



SAPIENZA
UNIVERSITÀ DI ROMA

Study of the MicroMegas chambers performance for the upgrade of the ATLAS experiment at LHC

Facoltà di Scienze Matematiche, Fisiche e Naturali
Corso di Laurea Magistrale in Fisica

Candidate

Luca Martinelli

ID number 1479755

Thesis Advisor

Prof. Cesare Bini

Academic Year 2016/2017



**Study of the MicroMegas chambers performance for the upgrade of the ATLAS
experiment at LHC**

Master thesis. Sapienza – University of Rome

© 2017 Luca Martinelli. All rights reserved

This thesis has been typeset by L^AT_EX and the Sapthesis class.

Author's email: luca.martinelli@roma1.infn.it

Contents

Introduction	v
Introduzione	vii
1 LHC and ATLAS experiment	1
1.1 The Large Hadron Collider (LHC)	1
1.1.1 Main results	3
1.1.2 LHC future programme	4
1.2 ATLAS	5
1.2.1 The ATLAS requirements	7
1.2.2 The magnetic system	8
1.2.3 Inner tracker	11
1.2.4 Electromagnetic calorimeter	12
1.2.5 Hadronic calorimeter	12
1.2.6 Muon chambers	13
1.2.7 The trigger system	22
1.3 ATLAS upgrade	24
2 The New Small Wheel (NSW) Project	25
2.1 Present Small wheel layout	25
2.2 Limitations of the present Small Wheel	25
2.3 Upgrade requests	27
2.4 NSW Layout	29
2.5 small Thin Gap Chambers (sTGC)	32
3 The MicroMegas chambers	35
3.1 The MicroMegas technology	35
3.2 Detector gain	36
3.3 Spark-protected MicroMegas	37
3.4 MicroMegas in the New Small Wheel	38
3.4.1 MicroMegas layout in the New Small Wheel	39
3.5 Single strip response and track reconstruction	41
3.5.1 Methods for reconstructing the position	42
3.5.2 Performance inside a magnetic field	46

4	Production quality control and construcion	49
4.1	Drift Panel structure	49
4.2	Components QA/QC measurements	53
4.2.1	Frames	53
4.2.2	PCB	55
4.2.3	Interconnections set 1 (built in South Africa)	57
4.2.4	Interconnections set 2 (built in MBC Company)	59
4.2.5	Honeycomb	62
4.3	Drift Panel construction	64
4.4	Drift panels QA/QC	68
4.4.1	Planarity measurements	68
4.4.2	Drift panel thickness	77
4.4.3	HV test	77
4.4.4	Conclusions	78
5	Cosmic Ray Stand @LNF	79
5.1	Tmm chambers	81
5.1.1	Tmm event display	84
5.1.2	Basic raw distributions	84
5.1.3	Event selection	89
5.1.4	Tmm hardware Efficiency and Electronic Efficiency	89
5.2	Analysis of the Module 0 the cosmic rays	90
5.2.1	Basic raw SM1 Mod.0 distributions (run 275 - run 280)	93
5.2.2	Module 0 event display	96
5.2.3	Hardware efficiency	97
5.2.4	Software efficiency	99
5.2.5	Resolution studies	102
6	First results from SM2 test beam	109
6.1	Experimental setup	109
6.2	Beam profile	110
6.3	Event selection	110
6.4	Basic raw SM2 Mod.0 distributions (P16)	111
6.5	Preliminary data analysis	116
6.5.1	Uniformity response studies	116
6.5.2	Resolution of eta layers	117
6.6	Resolution stereo layers	120
	Conclusions	123
	Conclusioni	125
	Bibliography	125

Introduction

The Large Hadron Collider (LHC), located at CERN (Conseil Européen pour la Recherche Nucléaire), is the biggest (circumference of 27 km) and most powerful (the energy of the center of mass is equal to $\sqrt{s} = 14\text{ TeV}$) particle accelerator that can accelerate protons and heavy ions.

LHC started to work in 2009 and during its first run (with a $\sqrt{s} = 7 \div 8\text{ TeV}$ center of mass energy and with a peak luminosity of $\mathcal{L} = 6 \cdot 10^{33}\text{ cm}^{-2}\text{s}^{-1}$), which ended at the end of 2012, reached one of the most important discoveries of particle physics: the Higgs boson with the properties predicted by the Standard Model.

