident angle using the combination method that was described above. However, the displayed performance of the \( \mu \)TPC method alone could not achieve the 100 µm requirement for inclination angles smaller than 30°. More specifically, in the case of 10° the measured resolution was of the order of \( \sim 150 \) µm, 50% worse compared to the results of larger inclination angles. In addition to this, the distributions of the reconstructed angle, calculated using the slopes of the \( \mu \)TPC tracks, were showing significant biases in the peak angle value with respect to the real inclination angle of the chambers. The worst case, corresponding to 10° inclination angle is presented in Fig. 5.14 (top left), where the determined peak value is 17°. The 70% deviation from the true angle value, for the small track angles, cannot be explained by the smaller cluster sizes and the reduced lever arm, but it rather indicates that there is some bias introduced by the \( \mu \)TPC reconstruction method that was used at that time. Detailed studies using test beam data and simulation have been performed in order to understand and correct the cause of the mis-reconstruction of the \( \mu \)TPC tracks and are discussed in the following sections. The updated \( \mu \)TPC performance measurements, after the refinement of the method, are presented and compared to the early results.
5.3.2 Effect of the charge position assignment along the strip pitch

One possible way of introducing a bias in the track reconstruction is coming from the artificial assignment of the primary cluster that is detected by a strip in the middle of the strip pitch. The validity of this treatment and the possible effect it may have on the resulting µTPC track of the raw data has been studied in simulation tool developed for the MM chambers described in [9].

The assignment of the primary cluster position in the middle of the strip pitch is not random but it is justified in the case where the full width of the strip pitch can be populated by primary clusters with a uniform probability. The strip pitch uncertainty is always a factor that limits the position reconstruction uncertainty but it cannot contribute to the systematic bias in the position reconstruction that has been observed. Using a detailed Monte-Carlo simulation the initial positions of the generated primary clusters are known by definition. Allowing the cluster electrons to drift towards the detector readout, under the influence of the electric field and the diffusion coefficients of the gas mixture, signal is induced on the readout strips and the primary cluster is assigned in the middle of the corresponding strip pitch. A MM chamber with 5 mm drift gap and 400 µm strip pitch operated with Ar+7%CO₂ gas mixture has been simulated in order to study the distribution of the primary cluster position with respect to the middle of the strip pitch for track inclination angles of 10°, 20° and 30°. The distributions of the difference between the initial position of the ionisation and the assigned position (middle of the strip pitch) for three different track inclination angles are shown in Fig. 5.9. Three different categories of strips are examined:

- The strip with the earliest time within a cluster (First Strip).
- The strip with the largest time within a cluster (Last Strip).
- A strip of the cluster different from the First and the Last strips (Middle Strip).

![Image of graph showing spatial resolution as a function of track incident angle for different reconstruction techniques.](image_url)

**Figure 5.8:** Spatial resolution as a function of the track incident angle for three different reconstruction techniques. The plot is taken from [8].
5.3 The \( \mu \)TPC method

Figure 5.9: The difference between the initial position of the primary ionisation cluster and the finally assigned position (middle of the strip pitch) for the first (earliest), the last (latest) and the middle strips of the cluster respectively. The results are coming from the simulation of a T type MM for 10\( ^\circ \), 20\( ^\circ \), 30\( ^\circ \) track inclination angles.

From the plots of Fig. 5.9 it is evident that the assumption of uniformly distributed primary clusters along the strip pitch holds only for the middle strips of a cluster. The difference between assigned and actual primary cluster position is uniformly distributed between \( \pm \)pitch/2 for the strips in the middle of the cluster\( ^6 \) for the track inclination values that are examined. The same argument is not valid for the cluster edges where the distributions are highly asymmetric towards the edges of the strip pitch with an opposite effect observed between the first and the last strip of the cluster. This can be seen in the histograms of the first and third rows in Fig. 5.9 where the distributions favour a position assignment closer to the strip edge.

\( ^6 \)Clusters with at least three strips are used in this analysis.
neighbouring the cluster center. Moreover, it can be noticed that the shape of the distributions for the cluster edges changes for different track inclination angles with a tendency to become more uniform with increasing angle values.

The effect that has been observed in the simulation studies is purely geometrical coming from the incomplete overlap of the outer cluster strips with the particle’s trace inside the MM gas gap combined with the diffusion of the ionisation electrons. Thus, by assigning the primary cluster position in the middle of the strip pitch, for the cluster edges, the reconstructed track angle is artificially enlarged. The μTPC method has been applied in the simulated data as well, in order to produce the track angular distributions corresponding to the different track inclination angles. Similar distributions with the ones from the test beam data (Fig. 5.14) are obtained from the simulation. A bias in the peak reconstructed angle is also observed in the simulated angular distributions, but the bias magnitude is smaller. This can be explained by the fact that only the physical processes related to the gas are implemented in the Monte Carlo simulation and not the fully equivalent electrical circuit composed of resistive and readouts strips. Thus the effect of the charge sharing between readout-readout and resistive-resistive strips along with the propagation of the signal along the readout strip is not included in the simulation. As will be discussed in the next sections the effect of the capacitive coupled charge between neighbouring strips is another factor that should be taken into account for an accurate μTPC reconstruction.

By simulating the μTPC angular distribution for different track inclination angles the peak reconstructed angle is calculated. Initially, the common notation of assigning the primary cluster position in the middle of the strip pitch is used for all the strips in the cluster. Then, taking into account the geometrical effect presented in Fig. 5.9 the position in the first and last strips of the cluster is corrected in steps of 20 μm from −pitch/2 up to +pitch/2. Since the effect appears to be opposite in the two cluster edges the applied correction is also opposite. For each correction value the peak angle value is extracted from the simulated μTPC angular distribution. In Fig. 5.10 the bias measured in the peak reconstructed angle, with respect to the true track angle, is plotted as a function of the correction value applied for 10°, 20° and 30° respectively.

**Figure 5.10:** The absolute value of the measured bias in the reconstructed μTPC track angle as a function of the correction in the charge position assignment with respect to the middle of the strip pitch. Only the first and the last strips of the cluster are corrected. A T type MM chamber, operated with Ar+7%CO₂, is simulated.

In the case where no correction is applied, corresponding to zero value in the x-axis, a certain
bias in the determined peak angle value can be observed for all the three track inclination angles that are simulated. This offset becomes larger for smaller inclination angles ranging from 0.2° for the 30° case up to 4° for the 10° angle. By testing different correction values for the position of the first and the last strip of the cluster, the angle bias can be eliminated as is presented in Fig. 5.10. However, the correction value that results in a perfect agreement between actual and reconstructed angles is different between different track inclination angles as can be seen in the plots of the same figure. This fact amplifies the initial idea of a purely geometrical effect emanating from the, most probably, incomplete overlap between the track and the cluster edges. It should also be stated that the correction should be applied with caution as a possible over-correction may also result in a biassed reconstructed angle.

5.3.3 Effect of capacitive coupled only strip charge

The fine strip pitch of the MM detectors results in a non-negligible capacitance between neighbouring strips. In the case of the resistive-strip MM the effect of the capacitive coupling does not concern only the readout strips but the resistive strips as well. In order to have a concrete idea of the effect, a detailed electromechanical simulation of the equivalent circuit-structure model is needed. The simulation of a simplified resistive-strip MM detector model with five strips has been implemented using ANSOFT’s Maxwell [10] and Simplorer [11] software. By simulating the resistive T chamber case with 400 µm strip pitch and using a resistivity value of 20 MΩ/cm the charge leakage from a strip with signal to its nearest neighbours is ~ 10%. Some more information regarding the resistive-strip MM simulation is presented in Sec. 7.2. For the strips that occupy the middle of the cluster, with neighbouring strips having signal above threshold, the excessive capacitively coupled charge from the neighbours is absorbed within the primary ionisation signal of the strip which is usually significantly larger. This may slightly affect the signal amplitude in this strip and the timing measurement that is extracted using the APV25 integrated charge but the effect in most cases is negligible. In the case of the strips in the cluster edges however, the size of the cluster is artificially increased due to the charge that is coupled from the edge strips to their neighbours that do not develop any signal from ionisations.

This effect has been studied in the test beam data by looking into the relation between the cluster strip signal amplitudes. In general, owing to the primary cluster and avalanche charge fluctuations no correlation is expected between the charge amplitude values of neighbouring strips. The random relation between the charge amplitude of adjacent strips is shown in the rightmost plot of Fig. 5.11 for all the strips of the cluster except for the ones that occupy the edges. However, this is not the case for the first and the last strips of the track footprint the charge amplitude of which is highly correlated with the amplitude of the second and one before the last strips respectively. The correlation is evident in the first two plots of Fig. 5.11 that represent the first and the last strip respectively with the slope indicating a ~ 15% of the charge sharing. Of course, the charge sharing between neighbouring strips is the same independently of the strip position within the cluster. The fact that the correlation is visible only for the cluster edges illustrates that in the vast majority of the clusters the first and the last strip of the cluster have only charge that is capacitively coupled from their inwards neighbours. Moreover, it can be extracted from the plots that most likely the charge amplitude in the edge strips is small (≤ 300 ADC) while for the middle the strips the values span from very small up to > 1600 ADC.
Figure 5.11: Correlation plots of the charge in neighbouring cluster strips for three different strip pairs: (first)-(second), (last-1)-(last) and (second)-(third). The T type MM chamber was inclined with respect to the beam axis by 10°.

A quantitative observation of the charge sharing between the edge strips and their neighbours can be made by constructing the distribution of the charge amplitude ratio between adjacent strips. The result is illustrated in Fig. 5.12 where the two first plots show the charge ratio between first and second strip and between last and one before last respectively. These should be compared with the right plot that corresponds to the middle strips of the cluster. The shape of the distributions for the edge strips is completely different compare to the one of the middle strips mainly due to the fact that the edges show much smaller signal amplitudes compared to their neighbours. Moreover in the case of the earliest strip a peak can be observed in the magenta distribution for a ratio of about six. This value is in good agreement with the simulation expectations of 15% charge sharing from one strip to its neighbour. In the case of the last cluster strip the peak is not very pronounced mainly due to the larger, compare to the earliest strip, drift path of the primary cluster electrons that smears the effect.

Figure 5.12: Plots of the charge ration between neighbouring cluster strips for three different strip pairs: (first)-(second), (last-1)-(last) and (second)-(third).

These results confirm the initial speculation that the earliest and/or the latest strip of the cluster are very likely to have signal coming only from the capacitive coupling with their neighbours. Moreover, the strips with capacitively coupled only signal from their neighbours inherit the neighbouring time measurement as well. Thus, the effective cluster length is artificially increased by one or two strips that carry the time measurement of their inward neighbours resulting in a distorted µTPC track reconstruction when the linear fit is applied.
5.3 The $\mu$TPC method

5.3.4 The refined $\mu$TPC recipe and performance results

The two phenomena described in the previous sections can distort the $\mu$TPC track reconstruction biasing the final single chamber segment. This is described in the graphical representation of Fig. 5.13. Effectively the reconstructed $\mu$TPC angle is larger than the true value and this introduces a bias in the track angle estimation and the $x_{\text{half}}$ hit position reconstruction. The impact of these effects becomes more significant as the size of the cluster decreases due to the fact that there is a smaller number of precise 2-D points to rely on for the track reconstruction. This results in a larger bias in the measured track angle and a less precise track reconstruction when the track inclination angle is small.

To correct the two effects, the basic $\mu$TPC recipe described in Sec. 5.3 has been evolved with the addition of a filtering and correction step after the two dimensional clustering and before the final $\mu$TPC track linear fit. The steps added in the $\mu$TPC algorithm are:

1. The algorithm initially checks the charge relation of the cluster edges with their neighbours. In the case where the charge amplitude of the edge is significantly smaller than the one of its inward neighbour ($< 15\%$) the strip is discarded from further processing.

2. The remaining points define the $\mu$TPC track. The charge assignment position in the first and last strips of the cluster, initially assigned at $\text{pitch}/2$, is refined using the corrections given by Eqs. (5.4), (5.5). The correction amplitude is weighted by the relative charge ratio between the edge strip and the inward neighbour along with the size of the cluster in order to have smaller corrections for larger inclination angles.

\[
x_{\text{first}}^{\text{cor}} = \frac{\text{pitch}}{2} \left[ 1 - \left( \frac{\text{size}_{\text{cluster}}}{6} \right)^2 \cdot \left( \frac{q_0}{q_1} \right)^2 \right]
\]

\[
x_{\text{last}}^{\text{cor}} = \frac{\text{pitch}}{2} \left[ \left( \frac{\text{size}_{\text{cluster}}}{6} \right)^2 \cdot \left( \frac{q_n}{q_{n-1}} \right)^2 - 1 \right]
\]

Track angle reconstruction studies

The refined $\mu$TPC algorithm has been applied in the same test beam data that were used to provide the early performance results shown in Figs. 5.8, 5.14. The results concerning the angle reconstruction and the spatial resolution estimation have been produced before and after the correction for comparison reasons. The angular distributions reconstructed with the $\mu$TPC recipe, without the correction, are presented in Fig. 5.14. A Gaussian fit is performed around the peak of the angular distribution, for the determination of the mean reconstructed angle. A bias in the peak angle is observed with the effect becoming smaller as the track inclination angle increases. In the case of $40^\circ$ the bias is negligible. Moreover, the $\sigma$ of the Gaussian gives an estimate of the angular resolution that can be achieved with the $\mu$TPC reconstruction in the MM detectors. In Fig. 5.14 it can be observed that the angular resolution improves for larger inclination angles owing the more points that are used in the fit and the increased lever arm of the cluster. The asymmetric Gaussian shape of the angular distributions is due to the non-linear transformation from the measured slope to angle. As the width of the slope distribution increases, the angular distribution starts to develop a tail towards larger angle values. The tail becomes less pronounced as the track angle increases since the accuracy of the
slope measurement also improves for the same reasons that affects also the measured angular resolution.

Figure 5.13: Graphical representation of the bias introduced in the μTPC track reconstruction, cause by the charge position assignment in the cluster edges and the capacitively coupled charge sharing along with the algorithm for the refinement of the method.

The same studies are repeated with the refined μTPC algorithm. The tracks identified with the
Hough transform pattern recognition technique, are first filtered from the capacitive coupling effect. In the next step the assigned position in the cluster edges is corrected using Eqs. (5.4), (5.5) and the µTPC track is then reconstructed. The distributions of the reconstructed angle after the correction, for the same set of track inclination angles presented in Fig. 5.14, are shown in Fig. 5.15.

Figure 5.14: Distributions of the µTPC reconstructed angle for four different track inclination angles (10°, 20°, 30°, 40°) without using the correction for the refinement of the method. A bias in the measured peak angle is observed with respect to the true inclination angle. The misreconstruction effect is more severe for smaller inclination angles.
The results for the angle reconstruction with and without the refinement of the $\mu$TPC algorithm are summarised in Fig. 5.16. The left plot compares the peak reconstructed angle results with different colours for before (red markers) and after the correction (blue markers) of the $\mu$TPC method. The superimposed black dotted line corresponds to the theoretical case where the measured angle agrees perfectly with the true track inclination angle. A significant improvement in the peak angle bias is obtained after the refinement of the $\mu$TPC method for all the different inclination angles. The small remaining bias is most likely coming from the capacitive coupling between the middle strips of the cluster that is not corrected with the procedure described above. Apart from the improvement in the peak value determination the width of the angular distributions becomes smaller by using the refined algorithm. By taking the $\sigma$ of the Gaussian fit around the peak, the width of the distribution (indicative of the angular resolution) for each inclination angle is calculated with and without the corrections. The angular resolution
results are summarised in the right plot of Fig. 5.16. The improvement in the accuracy of the incident track angle reconstruction is more pronounced in the case of 10° where the angle bias is reduced by 5° after the correction while the width of the distribution is reduced by 1°. This is expected also from the simulation studies that have been described above, since for smaller track angles less points are used for the µTPC track reconstruction. As a result, the effect of the capacitive coupling and the biased strip position assignment in the cluster edges, becomes more significant.

![Figure 5.16](image)

**Figure 5.16:** Summary plots comparing the peak reconstructed angle and the width of the angular distributions before and after the correction of the µTPC method for four different track inclination angles (10°, 20°, 30°, 40°) in a T type MM chamber. A significant improvement is obtained in the peak value and the width of the distributions with the refined algorithm.

In order to properly take into account the non-linear transformation from the measured slope to angle the angular distributions should be presented in histograms of variable binning [12] as described in Appendix C. However, the effect is very small for the angular resolution of the MM chambers and thus the results presented are not really affected by the transformation features.

The σ parameter of the angular distributions, that is plotted as a function of the track angle in Fig. 5.16 (right), can also be used as a merit for the estimation of the single plane timing resolution. The error of the track slope α, that is the parameter actually measured from the reconstructed µTPC track, is expressed as a function of the errors along the drift gap (x) and along the readout (y) respectively using Eq. (5.6). The cot θ is derived from the fact that as shown in Fig. C.5 the track angle is φ while the slope of the complementary θ is measured.

\[
\sigma_\alpha = \sigma_{\cot \phi} = \sqrt{\frac{1}{n-2} \left( \frac{\sum_{i}(y_i - \hat{y})^2}{\sum_{i}(x_i - \hat{x})^2} \right)} \quad (5.6)
\]

If all the individual \( y_i \) errors are characterised by a mean error \( \sigma_y = \sigma_{\text{vD}} \), where \( \text{vD} \) is the electron drift velocity, then the time resolution \( \sigma_t \) can be expressed as a function of \( \sigma_\phi \) using...
the form
\[
\sigma_t = \frac{\sigma_\phi}{v_D \sin^2 \phi} \sqrt{\frac{n-2}{n^2}} \sqrt{n \sum \chi_i^2 - \sum i \sum x_i^2} \tag{5.7}
\]
Assuming a simple geometrical model of a track, with an angle \( \phi \), the number of strips that are covered by the track for a drift gap size \( d \) will be \( n = d \tan \phi / p \), where \( p \) is the strip pitch. However, if the diffusion is also taken into account, the actual track footprint on the MM readout is increased by \( \sim 1 \) strip and a more realistic model should be \( n = d \tan \phi / p + 1 \). Using these expressions to expand the \( x_i \) terms of Eq. (5.7) the final expression for the time error is given, for the \( n \) and \( n + 1 \) cases, by the form
\[
\sigma_t = \frac{p \sigma_\phi}{2v_D \sin^2 \phi} \sqrt{\frac{(n-2)(n^2-1)}{3}} \tag{5.8}
\]
The timing resolution values that are calculated using Eq. (5.8) for 10\(^o\), 20\(^o\), 30\(^o\), 40\(^o\), for the case of the T type MM chambers, are listed in Table 5.1. The calculations are made both for \( n \) and \( n + 1 \) models. The \( \sigma_\phi \) values for the different track angles are extracted from the \( \sigma \) values of the distributions shown in Fig. 5.15. The results of the \( n + 1 \) model are in sensible agreement with the timing resolution values calculated, for 10\(^o\), 20\(^o\), 30\(^o\), 37\(^o\) track angles, using the earliest time and are presented in Fig. 4.14 (black markers). Using the same technique, the single MM plane timing resolution, combining all the \( n + 1 \) drift time measurements, will be \( \sigma_t^{n+1} = \sigma_t / \sqrt{n} \) and the extracted values are shown in the third row of Table 5.1.

**Table 5.1:** Timing resolution calculated using Eq. (5.8) for \( d \) and \( p \) values corresponding to a T type MM and \( v_D = 0.047 \text{mm/ns} \) is the nominal drift velocity that is used throughout this chapter. The third row corresponds to the time resolution per plane obtained from Eq. (5.8) divided by \( \sqrt{n} \).

<table>
<thead>
<tr>
<th>Track Angle</th>
<th>10(^o)</th>
<th>20(^o)</th>
<th>30(^o)</th>
<th>40(^o)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( n, \sigma_t ) (ns)</td>
<td>8.6</td>
<td>8.6</td>
<td>7.5</td>
<td>7.4</td>
</tr>
<tr>
<td>( n + 1, \sigma_t ) (ns)</td>
<td>18.0</td>
<td>12.1</td>
<td>9.4</td>
<td>8.6</td>
</tr>
<tr>
<td>( n + 1, \sigma_t^{n+1} ) (ns)</td>
<td>9.2</td>
<td>5.0</td>
<td>3.3</td>
<td>2.6</td>
</tr>
</tbody>
</table>

**Spatial resolution studies**

The results on the improved accuracy of the \( \mu \)TPC angle reconstruction, presented in Fig. 5.16, confirm the need for the corrections described above. However, the reduction in the angle bias is naively expected since the corrections tend to rotate the reconstructed \( \mu \)TPC segment around its middle towards smaller inclination angles. The improvement in the angular resolution gives a first hint about the validity of the procedure but in order to give concrete answers regarding the effectiveness of the applied corrections in the MM performance the tracks reconstructed in different MM chambers should be compared.

Repeating the same procedure that was applied for the angular distribution studies, the reconstructed tracks in two identical MM chambers (T type) are used to estimate the single plane spatial resolution after the refinement of the \( \mu \)TPC method. Each \( \mu \)TPC segment is interpolated in the middle of the drift gap and a single \( x_{\text{half}} \) hit position is reconstructed per chamber per
5.3 The μTPC method

The TPC method can be estimated. The distributions of the hit position difference, divided by $\sqrt{2}$, are shown in Fig. 5.17. The distributions are fitted with a double Gaussian function to describe also the tails of the distribution. The $\sigma$ of the core Gaussian provides an estimate of the single plane spatial resolution that can be achieved with the μTPC method.

![Figure 5.17](image-url)

**Figure 5.17:** Distributions of the $\chi_{\text{half}}$ hit position difference, divided by $\sqrt{2}$, between two T type MM chambers for $10^\circ$, $20^\circ$, $30^\circ$ and $40^\circ$ track inclination angles. The refined μTPC recipe is used for the single plane segment reconstruction.

The events that occupy the tails of the distributions correspond to misreconstructed μTPC segments in one of the two chambers that are compared. These are mostly coming from very small clusters (e.g. clusters with three strips) and/or are based on not very accurate strip time measurements due to the strip time extraction procedure described in Sec. 4.1. Thus, these are not
included in the spatial resolution estimation that is coming from the core Gaussian only. The \( \sigma \) of the core along with the weighted \( \sigma \) of the two Gaussian functions are quoted on the plots for completeness. The weighted \( \sigma \) is given by Eq. (4.3). In all four distributions, more than 80\% of the events are described by the core Gaussian, as listed in Table 5.2.

<table>
<thead>
<tr>
<th>( \mu \text{TPC} ) events ( % ) in core Gaussian</th>
<th>10(^{\circ} )</th>
<th>20(^{\circ} )</th>
<th>30(^{\circ} )</th>
<th>40(^{\circ} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>81.5%</td>
<td>89.8%</td>
<td>88.4%</td>
<td>86.2%</td>
<td></td>
</tr>
</tbody>
</table>

For comparison purposes, the resolution measurements are also performed using the uncorrected \( \mu \text{TPC} \) method and results similar to the ones reported in the early results of Fig. 5.8 are obtained for the core Gaussian widths. The comparison between the original and the corrected \( \mu \text{TPC} \) algorithm is presented in the left plot of Fig. 5.20. The measured performance after the refinement of the \( \mu \text{TPC} \) method (blue markers) is significantly improved by introducing the corrections in the segment reconstruction with the improvement being dependent on the track angle. A \( \sim \) 30\% improvement is obtained in the measured hit reconstruction accuracy for the 10\(^{\circ} \) inclination angle where the corrected algorithm yields \( \sigma = 105 \mu m \) (compared to 150 \( \mu m \) before the correction shown with red markers). The refined \( \mu \text{TPC} \) algorithm provides a much more uniform spatial resolution, on the level of \( \sim 100 \mu m \), along the different values of track inclination angle (10\(^{\circ} \) – 40\(^{\circ} \)). Based on the proposed refined algorithm, an additional correction for the remaining bias in the peak reconstructed angle may be envisaged to further improve the \( \mu \text{TPC} \) performance for track angles \( \geq 10^{\circ} \).

**Check for systematics from the \( \mu \text{TPC} \) corrections**

In order to fully validate the correction method the last step is to check for possible systematics introduced by the filtering of the low charge edges and the correction in the position assignment for the first and the last strips of the clusters. The \( \mu \text{TPC} \) algorithm is applied with and without the corrections and the position difference between the corrected and not corrected \( \kappa_{\text{half}} \) hits is calculated in a single MM for each event. The \( \kappa_{\text{half}} \) hit position difference distributions have a symmetric Gaussian shape and can be described by single Gaussian functions. The mean and the \( \sigma \) values obtained from the Gaussian fits are plotted as a function of the track angle in the left and right plots of Fig. 5.18 respectively.

The mean values of the hit position difference distributions, illustrated in the left plot of Fig. 5.15 show a maximum deviation of 7 \( \mu m \) for the case of 10\(^{\circ} \) which is well within the tolerance limits since it is an order of magnitude smaller than the detector’s resolution. Looking at the correlation of the mean value with the track angle, a decreasing trend can be observed as the inclination angle value increases reaching a minimum of 2 \( \mu m \). The \( \sigma \) value dependence from the track angle is presented in the right plot of the same figure. As expected the largest \( \sigma \) value corresponds to the 10\(^{\circ} \) case where the more substantial correction in the \( \mu \text{TPC} \) algorithm is applied. The \( \sigma \) values also decrease with increasing track angles with the effect of the correction becoming smaller as the track footprint increases.
Figure 5.18: The mean and $\sigma$ values coming from the distributions of the difference between the $x_{\text{half}}$ calculated position before and after the correction as a function of the chamber inclination angle. A maximum mean value difference of 7 $\mu$m can be observed for the 10° case in the left plots. The values of both mean and $\sigma$ parameters decrease with increasing track angle values.

5.4 Combination of $\mu$TPC & Centroid

The combination of the $\mu$TPC & Centroid methods has been also studied using the corrected $x_{\text{half}}$ point provided by the refined $\mu$TPC algorithm. The method exploits the anti-correlation between $\mu$TPC & Centroid hit position differences, between two MM chambers, to provide a spatial resolution below 100 $\mu$m independently of the track angle. The measured performance of the combination method, in terms of spatial resolution, has been presented in the early results shown in Fig. 5.8 (black markers). The position difference distributions of the combined hit defined according to Eq. (5.1), between two chambers, after the refinement of the $\mu$TPC method, are shown in Fig. 5.19. The same data set that have been used for the results presented in the previous section, is used. The residual distributions for the combined hits are fitted with a double Gaussian and both the $\sigma$ of the core Gaussian along with the weighted $\sigma$, calculated using Eq. (4.3), are quoted on the plots. Table 5.3 reports the percentage of events that occupy the core Gaussian fit and are then used for the estimation of the combined point spatial resolution.

A spatial resolution better than 100 $\mu$m uniform along the different track angles is obtained as shown in the right plot of Fig. 5.20 (black markers). The curves for the Centroid and the refined $\mu$TPC methods are also superimposed with different colours (blue and red markers respectively) for comparison reasons. In the case of perpendicular tracks the reconstructed combination hit is equivalent to the Centroid hit, well below 100 $\mu$m while at large track angles (30°, 40°) it is almost solely defined by the $\mu$TPC $x_{\text{half}}$ point. The combination method is extremely useful for the NSW MM detectors since they will have to provide a single plane hit reconstruction with an accuracy better than 100 $\mu$m independently of the track angle. As discussed in Chap. 6, by taking also the toroid magnetic field in the ATLAS NSW region into account, the apparent track angles in the NSW detectors will range between 0° – 40°. Thus, the use of a hit reconstruc-
tion technique independent of the magnetic field and the track angle, like the µTPC-Centroid combination, is of particular importance.

### Table 5.3: Percentage of events described by the core Gaussian distributions for the µTPC-Centroid combination method results shown in Fig. 5.19.

<table>
<thead>
<tr>
<th>Combined events % in core Gaussian</th>
<th>(10^\circ)</th>
<th>(20^\circ)</th>
<th>(30^\circ)</th>
<th>(40^\circ)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>82.9%</td>
<td>82.3%</td>
<td>78.9%</td>
<td>81.2%</td>
</tr>
</tbody>
</table>

**Figure 5.19:** Combined hit position difference distributions between two T type MM chambers, divided by \(\sqrt{2}\) for \(10^\circ, 20^\circ, 30^\circ\) and \(40^\circ\) track inclination angles. The hit position is calculated by combining the µTPC and Centroid methods weighted by the cluster size using Eq. (5.1). The refined µTPC recipe is used for the calculation of the \(\chi_{\text{half}}\) hit.
5.5 Hit and Track reconstruction using a MM hodoscope

In order to exploit the excellent spatial resolution of the resistive-strip MM chambers, that have been presented in the previous sections, a multi-station hodoscope can be used for precise measurements of the beam characteristics such as the angular spread and the multiple scattering of the charged particles in the material of the chambers. Two such applications are presented that demonstrate the usability of a MM hodoscope using test beam data. For these studies the chambers were always kept perpendicular with respect to the beam axis and the hit position in each MM station is reconstructed using the Centroid method. A photo of the MM hodoscope that will be studied in this section is along with detailed characteristics of the MM stations consisting the hodoscope are presented in Appendix B.

5.5.1 Studying the beam characteristics

A MM hodoscope consisting of eight MM chambers was studied in a muon and pion beam during the test period of November 2014 in the H4 beam line of the SPS accelerator. More details on the hodoscope and the experimental set-up are given in Appendix B. During a high statistics run (~ 300k particle tracks) the initial muon beam was switched to pions of the same momentum (120GeV/c) during the same run. The goal was to understand the different characteristics of the beam, between muons and pions using the four reference Tmm and Tmb type chambers of the hodoscope in the different beam conditions.

The four MM chambers, which for this study have been kept perpendicular to the beam axis, were used to reconstruct the particle tracks. In order to ensure the precise reference track reconstruction the four MM stations have been aligned offline using the events recorded with the pion beam only. The same alignment constants have then been used for the data recorded.
with the muon beam for consistency. Figure 5.21 (left) shows the hit position difference between two of the MMs, that were installed with an intermediate distance of 2.2 cm, as a function of the reconstructed reference track angle taking into account the total 300k events of the run (including muons and pions). A high density, almost circular, region can be distinguished with an additional asymmetric tail towards the positive angle values. In the right plot of the same figure, the hit position difference value is plotted as a function of the run event number. The event number ranges that correspond to the different beam conditions are also noted on the plot. As small difference in the mean value of the scatter plot along the y axis can be observed between muon and pion beam. The time of change can also be discerned around the event number 150k.

![Figure 5.21](image)

**Figure 5.21:** Left: Hit position difference in two resistive MM chambers of Tmb type as a function of the reference track angle reconstructed using the four identical MMs of the hodoscope. Right: Hit position difference in two resistive MM chambers of Tmb type as a function of the run event number. The data correspond to a high statistics run taken with mixed beam conditions. The moment of change of the beam conditions in the middle of the run can be identified.

The same study is also performed for muons and pions separately in an attempt to disentangle the effect of the different beam conditions. Similar scatter plots as the ones of Fig. 5.21 are shown for the pion beam case only in Fig. 5.22. A very well concentrated scatter plot is obtained on the left plot owing to the small angular spread of the pion beam. The six bands in a star-shape that can be observed are coming from the coverage limits of the collimators that are employed to define a relatively fine beam profile. When the pions are totally blocked a muon beam is obtained with a significantly larger angular spread compared to the pions. The right plot of Fig. 5.22 shows the hit position difference as a function of the event number for the pion beam beam case only.
5.5 Hit and Track reconstruction using a MM hodoscope

The distributions of the reconstructed reference track angle for muons and pions respectively are shown in Fig. 5.23. In the muons case the angular spread of the beam is three times larger compared to the pions. Moreover, the mean angle of the particle tracks is not the same in the two cases with a difference measured to be of the order of $0.03^\circ$ (0.52 mrad) using a simple Gaussian fit on the central part of the distributions.

![Figure 5.23: Distribution of the reconstructed reference track angle for the muon (left) and pion (right) beam. The reference track is reconstructed using four Tmb type chambers.](image)

It is interesting to see how this difference in the track angle spectrum affects the hit and track...
reconstruction with the hodoscope MMs. The hit position difference distributions for the two different beam configurations, between the chambers that are also studied in the right plots of Figs. 5.21, 5.22, are shown in Fig. 5.24. The distributions are fitted with double Gaussian functions to describe also the tails. The first thing that can be observed is the difference in the mean value of the core Gaussian between muons and pions which is measured to be $\sim 14 \mu m$. From the results of the beam angular spread (Fig. 5.23), the difference in the mean track angle value, for the 2.2 cm distance between the chambers, yields an expected offset of $\sim 12 \mu m$. This value is in relatively good agreement with the offset calculated by the position difference distributions of Fig. 5.24. For what concerns the measured spatial resolution in the two cases, by looking in the $\sigma$ of the core Gaussian (parameters p5 and p2 in the left and the right histograms respectively) a slightly better performance can be measured for the case of the pion beam as a consequence of the smaller angular spread of the beam ($64 \mu m$ for pions and $67 \mu m$ for muons).

![Figure 5.24: The hit position difference distributions from the two resistive MM chambers of Tmb type for muon (left) and pion (right) beam respectively.](image)

### 5.5.2 Measurement of an electron beam multiple scattering

During the summer of 2013 a MM hodoscope with eight small resistive chambers was tested with an electron beam at the DESY accelerator in Hamburg. The main objective of this test was to study the performance of the resistive MM chambers under the influence of a magnetic field, thus the hodoscope was installed inside the magnet structure occupying the experimental area. A photo of the experimental set-up along with a schematic drawing of the different MM chambers used can be seen in Fig. 5.25. The synchrotron accelerator of DESY is able to provide an electron beam of up to 6 GeV energy [13].

Owing to the orientation of the magnet with respect to the beam the electron travel through the magnet structure material before they traverse the MM detection planes of the hodoscope. For this reason a sizable uncertainty was introduced in the measurements coming from the multiple scattering of the beam. On top of this, the energy of the particles is reduced with respect to the initial set value when they go through the material and there is also a non-negligible beam...
angular spread. In order to proceed to detailed studies with the magnetic field, it was essential to measure and if possible correct the additional uncertainty contributions coming from these effects.

Figure 5.25: A photo of the MM hodoscope during the installation inside the magnet at DESY is shown on the left. The sketch on the right shows a graphical representation of the set-up with the different MM chambers of the hodoscope along with the distances between the eight detection planes.

In the first place, the effect of the beam angular spread was put under investigation by comparing the hit position difference for the different T type chamber pairs with the one between the reference chambers that occupy the edges of the hodoscope (Tmm2, Tmm6). The correlation between the two quantities, for a beam energy of 6 GeV, is shown in the top left plot of Fig. 5.27 for one pair of the T chambers. The slope of the correlation gives a measurement of the beam angular spread with the size of the effect depending on the distance between the T chambers compared. The resulting one-dimensional hit position difference distributions are presented in the top right plot of the same figure with the extracted spatial resolution values significantly larger than the expectations. The same plots, after the correction of the track angles spread, using the measured slope of the correlation, are presented in the bottom row of Fig. 5.27. The corrected one-dimensional residual distributions yield a measured spatial resolution of the order of $\sim 70 \mu m$ depending on the distance between the chambers that are compared (99 mm for T1-T3).

The same procedure was repeated for six different values of the beam energy (1–6 GeV) and for four different T chamber pairs. The measured spatial resolution, after the correction of the beam angular spread, is plotted as a function of the corrected beam energy\(^7\). The different pairs are indicated with markers and lines of different colours in the graph which can be split into two groups (T2-T1, T8-T3 and T3-T1, T8-T2) depending on the intermediate distance (22 mm and 99 mm respectively) between the chambers compared. Moreover, it is evident that for smaller values of the beam energy the measured resolution becomes worse with the measured value increasing rapidly for corrected beam energy values smaller than 1.2 GeV.

\(^7\)The actual energy of the beam after the passage of the particles through the magnet material has been measured exploiting the curvature of the tracks because of the magnetic field. According to these measurements a total radiation length of 35\% is attributed to the material of the scintillators upstream of the hodoscope and the magnet material.
The measured value of the spatial resolution is the combination of the detector’s spatial resolution and the contribution of the multiple scattering on the material of the experimental set-up and the air. Moreover, the effect of the multiple scattering is dependent on the beam energy\(^8\), thus the measured spatial resolution can be expressed as a function of the beam energy using Eq. (5.9). The experimental measurements (data-points) are fitted with the function of Eq. (5.9) in order to disentangle the different uncertainty contributions. An average single plane resolution \((\sigma_{\text{intr}})\) of \(\sim 63.5\,\mu\text{m}\) is measured (parameter \(p_1\)) for the T chamber pairs which is in good agreement with measurements from different test beam studies (Fig. 5.4). The uncertainty due to the multiple scattering is measured (parameter \(p_0\)) to be on average \(37.4\,\mu\text{m} 72.4\,\mu\text{m}\) proportional to the distance between the detector planes compared, 22 mm and 99 mm respectively, and the interfering detector material.

\[
\sigma_{\text{meas}}(E)^2 = \sigma_{\text{scatt}}(E)^2 + \sigma_{\text{intr}}^2 \Rightarrow \sigma_{\text{meas}}(E) = \sqrt{\left(\sigma_{\text{scatt}}/E\right)^2 + \sigma_{\text{intr}}^2}
\]  

\[8\]The generic expression for the angular spread because of multiple scattering is in the case of electrons

\[
\theta = \frac{11.6\,\text{MeV}}{\beta\gamma} \sqrt{\frac{1}{X_0} \sum_k \left[ 1 + 0.038 \ln(x - X_0) \right]} \text{ where } \beta, \gamma, \text{ and } z \text{ are the momentum, velocity, and charge number of the incident particle and } x/X_0 \text{ is the thickness of the scattering medium in radiation lengths } [14]\]
5.6 Efficiency measurement

Apart from the precise hit position reconstruction, that the MM should be able to provide as the primary NSW tracker, the detector has to be fully efficient even at the highest rates of 15 kHz/cm² that are expected after the HL-LHC upgrade. In this direction, the efficiency of the small MM chambers was studied in test beam in order to fully characterise and understand possible contributions to detector inefficiency examining prototypes with different characteristics and under different track inclination angles.

The standard experimental set-up based on the small resistive MMs read-out with the SRS system is used in this study. The main parameters of the apparatus are described in Appendix B. A quick way to get a qualitative efficiency result is to make an efficiency map of a MM chamber by reconstructing the profile of the beam. By using the Tmm and Tmb type MM chambers, with two-dimensional readout, the hit position is reconstructed using the Centroid method in both readout layers. The two chambers examined, Tmm and Tmb, are almost identical with the only difference being the pattern of the spacers that are deposited below the mesh defining the amplification region thickness (pillars), which have 2.5 mm pitch with 300 µm diameter in the Tmm case and 5 mm pitch with 500 µm diameter for the Tmb. A reconstructed two-dimensional beam profile in two Tmm type chambers, using a high statistics run taken in November 2014 with the chambers placed perpendicularly to the beam, is shown in the contour plots of Fig. 5.28. Only a small rectangular area of the detectors is shown corresponding to the central area of the beam with the highest statistics. The histogram population increases by going from the green/yellow coloured areas to the orange ones. Several inefficient spots can be distinguished on the two di-

Figure 5.27: Measured spatial resolution as a function of the corrected electron energy measurement. The resolution is extracted from the hit position difference distribution between the different chamber pairs (T1,T2,T3,T8). The data-points are fitted with the expression quoted where \( p \) is the corrected beam energy, \( p_0 \) is the multiple scattering uncertainty and \( p_1 \) is the single detector plane spatial resolution.
mensional maps corresponding to the cylindrical pillar structure. The different pillar pattern in the two chambers can be perfectly seen by comparing the two plots where not only the different distance between the pillars is observed but the difference in the pillar diameter is visible as well.

Figure 5.28: Contour plots of the two-dimensional beam profile reconstructed in a Tmm type (left) and Tmb type (right) MM chamber which feature two layers of readout strips perpendicular to each other. The inefficient circular areas correspond to the pillar structure that is different in the two chambers. Left: Cylindrical spacers of 300 µm diameter and 2.5 mm pitch. Right: Cylindrical spacers of 500 µm diameter and 5 mm pitch.

A quantitative result regarding the contribution of the pillars in the chamber’s inefficiency, can be extracted if the chamber efficiency is plotted as a function of the particle’s track position on the chamber. By using a precise reference track, provided by three other Tmm chambers of the hodoscope (Appendix B), the beam profile is reconstructed from the extrapolated reference hit on the test chamber plane for two different cases.

- One distribution holds the beam profile reconstructed for the events where there is also a hit in the test chamber.
- A second beam profile distribution is reconstructed using the reference track regardless if a hit is reconstructed also in the test chamber or not.

It is quite evident that in the first case the beam profile histogram will always have less entries than the second. The difference in the number of entries between the two histograms will give a measurement of the geometrical inefficiency of the chamber because of the pillars. By dividing the two histograms, with the first case histogram being the numerator and the second histogram the denominator, the efficiency can be determined as a function of the extrapolated reference hit position on the test chamber plane.

This kind of efficiency maps are shown in Fig. 5.29 for a Tmm chamber with 2.5 mm pitch and 300 µm diameter pillars. The two columns correspond to X and Y readout respectively with the X readout strips being parallel to the resistive strips and Y perpendicular to them. Each row represents a different selected area of the chamber with respect to the pillars:
1. Area of $2 \times 2 \text{cm}^2$ in the middle of the chamber.

2. Area of $2 \times 2 \text{cm}^2$ in the middle of the chamber but selecting only bands along the Y (X) direction, for the X (Y) readout, that are around the pillar regions.

3. Area of $2 \times 2 \text{cm}^2$ in the middle of the chamber but selecting only bands along the Y (X) direction, for the X (Y) readout, that are in between the pillar regions.

The measurement of the chamber’s efficiency using each readout layer separately is realised using the first row histograms of Fig. 5.29. The efficiency dips that appear every 2.5 mm correspond to the pillars. The local inefficiency in the pillar region can be as large as 15% for the X readout layer. By calculating the ratio of the histogram integral with the 100% efficiency equivalent, the efficiency of the selected MM area is calculated for both X and Y readout layers. The Y readout layer reaches higher efficiency values with respect to the X close to the values that are theoretically expected if the only source of inefficiency is attributed to the pillars. The difference between the two layers can be attributed to the charge ratio between the two layers that is in favour of the Y readout layer due to its placement right below the resistive strips. Moreover, since the Y readout strips are oriented perpendicularly to the resistive the mean cluster size is larger compared to the X layer. This can have an impact on the measured efficiency as only good clusters (with two or more strips) are considered as hits in the analysis.

When the efficiency is measured only along selected areas (bands) around the pillars, the local inefficiency dips in the pillar regions become much more pronounced as presented in the second row histograms of Fig. 5.29. Because of the amplified effect of the pillars the measured efficiency in these regions is lower than when scanning through the whole surface of the chamber. If instead, the areas in between the pillar regions are used high efficiency values are obtained as can be seen in Fig. 5.29 third row. Moreover, because of the area selected, the pillar structure cannot be seen in the efficiency map. The efficiency of the Y readout layer is measured to be higher than the X in all the cases.

The results illustrated in Fig. 5.29 and discussed before correspond to the case where the chambers are positioned perpendicularly to the beam. In this case we expect the efficiency to be sensitive to the pillars due to the small cluster size. The same study is performed in two T type MM chambers, namely T2 and TQF which feature a single layer of readout strips oriented parallely to the resistive strips and are described in Appendix B. One particularity of the TQF chamber is the different pillar structure compared to the T chamber. The TQF features cylindrical pillars with 5 mm pitch and 500 µm diameter while for the T chamber pillars with 2.5 mm pitch and 300 µm diameter are used. The efficiency map as a function of the extrapolated reference track hit position is presented in Fig. 5.30 for both T2 and TQF chambers for perpendicular tracks. Similar efficiency values, better than 98%, are calculated for both chambers which are operated with the same gas mixture and equivalent electric drift and amplification fields. The good agreement between the values obtained for the two chambers illustrate that the choice of larger distance between the pillars does not suppress their effect in the chamber efficiency. However it should be noted that apart from the pitch, the two chambers differ also in the diameter of the pillars, and this may reduce the efficiency that is initially recovered by the increased distance between the spacers.
Figure 5.29: Efficiency map for the two readout layers (X left, Y right) of a Tmm type resistive MM chamber for three different chamber area selections. The first row corresponds to a $2 \times 2 \, \text{cm}^2$ area in the middle of the chamber. The second row shows the efficiency measurements for selected bands along the Y (X) direction, for the X (Y) readout, that are around the pillar regions. The results for the areas in between the pillar bands are shown in the third row.
5.6 Efficiency measurement

Figure 5.30: Efficiency map for two T type resistive MM chambers with different pillar structure (2.5/5 mm pitch and 300/500 µm diameter) for perpendicular tracks.

When the charged particle tracks traverse the chamber under an angle the track footprint on the chamber readout increases and the ionisation charge is induced in a larger number of strips compared to the perpendicular tracks. In this case, we expect the chamber efficiency to remain unaffected by the pillars. The efficiency map of the T2 and TQF chamber for tracks inclined by 30° is presented in Fig. 5.31. The measured efficiency approaches the 100% being completely transparent to the pillar structure. Although the hit position reconstruction accuracy is not ideal in the 30° case, since the Centroid method is used, the efficiency should be independent of the spatial resolution.

Figure 5.31: Efficiency map for two T type resistive MM chambers with different pillar structure (2.5/5 mm pitch and 300/500 µm diameter) for tracks inclined by 30°.
5.7 Studying the effect of pillars in the hit reconstruction

The effect of the spacers on the MM performance has been extensively studied in simulation [15]. According to the simulation results the electric drift field lines in a MM gap are distorted by the introduction of the pillars. Thus, depending on the distance from the mesh that the primary ionisation happens above a pillar, the ionisation electrons are either deviated from the original vertical drift path or they end up on the pillar without being detected by the readout. In the case where the primary electrons released above a pillar are detected by the readout, a bias is introduced in the hit reconstruction coming from the deviated drift paths.

The measured MM chamber inefficiency owing to the spacers structure has been discussed in detail over the previous section. Exploiting the excellent spatial resolution of the MM chambers the effect of the pillars in the hit reconstruction accuracy can also be measured from the test beam data. For this study four Tmm type MM chambers with two dimensional readout are placed perpendicularly to the beam axis. A reference track is reconstructed using three out of the four stations and is then extrapolated to the excluded station plane. For the hit reconstruction per plane the Centroid method is used. The residual between the reference track and the reconstructed hit in the test chamber is calculated per particle track by looking into events reconstructed inside bands around the area of the pillar areas of the test chamber as defined in Fig. 5.32 (bottom) by the black lines. The top plot of the same figure shows the residual value as a function of the hit position along the test chamber readout. The two histograms have the same scale on the x-axis. A larger position difference value can be noticed for the hits that are reconstructed in the vicinity of the pillars which has been measured to be as high as 150 µm. In each pillar region, expanding by ±0.3 mm from the pillar center, a perfect linear correlation of the residual value with the distance from the center of the pillar can be noticed, with the maximum deviation obtained at a radial distance ~ 0.3 mm from the pillar center. This corresponds to 0.15 mm from the edge of the pillar which in this specific case is made with a diameter of 0.3 mm. This result is in qualitative agreement with the simulation estimations [15] that predict a somewhat larger maximum deviation of 400 µm but with a different gas mixture than the one used in the test beam and for a non-resistive MM.

The local bias introduced in the hit position reconstruction in the region around the pillars has been measured using the test beam data and is also confirmed by simulation. However it is interesting to study the effect that these locally confined distortions can have on the measured spatial resolution of the MM chambers. Along these lines, and expecting that the distortion of the field lines is symmetrically distributed around the cylindrical pillar, a more delicate selection of different regions with respect to the pillars has been implemented for comparison of the measured performance. Instead of defining bands around the pillar regions a circular selection is now employed to limit the pillar neighbourhood as shown in Fig. 5.33 for the two Tmm chambers. In the specific case a radius of 0.5 mm around the center of the pillar is selected to cut-out the pillar regions from the rest of the chambers. The two complementary area selections are shown in the top and bottom rows of Fig. 5.33.

Using two Tmm chambers the spatial resolution that has been measured in the different areas, by calculating the hit position difference between the two chambers. For this study it is crucial to have the two chambers aligned as precisely as possible with respect to the pillars. A precise aluminium frame has been used during the test beam with the two detectors mounted on the
5.7 Studying the effect of pillars in the hit reconstruction

two sides of the frame in opposite orientations of their gas gaps (back-to-back). As can be seen in Fig. 5.33, where the same selection criteria are used in both chambers for defining the (non-)pillar areas, a relatively good alignment has been obtained by fixing the two chambers on the hodoscope.

![Figure 5.32: Residuals of the reconstructed hit position from the extrapolated reference track hit as a function of the reconstructed hit position for events within bands around the pillars region. The bias in the hit position reconstruction around the pillars is visible.](image-url)
Figure 5.33: Selection of different areas with respect to the pillars to study their effect in the spatial resolution. The hits reconstructed inside circles of radius 0.5 mm around the center of the pillars are shown in the top row and their complementary regions in the bottom one.

The hit position difference distributions for the full $17 \times 23 \text{ cm}^2$ area, the selected areas around the pillars and the area outside the pillar region of the two Tmm chambers respectively, are presented in Fig. 5.34. The border of the pillar neighbourhood is set at a radius of 0.5 mm from the pillar center. By comparing the middle and rightmost plot we can see the deterioration of the spatial resolution in the pillar's region compared to the measurement done using the areas between the pillars. The measured resolution degrades by 20% in the vicinity of the pillars because of the distortion of the electric field lines by the pillar structure. However, the effect in the resolution measured for the total $17 \times 23 \text{ cm}^2$ area is not significant. The comparison between the leftmost with the rightmost plot shows that the $\sigma$ of the core Gaussian is the same.
in both occasions. The effect of the pillars seems to contribute only in the tails of the distribution where a slight increase (2 µm) can be noticed in the first distribution compared with the third one.

**Figure 5.34:** Hit position difference distributions between two Tmm type M chambers for three different chamber areas with respect to the pillars. Left: Using all the hits reconstructed inside a $17 \times 23 \text{mm}^2$ area of the two chambers. Middle: Selecting only the hits that are reconstructed inside circles of radius 0.5 mm around the center of the pillars in both chambers. Right: Selecting all the hits outside circles of radius 0.5 mm around the center of the pillars in both chambers.
Bibliography


Micromegas inside magnetic field

The NSW (and SW) system will be located next to the ATLAS end-cap toroid magnet [1] as illustrated in Fig. 1.10. As a consequence, the NSW MM detectors will be exposed to a moderate magnetic field. The orientation and the intensity of the field varies depending on the radial and the z position with a maximum intensity of the field not larger than 0.3 T. Figure 6.1 shows two maps of the magnetic field in the SW region. The measurements shown correspond to a cross-section of the three dimensional field map in $z = 7800$ mm (SW outermost region) position along the beam axis. The CSC and MDT detectors of the current SW are shown in the left plot for reference. It can be seen that the magnetic field changes direction even between neighbouring sectors of the same detector technology. The absolute magnitude of the field doesn’t exceed the 0.4 T as can be extracted from the right contour plot of Fig. 6.1 that shows the $\phi$ component of the field. The circular areas of maximum intensity correspond the position of the coils of the end-cap toroid magnet coils.

**Figure 6.1:** Measurements of the magnetic field in the current SW region (CSC and MDT detectors) performed using magnetic probes and reconstructed using the Persint [2] software of the ATLAS experiment. Left: Map of the field orientation along a cross-section of the SW taken at distance of $z = 7800$ mm from the IP. Right: The $\phi$ component of the magnetic field at a distance $z = 7800$ mm from the interaction point. The plots are taken from [3].