After the end of the first long shut-down (LS1), during the two-year period 2013-2014, the energy of the CERN LHC collider was increased to the value of $\sqrt{s} = 13\text{ TeV}$ with a luminosity greater than the nominal value ($10^{34}\text{ cm}^{-2}\text{s}^{-1}$). To further extend its discovery potential, LHC will need a substantial upgrade in luminosity that will be done in two steps: a first step during the LS2 shut-down scheduled in 2019-2020 and a second step during the LS3 shut-down scheduled in the years 2024-2026. The project is called High Luminosity LHC (HL-LHC). This will provide an increase of the instantaneous luminosity of a factor of $5 \div 7$ compared to the project value and the integrated luminosity of a factor of 10. The higher available statistic makes it possible to measure precision properties of the Higgs boson and to increase the chance to observe possible signals of physics beyond the Standard Model at the TeV scale.

To support this LHC luminosity increase, an upgrade project was also scheduled for the ATLAS experiment in order to maintain its current excellent performance.

This involves in particular an upgrade of the muon spectrometer and, more specifically, the replacement of the present innermost stations of the forward muon spectrometer (the Small Wheel) with two completely new station (the New Small Wheel) that must be able to work with a high particle rate, a direct consequence of the luminosity increase, maintaining (and possibly improving) its actual characteristics in terms of resolution ($\sigma_x \simeq 100\text{ }\mu\text{m}$ for each detector plane) and its efficiency ($\varepsilon > 95\%$).

The New Small Wheel will be installed in the ATLAS experiment during the LS2 so that the construction of the detectors is starting already now.

The New Small Wheels will consist of two types of detectors:

- small-strip Thin Gap Chambers (sTGCs) that have the primary task of adding information to the first level trigger;
- MicroMegas (MM) dedicated to precision measurements of the forward muon tracking.

INFN participates at the construction of 32 MM chambers. In particular the ATLAS Roma1 group is committed in the construction of the drift panels, one of the pieces of the MM Q-plets (called SM1 Q-plet).

The plan of this master thesis is the following.

In chapter 1 the LHC accelerator system and the ATLAS detector are described. Particular attention is posed on the description of the ATLAS Muon Spectrometer.

In chapter 2 it is explained why ATLAS needs an upgrade to maintain its high performance in the Small Wheel regions, and in chapter 3 the working principle and the main properties of the MicroMegas chambers are described in more detail.

Chapters 4 to 6 describe the original work done during the master thesis.

Chapter 4 is dedicated to the quality control tests that have been carried out on the various elements that are and will be used for the construction of drift panels in the INFN section of Roma1.

The built drift panels were also subjected to further checks on their thickness planarity and HV behaviour needed for the integration in the experiment and for their correct operation in the MicroMegas chambers.

Chapter 5 is dedicated to the study of the operation of the first SM1 prototype located on the Cosmic Ray Stand at INFN's National Laboratories in Frascati, obtaining the hardware efficiency, the software clustering efficiency along a coordinate and characterizing the spatial resolution of the eta layer. In addition, the 2D efficiency maps of each SM1 layer have been obtained by extrapolating the expected particle hit position using two external MicroMegas (Tmm) chambers.

Finally, chapter 6 describes the test beam done at CERN during August where it was possible to study the behaviour of the first SM2 MicroMegas prototype on the muon/pion beam of the CERN SPS obtaining the resolution of the two eta and stereo layers.

Introduzione

Il Large Hadron Collider (LHC), situato presso il CERN (Conseil Européen pour la Recherche Nucléaire), è l'acceleratore di particelle più grande (27 km di circonferenza) e più potente (l'energia di progetto del centro di massa è pari a $\sqrt{s} = 14 \text{ TeV}$) in grado di accelerare protoni e ioni pesanti.