Because of the magnetic field NSW detectors will face, extensive studies have been performed in order to understand and characterise the performance of the MM chambers when operated inside a magnetic field. The effect of the field on the detector operational parameters has
been studied theoretically using simplified models. In addition to these small resistive MM chambers have been installed and operated inside a magnet during two test beam periods and results focussing on the understanding of the magnetic field effect along with performance measurements are presented and compared to theoretical expectations.

### 6.1 Electrons drifting inside combined electric and magnetic field

The drifting of an electron, inside the drift gap of a MM detector, in the presence of a homogeneous magnetic field $B$, perpendicular to the electric field $E$, is put under consideration. The electron movement, under the influence of combined electric and magnetic fields, has been simulated in Garfield [4, 5]. An example for a particle track traversing the chamber under an angle and the resulting drifting paths are shown in Fig. 6.2. The electron path deviates from the direction of the electric field lines by the Lorentz angle $\alpha$ and the electrons drift under the influence of the Coulomb and Lorentz forces. Two cases corresponding to different opposite orientations of the magnetic field are presented. In the first case, shown on the left plot, the ionisation electrons are deviated from the electric field lines by a Lorentz angle that makes the track footprint larger. On the second case, shown on the right plot of the same figure, the electrons are deviated by the magnetic field in such a way that they induce signal to a smaller number of strips compared to the no magnetic field case. In both cases the electron drift paths are larger owing to the Lorentz angle.

![Figure 6.2: Garfield simulation demonstrating the effect of the magnetic field on the drifting of the ionization electrons [3]. In the case of a charged particle traversing the chamber under an angle, depending on the orientation of the magnetic field with respect to the electric field lines, the ionization electrons can be spread (left) or squeezed (right).](image)

In the no magnetic field case, the electron drift velocity ($v_D$) depends solely on the applied electric field and the gas mixture that is used. With the introduction of a magnetic field, $v_D$
is now governed by the combination of the electric and magnetic fields applied. By definition, the $v_D$ direction follows the drift path and, because of the deviation of the drifting paths by the Lorentz angle $\alpha$, the magnitude of the electric field along the drifting direction is $E \cos \alpha$. Consequently, when the electrons drift under the influence of a magnetic field $v_D \propto E \cos \alpha$ rather than $v_D \propto E$ (no magnetic field case). The electric field force, $F = q_e E$, oriented along the electric field lines, can be analysed into a component along the electron drift path $F_{||} = q_e E \cos \alpha$ and a component perpendicular to it $F_{\perp} = q_e E \sin \alpha$ as shown in Fig. 6.3.

Figure 6.3: The electron drift path is deviated from the direction of $E$, by a Lorentz angle $\alpha$ because of the applied magnetic field $B$. The relative orientation between electric and magnetic field corresponds to the case shown in Fig. 6.2 (left).

The deviation of the electron drift path is caused by the presence of the magnetic force $F_B = q_e [v_D \times B] = q_e v_D B$. Since, on average, the electron follows a straight path, as illustrated in Fig. 6.2, by balancing the two forces perpendicular to its trajectory, the Lorentz angle expression of Eq. (6.1) can be extracted.

\[
q_e E \sin \alpha = q_e v_D B \quad \Rightarrow \quad \sin \alpha = \frac{B}{E} v_D
\]

(6.1)

The dependence of the drift velocity from the electric field is governed by the microscopic interactions of the drifting electrons with the gas molecules, as has been discussed in Sec. 3.2.2. As a result, it is not possible to accurately describe it numerically. Nevertheless, an attempt to reproduce the Garfield simulation predictions for the Lorentz angle using simple theoretical models has been put into practice. Initially a linear dependence between the drift velocity and the electric field component along the direction of the electron motion is supposed such that $v_D = \mu(E)E \cos \alpha$. For zero magnetic field this yields $v_D(E, B = 0) = \mu(E)E = v_D^0(E)$. So, the drift velocity, for certain electric and magnetic field values, can be expressed as a function of the drift velocity in the zero magnetic field case such that $v_D = v_D^0(E) \cos \alpha$ and the Lorentz angle expression of Eq. (6.1) will take the form

\[
\tan \alpha = \frac{B}{E} v_D^0(E)
\]

(6.2)
In the derivation of Eqs. (6.1),(6.2) we assumed that the electron mobility $\mu$ depends on the electric field but not on the magnetic field $\mu = \mu(E)$. If the interaction of the electron with the gas molecules is taken into account Eq. (6.2) can be parametrised as shown in Eq. (6.3), where $\psi = \psi(E, B)$ is a dimensionless empirical factor called magnetic deflection coefficient [6].

$$\tan \alpha = \frac{B}{E} \psi_0^\theta (E)$$  \hspace{1cm} (6.3)

The Lorentz angle is calculated analytically, for magnetic field intensities up to 2T, using Eq. (6.1),(6.2) and we compare the results with the values obtained from Garfield simulation. The gas mixture is always assumed to be Ar+7%CO$_2$ and the drift electric field\(^1\) $E = 0.6$ kV/cm. Figure 6.4 shows the Lorentz angle $\alpha$ as a function of the magnetic field $B$, calculated using three different methods:

(a) The red curve shows the results of Garfield simulation.

(b) The green curve shows this dependence obtained numerically from

$$\sin \alpha = \frac{B}{E} \psi_0^\theta (E \cos \alpha).$$

$\psi_0^\theta$ is the drift velocity versus the drift electric field, for $B = 0$, given by Garfield.

(c) The blue curve shows the dependence of the Lorentz angle from the magnetic field assuming

$$\tan \alpha = \frac{B}{E} \psi_0^\theta (E)$$

where $\psi_0^\theta (E)$ is given by Garfield.

It is evident that case (b) is in almost good agreement with Garfield values, case (a), which is of course due the fact that we use accurate drift velocity values. This validates our simplified model since in case (b) we do not use the drift velocity extracted from Garfield for given electric and magnetic fields but we use instead the drift velocity that corresponds to an effective drift electric field of $E \cos \alpha$ with $B = 0$ T . The model of the linear dependence on the other hand, case (c), shows significant disagreement with the Garfield simulation discarding the initial assumption of the linear relation between the drift velocity and the electric field component along the electron’s drift path. None of the two theoretical models tested agrees perfectly with the simulation results. However, by simply using $v_D = \psi_0^\theta (E \cos \alpha)$ in Eq. (6.1) a fairly good estimation of the Lorentz angle is achieved, for magnetic field intensities up to 2T, with a maximum deviation of $\sim 20\%$ from the Garfield simulation values as shown in Fig. 6.4.

\(^1\)This corresponds to the nominal drift electric field applied to MM detectors with 5 mm drift gap using Ar+7%CO$_2$ gas mixture.
6.1 Electrons drifting inside combined electric and magnetic field

The drift velocity can also be calculated numerically using a theoretical model. The Langevin Eq. (3.11) of motion, for an electron with mass \( m \), inside a gas in the presence of a combination of electric and magnetic fields, \( E, B \), contains the electric force, \(-eE\), the magnetic force, \(-ev \times B\), and a drag friction force \(-v/\tau\) [6, 7]. Moreover, for the case of electric and magnetic fields perpendicular to each other and assuming the knowledge of the Lorentz angle \( \alpha \), the drift velocity for given field intensities can be expressed using the simplified model described before \( v_D(E, B) = v_D(E \cos \alpha) \). By solving the Langevin equation analytically, as described in the Appendix D, the magnitude of the drift velocity is derived from Eq. (6.4) where

- \( \omega = (e/m)B \) is the cyclotron frequency.
- \( \mu = (e/m)\tau \) is the electron mobility.
- \( \tau \) is the average time between collisions.

\[
v_D = \mu E \sqrt{\frac{1 + (\omega \tau)^2 (E \cdot B)^2}{1 + (\omega \tau)^2}} \tag{6.4}
\]

In general \( \tau = \tau(E, B) \) and \( \mu = \mu(E, B) \) thus, if \( \tau \) is constant then \( \mu \) is constant as well corresponding to the simplest linear case. In the case of electric and magnetic fields perpendicular to each other, \( \hat{E} \cdot \hat{B} = 0 \) and \( \vert \hat{E} \times \hat{B} \vert = 1 \). Thus Eq. (6.4) simplifies in Eq. (6.5)

\[
v_D = \frac{\mu E}{\sqrt{1 + (\omega \tau)^2}} \tag{6.5}
\]

In general the mobility \( \mu \) depends on the applied electric and magnetic fields \( \mu = \mu(E, B) \). If it is considered independent of the magnetic field \( \mu = \mu(E) \) then the expression for the drift velocity in the linear dependence case is

\[
v_D = \frac{v_D^0_B}{\sqrt{1 + \tan^2 \alpha}} = v_D^0 \cos \alpha, \quad v_D^0 = v_D^0(E) \quad \text{and} \quad \tan \alpha = \omega \tau = B \mu = \left(\frac{B}{E}\right) v_D^0 \tag{6.6}
\]
\[ \Rightarrow v_D = \frac{v_D^0(E)}{\sqrt{1 + \left( Bv_D^0/E \right)^2}} \]

For \( E = 0.6 \text{kV/cm} \) and \( v_D^0 = 47 \mu\text{m/ns} \) (nominal values for Ar+7%CO2), the Lorentz angle and the drift velocity will be

\[ \tan \alpha \approx 0.8B, \quad v_D = \frac{47}{\sqrt{1 + 0.64B^2}} \left( B \text{ in T and } v_D \text{ in } \mu\text{m/ns} \right) \quad (6.7) \]

Based on Eq. (6.5) the Lorentz angle can be derived from Eq. (6.8)

\[ \tan \alpha = \omega \tau \frac{|\hat{E} \times \hat{B}|}{\sqrt{1 + (\hat{E} \cdot \hat{B})^2(\omega \tau)^2}} \quad (6.8) \]

A better approximation with \( \tau = \tau(E, B), \quad \mu = \mu(E, B) = (e/m) \tau = (\omega/B) \tau(E, B) \) leads to the following

\[ v_D = v_D(E, B) = \mu(E, B)E \cos \alpha. \]

For \( B = 0 \) \( v_D^0(E) = \mu(E, B = 0)E \) and since \( \sin \alpha = Bv_D/E \) these are combined to

\[ \sin \alpha = \frac{B}{E} \mu(E, B)E \cos \alpha \]

Using the parametrization with the magnetic deflection coefficient \( \psi = \psi(E, B) \) we have

\[ \sin \alpha = \psi(E, B) \frac{B}{E} v_D^0(E) \cos \alpha \Rightarrow \tan \alpha = \psi(E, B) \frac{B}{E} v_D^0(E) \quad (6.9) \]

In Fig. 6.5 we compare the values of the drift velocity calculated using the simplified models described above, namely the generic equation \( v_D(E, B) = v_D(E \cos \alpha) \) and the linear dependence case Eq. (6.7), with the values expected from the Garfield simulation. It is obvious that none of the simplified models can describe accurately the microscopic interactions of the electrons with the gas that are taken into account from Garfield. However, by simply calculating for zero magnetic field, the drift velocity that corresponds to \( E \cos \alpha \) electric field amplitude with Garfield (green circles) we obtain a description that is in general in better agreement with the Garfield predictions (red dots) than the one based on the Langevin equation assuming a linear dependence of the drift velocity as a function of the magnetic field (blue line). The linear dependence assumption is not true in the case of the Ar+7%CO2 gas mixture for the region of electric field around 0.6 kV/cm. The simplified model on the other hand is not justified from theory but it works reasonably well.
6.1 Electrons drifting inside combined electric and magnetic field

![Graph showing Drift Velocity vs Magnetic Field, 600 V/cm](image)

**Figure 6.5:** Drift velocity dependence on the magnetic field $|B|$ for three different cases.

The simplified theoretical models presented help in understanding the magnetic field effect on the drifting of the primary ionization electrons in a MM detector. The deviation of the drifting path affects the drift velocity of the electrons which depends on the component of the electric field that is parallel to the path, $v_d(E, B) = v_d(E \cos \alpha)$. However, none of the theoretical models cannot reproduce the microscopic picture of the interactions between the electrons and the gas atoms. Thus, for the test beam data analysis that follows, the drift velocity values that are extracted from Garfield will be used while the Garfield Lorentz angle expectations will serve as references (Fig. 6.6).

![Garfield simulation plots](image)

**Figure 6.6:** Garfield simulation plots taken from [3]. Left: Total drift velocity in Ar+7%CO$_2$ gas mixture for magnetic field up to 2 T. Right: The expected Lorentz angle as a function of the drift electric field for five different magnetic field values. The electric and magnetic field vectors are perpendicular to each other and the nominal drift electric field for the MM is 600 V/cm.
6.2 MM in the SPS/H2 Test Beam Magnetic Field

In order to study the performance of MM chambers under the influence of a magnetic field, a dedicated test beam campaign at the SPS/H2 beam line at CERN was held during June 2012. A set of four T type MM chambers (called T1, T2, T3, T4) together with four reference Tmm type MM chambers (DUB1, ROM, DUB2, LNF), used as reference detectors, were installed inside the superconducting magnet with a magnetic field of up to 2 T. The specifications of the chambers and the apparatus are described in Appendix B.

A sketch of the experimental setup is presented in Fig. 6.7. The four MM test chambers where installed on an aluminium frame in two doublets in a back to back configuration\(^2\). The other four MM chambers, forming two doublets, were used to provide an accurate reference track. The test chambers could be rotated in different angles \([-40^\circ, +40^\circ]\) with respect to the beam axis while the reference chambers were fixed on the frame perpendicular to the beam axis. Photos of the experimental apparatus are shown in Fig. 6.8.

For two of the test chambers, namely T3 and T4, a drift gap size of 10 mm was chosen in order to amplify the effect of the field while the standard 5 mm gap was used for the rest. The magnetic field was always orthogonal to the drift electric field of the chambers. For the amplification region the high voltage was 500 V (39 kV/cm) resulting in gas gain significantly lower in comparison to the nominal \(10^4\) gas gain. The reduced gain does not affect the smooth operation of the chambers but it may result in worsening the measured performance [8].

\(^2\)In this configuration two MM are installed with oppositely oriented drift gaps with respect to the beam direction. This results in opposite electric fields orientation and opposite magnetic field effects in the two chambers of the doublet.
6.2 MM in the SPS/H2 Test Beam Magnetic Field

Figure 6.8: Eight small MM chambers mounted on a aluminium frame were installed inside the superconducting magnet in SPS/H2 CERN on June 2012 (Left: Front view, Right: Side view). The coils of the magnet are visible.

6.2.1 Effect of the magnetic field on the cluster size

Depending on the orientation of the magnetic field and the track inclination angle, the ionization electrons are either spread or squeezed as a result of the $E \times B$ effect. In Fig. 6.2 the two possible orientations of the electron drifting under the influence of the magnetic field, oriented perpendicularly to the electric field, are shown for a track inclined by 30°. The cluster size increases or decreases, with respect to the zero magnetic field situation, for spreading and focussing configuration accordingly.

![Graphs showing the effect of magnetic field on cluster size](image1)

Figure 6.9: Effect of the magnetic field on the cluster size (number of strips per cluster) for $B = 0$ T and $B = 0.2$ T. The chambers were inclined by +10° and −10° with respect to the beam axis, respectively. The different inclination angles result in different effect of the magnetic field on the drifting of the electrons. The two most left plots show the cluster size without magnetic field for +10° and −10° inclination angle respectively. The last two plots represent the case of $B = 0.2$ T for the two inclination angles respectively.

The effect is evident on the test beam data for four different magnetic field and track angle combinations. The cluster size distributions are shown in Fig. 6.9 for two values of the magnetic field with incident track angles −10° and +10°. The negative value of the angle corresponds to

---

3The clustering is done with the Centroid method described in Sec. 5.1.
the configuration where the electrons focus while the positive angles illustrate the spreading of the electrons, owing to the $E \times B$ effect. In the absence of the magnetic field both distributions for $+10^\circ$ and $-10^\circ$ have similar mean values with almost equal spreads. By introducing a magnetic field of 0.2 T the mean values of the distributions move towards opposite directions. For the focussing configuration ($-10^\circ$), the mean value moves to lower values with a smaller standard deviation while for the spreading configuration, it moves to larger clusters accompanied by a wider range of cluster size values.

### 6.2.2 Apparent and incident angle measurement

The $\mu$TPC method can also be adopted in the case of a non-zero magnetic field environment for a track reconstruction using a single chamber. However, it is important to use the correct value of the drift velocity that corresponds to the applied magnetic field intensity as described in Sec. 6.1. The reconstructed track using this method will be different from the incident track angle because of the additional contribution due to the Lorentz angle. The apparent angle can be predicted with a simple geometrical model as described in the sketch of Fig. 6.10. The expected apparent angle $\theta'$, as a function of the incident track angle $\theta$ and the Lorentz angle $\alpha$, will then be given by Eq. (6.10). The left plot of Fig. 6.11 shows an example of a reconstructed $\mu$TPC track in one of the test chambers (T3). The chamber was inclined by $20^\circ$ and a magnetic field of 1 T was applied. The apparent reconstructed angle is $\sim 45^\circ$.

$$\tan \theta' = \cos \alpha (\tan \theta + \tan \alpha)$$  \hspace{1cm} (6.10)

![Figure 6.10:](image)

**Figure 6.10:** Calculation of the apparent angle owing to the magnetic field. $\theta$ is the incident track angle, $\alpha$ is the Lorentz angle and $\theta'$ stands for the reconstructed apparent angle.

The $\mu$TPC method has been applied in the test beam data always using the drift velocity corresponding to the specific magnetic field and the results for the apparent angle calculation are summarised in Fig. 6.11 (right). The different colours correspond to two different incident track angles, red and green for $10^\circ$ and $20^\circ$ respectively. The empty full circle points show the angles reconstructed from the test beam data and the curves are the representations of the apparent angle function given by Eq. 6.10 for $10^\circ$ and $20^\circ$ incident angles and for different values of the magnetic field in the range 0 – 1 T. The calculated angles follow the Garfield curve with a small deviation for the 1T case. This small difference between data and simulation points can be attributed to the incident track angle measurement resolution ($\approx 2 - 3^\circ$) and the magnetic field value uncertainty (5%).
Exploiting the knowledge of the drift velocity for the applied magnetic field, we can go a step further and reconstruct the incident track by correcting the position of the primary ionisation clusters. The correction method is schematically described in Fig. 6.12 where the apparent track points are shown with blue open circles and the incident track after the correction is shown with the magenta circles. Using the calculated components of the drift velocity to correct the x, y positions of the reconstructed two dimensional space points the primary clusters are placed in their true initial positions.

The effectiveness of this correction technique is demonstrated in Fig. 6.13 for an incident track angle of 20° and a magnetic field of 0.5 T. In the left plot, the angular distribution for the
apparent angle is presented while on the right the distribution of the incident track angle after the applied correction is shown. The mean values in both histograms are in good agreement with the expected angles (38° and 20° respectively), within the uncertainty limits of the angle measurement (≈ 2°). The angular resolution, mainly deriving from our convoluted time uncertainty, includes multiple contributions

- The intrinsic detector time resolution (few ns) owing to the ionization-avalanche fluctuations in gaseous detectors.
- The uncertainty introduced by the time extraction procedure using the integrated charge per channel.
- The accuracy of the μTPC reconstructed track which is degraded by the decreasing footprint size of the track (difference between the first and the last strip of the cluster). It is evident that for larger apparent angles, we observe better angular resolution because of the larger lever arm.

**Figure 6.13:** Incident angle determination (run with 20°, 0.5 T). Left: Distribution of the reconstructed μTPC angle. Right: The angular distribution after the correction of the magnetic field effect. The long tails correspond to badly reconstructed tracks because of wrong timing determination or owing to clusters with small number of strips.

### 6.2.3 Spatial resolution of MM in magnetic field

The spatial resolution of the test chambers in the non-zero magnetic field environment has been studied for various magnetic field and incident angle configurations. The test values for the magnetic field have been 0, 0.2, 0.5 and 1 T and the data analysed correspond to incident track angles ∈ [−20°, −10°, +10° and +20°]. Both the Centroid and the μTPC methods, along with their combination, described in Sec. 5.1, have been used for determining the hit position per MM chamber and the position uncertainty has been calculated by subtracting the hit positions of a chamber pair. The results are presented in Fig. 6.14 for the four different incident angles and the spatial resolution determined is plotted as a function of the magnetic field intensity.

Although the measured spatial resolution of the combined method remains stable along the different values of the magnetic field, it is slightly worse than for the zero magnetic field case shown in Fig. 5.20. This is not only attributed to the presence of the magnetic field, but it is
mostly owing to the fact that the amplification field applied on the MMs in the SPS/H2 test beam magnetic field was lower than the nominal one. This affects directly the chamber performance increasing the uncertainty in the position measurement as described in [8]. A similar measurement has been repeated during a second test beam in magnetic field, where the amplification field used was the optimal one and a better performance could be measured (Sec. 6.3.2).

![Graphs showing spatial resolution vs magnetic field](image)

**Figure 6.14:** Spatial resolution, determined with μTPC and Centroid method, as a function of the applied magnetic field for 4 different incident angles (−20°, −10°, 10°, 20°).

In the example of negative inclination angles the ionization charges are squeezed (focussing) because of the magnetic field while for the positive values the \( E \times B \) effect compensates the incident angle providing larger reconstructed apparent angles. For the defocussing configuration the μTPC method always provides a more accurately reconstructed hit in comparison with the Centroid. In the single cases however, of almost perpendicular apparent tracks, the Centroid hit is more precise as shown in the top right histogram of Fig. 6.14 (0.2 T, −10°). By combining the μTPC and the Centroid methods, as described in Sec. 5.1, these singularities can be recovered providing a uniform spatial resolution for every possible magnetic field configuration.

Figure 6.15 (left) shows the Centroid hit position difference between two chambers of the same doublet \((T1, T2)\) divided by \(\sqrt{2}\) for the case of perpendicular tracks and no magnetic field. The measured single plane spatial resolution is \(\sim 56 \mu m\). The performance of this method degrades for track angles greater than 10° because of the spreading of the charges in multiple strips while the μTPC cannot provide meaningful information for track angles less than 10° where we are dominated by small clusters. The case where the magnetic field cancels out the incident track angle is shown in Fig. 6.15 (right). The effect of the magnetic field is the same in both chambers of the doublet because of the back-to-back orientation, thus the same spatial resolution as
in the no magnetic field case is measured. The mean values of the distributions agree within $1 - 2 \mu m$ and no bias is introduced by the application of the magnetic field.

*Figure 6.15:* Left: Residual distribution between the Centroid hit position of two MM chambers placed with an intermediate distance of 2 cm. The data correspond to a test beam run with no magnetic field and the chambers oriented perpendicularly to the beam. Right: The same distribution for a test beam run with $B = 0.2 T$ and the chambers inclined by $10^\circ$ with respect to the beam axis. The distributions are fitted with double Gaussian functions to properly take into account the tails and the resolution quoted corresponds to the width of the core Gaussian ($\geq 90\%$ of the events).

### 6.2.4 Measurement of the Lorentz angle

When the ionization electrons deviate from their trajectories because of the Lorentz force, a displacement of the beam profile with respect to the zero magnetic field case is expected. For the study presented here, the chambers were kept perpendicular to the beam axis, while increasing the magnetic field. For each event the ionisation charge is spread along several strips and the single plane hit position is reconstructed using the Centroid method (Sec. 5.1). Figure 6.16 shows the beam profiles of one chamber for different values of the magnetic field using the test beam data.

The SPS/H2 beam profile had a Gaussian shape owing to the scintillators’ setup and the settings of the beam collimators. By measuring the displacement and using the chambers’ drift gap dimensions the Lorentz angles for the different field values are calculated and compared to the theoretical Lorentz angles expected from Garfield. The comparison between the Lorentz angles measured from SPS/H2 data with Garfield expectations is illustrated in Fig 6.17. The red curve shows the Lorentz angle versus the magnetic field value as calculated with Garfield, while the black points show the Lorentz angles measured by applying the technique described above on the data.
Figure 6.16: Lorentz angle measurement using the beam profile displacement because of the magnetic field for T3 chamber (data). From top left to middle right plot the beam profile for 0.1, 0.2, 0.5 and 1 T magnetic field is compared with the 0 T magnetic field case.

Figure 6.17: The measured Lorentz angle for different magnetic field intensities (black markers). The Garfield predictions are overlayed for comparison (red line).
Despite the small systematic shift, the data points follow nicely the Garfield expectations and the measurement method is validated. A factor that contributes to this deviation is the non-homogeneity of the magnetic field intensity inside the magnet. Depending on the distance from the center of the magnet, the magnetic field could vary as much as 5% of the set value \[9\]. It should be also noted that the accuracy of the Centroid hit reconstruction method decreases significantly as the cluster size increases (Fig. 5.20). The size of the track footprint increases either for larger track incidence angle or larger magnetic field intensities (Lorentz angle) in the spreading magnetic field configuration. The broadening of the beam profile that is observed when increasing the magnetic field intensity, because of the spreading of the charges owing to the Lorentz force, can also be attributed to the Centroid method. Thus, for a more precise hit reconstruction during this magnetic field scan the \(\mu\)TPC method, discussed in Sec. 5.3, should be used.

### 6.3 MM in the SPS/H4 Test Beam Magnetic Field

In November 2014 another test beam campaign has been realised for studying the performance of resistive MM chambers inside a magnetic field. A set of four T type MM chambers together with four reference Tmm type MMs were installed inside the Goliath magnet of the SPS/H4 beam line at CERN that could provide a magnetic field with an intensity of up to 1.5 T (Fig. 6.18). The test chambers (called T4, T2, T8 and T5) featured the same characteristics as the ones of the H2 test beam with a 5 mm thick drift gap used for all of them. For the amplification region the high voltage was 540 V (42 kV/cm) resulting in a higher gas gain compared to the H2 test beam.

![Figure 6.18: Left: Photo of the MM experimental set-up installed inside the Goliath magnet of the H4 North area beam line. Right: A graphical representation of the small MM chambers as they were installed on the hodoscope.](image)

The magnetic field intensity inside the Goliath magnet changes depending on the distance from the magnet’s geometrical centre where the intensity of the field equals the set value. A two dimensional map of the Goliath field is presented in Fig. 6.19 (left). It can be seen that the fringe magnetic field drops rapidly in the area close to the edges of the magnet coils. Owing to this, a set of four magnetic probes, able to provide a three dimensional measurement of the magnetic field vector, has been installed in the MM hodoscope in order to reconstruct the field map along the different doublets positions. The measured field intensity values as a function of the set values are shown in Fig. 6.19 (right). The effect of the field attenuation, proportional
to the distance from the center of the magnet, is visible in the green curve corresponding to the outer doublet of the hodoscope. Differences in the intensity of the field between the different doublets up to 10% are measured. Moreover, a saturation effect can be observed with increasing the value of the field intensity above 0.5 T. Owing to the non-uniform field the drift velocity value that corresponds to the field intensity in the area of each chamber has been used in the analysis that follows.

![Figure 6.19](image)

**Figure 6.19**: Left: Two dimensional map of the Goliath magnet field. Right: Measured magnetic field intensity as a function of the set value using four magnetic probes installed in different positions on the MM hodoscope.

### 6.3.1 Measurement of the drift velocity

Using the distribution of the measured arrival times for a single chamber, as described in Sec. 4.1, the electron drift velocity can be calculated. With the magnetic field intensity increasing, the electron drift paths become larger and the inclusive time distribution (Fig. 4.6) gets wider. Since the knowledge of the drift gap size of 5 mm can be presupposed, the larger width of the distribution results in a lower drift velocity. The test MM chambers are positioned perpendicularly to the beam and the drift velocity component along the electric field lines is measured for different values of the magnetic field intensity. By using also the Lorentz angle that corresponds to the specific values of the magnetic field intensity the drift velocity along the electron drift path can be extracted (Fig. 6.3). The measurements of the two components are plotted as a function of the magnetic field intensity in Fig. 6.20. Only the runs taken with magnetic field set values ≥ 0.3 T are used in order to have an apparent track angle larger than 20° and thus a smaller uncertainty in the timing measurement. In this case, where the chambers are kept vertical with respect to the beam axis, the apparent angle is only due to the Lorentz force. The agreement between the data and Garfield expectations is very good validating the measurement method along with the field measurements that are used to calibrate the magnetic field values.
Figure 6.20: Drift velocity measurement as a function of the applied magnetic field and comparison with Garfield expectations. The drift Garfield drift velocity values are extracted from the data of Fig. 6.6. Left: Resultant drift velocity along the electron drift path. Right: Drift velocity component along the drift electric field. The MM was inclined by 30° with respect to the beam axis for all the magnetic field intensities.

6.3.2 Hit and track reconstruction studies

Let’s consider again the apparent track owing to the combination of the track incident angle with the Lorentz angle as described schematically in Fig. 6.10. If instead of the resultant drift velocity the component along the electric field lines is used to transform the measured time into distance then the equivalent to Eq. (6.10) form will be given by Eq. (6.11). Thus, in the case where the track inclination angle is zero, the apparent angle matches the Lorentz angle.

\[ \tan \theta' = \tan \theta + \tan \alpha \]  

(6.11)

Owing to this, by using the runs where the chambers were positioned perpendicularly to the beam at different magnetic field intensities, the reconstructed \( \mu \)TPC angle should match the Lorentz angle corresponding to the field value. The distributions of the reconstructed \( \mu \)TPC angle for the four test chambers of the hodoscope, in the case of \( B = 0.5 \) T are shown in Fig. 6.21. The Lorentz angle expected from Garfield simulation is \( \sim 27^\circ \) for 0.5 T magnetic field intensity as can be extracted from Fig. 6.17. If the peak angle value is extracted from each angular distribution, using the mean value of a Gaussian fit around the peak, the agreement with the Garfield value is very good. However, a small difference, of the order of \( \sim 1^\circ \), between the peak angle values of the first and second row distributions can be observed. This difference is directly related to the attenuation of the field intensity as we move from chamber T4 towards T5 along the hodoscope and is quantified in Fig. 6.19 to be of the order of 0.02 T. This difference in the field value corresponds to a difference of \( \sim 1^\circ \) in the expected value of the Lorentz angle which confirms the data observations.
The same measurement is also performed for different values of the magnetic field intensity. The values of the peak reconstructed angle are shown as a function of the field intensity in Fig. 6.22 (left). The drift velocity value that corresponds to the measured magnetic field values, in the position of the T chambers (Fig. 6.19), has been used for the \( \mu \)TPC reconstruction. The errors that are assigned in each measurement are coming from the magnetic field value uncertainty and the \( \sigma \) of the Gaussian fit around the peak of the angular distribution. The magnetic field uncertainty has been measured by measuring the magnetic field along different areas of the detector depending mainly on the position along the magnetic field lines. The measurements are in good agreement with the Garfield expectations that are represented by the superimposed curve for field intensities higher than 0.4 T. For smaller field intensities the resulting \( \mu \)TPC angle becomes smaller than 20° and the angle bias coming from the incorrect charge position assignment of the hit in the cluster edges results in a deviation from the expected values. This disagreement for the small Lorentz angle values is not related to the magnetic field but it is purely coming from the applied \( \mu \)TPC algorithm that in this case has not been refined as described in Sec. 5.3.
The chamber spatial resolution has been also measured using the same data-set. Since the particle tracks are effectively inclined, owing to the de-focussing configuration of the magnetic field, the µTPC method has been employed for the hit position reconstruction. The two-dimensional particle trace is reconstructed in each chamber by combining the strip address and time information as described in Sec. 5.3 and the hit position is calculated by interpolating the track in the middle of the chamber’s drift gap ($x_{\text{half}}$). The resolution is then measured by calculating the hit position difference between two chambers. The results are summarised in Fig. 6.22 (right) as a function of the magnetic field intensity for two of the possible chamber pairs that can be formed. A spatial resolution as good as 110 µm has been measured showing a significant improvement compared to the H2 results presented in Fig. 6.14. The rapidly decreasing performance for the small field intensity values is again attributed to the µTPC method that has not been enhanced with the corrections described in Sec. 5.3. In addition to this the method’s performance deteriorates with smaller track incident angles due to the smaller number of strips. Overall, the uncertainty in the hit reconstruction seems to slightly increase with the introduction of the magnetic field probably due to the larger drift paths. However, no significant correlation between the measured performance and the magnetic field intensity has been observed.

**Figure 6.22:** Results from performance studies for different magnetic field intensities. Left: Reconstructed Lorentz angle using the µTPC as a function of the magnetic field intensity. Right: Measured spatial resolution using the µTPC method as a function of the magnetic field intensity. The resolution is calculated using the hit position difference distribution using two resistive MM chambers T type.
Bibliography


Chapter 7

Characterisation of different Micromegas readout layouts and electronics

In parallel with the tests of the Tmm and T type chambers several other MM prototypes with different characteristics and sizes have been studied in test beams towards validating and optimising the MM layout and design. Performance studies of MM prototypes with different readout layouts including stereo strips, strips of different capacitance and multiplexed strips are presented in this chapter. In addition, the T type MMs have been used for the performance characterisation of the first version of the VMM front-end ASIC that will be employed for the readout of the NSW detectors. Some results on the MM performance that has been measured with the VMM1 chips are also discussed.

7.1 The MM for the SW quadruplet prototype (MMSW)

During the first half of 2014 a step forward in the large MM prototype production was made, towards establishing the construction and assembly procedures for the NSW MM modules, with the realisation of the first MM quadruplet detector (MMSW). This $1 \times 0.5 \text{m}^2$ prototype follows a configuration similar to the one foreseen for the NSW MM quadruplets consisting of four MM active gaps stacked together in a back-to-back configuration featuring also a stereo configuration of strips for half of the layers allowing for two-dimensional hit reconstruction. In this section the MMSW design and layout characteristics are briefly described and followed by test beam performance studies carried out at CERN PS accelerator during the summer of 2014.

7.1.1 Construction and operational parameters of the MMSW

A schematic representation of the MMSW structure cross-section is shown in Fig. 7.1 (left). The four readout planes are disposed in a "back-to-back" configuration on two stiffening panels with an aluminum honeycomb internal structure (readout panels). One of them hosts two layers of strips measuring the precision coordinate while the two readout layers of the second panel have stereo strips, tilted by $\pm 1.5^\circ$ with respect to the precision ones. The rotation axis that defines the stereo geometry of the MMSW readout layers passes through the geometrical middle of the PCBs. One central, double sided panel and two external panels sustaining the stainless steel mesh (drift panels) are then coupled to the two readout panels to form the four gas gaps of the quadruplet. The detector has been realized using the mechanical floating-mesh technique.
where the mesh is stretched on an aluminium frame and is then integrated in the drift panel. In this way the mesh is decoupled from the readout structure and is sustained in contact with the pillars by the electrostatic force. As discussed in Sec. 3.6, this scheme simplifies the construction of large size MM detectors and allows for re-opening of the chamber for cleaning in case of possible residues in the amplification volume.

Another innovation that has been adopted in the MMSW prototype is the use of new connectors between the readout electronic channels and the detector strips. In the case of the MMSW, instead of the standard 130-pin Panasonic [1] no connectors are mounted on the readout PCB but the front-end electronics are linked to the readouts strips using Zebra [2] elastomeric connectors between the front-end boards and the strip footprint on the PCB. In order to ensure good contact between the Zebra and the readout strip edges the connector is mechanically pressed while the accurate positioning of the connector in the perpendicular to the strips direction is ensured by fixed precision pins that act as guides. The edge profile of the MMSW readout and drift panels is shown in the photo of Fig. 7.1 (right). The mezzanine board, that hosts the APV25 hybrids, with the zebra connector is pressed on the readout PCB by the aluminium suppression bars that are visible for two of the four layers in the photo.

The resistive foils that were used in the MMSW were made with the sputtering technique [4] that guarantees a very good mechanical accuracy of the strip structure (in the order of a few tens of µm). A zoom-in photo of one of the resistive foils used in the MMSW is shown in Fig. 7.2 (left). As can be seen in the photo, the resistive strips were interconnected every 10 mm to accelerate the evacuation of the charge formed in the resistive material mitigating the effect of long strips. The four readout planes are segmented into strips with a pitch of 415 µm comprising a total of 4096 strips. A photograph from one MMSW readout PCB during the assembly procedure can be seen in Fig. 7.2 (right). As can be seen also in the photo, the readout strips and the HV supply are routed in opposite directions for the top and bottom half of the PCB.
7.1 The MM for the SW quadruplet prototype (MMSW)

Figure 7.2: Left: A zoomed photo of one MMSW resistive foil realised with the sputtering technique. Right: Photo of one of the four MMSW PCBs with readout strips for the MMSW during the module assembly.

7.1.2 Study of the MMSW in test beam

During the summer of 2014 the MMSW chamber was installed in the T9/PS experimental area along with the eight-station reference hodoscope of small MM detectors. The set-up was exposed to proton beam of up to 10 GeV/c momentum with particle rates of $\sim 10$ kHz/$cm^2$ in order to study the performance of the multilayer prototype. The reference telescope consisted of four small Tmm type and four T type MMs. The efficiency of each of the four MMSW layers has been measured independently by exploiting the very precise reference track, reconstructed by combining the hodoscope chambers. During the test the MMSW was always kept perpendicular to the beam and the Centroid method, described in Sec. 5.1, has been used for the single plane hit position reconstruction. Very high efficiency values have been obtained for all four layers with only $\sim 2\%$ geometrical inefficiency measured attributed to the pillar structure. A position scan has also been performed by centering the beam at different spots along the readout strips for spotting possible hot or inefficient areas of the detector. A schematic representation of the relative orientation between the different layers of readout strips is shown in Fig. 7.3 (left). The strips in two of the layers are inclined by $+1.5^\circ$ and $-1.5^\circ$ with respect to the parallel layers. The MMSW installed in the test beam experimental apparatus at T9 beam line can be seen in the photo of Fig. 7.3 (right).

Precision coordinate hit reconstruction accuracy

The spatial resolution of the layers with strips measuring the precision coordinate has been estimated by calculating the difference between the reconstructed hit position in the two upstream layers of the MMSW. Both layers used in this measurement have readout strips with orientation parallel to each other. Only events with a single cluster enter the analysis in order to remain unaffected by multiple track events. The hit position difference distribution is shown in Fig. 7.4 (left) where a double Gaussian function is used to describe the measurements. The width of the core Gaussian divided by $\sqrt{2}$ gives an estimate of the single layer spatial resolution\(^1\). The uncertainty that is measured, using this method without further processing, is slightly worse than the intrinsic resolution of the detector since it can be affected by several factors:

\(^1\)Assuming equal uncertainty in the hit position reconstruction for the two layers.
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Figure 7.3: Left: Schematic representation of the relative orientation between the strips of the different MMSW readout layers. Right: A photo of the MMSW prototype installed in the T9 experimental area at CERN during the summer of 2014 test beam.

- The angular spread of the beam or the inclination of the chamber with respect to the beam axis.

- The relative rotation between the two layers.

- The multiple scattering of the traversing particle in the material between the two layers.

The effect of the beam angular spread or the inclination of the chambers with respect to the beam axis can be calculated and corrected using test beam data. This can be achieved by measuring the angular spread of the reference tracks or by measuring the correlation between the position difference of the reconstructed hits in two of the MMSW layers and one of the two hit positions. The latter has been used and the correlation plot that is obtained is shown in Fig. 7.4 (right). In the ideal case of perfectly perpendicular tracks the residual value should not depend on the hit position and the slope of the correlation should be zero. By fitting the scatter plot with a first order polynomial function the slope can be used to correct the position difference value depending on the reconstructed hit position along the readout. The distribution presented on the left of the same figure is reconstructed after correcting the effect of the beam angular spread. An improvement of ~ 12% has been obtained in the measured spatial resolution value by applying these corrections. Owing to the very precise construction procedure followed during the realisation of the MMSW prototype, the rotation between the two layers is considered to be negligible.

Precision and second coordinate hit reconstruction using the stereo information

The introduction of the small stereo angle in the MM detectors provides a measurement of the second coordinate and reduces significantly the number of electronic channels of the NSW system compared to a complete 2D readout configuration (chamber layout similar to Tmm). This idea has also been implemented in the two of the four layers of the MMSW and hit reconstruction accuracy that can be achieved by combining the stereo information is studied.
7.1 The MM for the SW quadruplet prototype (MMSW)

Figure 7.4: Left: Distribution of the residuals between the reconstructed hit positions in the first two layers of the MMSW quadruplet both with parallel readout strips measuring the precision coordinate. The result is shown after the correction described in the right plot. Right: By calculating the correlation between the residual difference and the hit position in one of the two layers the effect of the beam angular spread can be mitigated.

The case where two coordinate systems \((\phi', \eta')\) and \((\phi'', \eta'')\) have been rotated with respect to the \((\phi, \eta)\) by an angle \(\theta\) and \(-\theta\), respectively\(^2\), as shown in Figure 7.5 (left) is first considered. The transformations that describe an arbitrary point \(A\) in the different coordinate systems are given by the following equations:

\[
\begin{align*}
\eta' &= \eta \cos \theta - \phi \sin \theta \\
\phi' &= \eta \sin \theta + \phi \cos \theta
\end{align*}
\]

\[
\Rightarrow
\begin{align*}
\eta &= \eta' \cos \theta + \phi' \sin \theta \\
\phi &= -\eta' \sin \theta + \phi' \cos \theta
\end{align*}
\]

and

\[
\begin{align*}
\eta'' &= \eta \cos \theta + \phi \sin \theta \\
\phi'' &= -\eta \sin \theta + \phi \cos \theta
\end{align*}
\]

\[
\Rightarrow
\begin{align*}
\eta &= \eta'' \cos \theta - \phi'' \sin \theta \\
\phi &= \eta'' \sin \theta + \phi'' \cos \theta
\end{align*}
\]

By combining the information from the two stereo frames, \((\eta', \phi')\) and \((\eta'', \phi'')\) and assuming that these two coordinate systems share a common center of rotation the precision coordinate \(\eta\) of point \(A\), expressed in the \((\phi, \eta)\) frame, can be extracted using Eq. (7.1) while the error in the measurement of the \(\eta\) variable, by propagating the errors of the dependent parameters, is expressed by Eq. (7.2).

\[
\eta = \frac{\eta' + \eta''}{2 \cos \theta} \tag{7.1}
\]

\[
\sigma_\eta = \frac{\sigma_{\eta'}}{\sqrt{2 \cos \theta}}, \quad \text{assuming} \quad \sigma_{\eta'} = \sigma_{\eta''} \tag{7.2}
\]

When \(\theta = 1.5^\circ\) (similar to the MMSW case, where the two systems \((\phi', \eta')\) and \((\phi'', \eta'')\) are rotated by \(3^\circ\) with respect to each other) the combined error of the precision coordinate \(\eta\) will be

\(^2\)The relative angle between the two coordinate systems \((\phi', \eta')\) and \((\phi'', \eta'')\) is \(2\theta\).
almost equal to the one that can be achieved by combining two MM layers oriented in a parallel configuration (all readout strips from both layers parallel to each other).

By using a similar combination of the stereo information, like the one of Eq. (7.1), the second coordinate ($\phi$) can be extracted as well from the expression of Eq. (7.3) with the corresponding error on the second coordinate $\phi$ given from Eq. (7.4):

\[
\phi = \frac{\eta'' - \eta'}{2 \sin \theta}
\]  
\[
\sigma_\phi = \frac{\sigma_{\eta'}^{\prime}}{\sqrt{2} \sin \theta}, \quad \text{assuming} \quad \sigma_{\eta'}^{\prime} = \sigma_{\eta''}^{\prime}
\]  

Fig. 7.5 (right) shows the ratio value between the hit position reconstruction errors ($\sigma_\eta/\sigma_{\eta'}$) as a function of the stereo angle $\theta$. For example, by using $\theta = 1.5^\circ$ and assuming that the hit position reconstruction uncertainty of a single layer in its reference frame is $\sigma_\eta = 100 \mu$m the expected error in the reconstruction of the $\phi$ coordinate, extracted by combining two identical stereo layers, will be $\sigma_\phi = 2.7$ mm. For the precision coordinate on the other hand, using the same stereo angle, by combining the two stereo layers an improvement in the position resolution of $\cos(1.5^\circ) \cdot \sqrt{2}$ is obtained.

If we also envisage a separation between the two stereo layers ($\phi', \eta'$) and ($\phi'', \eta''$) by a known distance of $\Delta z$ in the case where a known track of polar angle $\Theta$ and azimuthal angle $\Phi$ traverses the two planes then $\eta$ (Eq. (7.1)) and $\phi$ (Eq. (7.3)) are modified to adhere to the following equations:

\[
\eta = \frac{\eta' + \eta''}{2} - \frac{\tan \Theta \sin \Phi}{2} - \frac{\tan \Theta \cos \Phi}{2} \tan \theta, \quad \phi = \frac{\eta'' - \eta'}{2 \sin \theta} - \frac{\Delta z \tan \Theta \sin \Phi}{2 \tan \theta} - \frac{\Delta z \tan \Theta \cos \Phi}{2}
\]  

Here the coordinates $\eta$ and $\phi$ are defined on the plane of $\eta'$, $\phi'$, the value $\Theta = 0$ corresponds to vanishing values of $\eta'$, $\phi'$, $\eta''$, and $\phi''$, and the $\phi$ axis defines $\Phi = 0$. The total uncertainty in $\eta$ and $\phi$ in this case will be given by

\[
\sigma_\eta = \frac{\sigma_{\eta'}^{\prime}}{\sqrt{2} \cos \theta} + \sigma_{\Delta z} \frac{\tan \Theta \sin \Phi + \tan \Theta \cos \Phi \tan \theta}{2} + \sigma \left( \tan \Theta \sin \Phi + \tan \Theta \cos \Phi \tan \theta \right) \frac{\Delta z}{2}
\]

\[
\sigma_\phi = \frac{\sigma_{\eta'}^{\prime}}{\sqrt{2} \sin \theta} + \sigma_{\Delta z} \left( \frac{\tan \Theta \sin \Phi + \tan \Theta \cos \Phi}{2 \tan \theta} + \frac{\tan \Theta \cos \Phi}{2} \right) \frac{\Delta z}{2} + \sigma \left( \frac{\tan \Theta \sin \Phi}{\tan \theta} + \tan \Theta \cos \Phi \right) \frac{\Delta z}{2}
\]

From these expressions, it can be derived that the contributions to the uncertainties related to the separation between the measuring planes are negligible if

\[
\sigma_{\Delta z} \ll \frac{\sigma_{\eta'}^{\prime}}{\tan \Theta \cos \Phi}, \quad \frac{\sigma_{\phi}}{\cos^2 \Theta} \ll \frac{\sigma_{\eta'}^{\prime}}{\Delta z \cos \theta}, \quad \sigma_{\phi} \tan \Theta \ll \frac{\sigma_{\eta'}^{\prime}}{\Delta z \cos \theta}
\]

The last two conditions are met if the incidence angle of the track to the plane ($\eta, \phi$) is known with an accuracy better than what can be obtained from the values of $\eta''$, $\phi''$. In the case of the MMSW detector, $\Delta z = 11$ mm, for two consecutive layers [5], and thus $\sqrt{2} \sigma_\eta^{\prime}/\tan \Theta \cos \theta = 390 \mu$m, $\sqrt{2} \sigma_\eta^{\prime}/\Delta z \cos \theta = 0.013$ for an average track angle $\Theta = 10^\circ$ and expected resolution less than $\sigma_\theta = 1$ mrad. The error in the plane resolution is expected to be much better than $\sigma_{\Delta z} = 50 \mu$m since the tracks are mostly perpendicular with respect to the MMSW planes. However, owing
to the material that fills the gap between two MMSW readout layers, the contribution of the multiple scattering in the measured uncertainty should be taken into account.

![Diagram of coordinate systems](image)

**Figure 7.5:** Left: Two coordinate systems \((\phi', \eta')\) and \((\phi'', \eta'')\) are rotated by an angle \(\theta\) and \(-\theta\) with respect to the system \((\phi, \eta)\). An arbitrary point \(A\) can be described by \((\phi, \eta)\) or \((\phi', \eta')\) or \((\phi'', \eta'')\). The relative angle of rotation between the coordinate systems \((\phi', \eta')\) and \((\phi'', \eta'')\) is \(2\theta\).

Right: \(\sigma_\eta/\sigma_{\eta'}\) and \(\sigma_\phi/\sigma_{\eta'}\) as a function of \(\theta\) angle of rotation between two coordinate systems \((\phi', \eta')\) and \((\phi'', \eta'')\) with respect to the system \((\phi, \eta)\). In the MMSW case \(\theta = 1.5^\circ\). The figures are taken from [6].

In the MMSW case the information of the two stereo layers can be combined for the two-dimensional reconstruction of the hit position. Requiring single-cluster events in both stereo layers, the precision (\(\eta\)) and second (\(\phi\)) coordinates of the hit position are reconstructed using the equations (7.1) and (7.3) respectively. In order to measure the single (stereo) layer spatial resolution the reconstructed hit in each coordinate is compared to a reference frame by calculating its position difference from the reference hit on an event-per-event basis.

Figure 7.6 shows the hit position difference distributions between the hit precision coordinate reconstructed by combining the two stereo layers and the reconstructed hit position in the two precision layers of the MMSW. In the left histogram the first layer is used as a reference while the hit position reconstructed in the second layer is the reference hit for the right distribution of the same figure. For extracting the resolution measurement the distributions are fitted with double Gaussian functions and the estimation of the intrinsic resolution per layer is determined by the width of the core Gaussian in both cases. Assuming equivalent performance of readout layers in terms of spatial resolution the \(\sigma\) of the core Gaussian is divided by \(\sqrt{1.5}\) to extract the hit position reconstruction uncertainty in a single layer. The choice of the \(\sqrt{1.5}\) division factor is justified in the equation below and is coming from the combination of the two stereo layers.

\[
\sigma^2_{\text{Gauss}} = \sigma^2_{\text{stereo}} + \sigma^2_{\text{precision}} = \left( \frac{\sigma}{\sqrt{2}} \right)^2 + \sigma^2 \quad \Rightarrow \quad \sigma = \frac{\sigma_{\text{Gauss}}}{\sqrt{1.5}}
\]
Figure 7.6: Distributions of the residuals between the hit positions in one of the two precision layers and the virtual precision layer reconstructed by combining the two stereo readout layers. For the left plot the first precision used for the reference point while the precision layer closer to the stereo ones is used in the right plot.

The values obtained for the spatial resolution, 92 µm and 81 µm, for the combinations $x_{\text{first}} - x_{\text{stereo/third/fourth}}$ and $x_{\text{second}} - x_{\text{stereo/third/fourth}}$, respectively, indicate that the precision coordinate reconstruction using the stereo information concept works as expected. The resolution values measured are well bellow the 100 µm requirement and the results are comparable between the two plots of Fig. 7.6. On top of this, there is an evident deterioration of the measured uncertainty depending on the distance between the layers that are compared in each case. The smallest uncertainty (75 µm) in the hit position reconstruction is measured for the two precision layers of the MMSW that are placed back-to-back on the same readout panel. From the hit position difference between the second precision layer and the virtual precision layer reconstructed by combining the stereo layers we extract a resolution measurement of 81 µm. If instead the first precision layer is compared to the combination of the stereo layers the resolution is measured at 92 µm. The measured hit reconstruction uncertainty per layer deteriorates by increasing the distance between the layers compared. This is attributed to the multiple scattering of the charged particles in the MMSW internal structure material with the thickest components listed in Table 7.1. By examining the difference between the measured values for the different layer pairs, the additional uncertainty owing to the multiple scattering in the intermediate PCBs, honeycomb and air is ~ 30 µm.