LHC ha iniziato a lavorare a regime nel 2009 e durante il primo run (con un'energia del centro di massa $\sqrt{s} = 7 \div 8 \text{ TeV}$ con una luminosità di picco di $\mathcal{L} = 6 \cdot 10^{33} \text{ cm}^{-2}\text{s}^{-1}$), che si è concluso alla fine del 2012, ha raggiunto uno dei risultati più importanti della fisica delle particelle: la scoperta del bosone di Higgs previsto dal Modello Standard.

Dopo la fine del primo lungo shutdown (LS1), durante il biennio 2013-2014, l'energia del collider LHC del CERN è stata aumentata fino al valore di $\sqrt{s} = 13 \text{ TeV}$ con una luminosità superiore a quella nominale ($10^{34} \text{ cm}^{-2}\text{s}^{-1}$). Per estendere ulteriormente il suo potenziale di scoperta, LHC avrà bisogno di un sostanziale upgrade della luminosità che sarà effettuato in due fasi: un primo step durante lo shutdown LS2 programmato per il 2019-2020 e un secondo step durante lo shutdown LS3 previsto negli anni 2042-2026. Il progetto è chiamato High Luminosity LHC (HL-LHC). Questo prevede un aumento della sua luminosità istantanea di un fattore $5 \div 7$ rispetto a quella di progetto e della sua luminosità integrata di un fattore 10. La maggiore statistica a disposizione renderà possibile misure di precisione delle proprietà del bosone di Higgs e aumenterà la possibilità di osservare possibili segnali di fisica beyond Standard Model alla scala del TeV .

Per sostenere questo aumento di luminosità di LHC, mantenendo le sue attuali eccellenti prestazioni, anche per l'esperimento ATLAS è stato programmato un progetto di upgrade.

Questo coinvolge, in particolare, il progetto dello spettrometro a muoni e, più in particolare, la sostituzione della prima stazione dell'end-cap dello spettrometro a muoni (la Small Wheel) con due stazioni completamente nuove (la New Small Wheel) che dovranno essere in grado di lavorare con un'alta rate di particelle, conseguenza diretta dell'aumento di luminosità, mantenendo (e possibilmente migliorando) le prestazioni attuali in termini di risoluzione ($\sigma_x \simeq 100 \mu\text{m}$ per ogni piano di rivelatore) e di efficienza ($\varepsilon > 95\%$).

La New Small Wheel sarà installata nell'esperimento ATLAS durante il periodo del LS2 pertanto la costruzione dei rivelatori è già iniziata.

La New Small Wheel consiste in due tipologie di camere:

- small-strip Thin Gap Chambers (sTGC) che hanno il compito principale di aggiungere informazioni al trigger di primo livello;

- MicroMegas (MM) dedicate alle misure di precisione per il tracciamento di muoni in avanti.

L'INFN partecipa alla costruzione delle 32 camere MM. In particolare, il gruppo ATLAS di Roma è coinvolto nella costruzione dei pannelli di drift, uno dei pezzi dei quadrupletti MicroMegas.

La struttura di questa tesi magistrale è la seguente.

Nel capitolo 1 è stato descritto il sistema di acceleratori di LHC insieme all'esperimento ATLAS. È stata posta una particolare attenzione sulla descrizione dello spettrometro a muoni di ATLAS.

Nel capitolo 2 sono spiegati i motivi per cui ATLAS necessita di un upgrade per mantenere le sue ottime prestazioni anche ad alto rate nella regione della Small Wheel e, nel capitolo 3 sono descritte più nel dettaglio il funzionamento e le principali caratteristiche delle camere MicroMegas.

I capitoli da 4 a 6 descrivono il lavoro originale svolto durante questa tesi di laurea.

Capitolo 4 è dedicato alla spiegazione di tutti i test di quality control che sono stati effettuati sui vari elementi che sono e saranno usati per la costruzione dei pannelli di drift dal gruppo di Roma¹ dell'INFN.

I pannelli di drift costruiti inoltre sono stati sottoposti ad ulteriori controlli (spessore, planarità e correnti parassite) necessari per la corretta integrazione all'interno dell'esperimento e per il loro corretto funzionamento all'interno delle camere MicroMegas.