<table>
<thead>
<tr>
<th>Table 7.1: Thickness of MMSW internal panel structure</th>
</tr>
</thead>
<tbody>
<tr>
<td>single drift panel</td>
</tr>
<tr>
<td>single readout panel</td>
</tr>
<tr>
<td>double drift panel</td>
</tr>
<tr>
<td>double readout panel</td>
</tr>
</tbody>
</table>

Complementary to the precision coordinate reconstruction, the information from the stereo
layers can also be combined in such a way that the perpendicular to it coordinate (second coordinate $\phi$) is determined. Assuming a stereo angle $\theta$ the second coordinate of the stereo reconstructed hit will be given by Eq. (7.3). The expected uncertainty of the second coordinate measurement using the stereo readout layers is predicted by Eq. (7.4). In the MMSW case, owing to the small stereo angle $\theta = 1.5^\circ$, the spatial resolution for the second coordinate reconstruction is expected to be $\sim 27$ times worse than the precision one as can be seen in Fig. 7.7.

**Figure 7.7:** Distribution of the position difference between the hit reconstructed in the virtual second coordinate layer (combination of the two stereo layers) and second coordinate layer of a reference Tmm type Micromegas chamber.

Using the test beam data, hit positions reconstructed in the two stereo layers are combined according to Eq. (7.3) allowing for the extraction of the second coordinate in the reference frame of the MMSW precision layers and the small MM chambers of the hodoscope. In order to measure the accuracy of the second coordinate reconstruction the stereo hit is compared to a second coordinate reference point coming from one of the hodoscope reference chambers (Tmm type). The residual distribution between the reconstructed and the reference hit position in the second coordinate is shown in the right histogram of Fig. 7.7. The $\sigma$ of the core Gaussian is $\sim 2.2$ mm and gives a good estimate of the second coordinate spatial resolution per plane that can be achieved with the MMSW stereo configuration. According to the theoretical expectations that are presented in Fig. 7.5, if the ratio between the precision and the second coordinate spatial resolution is assumed to be 27 then from the 2.2 mm for the second coordinate a value close to 80 $\mu$m is expected for the precision coordinate reconstruction using the MMSW precision layers (calculated 75 $\mu$m). The agreement of our measurement with the theoretical expectation is very satisfactory if one also takes into account the distance ($\sim 30$ cm) along with the multiple scattering in the air and the material between the chambers compared.

**Measurement of the alignment between MMSW planes**

Owing to the relatively large size of the MMSW prototype and the multilayer structure the mechanical precision that can be achieved in the module assembly is a challenge. In order to test the uniformity of the chamber a horizontal position scan was performed by centering the beam...
at different positions along a single readout strip. In total, nine different positions were examined, as shown in the three-dimensional schematic of Fig. 7.8 (right), with the spatial resolution and efficiency remaining almost constant along the full length of the strip. The only exception was an inefficient single position at 10 cm from the middle of the chamber owing to a known defect in the internal structure created during the construction procedure.

On top of these studies, the relative alignment between the different readout planes of the MMSW was also measured. The offset between two layers is defined as the mean value of their position difference distribution as determined by the core Gaussian fit (Figs. 7.6, 7.4). Three different combinations are examined with respect to their relative alignment using also the precision coordinate from the combination of the two stereo layers. The evolution of the offset for the different layer pairs is presented with different colours in Fig. 7.8 (right).

![Relative Misalignment](image)

**Figure 7.8:** Left: Three-dimensional of the MMSW chamber illustrating the approximate scan positions during the inter-plane alignment study. Right: The mean value of the hit position difference as a function of the relative position along the MMSW readout strips for 9 different positions.

A clear difference, of the order of 90 µm, is evident between the left and right side of the MMSW in the cases where the first precision layer is included in the measurement (red and blue coloured lines). The difference between the two halves of the first layer does not appear as a step in a specific point but it is rather evident as a slope indicating a possible small rotation of the first layer readout board with respect to the other three readout layers. The other layers show a uniform alignment offset along the total length of the readout strip (green coloured line) with the non-zero value coming from the not perfectly perpendicular detector plane with respect to the beam.

### 7.2 Test of a MM chamber with different strip capacitance areas

On the scope of optimising the MM layout for the NSW needs the effect of the strip capacitance on the chamber’s measured performance has been studied. A prototype small bulk MM with
resistive strips, called T4C, has been built in 2015 featuring four areas with different readout strip capacitances (strip width). The drawing of the T4C readout PCB is shown in Fig. 7.9 (left). The readout strips are separated in four different areas according to their width, 320 µm, 220 µm, 120 µm and 80 µm respectively, with 64 strips in each area while the strip pitch is 400 µm across all areas. The resistive strips are made with the same pitch and are 320 µm wide across all areas. The chamber was tested in a pion test-beam and it was read out with the APV25 based SRS system (Appendix B). The chamber was initially tested without beam in order to have a rough estimate of the effect that the strip width has on the measured noise per electronic channel. By acquiring data with a random trigger and without beam, the pedestal charge is measured for all electronic channels. The channel noise is defined as the standard deviation of the channel’s pedestal charge distribution. The measured noise level, in ADC units, for all the 256 strips of the T4C chamber is presented in Fig. 7.9 (right). A decreasing trend can be observed for the noise value as the strip width becomes smaller. This is evident not only by comparing the strips readout from different chips but also within the strips of the same chip. A maximum difference in the measured noise of ~20% is measured between the thinnest and the widest strip areas. A slope can also be observed by going through the different areas of the detector with a decreasing trend when going towards thinner strips (larger strip numbers). It should be noted however that, owing to the APV25 master-slave configuration (Appendix B) of the two chips, the slave chip (called APV2) sits on a lower pedestal charge level and thus the actual difference between the 320 µm and 80 µm areas is smaller than the one shown in the plot.

Using the 150 GeV/c pion beam centered at the four T4C areas, the detector performance is measured and compared between the four different strip capacitance areas. The reconstructed beam profiles for four physics runs, with the beam centered in each of the four areas, are illustrated in Fig. 7.10. For these specific runs that are used in this plot the chamber was inclined by 30° with respect to the beam axis and the calculated hit position in the T4C is coming from the x_half position of the μTPC method. A detailed description of the method is given in Sec. 5.3. The same scan of the four areas was also performed for perpendicular tracks with chamber hit defined by the Centroid method. All the other parameters including trigger rate, gas and high

![Figure 7.9:](image-url) Left: The drawing design of the T4C readout PCB. The four areas of different strip width can be distinguished. Left: The measured noise level per strip for the T4C chamber. The different strip capacitance areas are marked with different colours.
voltage settings are kept at the nominal values\textsuperscript{3} between the testing of the different areas.

The total accumulated charge per particle track is proportional to the strip capacitance and consequently to the strip width. Thus, a larger mean charge per event or per cluster is expected as the width of the strip increases. Different parameters of the charge have been examined with the chamber plane oriented perpendicularly with respect to the beam axis with the results shown in Fig. 7.11 (left).

- Most probable value (MPV) of the Landau fit on the cluster charge distribution (full blue circles).
- Mean value of the cluster charge distribution for events with a single track (full red circles).
- Mean value of the cluster charge distribution (open blue circles).
- Mean value of the total strip charge distribution (full magenta circles).

![Figure 7.10: The reconstructed beam profiles centered at the four T4C areas of different readout strip capacitance (each area is ~ 25.6 mm wide).](image)

A similar trend can be observed for all the measured charge quantities, with the mean or MPV charge value increasing with the readout strip width. The slow-down of the charge increase rate that can be observed in the area between 220\,µm and 320\,µm is an effect of the limited dynamic range of the APV25. The increased strip capacitance in the 320\,µm strip width area results in larger signal amplitude. In the case of massive ionisations with a large fraction of the amplitude signal lost by exceeding the saturation limit of the APV25 with the effect becoming more pronounced in the wide strip region.

\textsuperscript{3}The nominal settings are determined from the experience with T type chambers which have the same strip pitch and 300\,µm strip width.
In addition to the charge study for the different strip capacitance areas, the performance of the detector in terms of efficiency and hit/track reconstruction accuracy has been also measured. An almost equivalent performance has been measured along the four readout groups with the very high detector efficiencies achieved. The Centroid hit resolution is slightly improved with increasing the strip width, owing to the larger charge that allows for more accurate charge interpolation, with the effect being $< 10\%$. The $\mu$TPC performance has been tested as well, as a function of the readout strip width. The peak $\mu$TPC reconstructed angle in the four areas is shown in Fig. 7.11 for runs taken with the T4C detector inclined by $30 \pm 0.5^\circ$ with respect to the beam. A maximum difference of $1^\circ$ is measured between the largest and smallest strip width values with the opposite trend compared to the charge measurement. The offset from the theoretical angle of $30^\circ$ becomes smaller as the strip width increases. It is worth noting here that the refined $\mu$TPC algorithm that has been described in Sec. 5.3 has not been applied in the T4C studies. Thus, the biasing of the reconstructed $\mu$TPC track, because of the capacitive coupling effects and the inaccurate strip position assignment in the cluster edges, is present in the measurements of the four different areas. These effects have a dependence on the strip charge as well and this has been discussed in Sec. 5.3. The difference in the average charge value between the different areas could partly explain the small trend observed for the peak reconstructed angle.

Apart from the performance studies, the effect of the capacitive coupling between neighbouring readout strips and its dependence on the strip width was also put under study. The ratios between the charges of neighbouring strips are shown in Fig. 7.12. In the first row the distribution of the charge ratio between second and first strip$^4$ in a cluster is shown for the 80 $\mu$m and 320 $\mu$m areas respectively. Comparing between the two different areas, a second peak can be observed around the ratio value of four for the 80 $\mu$m case that is not present in the second plot representing the 320 $\mu$m area. This peak is coming from the capacitively coupled charge from the strip occupying the cluster edge that is in the region of the earliest times.

$^4$The strip occupying the cluster edge that is in the region of the earliest times.
the second to the first strip of the cluster in the cases where the first strip’s signal is almost exclusively inherited from its neighbour and not from an ionisation above the first strip. Similar distributions are constructed also for the charge ratio between the middle strips of the cluster (third and second in this case) in the same two areas and are shown with red colour in the second row of Fig. 7.12. The distributions for the two different areas are indistinguishable since in the middle strips of the cluster the possibility of having a strip with capacitively coupled only charge from its neighbour is very small and is smeared away by the fluctuations of the ionisation charge.

![Graphs of charge ratios](image)

**Figure 7.12:** Top: Distribution of the charge ratio between the second and the first strip of a cluster for the 80 µm (left) and the 320 µm (right) areas. Bottom: Distribution of the charge ratio between the third and the second strip of a cluster for the 80 µm (left) and the 320 µm (right) areas.

The effect of the capacitive coupling has been also studied using ANSOFT’s Maxwell [7] and Simplorer [8] software to simulate the resistive strip MM. A graphical representation of the calculated inter-strip (readout and resistive) capacitance matrix for a Maxwell model of five strips is illustrated in Fig. 7.13 (left). By adopting the T4C design parameters (fixed resistive strip geometry and varying readout strips width) the simulation of a pulse in the middle resistive strip only yields a 23% of the strip charge shared to its first neighbour for a readout strip width
7.3 Test of a MM chamber with a multiplexed readout

of 80 µm that is in good agreement with the value measured from the data. Using the simulation machinery, the percentage of the charge that is shared from a strip to its neighbours is measured as a function of the readout strip width and the results are shown in Fig. 7.13 (right). The charge sharing becomes smaller as the strip width increases reaching a minimum of 11% for the 320µm strip width. This argument however is only valid for the resistive strip MM of T4C type, where the resistive strip geometry does not change according to the readout strips but maintains the same strip pitch and width for all the different readout configurations.

![Figure 7.13](image)

**Figure 7.13:** Left: Drawing of the resistive-strip MM model that has been simulated with ANSOFT’s software. The inter-strip capacitances for the 320µm case are also shown. Right: The charge sharing between the middle strip, where the charge is induced as a function of the strip readout strip width. The different colours indicate the first (red line) and the second (blue) neighbour respectively.

### 7.3 Test of a MM chamber with a multiplexed readout

The MM detector is a very attractive technology for tracking applications. Because of the fine readout strip structure the MM chambers are characterised by excellent spatial resolution independently of the track angle as have been extensively discussed in Chap. 5. However, in the case of large size experiments, the detector modules, that must be realised to cover the required surface, consist of thousands (millions in the case of the NSW) of readout elements (strips) and equal number of electronic channels. This is a major constraint for large scale applications of the MM technology as it not only increases the financial cost of the project but it also leads to several implications in the powering and services infrastructure design and implementation.

A very promising and innovative idea, suggested in [9], profits of genetic algorithms to multiplex the readout elements of a MM detector into a smaller number of electronic channels. This approach offers the possibility of reducing the number of electronic channels on the scope of enhancing the feasibility of large area applications of MM.
7.3.1 Test Beam Experimental Set-up

During the summer of 2015 a small prototype MM chamber with multiplexed readout has been developed for the needs of the P348 experiment [10] by the ETH Zurich group [11]. The chamber was tested in the H4 beam line at CERN North Area under the courtesy of the RD51 collaboration[12],[13] in combined beam time with the ATLAS NSW Micromegas and ETH Zurich groups[5]. The MM chamber tested was a $8 \times 8$ cm$^2$ resistive strip MM with two-dimensional readout (similar to the Tmm type described in Appendix B) with the resistive/readout strip geometry characteristics listed in Table 7.2. The orientation of the resistive strips with respect to the readout strips is similar to the one shown in Fig. 3.16. The readout strips are multiplexed before the front-end card connector by a factor five and are then connected to the corresponding connector pins. A standard 130-pin Panasonic connector [1] was used for the readout.

The multiplexed MM was placed in between the GEM sequence in order to minimise the reference track extrapolation error. Owing to the detector mechanical design it was necessary to be rotated by $\sim 45^\circ$ with respect to the reference chambers’ coordinate system in order to be firmly attached on the hodoscope frame. Having the chamber in such orientation requires the combination of the two dimensional readout information (stereo) to reconstruct the two coordinates of each hit in the reference coordinate system using Eq. (7.6). A set of four scintillators has been employed to provide the trigger with a combined active area matching the one of the hodoscope detectors ($10 \times 10$ cm$^2$).

The multiplexed MM chamber was installed on the RD51 hodoscope equipped with three triple GEM detectors that featured two-dimensional readout (400 $\mu$m strip pitch) and could serve as reference chambers. All the chambers of the set-up were readout with APV25 [14] based SRS system [15]. A graphical representation of the experimental set-up is presented in Fig. 7.14.

Table 7.2: Design characteristics of the multiplexed MM chamber

<table>
<thead>
<tr>
<th>x/y readout strip pitch</th>
<th>250/250 $\mu$m</th>
</tr>
</thead>
<tbody>
<tr>
<td>x/y readout strip width</td>
<td>150/80 $\mu$m</td>
</tr>
<tr>
<td>resistive strip width</td>
<td>150 $\mu$m</td>
</tr>
<tr>
<td>resistive strip pitch</td>
<td>250 $\mu$m</td>
</tr>
</tbody>
</table>

The multiplexed MM was placed in between the GEM sequence in order to minimise the reference track extrapolation error. Owing to the detector mechanical design it was necessary to be rotated by $\sim 45^\circ$ with respect to the reference chambers’ coordinate system in order to be firmly attached on the hodoscope frame. Having the chamber in such orientation requires the combination of the two dimensional readout information (stereo) to reconstruct the two coordinates of each hit in the reference coordinate system using Eq. (7.6). A set of four scintillators has been employed to provide the trigger with a combined active area matching the one of the hodoscope detectors ($10 \times 10$ cm$^2$).

$$x_{\text{ref}} = \frac{x_{\text{multix}} - y_{\text{multix}}}{\sqrt{2}}, \quad y_{\text{ref}} = \frac{x_{\text{multix}} + y_{\text{multix}}}{\sqrt{2}}$$ (7.6)

---

\(^5\)The author would like to express his gratitude to Eraldo Oliveri (CERN) for the realisation of the test beam apparatus and his constant willingness to help.

\(^6\)The results that are presented focus on the study of the multiplexing algorithm with which the MM chamber was realised for use in future ATLAS upgrades and are not related to the original P348 project under the courtesy of which this prototype was constructed. The author is grateful to the D. Banerjee (ETH) for providing the prototype multiplexed MM chamber for the ATLAS tests.
7.3 Test of a MM chamber with a multiplexed readout

Figure 7.14: Graphical representation of the test beam experimental setup composed of three GEM detectors and the multiplexed chamber. All the detectors of the set-up had a two-dimensional readout. The multiplexed detector had to be rotated by $\sim 45^\circ$ with respect to the GEMs in order to be mounted on the hodoscope frame.

The (de)multiplexing algorithm

The multiplexing algorithm realised in the chamber layout is based on the genetic algorithm described in [9] using a factor five of multiplexing. This means that for the 640 readout strips of the chamber (320 per readout layer) only a single 128-channel APV25 chip is required for the readout of the full chamber. However, owing to the multiplexing, for each channel with signal there are five candidate readout strips containing the one real strip and four fakes. A graphical representation of the multiplexing map of the precision readout strips layer is shown in Fig. 7.15. A similar pattern shifted by one chip channel is used for the second coordinate layer as well. The first 320 strips correspond to the precision coordinate readout and the rest represent the readout strips that are perpendicular to the resistive ones.

Figure 7.16 shows a typical event recorded during the test beam. On the left plot the channels with signal above threshold in the specific event are shown. Eight channels with signal can be seen. By decoding the mapping information the data are de-multiplexed by artificially assigning the charge of each channel to the strips that it is multiplexed with. The result of the decomposition of the channel into strips can be seen in the right plot of Fig. 7.16 where forty strips in total are used for the eight channels with signal. The real cluster, characterised by consecutive fired strips at around strip number 120, can be easily distinguished by eye from the fakes that are separated by at least one strip gap.

In order to reconstruct the charged particle’s trail inside the hodoscope the reference chambers are used. Two event displays with a single particle passing through the several detection layers of the hodoscope are presented in Fig. 7.17 after the de-multiplexing algorithm is applied. The strip charge is plotted as a function of the strip number. The third and fourth lines correspond to the two readouts of the multiplexed MM chamber and the rest, represent the reference GEM readout layers (x and y readouts respectively). In the event of the first column the real clusters in the multiplexed MM, one per readout, are distinguishable by eye owing to the consecutive strips with signal. The multiplexing-induced clusters on the other hand are characterised by several gaps in between their constituent strips and can be easily filtered out from the real
ones. In the event of the second column however, several clusters with consecutive strips can be seen in the y layer of the multiplexed MM. In this case the real cluster corresponds to the one with the largest number of strips. Moreover, the layer with readout strips perpendicular to the resistive (fourth line) shows a significantly larger cluster compared to the precision layer (third line). This is a well understood effect owing to the propagation of the signal along the resistive strips that has been discussed in Sec. 5.2.

![Graphical representation of the multiplexing algorithm for the precision coordinate layer of the multiplexed MM chamber. The 320 readout strips are multiplexed to 64 APV25 chip channels.](image)

**Figure 7.15:** Graphical representation of the multiplexing algorithm for the precision coordinate layer of the multiplexed MM chamber. The 320 readout strips are multiplexed to 64 APV25 chip channels.

![Hit maps](image)

**Figure 7.16:** Left: A raw hit map of one event in the x readout of the multiplexed chamber before the mapping is applied showing eight channels with signal. Right: After the mapping is applied, each channel is connected to five readout strips that are all artificially assigned the signals of the channels they are multiplexed with (40 strip in total).
Figure 7.17: Two events where a single particle traverses the experimental setup of the four chambers (eight readout layers). The charge amplitude in the y-axis is plotted as a function of the strip address. The two first along with the four last lines correspond to the GEM reference chambers of the telescope while the other lines show the reconstructed hits in the multiplexed MM.
Noise level study

It is interesting to check the effect that the strip multiplexing, by a factor five, has on the strip (channel) noise in comparison to the different MM chambers that have been used in other test beams. Figure 7.18 shows the noise level per readout strip for seven MM chambers with different characteristics. The noise, defined as the standard deviation of the pedestal charge distribution per electronic channel, is determined by acquiring data with a random trigger using the APV25 chip. The different characteristics of the chambers that are compared in Fig. 7.18, with the addition of the T4C MM, are listed in Table 7.3 and the measurements are shown with a different color for the strips of each chamber in Fig. 7.18. The peaks that appear every 64 or 128 strips are a feature of the APV25 chip and are visible for all the chambers.

Table 7.3: Readout characteristics for the chambers compared in the noise measurement. X represents readout strips that are oriented parallely to the resistive strips in contrast with the vertical Y strips.

<table>
<thead>
<tr>
<th>Chamber</th>
<th>Readout</th>
<th>Strip Width μm</th>
<th>Strip Pitch μm</th>
<th>Strip Length mm</th>
<th>Strip Area mm²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tmm</td>
<td>X</td>
<td>150</td>
<td>250</td>
<td>100</td>
<td>15</td>
</tr>
<tr>
<td>Tmm</td>
<td>Y</td>
<td>80</td>
<td>250</td>
<td>100</td>
<td>8</td>
</tr>
<tr>
<td>Multiplexed (x5)</td>
<td>X</td>
<td>150</td>
<td>250</td>
<td>80</td>
<td>60</td>
</tr>
<tr>
<td>Multiplexed (x5)</td>
<td>Y</td>
<td>80</td>
<td>250</td>
<td>80</td>
<td>32</td>
</tr>
<tr>
<td>T4C (1/4)</td>
<td>X</td>
<td>320</td>
<td>400</td>
<td>100</td>
<td>32</td>
</tr>
<tr>
<td>T4C (2/4)</td>
<td>X</td>
<td>220</td>
<td>400</td>
<td>100</td>
<td>22</td>
</tr>
<tr>
<td>T4C (3/4)</td>
<td>X</td>
<td>120</td>
<td>400</td>
<td>100</td>
<td>12</td>
</tr>
<tr>
<td>T4C (4/4)</td>
<td>X</td>
<td>80</td>
<td>400</td>
<td>100</td>
<td>8</td>
</tr>
<tr>
<td>T</td>
<td>X</td>
<td>300</td>
<td>400</td>
<td>100</td>
<td>30</td>
</tr>
<tr>
<td>ExMe</td>
<td>X</td>
<td>300</td>
<td>450</td>
<td>500</td>
<td>150</td>
</tr>
<tr>
<td>MMSW</td>
<td>X</td>
<td>300</td>
<td>415</td>
<td>700</td>
<td>210</td>
</tr>
</tbody>
</table>

Before arriving at any conclusions it should be noted that not all the chambers can be directly compared since some of them comply with quite different design schemes with respect to the readout-resistive layers relative position and orientation. The measured noise depends on the front-end electronics themselves and then on the readout strip capacitance. The capacitance that characterises each readout layer strongly depends on the length and width of the elements but also on the distance from the resistive strips that are combined into a single high voltage line. In addition to this, the routing of the strips outside the MM active space is different for different chamber categories. For these reasons the different readouts are arranged in groups with equivalent design, such that the noise can be studied as a function of the single readout element surface. The resulting groups are:

- T. T4C. ExMe and MMSW : One-dimensional readout with resistive strips matching the readout strip geometry. All three chambers have approximately the same readout strips width and pitch. Different case only for the T4C chamber that has four areas with the different strip widths and each area is treated separately.

- Tmm and Multiplexed X : The readout with strips parallel to the resistive strips in a two-dimensional readout chamber with equivalent readout strips width and pitch.
- Tmm and Multiplexed Y: The readout with strips perpendicular to the resistive strips in a two-dimensional readout chamber with equivalent readout strips width and pitch.

![Figure 7.18](image_url)

**Figure 7.18:** The standard deviation of the pedestal charge as a function of the strip number for five different resistive Micromegas chambers with different readout element sizes.

The scatter plots of the noise per readout channel are projected in the Y axis for each chamber. The most probable values of the noise per chamber (or readout region) are calculated by describing the distributions with a Landau function and plotted as a function of the single readout strip surface in Fig. 7.19. The extracted data-points are distributed in three sets, shown with different colours, with each one containing readouts of similar characteristics and are fitted with first order polynomial functions. The effect of the multiplexing on the channel noise level is evident by comparing the multiplexed chamber data-points with the Tmm measurements. A 30% increase in the preponderant noise value is attributed to the increase of the single readout element equivalent area by a factor four for both X and Y readout layers of the multiplexed (Mux) and Tmm chambers.

In order to reach a more quantitative conclusion the noise level of the bare APV25 hybrid front-end card, when it is not attached to any chamber, is superimposed in Fig. 7.19. This measurement reveals that there is a non negligible intrinsic noise (8 ADC) coming from the readout electronics that is included in our measurements. Moreover, a small difference can be observed between the bare front-end card measurement and the fit extrapolations to zero readout element area. This is attributed to the routing of the strips, outside the detector’s active area, up to the connector and the connector itself that insert an additional contribution to the pedestal noise measurement.

According to lab measurements that have been performed in [16] using test input pulses, one ADC unit measured by the APV25 chip corresponds to a charge equivalent to ~230 electrons. Thus the pedestal noise (green point) is roughly on the level of 1800 electrons. Using the black line we can estimate the noise level expected for the NSW MM modules which will have a
maximum single readout element surface of $\sim 660 \text{mm}^2$. Based on the APV25 measurements a maximum extrapolated noise level of 25.6 ADC (5888 electrons $\approx 0.94 \text{fC}$) can be expected. However, the noise level is expected to improve with the new VMM chip that will be used in the NSW detectors. Performance studies using the first VMM version (VMM1) with MM chambers reveal a noise of 0.16 mV when the front-end board with VMM1 is attached on a T chamber are presented in Sec. 7.4. Similar measurements performed with the VMM1 chip are shown in Figs. 7.27, 7.28. If the result is compared to the APV25 noise level measurements shown in Fig. 7.19, which for the T chamber is 0.37 fC, an improvement of $\sim 60\%$ owing to the new front-end electronics is obtained.