Il capitolo 5 è dedicato allo studio del funzionamento del primo prototipo di SM1 montato sul Cosmic Ray Stand ai Laboratori Nazionali di Frascati dell'INFN ricavandone l'efficienza hardware, l'efficienza di clustering del software lungo una coordinata, caratterizzando la risoluzione spaziale dei layer eta. In più sono state disegnate le mappe 2D delle efficienze di ogni singolo piano del Modulo 0 attraverso l'estrapolazione dell'hit aspettato tramite l'uso di due camerette MicroMegas (Tmm) esterne.

Infine, il capitolo 6 descrive il test beam svoltosi al CERN durante il mese di Agosto dove si è potuto studiare il comportamento del primo prototipo di camera MicroMegas di SM2 sul fascio di muoni/pioni dell'SPS del CERN ottenendo la risoluzione dei due layer eta e dei layer stereo.

Chapter 1

LHC and ATLAS experiment

1.1 The Large Hadron Collider (LHC)

The Large Hadron Collider [1] is presently the biggest and the most powerful particle accelerator in the world. It is located at CERN (Conseil Européen pour la Recherche Nucléaire) on the French-Swiss border close to Geneva and it works since 2009. The LHC was built in order to investigate the fundamental structure of matter and to search for new particles or phenomena at unprecedentedly high energy scales.

It is a 26.7 *km* circumference ring located 100 *m* below the surface consisting of superconducting magnets (cooled to 2°*K*) and radio-frequency cavities necessary to bend and accelerate the particles during their path.

The LHC was designed to collide either protons or heavy-ions which are circulating in opposite directions in two different beam pipes at high energy and frequency.

The beams are allowed to collide in four interaction points called IP1 - IP8, where the main experiments are located. ATLAS [2], an acronym for “A Toroidal LHC ApparatuS” is located in IP1. In IP2 there is ALICE [4] (A Large Ion Collider Experiment), then there is CMS [3] (Compact Muon Solenoid) which can be seen as the complementary partner to ATLAS at IP5, and LHCb [5] which stands for “LHC beauty” in IP8. ATLAS and CMS are multi-purpose detectors, designed to discover the Higgs boson and to explore the high energy scale; LHCb was designed for physics measurements concerning the b-quark sector, especially focusing on CP violation while ALICE is intended to first directly prove the existence of and to further investigate quark-gluon plasma in heavy-ion collisions.

The main parameters of a particle accelerator are the center of mass energy and the instantaneous luminosity, which is defined as

$$\mathcal{L} = \frac{N_1 N_2 n_b f}{4\pi\sigma_1\sigma_2} \quad (1.1)$$

where n_b is the number of circulating bunches, N_1 and N_2 are the number of particles/bunch, f is the revolution frequency and σ_1 and σ_2 are the bunch transverse dimensions. The number of events for second R (*rate*) for a process that has a cross section σ is proportional to the instantaneous luminosity

$$R = \mathcal{L} \cdot \sigma \quad (1.2)$$

For this reason, an increasing luminosity is one of the goal of the LHC upgrade for the next years.

The design center of mass energy for pp collisions is 14 *TeV* (7 *TeV* per beam) but due to machine safety concerns, the LHC ran at a center of mass energy of 7 *TeV* and an instantaneous luminosity of $\mathcal{L} = 6 \cdot 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$ with a bunch crossing every 50 *ns* until the end of 2011 and at 8 *TeV* during the 2012 run. Since 2015, after the first Long Shut-down (LS1) the data from proton-proton collisions at $\sqrt{s} = 13 \text{ TeV}$ are taken with a maximum instantaneous luminosity of $1.37 \cdot 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ and an inter bunch of 25 *ns*.

The protons are not accelerated in the LHC alone but fly through a number of consecutive pre-accelerators which were mostly part of older CERN experiments and which were altered to serve LHC purposes. The principal steps with which the protons are injected in the LHC are schematised in Figure 1.1.

After the protons have been produced, they are accelerated by the LINAC 2 to 50 *MeV* and injected into the booster PS. The booster accelerates the protons until they reach an energy of 1.4 *GeV* and then it injects them into the Proton Synchrotron (PS) that brings them to 26 *GeV*. The last step before the main ring of the LHC is the Super Proton Synchrotron (SPS) that is able to accelerate the protons to 450 *GeV*. Finally, when the protons reach the LHC, the center of mass energy of 13 *TeV* is achieved, 6.5 *TeV* for each beam.