![Graph](image)

**Figure 7.19:** The most probable value of the noise distribution for each chamber is plotted as a function of the single strip surface. The different colours correspond to different chambers while the green colour marker shows the noise measured with an APV25 not connected to the chamber.

### 7.3.2 Performance studies

The study of the multiplexed data mainly focusses on the efficiency with which the actual clusters can be distinguished from the fake ones that are introduced by the multiplexing. The outcome of this study depends on several factors:

- The efficiency of the detector and/or the electronics channels.
- The multiplexing pattern.
- The real cluster identification algorithm.
7.3 Test of a MM chamber with a multiplexed readout

- The hit rate.

Moreover, the quality of the clusters that are reconstructed is put under study followed by the estimation of the chamber's spatial resolution using the reference GEM chambers of the hodoscope. The experimental set-up has been exposed to a pion beam of 120 GeV/c with a maximum particle rate of 178 kHz cm\(^{-2}\). This value has been extracted by measuring the number of triggers coming from the coincidence of the scintillator signals per beam spill. On average \(4.6 \times 10^6\) triggers were recorded during a spill of 4.3 sec. The beam dimensions as have been recorded by the reference wire chambers of the beam instrumentation and confirmed by the hodoscope chambers as well has been \(\sim 6\) cm\(^2\).

### Clustering algorithm

The raw data are processed and combined into clusters by applying a topological clustering. The clusterisation algorithm looks for consecutive strips with signal above threshold to define a cluster. In our case, since it has been noticed from the raw data that there are a few single inefficient readout strips spread across the multiplexed chamber's readout, single strip gaps are also allowed between the cluster strips to avoid spoiling the clusterisation and reducing the statistics.

Using the reconstructed hit information from the reference chambers \(\sim 85\%\) of the events are identified as single tracks and these events are then used in the analysis. For the following results, the leading cluster (maximum charge) per event which is also characterised by the smallest number of gaps, is selected as the real one and all the remaining clusters in the multiplexed chamber are discarded.

Using the cluster information the beam profile is reconstructed in the different detectors of the set-up as shown in Fig. 7.20 for both coordinates of the reference chambers frame. For the multiplexed MM chamber, owing to its rotation by \(\sim 45\,^\circ\) with respect to the reference frame, the information of the two readout layers are combined to translate the 2-D position of the reconstructed hit in the reference frame using Eq. (7.6). The three first lines of Fig. 7.20 illustrate the reconstructed beam profile from the reference GEM detectors while the histograms of the bottom line represent the multiplexed MM chamber after the translation of the local hit position to the reference frame. Similar distributions are reconstructed in all the hodoscope chambers providing a first confirmation of the effectiveness of the clustering algorithm that is used.

### Reference track reconstruction

By combining the reconstructed hits of the three reference GEM planes per coordinate, the reference track can be reconstructed for each particle track. This reference segment can then be used for comparison with the hit reconstructed in the multiplexed MM. In order to ensure the best quality of the reconstructed reference track a refined algorithm has been developed that corrects possible additional effects contributing to the reference track error including

- Precise alignment of the reference GEM detectors and the multiplexed MM.

- Correct for small rotations between the chambers.
Figure 7.20: Beam profiles reconstructed using the hit cluster position in each readout layer of the four hodoscope chambers. The two first columns correspond to the two different readout layers of each chamber while the combination of the two results in the two dimensional beam profile in the third column.
The distributions of the hit position differences between two reference chambers for both the precision and the second coordinate readout layers, after applying the corrections discussed above, are shown in Fig. 7.21. A very good spatial resolution is determined for both readouts which goes as low as $40\mu m$ if one takes into account only the core Gaussian contribution corresponding to 97% of the events.

![Figure 7.21](image)

**Figure 7.21**: Distributions of the hit position differences between two of the reference chambers (GEM2 & GEM3). The left plot corresponds to the readout measuring the precision coordinate with the second coordinate shown in the right plot.

Similar results are obtained for all three possible GEM pairs that can be formed with the sigma of the Gaussian distribution slightly increasing with the distance between the two stations under test owing to the extrapolation error and the multiple scattering of the particle tracks in the set-up material and the air.

The three reference points that are reconstructed per event for each coordinate are combined to define a precise reference track which is then interpolated to the multiplexed MM chamber for the various studies. The distribution of the difference between the reconstructed hit in the multiplexed MM chamber and the reference track hit prediction are shown in the left column of Fig. 7.22. In the left plot the reference track is based on the reference track hits excluding the multiplexed MM hit (excluded). If the MM hit is also included in the track estimation algorithm the biased residuals distributions (included) shown in the right plot of Fig. 7.22 are obtained. The results presented refer to one of the two coordinates of the reference system but similar results are measured for the perpendicular to it coordinate as well. As, described in [17], using the sigma values of the included and excluded residual distributions the intrinsic resolution of the readout layer under test is defined as their geometrical mean using Eq. (7.7). However, owing to the better resolution of the GEM stations compared to the MM, the results is slightly biased towards smaller values [18]. The extrapolation error of the reference track, excluding the multiplexed MM, can be calculated as described in Appendix F for the case of three equivalent reference stations, to be $\sigma_{\text{ext}} = 30.28\mu m$. Thus, by using the measured $\sigma$ from the left plot of Fig. 7.22 (excluded) the intrinsic resolution of the multiplexed MM is measured to be $\sigma_{\text{int}} = \sqrt{68^2 - 30.28^2} = 60.88\mu m$ which slightly worse and closer to reality than what has
been obtained with Eq. (7.7).

\[ \sigma = \sqrt{\sigma_{\text{inc}} \cdot \sigma_{\text{exc}}} \]  

(7.7)

**Figure 7.22:** Left: Distribution of the (excluded) residuals between the reconstructed hit in the multiplexed MM and the reference track. Right: Distribution of the (included) residuals between the reconstructed hit in the multiplexed MM and the reference track reconstructed including the MM hit in the track calculation.

**Multiplexing ambiguity probability**

Owing to the particularity of the multiplexed MM chamber the efficiency with which the real cluster is reconstructed was also measured. In order to locate possible ambiguities coming from mis-reconstructed hit positions of the incoming particle the identified cluster position is compared to the expected interpolated hit of the excluded reference track. If the residual distance exceeds the $3\sigma$ requirement, where $\sigma$ is the MM chamber's single plane resolution, then the reconstructed hit is characterised as ambiguity. The ambiguity probability has been calculated over a run of 20K events and only events with at least one hit in all the chambers are inserted into the analysis.

For the specific run analyzed with the particle rate of 178 kHz cm$^{-2}$ that was discussed in Sec. 7.3.2 the ambiguity probability was calculated to be 11%. The same ambiguity definition has been used in [9] for the simulation studies of different multiplexing factors in different particle rate conditions. The simulation results are presented in Fig. 7.23 (left) for a simulated large chamber of 1024 channels. In the right plot the simulation curves, extracted from the simulation plot, are compared to the test beam measurement. The comparison of the test beam measurement with simulation demonstrates a sensible agreement when extrapolating the simulation expectations to higher rates.
7.4 Performance studies of resistive MM chambers with the VMM1 ASIC

The results that have been presented in the previous sections and chapters are all based on the readout of MM chambers with the APV25 base SRS system described in Appendix B. In the NSW a new chip called VMM will be used for the readout of both MM and sTGC NSW modules. Some introduction on the VMM characteristics is given in this section followed by results from the analysis of lab and test beam data acquired with VMM based front-end electronics installed on resistive MM detectors.

7.4.1 Description of the VMM1 and the test beam experimental set-up

The first version of the VMM, called VMM1 [19], is built with 130 nm CMOS technology combining 64 channels. Each channel is equipped with a low noise charge amplifier and a shaper able to provide baseline stabilisation and a discriminator with trimming capability. The transfer function of the VMM can be analysed as a third-order c-shaper with the combination of one real, a complex and its conjugate pole as described in Appendix E. Two 10-bit Digital-to-Analog Converters (DAC) are used for adjusting the amplitudes of the threshold and the internal test pulser. These are shared by all the channels along with the test pulse generator, the signal multiplexers, the control logic and the Address in Real Time (ART7). For the NSW needs the VMM1 chip was designed to satisfy the following operational parameters.

7The ART signal corresponds to the address of the earliest strip per event. This will be used for the trigger primitives of the NSW MM detectos but it will not be studied in the analysis presented here.
• Able to work with input capacitances from a few pF to 1 nF.
• Maximum input charge from 0.1 – 2 pC with resolution ~ 0.03 fC rms.
• Processing times from 100 ns – 1 s with resolution ~ 200 ps rms.

The VMM provides measurement of the peak amplitude and time with respect to the trigger signal in a data driven mode. Figure 7.24 shows a block diagram of the VMM1 architecture. The single channel signal is amplified and shaped before it can be compared to the individually set threshold value followed by the generation of the Time-over-Threshold or Time-to-Peak measurement detection circuit. The charge amplification and shaping provide adjustable gain (0.5, 1, 3, and 9 mV/fC) and peaking time (25, 50, 100 and 200 ns). Channels with charge above threshold are then processed for peak and timing measurements before they are multiplexed for readout. When the peak is detected, a Time-to-Amplitude Converter (TAC) is initiated and is then stopped by a signal controlled by the data acquisition system. The charge and time amplitude information are stored in an analogue buffer. They are then read out serially with a smart token passing scheme that only retrieves the address, charge and time measurements of the channels with signal above threshold. This processing accounts for an online zero suppression, significantly reducing the transmitted data bandwidth.

![Figure 7.24: Block diagram representing the VMM1 architecture. Figure taken from [19].](image)

It is also possible to acquire signals lower than the set threshold value by enabling the neighbour-readout logic of the VMM chip that forces the processing of the immediate neighbours of the signal above threshold channels. This logic can also be used for the edge channels as each chip can communicate with the corresponding edge channels of a neighboring chip through bi-directional low-voltage differential signals.

The VMM1 was released in early 2012 and the first performance studies of MM chambers using the new chip took place during autumn of the same year at H6 beam line of the CERN north area. In this first version of the chip only the analog part of the circuitry was integrated thus each chip was connected to a digitiser board called CDAQ [20] developed at Brookhaven National Laboratory. The link between the VMM1 and the CDAQ was realised through an LVDS signal translation front-end board developed at the University of Arizona [21] called Mini-1. A photo of one Mini-1 board is shown in Fig. 7.25. All the CDAQ boards were then connected to a Gigabit ethernet switch that transmits the acquired information to the Data Acquisition PC. The trigger
signal was provided by a set of three scintillators and was distributed along the different CDAQs via an evaluation FPGA board.

![Image](image1.png)

**Figure 7.25:** A photo of the Mini-1 front-end board equipped with one VMM1 chip. The board is plugged on the MM chambers via a 130-pin Panasonic connector [1] and features several outputs.

The hodoscope of the MM chambers along with a close view of the Mini-1 cards mounted on the MM chambers can be seen in Fig. 7.26. Eight resistive MM chambers (T type) were used for the test measurements each one equipped with two Mini-1 cards. Thus only 128 out of the 256 strips, occupying the middle area of the detector, were read out. The chambers were exposed to a 120 GeV/c pion beam with an intensity ranging between 5 – 30 kHz over an area of approximately 2 cm².

![Image](image2.png)

**Figure 7.26:** Photos from the test beam apparatus during autumn 2012. The MM chambers (T type) were installed on an aluminum frame and were equipped with Mini-1 front-end cards.
7.4.2 Performance studies

Calibration and extraction of the PDO pedestals

In order to fully exploit the intrinsic characteristics of the VMM1 chip the individual channels need to be calibrated. The calibration ensures uniform response of all the channels in terms of timing and charge measurement and improves the performance that can be measured using MM chambers. For the measurement of the charge and timing pedestal and gain values the built-in test pulser of the VMM1 chip has been used, injecting predefined pulses in selected channels and measuring their response.

![Graphs showing PDO vs Input Charge Amplitude and Pedestal from neighbours](image)

**Figure 7.27:** Measurement of the pedestal charge per channel using the VMM1 internal pulser feature with two different methods. Left: By injecting pulses of increasing amplitude in a single channel and measuring the PDO output. Right: By measuring the PDO values of the channels neighbouring to the pulsed one with the neighbour-readout logic enabled.

The first step of the calibration procedure concerns the equalisation of the channel thresholds for all the VMM1 chips that are tested. Using the internal pulser and the trimming capability of the individual channel discriminator the channel-to-channel threshold variation can be eliminated depending on the trimmer range as described in [22]. Exploiting the uniform discriminator thresholds, after the first calibration step, the PDO output of each channel is then measured for different DAC settings. Test pulses of predefined amplitude are injected in each of the 1024 channels and their PDO response is then analysed. A typical example of the PDO calibration procedure, for one VMM2 channel, is shown in the left plot of Fig. 7.27. Several PDO measurements are recorded for each internal pulser amplitude value and the determined mean PDO value is plotted as a function of the DAC setting. The perfect linear correlation that is observed between the set and the measured values is described with a linear fit from which the gain and the pedestal charge of the channel can be extracted. The neighbour-readout functionality of the VMM1 chip offers an alternative way of identifying the single channel pedestal charge. The distribution of the PDO measurement for a neigbouring to the VMM1 channel injected with

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8The DAC setting is translated from arbitrary units to fC by measuring the DAC output in an oscilloscope as shown in [23].
the lowest possible test pulse amplitude is shown in the right plot of Fig. 7.27. Several PDO measurements per neighbour channel are used to reconstruct the neighbour pedestal charge distribution and extract the pedestal (mean value) and moreover have an estimate of the noise level (sigma value). Of course, in the neighbour-channel method, the charge sharing between adjacent channels owing to electronic cross-talk or capacitive coupling between neighbouring readout strips should not be overlooked. The electronic cross-talk has been measured in [23] for one VMM1 chip, that was not attached on a chamber, to be $\sim 1\%$. Thus, the pedestal calculation method using the neighbouring channels can also be considered valid and is in good agreement with the extrapolation method as shown in Fig. 7.27 with both plots referring to the same channel. For the measurements presented, the chip gain was set to the maximum possible value of $9 \text{ mV/fC}$ and the chips were readout at a fixed time interval of $25 \text{ ns}$.

The mean and sigma values of the neighbour PDO distributions per electronic channel, for all 1024 VMM1 channels that were readout in the test-beam, are shown in Fig. 7.28. The calculations are based on the neighbour-readout method and the mean and sigma values are extracted from a Gaussian fit on the neighbour PDO distribution as shown in Fig. 7.27 (right). Apart from inefficient channels and/or failed fits, the pedestal values are characterised by relatively good consistency along the different elements.

![Figure 7.28: Left: The mean value (left) and the sigma (right) of the pedestal charge distribution per electronic channel for all 16 VMM1 chips.](image)

Apart from the pedestal charge value, the individual gain of each channel was also measured using the internal pulse amplitude scan procedure that was described before. The slope of the linear fit example, shown on the right plot of Fig. 7.27, gives a qualitative estimation about the amplification factor that is applied on the input pulse amplitude. For this specific example a multiplication factor $8.6 \text{ mV/fC}$ has been measured for a gain setting of $9 \text{ mV/fC}$. The channel-to-channel variation of the measured electronics gain is shown in the two plots of Fig. 7.29 for the 64 channels of all the 16 chips. Apart from the chip-to-chip variation which can be distinguished from the different bands of the left plot a decreasing trend towards the higher channel numbers can be clearly observed in the profile histogram of the right plot in the same figure. The latter has been identified to be coming from the chip’s power distribution which resulted in a voltage drop along the channels and is fixed in the next versions of the chip.
Characterisation of different Micromegas readout layouts and electronics

Figure 7.29: The measured gain per VMM1 channel for all 16 boards of the test beam apparatus. The right plot is the profile distribution of the scatter plot on the left.

A similar calibration procedure is also performed on the timing (TDO) measurement. However, since the analysis presented in the next section uses only the channel address and charge information the timing calibration is not discussed. A detailed description of the timing calibration procedure along with results on timing performance studies are presented in [22].

Hit reconstruction and spatial resolution studies

After the determination of the calibration constants, the pedestal charge values are subtracted from the PDO measurements of each channel. One test beam run is analysed for which the 9 mV/fC amplifier setting and a 50 ns peaking time were used. The calibrated raw strip data are then clustered into chamber hits by requiring more than one consecutive strips with signal in each detector plane. Some characteristics of the reconstructed clusters per event are shown on the distributions of Fig. 7.30.

As can be seen in the leftmost plot of Fig. 7.30 the multiple track events concern ~ 8% of the total events\(^9\). It can also be noticed however, that there is a non-negligible number of zero values that drops the measured efficiency of the chambers. This is due to the several inefficient electronic channels distributed along the VMM1 chips. These dead channels not only spoil the clusterisation requirement of adjacent strips with signal but they also produce artificial inefficient areas along the chamber readout. For the tracking analysis that follows only events were a single cluster, with more than one strips, is recorded in each of the eight MM chambers of the set-up are used. For these events, the distribution of the cluster size for a single chamber is presented in the middle histogram of Fig. 7.30. The mean value of 4.4 strips per cluster is in good agreement with similar measurements performed with the APV25 chip as has been shown in Fig. 5.1 for 0° tracks. The effect that the inefficient VMM1 channels have on the event selection can be seen in the rightmost plot of Fig. 7.30 where only the 44% of the events have at least one cluster reconstructed in all eight chambers of the set-up.

\(^9\)During the VMM1 test beam ~ 20k events were recorded in each run.
7.4 Performance studies of resistive MM chambers with the VMM1 ASIC

Figure 7.30: Left: Distribution of the number of clusters for a single chamber. Middle: Distribution of the cluster size for one chamber requiring only single cluster events. Right: Distribution of the number of chambers with at least one hit per event.

The charge distribution (PDO) per channel, for the leading channel of each cluster, and per reconstructed cluster are shown in Fig. 7.31 for a single MM chamber. The distributions can be described relatively well with a Landau function. In the case of the single channel charge distribution shown on the left the saturation limit of the chip is reached at \( \sim 1 \text{ V} \), thus some fraction of the charge information is lost owing to the limited dynamic range. The MPV of the cluster charge distribution is found to be \( \sim 290 \text{ mV} \) which corresponds to \( \sim 200 \text{ k electrons} \). If the gas amplification is taken into account, which for the amplification voltage used was \( \sim 10^4 \), the charge measurement boils down to \( \sim 20 \text{ primary ionisation electrons} \). This value is in good agreement with simulation results for the Ar\( + 7\% \text{CO}_2 \) gas mixture which foresee \( \sim 18 \text{ primary electrons} \) for a 5 mm long track [23].

Figure 7.31: Charge properties of the clusters. On the left plot the distribution of the maximum channel charge per cluster is shown. The distribution of the total cluster charge is shown on the right plot.

The accurate charge measurement with the VMM1 ASIC allows for a precise charge interpolation with the MM chambers used in the test beam. Since the studies presented focus solely
on the $0^\circ$ tracks the Centroid method is used for the identification of the charged particle hit position in each chamber plane as described in Chap. 5. A graphical representation of the MM chambers set-up is shown in Fig. 7.32 (left).

In order to minimise the distance between the planes of the same doublet the MMs are installed in a back-to-back configuration and the beam traverses the chamber hodoscope perpendicularly. The distribution of the Centroid hit position difference for the chambers of the second, with respect to the beam, MM doublet (named T3 and T4) is shown in the right plot of Fig. 7.32. The residual distribution, which is centered at zero after precise offline alignment of the chambers, is fitted with a double Gaussian function to take also properly into account the long tails that correspond to mis-reconstructed events in at least one of the two chambers. The $\sigma$ of the core Gaussian along with the weighted $\sigma$ (Eq. (4.3)), divided by $\sqrt{2}$ assuming that the MMs compared are identical and have the same resolution, are quoted. It can be seen that $\sim 98\%$ of the events occupy the core Gaussian which gives an estimate of the detector’s spatial resolution. The $59 \mu m$ resolution is slightly better than the results obtained with similar chambers using the APV25 (Fig. 5.4), where the beam and set-up configuration were slightly different. Nevertheless, the relatively good quantitative agreement reached between the results of the two different ASICs confirms and validates the very satisfactory performance of the VMM1 chip with the resistive MM chambers.

![Figure 7.32](image-url)

**Figure 7.32:** Left: Distribution of the hit position difference between two MM chambers for single cluster events. Middle: Residual distribution between the hit position in a single chamber and the extrapolated reference track hit excluding the chamber under study. Right: Residual distribution between the hit position in a single chamber and the extrapolated reference track hit including the chamber under study.

The single MM plane spatial resolution can also be measured using a different approach where all the eight hodoscope MM chambers are included in the calculations. The Centroid hits of all the MMs except for the one under test are used to reconstruct the charged particle track inside the hodoscope. The reconstructed track is then extrapolated to the test chamber plane and the position difference between the expected and the reconstructed hit is calculated in an event-by-event basis. The so-called excluded residual distribution obtained with this method...
is shown on the left plot of Fig. 7.33. If the same exercise is repeated with including the test chamber hit in the track identification the included residual distribution of the right plot is obtained. Since all the MMs included in this analysis are identical, the single plane spatial resolution will be given by Eq. (7.7) [18]. For the case of the T3 chamber this gives $\sigma = 62.2 \text{\(\mu\text{m}\)}$ which is in almost perfect agreement with the value obtained by comparing two MM chambers in Fig. 7.32.

\[ \chi^2 / \text{ndf} = 155 / 83 \]
\[ \chi^2 / \text{ndf} = 158.7 / 78 \]

**Figure 7.33:** Left: Distribution of the difference between the hit position in a single chamber and the extrapolated reference track hit excluding the chamber under study. Right: Distribution of the difference between the hit position in a single chamber and the extrapolated reference track hit including the chamber under study in the track estimation.
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Appendix A

Luminosity measurement using MDT DCS data

The algorithm for the MDT current offset calibration using the luminosity data [1] recorded in the DCS has been presented in Sec. 2.3. The same method can also be used to estimate the ATLAS luminosity using the DCS current readings of a single MDT chamber. The slope of the linear correlation should be characteristic of the chamber’s position and the particle rate it is exposed to for a given ATLAS luminosity value. The current offset on the other hand, at zero luminosity, should be a feature of the high voltage channel. The idea is tested using a dataset spanning over one month of normal ATLAS data-taking. Plots of the Average Instantaneous Luminosity per Luminosity Block (LB) and the current readings of the MDT EIL1A09 chamber as recorded in the DCS offline database are shown in Fig. A.1. The several physics runs can be distinguished from the luminosity plots while the current measurements seem to follow the luminosity trend.

![Image](image-url)

**Figure A.1:** Left: The LB Average Instantaneous Luminosity of ATLAS as a function of time for one month of ATLAS running. The luminosity data are acquired from the DCS archives. Right: The DCS current readings for MDT chamber EIL1A09 multilayer1 for the same time period.

The archiving of the luminosity and current values that are used in this analysis is completely asynchronous. In fact, even the archiving of the current readings between different high voltage channels is not synchronised at all since a value and time dependent smoothing is applied on

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1 The query of the DCS data offline database is realised using the ATLAS DCS DDV application [2].
2 More information about the luminosity used are given in Sec. 2.3.2.
the DCS readings\(^3\). In order to synchronise the different data streams the data are grouped with respect to time in intervals of 25 min and the average luminosity and current value is calculated for each interval. This ensures that at least a few values per interval are used to identify an accurate measurement and the result is independent on single value fluctuations. The number of measurements per interval is plotted as a function of luminosity in Fig. A.2 for luminosity and the MDT EIL1A09 current data (left and right respectively). It can be observed that the luminosity readings are more frequently archived compared to the current data with the frequency increasing for increasing average luminosity values.

\[ L \sim 10^{33} \text{cm}^{-2}\text{s}^{-1} \]

**Figure A.2:** The number of measurements in each time interval as a function of the average luminosity within the same interval for the LB average instantaneous luminosity (left) and the current of EIL1A09 MDT chamber (right).

The correlation between current and luminosity, averaged per time sample, for two MDT chambers (EIL4A09 and EIL1A09) is illustrated in the plots of Fig. A.3. A very good linearity can be observed in both chambers for luminosity values in the range $2 - 7 \times 10^{33} \text{cm}^{-2}\text{s}^{-1}$. The few outlying points are coming from low statistics time intervals that coincide in time with the very steep (almost instantaneous) luminosity transitions at the beginning and the end of the physics runs. The slopes are different for the two chambers, with a much steeper increase evident for the innermost EIL1A09 MDT chamber with respect to EIL4A09. This is actually expected since layer one is exposed to a significantly higher particle rate compared to layer four, being closer to the beam axis along the radial direction \(^4\). The data can be described pretty well with a straight line. A fit with first-order polynomial function has been applied in the first place that could follow the data sensibly well. A more robust description of the correlation between the two quantities exploiting the pattern recognition ability of the Hough transform\(^4\) was also studied. By translating the current-luminosity coordinates of the datapoints into the Hough space the accumulation point of the sinogram lines will represent the straight line that satisfies the vast majority of the datapoints in the original current-luminosity space. The datapoints for the two MDT chambers (EIL1A09 and EIL4A09) expressed in the Hough space are illustrated in Fig. A.4. The coordinates of the crossing-point satisfied by the majority of the curves define the slope

\(^3\)For the MDT current readings the archiving smoothing is value (0.2 µA) and time-dependent (900 sec). From the hardware specifications \(^3\) the current output value resolution is 0.01 µA.

\(^4\)The algorithm is described in Sec. 5.3 and in the Appendix of [5].
and the intercept of the straight line that describes the data-points in the original space and are superimposed on the two-dimensional plots of Fig. A.3. For the data of the MDT chambers that are analysed here a linear fit gives approximately the same results with the first-order polynomial becoming indistinguishable from the Hough line.

**Figure A.3:** The LB Average Instantaneous Luminosity of ATLAS as a function of time for one month of ATLAS running for EIL4A09 (left) and for EIL1A09 (right).

**Figure A.4:** The LB Average Instantaneous Luminosity of ATLAS as a function of time for one month of ATLAS running transformed into the polar Hough space for EIL4A09 (left) and for EIL1A09 (right).

Based on the knowledge of the correlation between current and luminosity, for the two MDT
chambers, the ATLAS luminosity can be estimated for a given current value with a certain accuracy. To estimate the uncertainty in the luminosity measurement using this method, without inserting the additional contributions of the outlying datapoints, the data are grouped in luminosity bins of $5 \times 10^{31} \text{cm}^{-2}\text{s}^{-1}$ width (~ 1% of the luminosity range examined). The profile histograms of Fig. A.3 are shown in Fig. A.5 and are fitted with a straight line to illustrate the good agreement with the Hough lines of Fig. A.3 (notice the different scales in the x-axis between Figs. A.3 and A.5).

The measured linear correlation, which for this study is the one derived from the Hough transform technique, is interpolated to the corresponding current value of each luminosity bin. Then, the relative error of each measurement is calculated for all the luminosity samples using the difference of each measurement with the fit expectation normalized to the luminosity value. The distributions of the relative error for the same E1 MDT chambers that were presented before are shown in Fig. A.6. By fitting the error distributions for the two chambers around the peak value we estimate a mean error better than $\delta L / L \approx 1\%$ for both chambers.

The tails that are observed in the error distributions, towards the larger values, are mostly measurements coming from the low luminosity region. This is illustrated in Fig.A.7 where the $\delta L / L$ quantity is plotted as a function of the measured $L$ and the deviation from the mean error value is evident for $L \leq 2.5 \times 10^{33} \text{cm}^{-2}\text{s}^{-1}$. This is mainly attributed to the reduced statistics at low luminosity values since the measurements of the low $L$ region have larger errors. Another systematic deviation from the mean error value can also be noticed in the large luminosity values $L \geq 6 \times 10^{33} \text{cm}^{-2}\text{s}^{-1}$ of Fig. A.7 which cannot be attributed to statistics. In fact, this deviation is also visible in Fig. A.5 for the high luminosity values and should be an indication of gas gain drop owing to space charge effects that are expected at very high particle rates$^5$.

$^5$For the ATLAS MDTs a $\sim 5\%$ gas gain drop is expect at particle rates of 500 Hz/cm$^2$ [6]
Figure A.6: Distributions of the luminosity measurement relative error for each luminosity bin. The mean error value is almost the same (< 1%) for the two EI MDT chambers that are studied.

Figure A.7: The relative luminosity measurement error is plotted as a function of the luminosity value for the two EI MDT chambers. In both cases it can be seen that the luminosity calculation using the current values is characterized by a larger uncertainty in the low luminosity region.
Bibliography


ATLAS Micromegas test beam apparatus

The results that are presented in this thesis correspond to data acquired at several test beam periods with different conditions. However, the same baseline design of the apparatus has always been used with modifications that depend on the objectives of the tests. A brief description of the various ingredients of the experimental apparatus is given to support the test beam data analysis results that are presented in the previous chapters.

Examples of two MM chamber set-ups are illustrated in Fig. B.1. Small (10 × 10 cm²) resistive-strip MM chambers are mounted on aluminium frames that can support multiple detection planes forming a MM hodoscope. Two different supporting frames have been employed in the studies presented with twelve and eight stations for the left and the right photo of Fig. B.1 respectively. The hodoscope frames could be rotated as can be seen in the same figure in order to have the MMs inclined with respect to the beam axis. In the two first and last stations Tmm (or Tmb) type MMs are used that are able to provide a precise two-dimensional reference track reconstruction while the other stations are usually occupied by T type chambers. Cross sections of the T and Tmm type MM chambers are shown in Figs. 3.10, 3.16 respectively.

Figure B.1: Typical test beam experimental set-ups featuring hodoscopes of several small MM chambers. Left: A set of 12 small resistive-strip MM chambers were installed in the H6 beam line of the CERN SPS North Area during the summer of 2012. Right: Eight small resistive-strip MM chambers installed in in the H6 beam line of the CERN SPS North Area in November of 2015.

The basic characteristics of the MM chambers that have been tested as a subject of this thesis
are summarised in Table B.1. The test beam results presented in Chaps. 4, 5, 6 are acquired using these types of MM chambers. From the rest of the chambers, the T4C and the multiplexed (Mux) prototypes are small MMs with special readout layouts that are described in Chap. 7. In the same chapter, the specifications of the medium-size MMSW quadruplet prototype are discussed. The TQF is a special MM featuring four areas with different alignment between the readout and the resistive strips in order to study its effect on the measured performance [1]. However, in this thesis only the area with perfect alignment is used to study the geometrical efficiency in Sec. 5.6. The medium-size ExMe, realised with the "mechanically floating mesh" technique, was built to study different meshes and is only used, along with the all the chambers listed in Table B.1, for the noise measurements presented in Sec. 7.3.

Table B.1: Specifications of the MM chambers that have been used in the beam tests of the ATLAS New Small Wheel MM activity.

<table>
<thead>
<tr>
<th>MM Name</th>
<th>Readout Width/Pitch (mm)</th>
<th>Resistivity (MΩ/cm)</th>
<th>Mesh Wire Diameter/Opening (mm)</th>
<th>Pillars Diameter/Pitch (mm)</th>
<th>Active Area (cm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tmm X</td>
<td>0.15/0.25</td>
<td>25</td>
<td>0.018/0.045 (403 lpi)</td>
<td>0.3/2.5</td>
<td>100</td>
</tr>
<tr>
<td>Tmm Y</td>
<td>0.08/0.25</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tmb X</td>
<td>0.15/0.25</td>
<td>25</td>
<td>0.018/0.045 (403 lpi)</td>
<td>0.5/5.0</td>
<td>100</td>
</tr>
<tr>
<td>Tmb Y</td>
<td>0.08/0.25</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mux X</td>
<td>0.15/0.25</td>
<td>40</td>
<td>0.018/0.045 (403 lpi)</td>
<td>0.3/2.5</td>
<td>64</td>
</tr>
<tr>
<td>Mux Y</td>
<td>0.08/0.25</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>T1-4</td>
<td>0.30/0.40</td>
<td>25</td>
<td>0.018/0.045 (403 lpi)</td>
<td>0.3/2.5</td>
<td>100</td>
</tr>
<tr>
<td>T5-8</td>
<td>0.30/0.40</td>
<td>8</td>
<td>0.018/0.045 (403 lpi)</td>
<td>0.3/2.5</td>
<td>100</td>
</tr>
<tr>
<td>TQF</td>
<td>0.30/0.40</td>
<td>25</td>
<td>0.018/0.045 (403 lpi)</td>
<td>0.5/5.0</td>
<td>100</td>
</tr>
<tr>
<td>T4C</td>
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<td>25</td>
<td>0.018/0.045 (403 lpi)</td>
<td>0.3/2.5</td>
<td>100</td>
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<tr>
<td>ExMe</td>
<td>0.30/0.45</td>
<td>25</td>
<td>0.028/0.050 (326 lpi), 0.030/0.070 (254 lpi)</td>
<td>0.5/5.0, 0.5/7.0, 0.5/8.5, 0.5/10</td>
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<tr>
<td>MMSW</td>
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<td>1</td>
<td>0.030/0.050 (318 lpi)</td>
<td>0.3/2.5</td>
<td>5000</td>
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</tbody>
</table>

In terms of the high voltage scheme used, the voltage was supplied to the drift electrode and the resistive strips while the mesh was grounded. This scheme, instead of keeping the resistive strips grounded, requires positive and negative voltages in a single chamber. The commercial CAEN A1821 [2] high voltage boards were used in the test beams powered and controlled from the CAEN SY2527 [3] Mainframe. For efficient monitoring and safe control of the chambers high voltage supplies, the Siemens WinCC Open Architecture SCADA system [4] (formerly known as PVSS) has been used. Two WinCC OA projects have been used over the several test beam periods: i) SloCSy [5] ii) TestBeamSCS [6]. During the test beams the MM chambers were always operated with the Ar+7%CO₂ gas mixture provided in most of the cases from pre-mixed bottles with an input pressure of ~ 4 mbar. This mixture is the one that will be used for the NSW MM
The readout of the MM chambers during the tests has always\(^1\) been carried out by APV25 [7] hybrid cards via the Scalable Readout System [8] (SRS) that has been developed within the RD51 collaboration [9]. A schematic representation of a minimal SRS system is shown in Fig. B.2. It consists of two APV25 front-end boards, a digitizer card (ADC), a Front-end Concentrator Card (FEC) and the Data Acquisition PC. The hybrid APV25 front-ends are mounted on the MM via 130-pin Panasonic connectors [10] and all electronic channels are protected against discharges via protection diodes. An APV25 hybrid board is by design either a master or a slave. The master hybrid is connected to the ADC via an HDMI cable. The slave board doesn’t host a micro-HDMI connector and is connected to the master via a flat cable. Master and slave are read in parallel delivering analog CR-RC shaped signals sampled at 40 MHz frequency. In order to provide a trigger signal (NIM pulse) to the SRS FEC that will initiate the reading of the data from the APV25 hybrids a set of scintillators is used. A typical scintillator set-up can be seen in the photos of Fig. B.3. The interface to the Data Acquisition (DAQ) computer is realized via copper based Gigabit Ethernet. One SRS ADC can read out up to 16 APV25 hybrid boards (eight masters and eight slaves). For experimental set-ups with more channels additional FEC-ADC pairs can be employed. In this case the Gigabit Ethernet links must be multiplexed through a Gigabit switch before they are connected to the DAQ computer. In addition to this, another Fan-in-Fan-out trigger module called CTF must be used to feed the scintillator trigger signal to all the FECs.

During some of the test beam periods an additional external and independent telescope of three Si detectors has been used as a reference tracker. The three stations of the so-called Bonn ATLAS Telescope (BAT) are visible in Fig. B.3 (right). The reference tracker was supplied with the same trigger signal that is used as input in the SRS but it is read out independently of the MM system. The synchronisation and merging of the different data streams is done offline as described in Appendix G.

\(^1\)Apart from the VMM1 studies presented in Sec. 7.4.
In terms of software the Scalable Detector Control [11] (SDC) is used for the slow control and configuration of the SRS. The transactions between the computer, where the SDC runs, and the SRS, including FEC, ADC and APV25 hybrids, are carried out using UDP over IP protocol on the Gigabit Ethernet communication. The data acquisition and saving into ROOT [12] ntuples is realised via the mmDAQ [13] software that has been developed within the ATLAS NSW MM collaboration. It features online zero suppression and pedestal subtraction and it can extend up to the full scalability of the SRS. The raw ntuples are processed using the RecoMM software, that is described in Appendix G, before they are analysed.

Figure B.3: A typical scintillator set-up providing the trigger signal for the readout of the MM chambers that was used during the test beam at the H6 beam line of the CERN SPS/H6 area.
Bibliography


Appendix C

Track slope to angle transformation
Monte-Carlo studies

The test beam scenario where a MM chamber is inclined at a known angle with respect to the beam axis is assumed. Slope values are generated following a Gaussian distribution (Eq. (C.1)) around the mean value \( \langle x_0 \rangle \) that corresponds to the slope of the inclination angle. Different \( \sigma \) values will be examined.

\[
\frac{dn}{dx} = e^{-(x-x_0)^2/2\sigma^2}
\]  

(C.1)

In Fig. C.1, three Gaussian distributions are shown which were generated using the same mean value \( x_0 = 0.7 \) but varying the \( \sigma \) parameter in the range 0.1 – 0.3 with a 0.1 step. For each case a 100k event sample was used. The transformation from the slope \( x \) to the angle \( y \) is given by Eq. (C.2) with a slope value of 0.7 corresponding to a track angle of 55° (0.96 rad). It is evident that the transformation is not linear.

\[
y = \arctan \left( \frac{1}{x} \right) \quad \Rightarrow \quad x = \frac{1}{\tan y}
\]  

(C.2)

If for each slope value included in the histogram of Fig. C.1 the corresponding angle is extracted using Eq. (C.2) the resulting angular distributions are shown in the left plot of Fig. C.2. The different colours correspond again to the different \( \sigma \) values that were used for the generation of the slope sample. The first thing that can be noticed is that the angular distributions are not Gaussian showing a tail towards larger angle values. Moreover, the peak angle value depends on the \( \sigma \) of the slope distribution with larger values leading to a move of the peak towards smaller angle values.

In order to understand this effect the distribution \( dn/dy \) for the angle variable is calculated analytically. Starting from Eq. (C.1) the expression for the distribution of the angle values is given by Eq. (C.3).

\[
\frac{dn}{dy} = \frac{dn}{dx} \left| \frac{dx}{dy} \right| = e^{-\left(\frac{1}{\tan y-x_0}\right)^2/2\sigma^2} \left( \frac{1}{\tan^2 y} + 1 \right)
\]  

(C.3)
Figure C.1: Three Gaussian distributions generated from a sample of 100k events with the same mean value (0.7) and three different $\sigma$ values 0.1, 0.2, 0.3.

Figure C.2: Left: Angular distributions extracted from the generated slope sample transformed using Eq. (C.2). Right: The distributions of the same angle values filled in a histogram with variable bin size.

The functions given by Eq. (C.3) are shown for the three different $\sigma$ values in the left plot of Fig. C.3. The same non-Gaussian shape can be observed in the analytic expressions as well with the angle value, corresponding to the function's maximum, moving with the $\sigma$ value. The maximum point of the $dn/dy$ distribution can be found by solving the cubic equation of the first
derivative of Eq. (C.3).

\[ \tan^3 y - b \tan^2 y + \tan y - d = 0 \quad \text{where} \quad b = \frac{1}{x_0} - \frac{2\sigma^2}{x_0}, \quad d = \frac{1}{x_0} \tag{C.4} \]

The real root of the cubic Eq. (C.4) can be calculated to be

\[
y_{\text{max}} = \arctan \left( b - \frac{2^{1/3}(3 - b^2)}{3(-9b + 2b^3 + 27d + 3 \sqrt{3} \sqrt{4 - b^2 - 18bd + 4b^3d + 27d^2})^{1/3}} \right) \\
+ \frac{(-9b + 2b^3 + 27d + 3 \sqrt{3} \sqrt{4 - b^2 - 18bd + 4b^3d + 27d^2})^{1/3}}{3 \times 2^{1/3}}
\]

The dependence of the maximum value of Eq. (C.3) from the parameter is shown in Fig. C.4 for \( x_0 = 0.7 \). The decrease in the angle value that corresponds to the maximum of the analytical expression for increasing \( \sigma \) values is evident.

The observed effect of the bias in the peak value of the angular distributions is understood to be due to the non-linear transformation between the variables slope and angle. This non-linearity should also be taken into account on the definition of the histogram parameters. Using an x-axis constructed with a fixed bin width results in the biasing of the angular distribution shape. This effect can be corrected if the transformation from slope to angle is also accompanied with the mutual transformation of the bin width resulting in a variable bin width histogram. The bin width can be iteratively calculated according to the following relation

\[
dx = x_{i+1} - x_i \rightarrow dy = f(x_{i+1}) - f(x_i) \quad f(x) = \arctan \left( \frac{1}{x} \right)
\]

If the transformation of the bin size is applied and the angle histograms are filled with the same angle values from the generated data the disagreement in the peak angle values for different \( \sigma \)
Figure C.4: The maximum point $y_{\text{max}}$ as a function of $\sigma$ for a fixed $x_0 = 0.7$

is no longer evident. This can be seen in the distributions of Fig. C.2 (right) and it is evident that the peak values are now aligned to the same value which corresponds to the mean slope that was used to generate the data in the first place. This effect can be disentangled from the analytical expression (Eq. C.3) as well. If the second term of the product in Eq. (C.3) is neglected (assumed close to 1) the function becomes

$$\frac{dn}{dy} = e^{-\left(\frac{1}{\tan y - x_0}\right)^2 / 2\sigma^2}$$

The graphical representation of the new analytic expression is shown in Fig. C.3 (right) and it is obvious also here that the distributions are perfectly aligned in the expected value. With the larger $\sigma$ resulting only in a larger tail.

### Slopes of complementary angles

Let’s consider that a slope $S_\phi$ is reconstructed from a track with angle $\phi$ as shown on Fig. C.5. The slope variable is assumed to follow a Gaussian distribution in $\phi$ as before

$$\frac{dn}{dS_\phi} = e^{-\left(S_\phi - S_{\phi_0}\right)^2 / 2\sigma^2_{\phi}}$$

Taking now the complementary angle $\theta$ into account the corresponding slope $S_\theta$ can be expressed as a function of the $S_\phi$ according to the relation

$$S_\theta = \frac{1}{S_\phi}$$
The analytical distribution of the $S_\theta$ can then be written as follows

$$\frac{dn}{dS_\theta} = \frac{dn}{dS_\phi} \left| \frac{dS_\phi}{dS_\theta} \right| = \frac{e^{-\left(1/S_\theta - S_\phi\right)^2/2\sigma_\phi^2}}{S_\theta^2}$$

(C.5)

The maximum point of the $dn/dS_\theta$ distribution can be found by solving the equation

$$S_\theta^2 + S_\theta \frac{S_\phi}{2\sigma_\phi^2} - \frac{1}{2\sigma_\phi^2} = 0$$

The positive root of the quadratic equation will be

$$S_{\theta,max} = -\frac{S_\phi}{4\sigma_\phi^2} + \sqrt{\frac{S_\phi^2}{4\sigma_\phi^2} + \frac{2}{\sigma_\phi^2}}$$

which gives the maximum point $S_{\theta,max}$ as a function of $\sigma_\phi$ for a fixed value of $S_\phi$. From the calculated slope $S_{\theta,max}$ the angle $\phi_{max} = \pi/2 - \theta_{max}$ ($\theta_{max} = \arctan(S_{\theta,max})$, $S_{\phi,max} = 1/S_{\theta,max}$) will be

$$\phi_{max} = \arctan\left(\frac{1}{S_{\theta,max}}\right) = \arctan\left\{\frac{1}{\tan\left(\phi_0\pi/180^\circ\right)} + \frac{\tan^2\left(\phi_0\pi/180^\circ\right)}{4\sigma_\phi^2} + \frac{2}{\sigma_\phi^2}\right\} \frac{180^\circ}{\pi}$$

where $S_{\phi_0} = \tan\left(\phi_0\pi/180^\circ\right)$ and $\phi_0$ is expressed in degrees.

The result of $\phi_{max}$ as a function of $\phi_0$ is shown in Fig. C.6 for five different values of $\sigma_\phi$ (0.01, 0.03, 0.05, 0.07, 0.1) and is expressed in degrees. In this plot, for an angle $\phi_0 = 10^\circ$ the corresponding reconstructed angle $\phi_{max} = 14^\circ$ assuming an of error in $\phi$ of 5.7° which corresponds to $\sigma_\phi = 0.1$.

Since the slope is $S_\theta = \tan \theta$, the probability density function of the angle $\theta$ can be calculated by using Eq. (C.5) through the following relation

$$\frac{dn}{d\theta} = \frac{dn}{dS_\theta} \left| \frac{dS_\theta}{d\theta} \right| = \frac{e^{-\left(\cot \theta - S_{\phi_0}\right)^2/2\sigma_\phi^2}}{\sin^2 \theta}$$

Also the probability density function of the angle $\phi$ is expressed as follows.
\[
\frac{dn}{d\phi} = \frac{dn}{dS_\phi} \left| dS_\phi \right| = e^{-\frac{(\tan \phi - S_{0})^2}{2\sigma^2}} \frac{\cos^2 \theta}{\cos^2 \theta}
\]

Figure C.6: $\phi'_{\text{max}}$ versus $\phi_0$ for various values of $\sigma_{\text{res}} = \sigma_\phi$. 
Appendix

Langevin Equation

At the steady state the general expression of the drift velocity \( \mathbf{v}_D = \langle \mathbf{v} \rangle \) can be derived by the equation of motion of an electron under the influence of electric and magnetic fields that is described in Eq. (D.1). By taking the inner and cross product of Eq. (D.1) with the magnetic field \( \mathbf{B} \), we get two more expressions for the \( \mathbf{v}_D \) given by Eqs. (D.2), (D.3).

\[
\frac{m}{\tau} \mathbf{v}_D - e \mathbf{B} \times \mathbf{v}_D = -e \mathbf{E} \quad \Rightarrow \quad \mathbf{v}_D \times \mathbf{B} = -\frac{m}{e\tau} \mathbf{v}_D \tag{D.1}
\]

\[
\frac{m}{\tau} \mathbf{v}_D \cdot \mathbf{B} - e (\mathbf{B} \times \mathbf{v}_D) \cdot \mathbf{B} = -e \mathbf{E} \cdot \mathbf{B} \quad \Rightarrow \quad \mathbf{v}_D \cdot \mathbf{B} = -\frac{e}{m} \mathbf{E} \cdot \mathbf{B} \tag{D.2}
\]

\[
\frac{m}{\tau} \mathbf{v}_D \times \mathbf{B} - e (\mathbf{B} \times \mathbf{v}_D) \times \mathbf{B} = -e \mathbf{E} \times \mathbf{B} \tag{D.3}
\]

By inserting Eq. (D.1) and Eq. (D.2) into Eq. (D.3) this breaks down to Eq. (D.4) since \( \frac{m^2}{\tau^2} e + eB^2 = m^2/\tau^2 e + e\omega^2 m^2/\omega^2 = (m^2/\tau^2 e)[1 + (\omega \tau)^2] \). Finally, by solving Eq. (D.4) for the \( \mathbf{v}_D \) Eq. (D.5) is derived.

\[
-\mathbf{v}_D \left( \frac{m^2}{\tau^2} e + eB^2 \right) = -\mathbf{v}_D \left( \frac{m^2}{\tau^2} e + eB^2 \right) \left( 1 + (\omega \tau)^2 \right) = -e \mathbf{E} \times \mathbf{B} + \frac{m}{\tau} e + \frac{e\tau}{m} (\mathbf{E} \cdot \mathbf{B}) \mathbf{B} \tag{D.4}
\]

\[
\mathbf{v}_D = \frac{e^2 \tau^2}{m^2} EB(\dot{\mathbf{E}} \times \dot{\mathbf{B}}) - \frac{m \tau^2 e^2}{m^2} \frac{E \dot{\mathbf{E}}}{1 + (\omega \tau)^2} - \frac{e^2 \tau e^2}{m} \frac{EB^2 (\dot{\mathbf{E}} \cdot \dot{\mathbf{B}}) \dot{\mathbf{B}}}{1 + (\omega \tau)^2} \tag{D.5}
\]

\[
\mathbf{v}_D = \frac{\mu E}{1 + (\omega \tau)^2} \left[ (\omega \tau)(\dot{\mathbf{E}} \times \dot{\mathbf{B}}) - \dot{\mathbf{E}} - (\omega \tau)^2 (\dot{\mathbf{E}} \cdot \dot{\mathbf{B}}) \dot{\mathbf{B}} \right], \quad \dot{\mathbf{E}} = \frac{E}{\dot{E}}, \quad \dot{\mathbf{B}} = \frac{B}{\dot{B}} \tag{D.6}
\]

The different constant terms of Eq. (D.5) will be

\[
\frac{e^2 \tau^2}{m^2} EB = \mu E \omega \tau, \quad \frac{\tau e}{m} = \mu E, \quad \frac{e^2 \tau e^2}{m} \frac{EB^2}{m^2} = \frac{e}{\tau} \frac{e^2 \tau^2}{m^2} = \mu E (\omega \tau)^2
\]

The magnitude of drift velocity \( \mathbf{v}_D \) will be

\[
\mathbf{v}_D \cdot \mathbf{v}_D = \frac{(\mu E)^2}{1 + (\omega \tau)^2} \left[ (\omega \tau)(\dot{\mathbf{E}} \times \dot{\mathbf{B}}) - \dot{\mathbf{E}} - (\omega \tau)^2 (\dot{\mathbf{E}} \cdot \dot{\mathbf{B}}) \dot{\mathbf{B}} \right] \left[ (\omega \tau)(\dot{\mathbf{E}} \times \dot{\mathbf{B}}) - \dot{\mathbf{E}} - (\omega \tau)^2 (\dot{\mathbf{E}} \cdot \dot{\mathbf{B}}) \dot{\mathbf{B}} \right]
\]
Therefore, the Lorentz angle, \( \alpha \), between the drift velocity and the electric field direction will be

\[
\tan \alpha = \frac{v_{Dz}}{v_{Dh}} = \frac{|\hat{E} \times \hat{B}|}{|\hat{E} \cdot \hat{B}|} \frac{1}{\sqrt{1 + (\hat{E} \cdot \hat{B})^2(\omega \tau)^2}}
\]  
(D.10)
The VMM Shaper

The VMM "semi-Gaussian" shaper responds to an event with an analog pulse, the peak amplitude of which is proportional to the event charge. The time needed to return to baseline after the peak, depends on the time constants and the configuration of poles. The VMM facilitates a $3^{rd}$ order c-shaper with the combination of one real, one complex and its conjugate pole \([1]\).