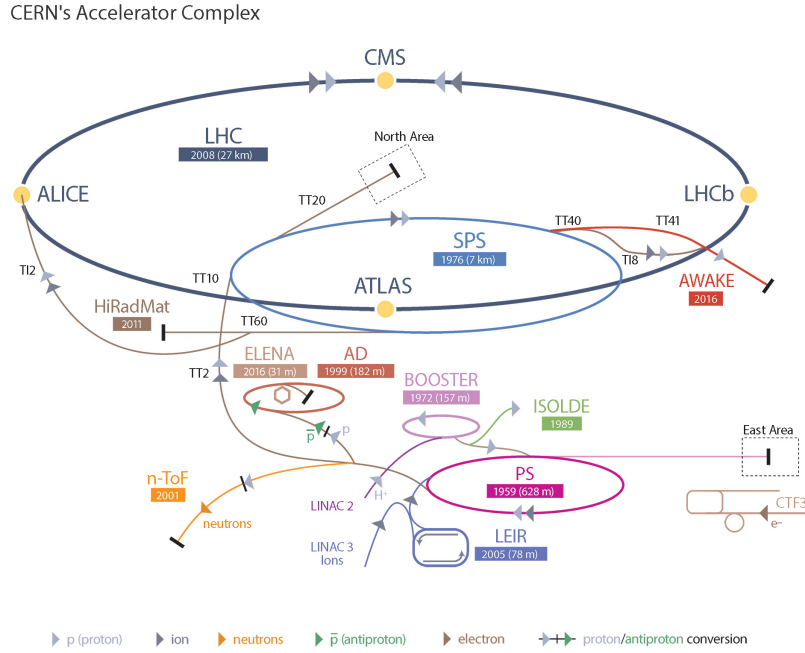


Figure 1.1. Schematic view of the LHC, its pre-accelerators and experiments. Until they reach their final energy of 6.5 *TeV* (in 2016 run conditions), the protons are successively boosted by different accelerators before being injected into the next sequential module. The protons, obtained by ionizing hydrogen atoms, start at the linear accelerator LINAC2 after which they are injected into the PS booster followed by the proton synchrotron (PS). After the PS, the protons are transferred to the super proton synchrotron before finally reaching the LHC ring.

1.1.1 Main results

The main result obtained by the LHC experiments between 2009 and 2016 was the discovery of the Higgs boson, which was announced by the ATLAS and CMS experiments on 4 July of 2012 [6].

The Figures 1.2 and 1.3 show the evidence of a new neutral boson with a mass of $m_H = 126.0 \pm 0.4(stat) \pm 0.4(sys) \text{ GeV}$ and a signal strength¹ of $\mu = 1.4 \pm 0.3$, which is compatible with the Standard Model Higgs.

With the data collected in the LHC Run I and II, no new evidence of Physics beyond the Standard Model (BSM) was observed and it was possible to set exclusion limits for different models of exotic and supersymmetric theories up to TeV scale.

Other interesting results come out from the heavy-ions physics analyzed by the ALICE experiment but also from the analysis of the data taken by the ATLAS and CMS experiments, such as the observation of the known process named “jet quenching” [7] in Pb-Pb collisions with a nucleon-nucleon center of mass energy of $\sqrt{s_{NN}} = 2.76 \text{ TeV}$, which is compatible with the formation of the Quark Gluon Plasma (QGP).

Another important result is the observation of an exotic structures in the $J/\psi p$ channel, that we refer to as pentaquark-charmonium states, in $\Lambda_b^0 \rightarrow J/\psi K^- p$ decays [8]. This resonance was announced by the LHCb collaboration on July 2015 with a significance of 9 standard deviation.