The transfer function \(H(s)\) for such shaper is given by the following expression

\[
H(s) = \frac{1}{\left(s + p_1\right)^{(n+1)/2}} \prod_{i=2}^{\infty} \frac{1}{\left(s + r_i + c_i^2\right)} \approx \frac{1}{\left(s + p_1\right)\left[(s + r_2)^2 + c_2^2\right]} \tag{E.1}
\]

where \(n\) is the order of the shaper (in our case \(n = 3\)), and \(r_i\), \(c_i\) are the real and imaginary parts respectively. The roots are

\[
(s + r_2)^2 + c_2^2 = 0 \Rightarrow s + r_2 = \pm jc_2 \Rightarrow s = -r_2 \pm j c_2, \ s = -p_1 \tag{E.2}
\]

so the transfer function can be written using simple fractions like

\[
H(s) = \frac{K_1}{s + p_1} + \frac{K_2}{s + r_2 - j c_2} + \frac{K_3}{s + r_2 + j c_2} \tag{E.3}
\]

where the real pole is \(p_0 = -p_1\) and the two complex poles are \(p_1 = -r_2 + j c_2\) and \(p_2 = -r_2 - j c_2 = p_0^*\). The real and imaginary parts of the complex poles are \(\Re p_1 = -r_2, \ \Im p_1 = c_2, \ \Re p_2 = -r_2, \ \Im p_2 = -c_2\).
The coefficients $K_i$ are

$$K_1 = \left. \frac{1}{(s + r_2 - jc_2)(s + r_2 + jc_2)} \right|_{s = -p_1} = \frac{1}{(-p_1 + r_2 - jc_2)(-p_1 + r_2 + jc_2)} = \frac{1}{(r_2 - p_1)^2 + c_2^2}, \quad \in \mathbb{R}$$

$$K_2 = \left. \frac{1}{(s + p_1)(s + r_2 + jc_2)} \right|_{s = -r_2 + jc_2} = \frac{1}{(-r_2 + jc_2 + p_1)(-r_2 + jc_2 + p_2 + jc_2)} = \frac{1}{2jc_2(p_1 - r_2 + jc_2)} = |K_2|e^{j\phi}, \quad \phi = \angle K_2, \quad \in \mathbb{C} \quad (E.4)$$

$$K_3 = \left. \frac{1}{(s + p_1)(s + r_2 - jc_2)} \right|_{s = -r_2 - jc_2} = \frac{1}{(-r_2 - jc_2 + p_1)(-r_2 - jc_2 + p_2 - jc_2)} = \frac{1}{-2jc_2(p_1 - r_2 - jc_2)} = K_2^*, \quad \in \mathbb{C}$$

From Eqs. (E.4), (E.3) the transfer function can be written in the form of Eq. (E.5).

$$H(s) = \frac{K_1}{(s + p_1)} + \frac{K_2}{(s + r_2 - jc_2)} + \frac{K_3}{(s + r_2 + jc_2)} \quad (E.5)$$

The impulse response function of Eq. (E.5) is obtained in the time-domain by the inverse Laplace transform $h(t) = \mathcal{L}^{-1}\{H(s)\}(t)$:

$$h(t) = K_1e^{-p_1t} + K_2e^{(-r_2 + jc_2)t} + K_2^*e^{(-r_2 - jc_2)t}$$

$$= K_1e^{-p_1t} + e^{-r_2t}[K_2e^{jc_2t} + K_2^*e^{-jc_2t}]$$

$$= K_1e^{-p_1t} + e^{-r_2t}2\Re(K_2e^{jc_2t}) = K_1e^{-p_1t} + e^{-r_2t}2\Re(K_2[e^{j\phi}e^{jc_2t}]) \quad (E.6)$$

$$= K_1e^{t_0\zeta} + 2|K_2|e^{-r_2t}\cos(c_2t + \phi), \quad \text{where } \phi = \angle K_2$$

$$= K_1e^{t_0\zeta} + 2|K_2|e^{R_{\text{pole}_1}t}\cos(\Im\text{pole}_1t + \angle K_2)$$

where

$$|K_2| = \frac{1}{2c_2\sqrt{(p_1 - r_2)^2 + c_2^2}} \quad (2) \Rightarrow 4c_2^2|K_2|^2 = K_1$$

$$K_1 = \frac{1}{(\text{pole}_0 - R_{\text{pole}_1})^2 + \Im\text{pole}_1^2} \quad (E.7)$$

The final function can be written in a computational form of Eq. (E.9) with its equivalent graphical representation, for $t_{\text{peak}} = 0.05 \times 10^{-6}$ s shown in Fig. G.1. The VMM shaper constants are
determined from the normalisation of Eq. (E.6) to be

\[
pole_0 = \frac{1.263}{\alpha} \\
pole_1 = \left(1.149 - j0.789\right) \frac{1}{\alpha} \\
K_1 = 1.584 \\
K_2 = -0.792 - 0.115j \\
\alpha = t_{\text{peak}}/1.5
\]  

(E.8)

\[
h(t) = \alpha^2 |pole_0|^2 \left|pole_1\right|^2 \left[K_1 e^{-\left|pole_0\right|} + 2|K_2|e^{-j\left|pole_1\right|} \cos \left(-t|pole_1| + \angle K_2\right)\right]
\]  

(E.9)

**Figure E.1:** The VMM response function for a peaking time of \(t_{\text{peak}} = 0.05 \times 10^{-6}\) s.
Bibliography

Reference track extrapolation error

If the multiple scattering within the MM hodoscope stations is considered negligible the reference track parameters are the parameters of a line (Eq. (F.1)), where $x$ is expressed in the detector plane and $z$ measures along the beam axis. The line equation can also be written in an equivalent form using matrices as described in Eq. (F.2).

$$x = \alpha + bz$$

(F.1)

$$F(p) = A \cdot p$$

(F.2)

The matrices $A$, $p$ are the positions of the telescope stations and the track parameters respectively and for the general case of $n$ stations they can be written as

$$p = \begin{pmatrix} a \\ b \end{pmatrix}, \quad A = \begin{bmatrix} 1 & z_1 \\ 1 & z_2 \\ \vdots & \vdots \\ 1 & z_n \end{bmatrix}$$

(F.3)

The uncertainty in the hit position reconstruction ($\alpha$) of the hodoscope stations can be written in the form of a weight matrix as shown in that is the inverse of the measurements covariant matrix and neglecting multiple scattering contributions can be written as

$$W = \begin{pmatrix} \sigma^{-2}_1 & 0 & \cdots & 0 \\ 0 & \sigma^{-2}_2 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & \sigma^{-2}_n \end{pmatrix}$$

(F.4)

The covariant matrix of the track parameters will be given by Eq. (F.5). Equation (F.6) illustrated the calculated covariant matrix for the simplest case of two reference stations.

$$C = (A^TWA)^{-1}$$

(F.5)

$$C_2 = \frac{1}{(z_1 - z_2)^2} \begin{pmatrix} \bar{z}_2^2 \sigma_1^2 + z_1^2 \sigma_2^2 - z_2 \sigma_1^2 - z_1 \sigma_2^2 \\ -\bar{z}_2 \sigma_1^2 - z_1 \sigma_2^2 \\ \bar{z}_2 \sigma_1^2 - z_2 \sigma_2^2 \\ \sigma_1^2 + \sigma_2^2 \end{pmatrix}$$

(F.6)
If all the hodoscope stations have the same resolution then $\sigma = \sigma_1 = \sigma_2 = \sigma_3$ and by inserting Eq. (F.6) becomes

$$C_2 = \frac{\sigma^2}{(z_1 - z_2)^2}\left(\begin{array}{cc} z_1^2 + z_2^2 - z_1 - z_2 \\ -z_1 - z_2 \\ 2 \end{array}\right)$$

The extrapolation error of the reference track reconstructed using the two stations at $z_1, z_2$, with the same resolution $\sigma$, on a third plane ($z_0$) can be calculated using the error propagation as follows

$$\sigma^2_e = \left[\frac{\partial F(p)}{\partial p}\bigg|_{z=z_0}\right]^T C_2 \left[\frac{\partial F(p)}{\partial p}\bigg|_{z=z_0}\right] = \left(\begin{array}{c} 1 \\ z_0 \end{array}\right) \frac{\sigma^2}{(z_1 - z_2)^2}\left(\begin{array}{cc} z_1^2 + z_2^2 - z_1 - z_2 \\ -z_1 - z_2 \\ 2 \end{array}\right)\left(\begin{array}{c} 1 \\ z_0 \end{array}\right) =$$

$$\frac{\sigma^2}{(z_1 - z_2)^2}\left[z_1^2 + z_2^2 - 2z_0(z_1 + z_2) + 2z_0^2\right]$$

The measured uncertainty $R$, from the position difference between the extrapolated reference track hit and the hit reconstructed in the detector under test will be the sum in quadrature of the intrinsic detector resolution $\sigma_I$ and the extrapolation error $\sigma_e$, for the most generic case where the different hodoscope stations are characterised by different resolution.

$$R^2 = \sigma^2_e + \sigma^2_I = A\sigma^2 + \sigma^2_I \quad (F.7)$$

Assume now that all the stations are characterised by the same resolution $\sigma$ and $z_i, i = 1, \ldots, n$ are the positions of the reference hodoscope stations while $z_0$ is the position where the extrapolated error needs to be estimated. The values of the parameter $A$, from Eq. F.7, for different numbers of reference stations are listed below.

- Two stations

$$A = \frac{2z_0^2 + z_1^2 + z_2^2 - 2z_0(z_1 + z_2)}{(z_1 - z_2)^2}$$

- Three stations

$$A = \frac{1}{2} \frac{3z_0^2 + z_1^2 + z_2^2 + z_3^2 - 2z_0(z_1 + z_2 + z_3)}{z_1^2 + z_2^2 + z_3^2 - z_2z_3 - z_1(z_2 + z_3)}$$

- Four stations

$$A = \frac{4z_0^2 + z_1^2 + z_2^2 + z_3^2 + z_4^2 - 2z_0(z_1 + z_2 + z_3 + z_4)}{3(z_1^2 + z_2^2 + z_3^2 + z_4^2) - 2z_3z_4 - 2z_2(z_3 + z_4) - 2z_1(z_2 + z_3 + z_4)}$$

- Five stations

$$A = \frac{5z_0^2 + z_1^2 + z_2^2 + z_3^2 + z_4^2 + z_5^2 - 2z_0(z_1 + z_2 + z_3 + z_4 + z_5)}{4(z_1^2 + z_2^2 + z_3^2 + z_4^2 + z_5^2) - 2z_3z_4 - 2z_2z_5 - 2z_4z_5 - 2z_2(z_3 + z_4 + z_5) - 2z_1(z_2 + z_3 + z_4 + z_5)}$$

The extrapolation error $\sigma^2_e$ for the most generic case where the different hodoscope stations are characterised by different resolution can also be calculated for different numbers of reference stations to be
• Two stations

\[ \sigma_e^2 = \frac{\sigma_2^2(z_0 - z_1)^2 + \sigma_1^2(z_0 - z_2)^2}{(z_1 - z_2)^2} \]

• Three stations

\[ \sigma_e^2 = \frac{\sigma_2^2\sigma_3^2(z_0 - z_1)^2 + \sigma_1^2(\sigma_2^2(z_0 - z_2)^2 + \sigma_3^2(z_0 - z_3)^2)}{\sigma_3^2(z_1 - z_2)^2 + \sigma_2^2(z_1 - z_3)^2 + \sigma_1^2(z_2 - z_3)^2} \]

• Four stations

\[ \sigma_e^2 = \frac{B}{C} \]

where

\[ B = \sigma_2^2\sigma_3^2\sigma_4^2(z_0 - z_1)^2 + \sigma_1^2(\sigma_2^2\sigma_3^2(z_0 - z_2)^2 + \sigma_3^2(z_0 - z_3)^2 + \sigma_1^2(z_0 - z_4)^2) \]

and

\[ C = \sigma_1^2\sigma_4^2(z_2 - z_3)^2 + \sigma_1^2(\sigma_2^2(z_1 - z_2)^2 + \sigma_1^2(z_2 - z_4)^2) + \sigma_2^2\sigma_3^2(z_1 - z_3)^2 + \sigma_3^2(z_1 - z_4)^2 + \sigma_1^2(z_3 - z_4)^2 \]

• Five stations

\[ \sigma_e^2 = \frac{D}{E} \]

where,

\[ D = \sigma_2^2\sigma_3^2\sigma_4^2\sigma_5^2(z_0 - z_1)^2 + \sigma_1^2(\sigma_2^2\sigma_3^2\sigma_4^2(z_0 - z_2)^2 + \sigma_2^2\sigma_3^2(z_0 - z_3)^2 + \sigma_3^2(z_0 - z_4)^2 + \sigma_4^2(z_0 - z_5)^2) \]

and

\[ E = \sigma_1^2\sigma_4^2\sigma_5^2(z_2 - z_3)^2 + \sigma_2^2(\sigma_2^2\sigma_3^2(z_0 - z_2)^2 + \sigma_2^2(z_1 - z_2)^2 + \sigma_1^2(z_2 - z_3)^2) + \sigma_2^2(\sigma_3^2\sigma_4^2(z_2 - z_3)^2 + \sigma_1^2(z_1 - z_2)^2 + \sigma_3^2(z_3 - z_4)^2) + \sigma_3^2(\sigma_2^2(z_1 - z_3)^2 + \sigma_3^2(z_1 - z_3)^2 + \sigma_1^2(z_4 - z_5)^2) \]
Appendix G

Software development for the Micromegas test beams

A data processing and reconstruction software developed for Micromegas test beam data - RecoMM

Owing to the extensive test beam activity and the growing size of the Muon Atlas Micromegas collaboration the need for a common data reconstruction software arose in 2011 that would allow the users to perform fast, coherent and reliable analysis of the test beam data using a generic and adjustable framework. For this purpose the RecoMM framework was designed and developed within the Muon ATLAS MM collaboration that comprises the data manipulation, filtering and reconstruction techniques of the group’s analysis team into a common software package.

RecoMM was built on C++ enhanced with Boost libraries [1] and with ROOT [2] compatibility for the reading and writing of the data in the commonly used data format of ntuples. It is coupled to the format of the data that are acquired with the mmDAQ [3] software that are used as input files. The parameters and the different options that can be used in the data processing phase can be defined and adjusted in the dedicated configuration file that is is used by RecoMM. These options can be distinguished in different categories

- Filtering & preprocessing.
- Strips data processing.
- Clustering.
- Tracking.

The possible options and configuration parameters are described in details in the following sections. RecoMM has an open-source policy and is available to all CERN users. The latest version source code can be downloaded from the dedicated recomm svn repository. Documentation regarding the installation and execution of the program along with a brief description of its structure and functionality is available at the recomm twiki page.
Table G.1: RecoMM preprocessing filter options

<table>
<thead>
<tr>
<th>Filter Type</th>
<th>Type</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>noisy strips</td>
<td>string</td>
<td>File with noisy strips</td>
</tr>
<tr>
<td>cross-talk strips</td>
<td>string</td>
<td>File with cross-talk strips</td>
</tr>
<tr>
<td>min strip charge</td>
<td>integer</td>
<td>Value of the minimum strip charge</td>
</tr>
<tr>
<td>max time difference</td>
<td>integer</td>
<td>Value of the maximum time difference between strips</td>
</tr>
</tbody>
</table>

Filtering & preprocessing

In order to ease the data analysis purposes a first pre-processing step of the data can be employed in the RecoMM process. This includes several channel-wide and event-wide filters that can be used as an additional suppression of the raw data file. Depending on the characteristics of the experimental set-up and the beam environment these options can be enabled/disabled and or adjusted using the corresponding configuration parameters. Some of the filters available to the users are described in Table G.1

Raw data processing

Between the preprocessing and the clustering phases an algorithm has been developed that allows the extraction of time and charge information from the raw channel data of the APV25 chips. The integrated charge for each APV channel per event is described with a function as described in detail in Sec. 4.1. The user is able to choose between two different functions depending on the needs of the analysis. A Fermi-Dirac fit in the rising edge of the distribution accounts for more precise timing measurement while a Landau convoluted with a Gaussian function over the full range of the distribution provides accurate reconstruction of the maximum charge. Both options can be enabled/disabled by the user from the configuration file and the parameters calculated for each function are saved in separate variables.

One additional filter utilizes the Fast Fourier Transform (FFT) of the integrated charge distribution to distinguish between signals coming from real ionization charges and noise. The filter calculates the FFT of the integrated charge distribution for each strip and compares it with the maximum harmonic value that is expected for charge induced by actual ionization. If the FFT harmonic exceeds this value, the strip charge is considered noise and the strip data are discarded.

Strip Clustering

One of the main and most crucial functionalities of the RecoMM processing is the clustering of the raw data. A cluster is defined as the ensemble of strips that are associated with a single particle track traversing a single chamber. Depending on the angle of the track and the design and operational parameters of the chamber different clustering algorithms can be applied. RecoMM utilises two different clustering techniques that can be enabled/disabled and configured from the configuration file.

- Topological clustering using only the strip address.
Table G.2: Recomm clustering options

<table>
<thead>
<tr>
<th></th>
<th>Type</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td># of gaps</td>
<td>int</td>
<td># of gaps allowed between consecutive strips</td>
</tr>
<tr>
<td>min cluster charge</td>
<td>integer</td>
<td>minimum cluster charge</td>
</tr>
<tr>
<td>min # of strips</td>
<td>integer</td>
<td>minimum # of strips per cluster</td>
</tr>
<tr>
<td>max # of strips</td>
<td>integer</td>
<td>maximum # of strips per cluster</td>
</tr>
<tr>
<td>max time bin gap</td>
<td>integer</td>
<td>maximum time difference between cluster strips</td>
</tr>
</tbody>
</table>

- Two dimensional clustering combining strip address and time information (Hough transform).

The experience has shown that both methods give accurate results with the accuracy of each method depending on the angle of the particle track with respect to the chamber plane. The performance of the topological clustering decreases with increasing the incident track angle, as the possibility of having gaps between consecutive fired strips becomes larger. Moreover, the ionization charge induced by each track is spread along several strips decreasing the accuracy of the charge interpolation method. The performance of the two dimensional clustering on the other hand is limited by the accuracy of the timing measurement which deteriorates with decreasing the size of the track footprint (Sec. 4.3.1). For these reasons the user may choose to employ both methods or one of the two for the definition of clusters by tweaking the corresponding options in the configuration file.

**Topological clustering**

The topological clustering algorithm searches for consecutive strips with signal above threshold per event to define a cluster. Several parameters govern the cluster definition and are tunable in the configuration file of the RecoMM software. These are listed in Table G.2.

For each cluster that is reconstructed, the position of the cluster (hit) is calculated using the individual strip address and charge information. Several definitions of the cluster position are implemented inside RecoMM that include the geometrical center of the cluster, average of the strips addresses, as well as the weighted average of the strip addresses with their charges (Centroid).

**Two dimensional clustering**

In the case of tracks traversing the chambers under an angle the timing information can also be used in the clustering. By transforming the measured drift time of each strip to distance the track footprint can be reconstructed in a single chamber. However, in the case where the real track footprint is contaminated by noise and/or delta rays or in multiple track events actual clusters need to be filtered out from the raw data.

For this purpose a pattern recognition filter based on the Hough transform, described in Sec. 5.3, has been implemented that distinguishes the actual track from noise and secondary clusters. A set of parameters defines the Hough space limits and the number of iterations used by the filter and are configurable in the configuration file.
Chamber alignment

In the case where the experimental set-up consists of several detection layers the track segment can be reconstructed per event by combining the hit positions in the different detection layers. For this purpose the detectors are first aligned using the distribution of the hit position difference between two layers. The alignment step follows the clusterisation process and calculates the alignment offsets for the different chambers of the set-up that are then used to correct the calculated hit positions in an event-by-event basis.

Synchronization and merging with BAT data

For the needs of the ATLAS NSW MM collaboration test beam activities that took place at CERN an external tracking system based on Silicon detectors (BAT) has been used to provide a precise reference track for the testing of the detectors (Appendix B). The BAT system uses a completely independent DAQ system than the MM set-up and in order to combine the two different data streams a merging process has been implemented inside recomm that can be enabled/disabled from the central configuration file. Apart from the merging of the two data-sets the merging process takes care of the event synchronization in case one of the two systems gets out of synch [4].

A versatile self-configurable online monitoring tool for test beams

Owing to the new VMM electronics, the first version of which was released in the 2012, a need for a new Data Acquisition (DAQ) system arose. In parallel to the DAQ developments that were initiated at that time a new graphical user interface tool was developed that should be able to complement the core DAQ, serving as online monitoring and run control interface between the user and the DAQ running in the background.

The mmddf_mon has been designed in such a way that is completely decoupled and independent from the DAQ. The tool source code is based on Qt4 [5] components enhanced with ROOT [2] libraries for the graphical representation of the data through histograms. A shared memory serves as the communication interface between the DAQ and the mmddf_mon in a bidirectional manner. There are two streams of information that are transmitted through the memory path

- The data stream that propagates the readout electronics information from the DAQ to the monitoring.
- The control stream that is fed by commands generated by the mddf_mon interface to configure and control the DAQ server.

The data and the commands are transferred through the shared memory in string messages of a predefined format that is adopted by both ends.

Configuration

The start-up window of the mmddf_mon application, that is shown in Fig. G.1 requires the selection of a valid configuration file that is used to adopt and configure the application according
to the experimental set-up that is used. In fact, the configuration does not depend only on a single file but it is rather realised using a tree structure of .xml files that describe the detector set-up, the front-end electronics and the readout chain. For the first application and testing of the software the mmddf_mon was chained to the DAQ that was developed for the test beams of the Atlas MM community (mmDAQ [3]). The mmDAQ configuration is implemented through the same files that are used in the monitoring configuration. Owing to this fact, upon loading the main configuration file in the start-up window of the mmddf_mon application, the system path of the file is sent to the DAQ server together with a configuration command via the shared memory. In this way both the DAQ server and the monitoring are configured almost simultaneously using the same configuration ensuring the integrity of the communication between the two ends of the shared memory link.

![Figure G.1:](image)

Figure G.1: Left: The start-up window of the mmddf_mon. Using the "Select Config" button the user can navigate to the location of the main configuration file. The file is then loaded and its full path is sent to the DAQ server for its configuration. Right: The configuration can also be changed at a latter stage using the "Settings" panel. Apart from the configuration option the pedestal and zero suppression can be adjusted via the "Settings" menu.

The structure of the configuration files chain is represented graphically in Fig. G.2. In the main file, called "server-config", the files that define the configuration of the readout electronics, the detector set-up and the chambers’ geometry are declared. Moreover, some system parameters are defined for dedicated use by the DAQ server. The readout configuration file describes the readout chain consisting of front-end cards (FECs) and ASIC chips. In the current architecture that is envisaged one or more chips are associated with one FEC which provides the interface between the on-chamber connector and the DAQ PC.

The detector set-up is described in the detector and chamber configuration files that are defined in the main file. The detector represents the experimental set-up of a test beam that is composed by a set of chambers. The position, orientation along with the drift gap size and HV settings of each chamber of the set-up are also defined in the detector configuration file along with the "chamber-config" file. At the lowest level of the detector configuration the connectors of each chamber that are occupied are declared and mapped to the corresponding front-end cards. One crucial point is the definition of a file that maps the connector pins to the chip’s channels for each single connector. In the small MM chambers that were used during the monitoring software tests the front-end cards were plugged on the chambers through Panasonic connectors[6]. These connectors are characterized by a non-linear correlation between the numbering of the chip channels and pins of the connector which is described by the mapping file. The structural and geometrical characteristics of each chamber are declared in the "chamber-config" file. This includes the multi-layers, layers and readout planes that the chamber is composed of along with the position and rotation information of each chamber element. Moreover, the connectors that are mapped to front-end cards in the detector-config file are declared.
**Figure G.2:** A graphical representation of the configuration chain that is used by the mmddf_mon and the mmDAQ software of the ATLAS Micromegas community.

In the same file. The connectors are being assigned names, for their unique identification, and mapping files for the description of the correspondence between the connector’s pins and the chamber’s readout elements.

**Run control**

The running DAQ application may also be controlled by the mmddf_mon. Using the graphical interface of the monitoring software the user is able to start or stop the acquisition cycle of the server and is also able to switch between different types of runs (Physics/Pedestals). According to the purpose of the run, monitoring or data taking, the saving of the data in an ntuple can also be enabled or disabled through the dedicated tick button.

When the need for a change in the experimental set-up or conditions arises the mmddf_mon and the DAQ server can be reconfigured by re-loading the configuration files from the “Settings” menu in a similar manner with the start-up configuration. In the case where the DAQ server application features also an online pedestal (baseline) subtraction and zero suppression on the raw data, like in the case of the mmdaq, the related essential parameters can also be configured from the “Settings” menu. These include the declaration of the pedestal file that will be used accompanied by the definition of a zero-suppression factor that controls the scale of the zero-suppression (the larger the factor is the more strict the zero suppression).
Monitoring

The main function of the mmdf_mon is the online monitoring of the data that are acquired and published by the DAQ server. An instance of the graphical user interface’s main window is shown in Fig. G.3. The right section of the window is dedicated to the graphical representation of the data while the left part allows for interaction of the user with the monitoring and the DAQ. The enabling/disabling of the monitoring for one or more chambers is performed from the selection list. This list is automatically created during the configuration procedure while in parallel histograms are created and assigned to the readout elements of the experimental set-up. The bottom left part of the main panel is dedicated to the run control functionality of the software. The user may start/stop a run and configure the data taking procedure of the DAQ according to the nature of the new run by selecting between Physics or Pedestal. The saving of the data into ROOT ntuples can also be enabled/disabled from this section of the panel.

![Screenshot of the mmdf_mon main window. The graphical tab that is visible serves as an event display for all the readout layers of the set-up.](image)

**Figure G.3:** Screenshot of the mmdf_mon main window. The graphical tab that is visible serves as an event display for all the readout layers of the set-up.

In the event display illustrated in Fig. G.3 the trace of a charged particle traversing the four Tmm type MM chambers is visible. During this test only one front-end readout card per chamber was physically attached to a connector. For all the chambers, the middle connector of the readout layer with strips perpendicular to the resistive strips was attached to a readout hybrid front-end card. Thus, only half of the histograms are populated corresponding to the readout layers that were connected to the readout chain.
There are several monitoring tabs that the user can choose from according to his needs which among others include the statistics histograms that hold cumulative information for the full statistics of the run. Moreover, additional information related to the DAQ cycle, such as the run and the current event number are also displayed in the lowest part of the panel.

**Software adaptability**

The main advantage of the mmddf_mon application is the fact that it is a completely separate process from the DAQ server. Owing to this the data taking and storing process cannot be affected by any possible problem or crash of the monitoring processes. Moreover, it works directly out of the box as soon as the required shared memory segment is created and updated with the information of the right format. As far as the configuration is concerned the monitoring software is completely independent but it may be used for the configuration of the DAQ server as well if this is adopted to the same configuration protocol.
Bibliography