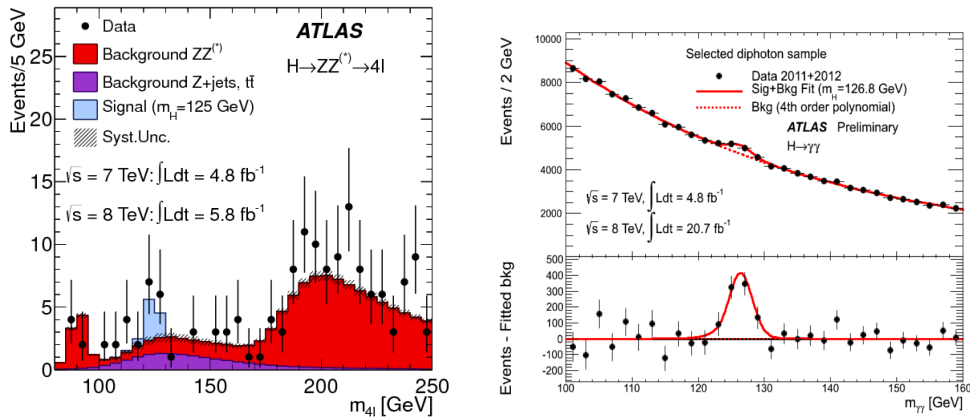


Figure 1.2. *Right:* 4 lepton channel invariant mass for the data of the p-p collisions at 7 – 8 TeV;
Left: $\gamma\gamma$ invariant mass for the data of the p-p collisions at 7 – 8 TeV;
 In this two plots is shown the presence of a new particle with a significance of about 6 standard deviations.

¹The signal strength is defined as $\mu = \frac{\sigma_{meas}}{\sigma_{theory}}$ and its value gives information about the theory analysed: $\mu = 1$ corresponds to the theory expectation while $\mu = 0$ corresponds to an absence of signal; any other value corresponds to a different rate for the theory.

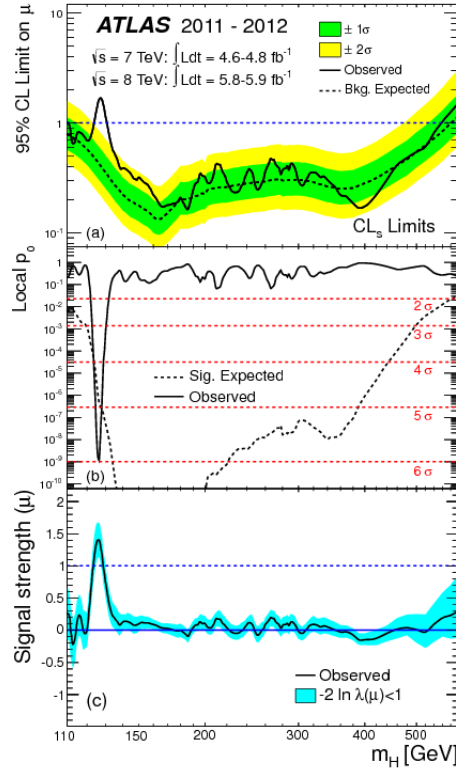


Figure 1.3. Up: ATLAS observed (solid line) 95% CL limits on the signal strength as a function of m_H and the expectation (dashed line) under the background-only hypothesis. The green (dark) and yellow (light) bands show the $\pm 1\sigma$ and $\pm 2\sigma$ uncertainties on the background-only expectation. The plot is obtained for the combined 7 TeV and 8 TeV datasets.

Middle: ATLAS observed local p -value (solid line) as a function of m_H in the low mass range. The dashed curve shows the expected local p_0 under the hypothesis of a SM Higgs boson signal at that mass with its $\pm 1\sigma$ band. The horizontal dashed lines indicate the p -values corresponding to significances of 1 to 6σ .

Down: signal strength ($\mu = \frac{\sigma_{measured}}{\sigma_{SM}}$) as a function of m_H . Where μ is < 1 a Standard Model Higgs boson production is excluded.

1.1.2 LHC future programme

In order to further increase its discovery potential around the mid-2020's (see Figure 1.4), LHC would eventually need an upgrade to increase the luminosity by a factor of 5-7. A more powerful LHC would provide more accurate measurements of new particles and enable observation of rare processes that occur below the current sensitivity level. This would make it possible to detect rare events not previously witnessed, and increase our understanding of the energy frontier. How this should be done is at the heart of the High Luminosity LHC project (HL-LHC) [9].

HL-LHC relies on a number of key innovative technologies, representing exceptional technological challenges, such as cutting-edge 13 Tesla superconducting magnets.

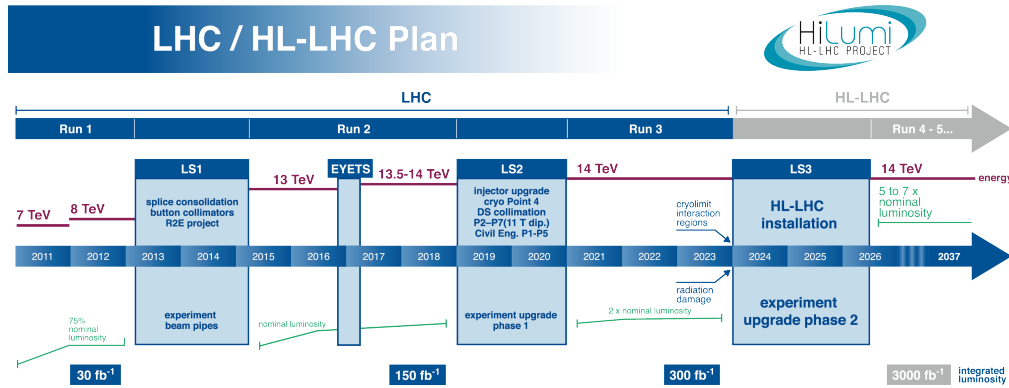


Figure 1.4. This is the LHC plan since 2011, when LHC started to work. Run II will ends in 2018 but already since Run III, an increase of a factor 2 of instantaneous luminosity is expected until a new increase to a factor 5-7 after HL-LHC installation.

1.2 ATLAS

ATLAS (Figure 1.5) is one of the four main particle detectors of the LHC collider. It is a cylindrical detector with layer structure, 44 m long with a diameter of 25 m and a weight of 7000 t, making it the largest particle detector ever built. Its structure is visible in Figure 1.5; the detector is divided into three regions: the main body that is called “*barrel*” and the two cylinder bases called “*end caps*”.

The muon spectrometer system will be described more accurately because it is the main topic of this thesis work.

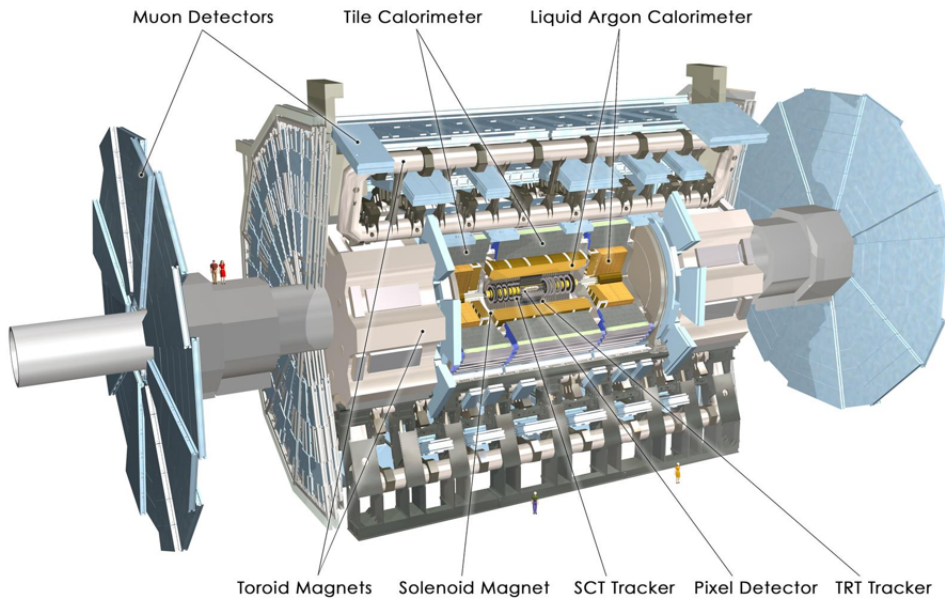


Figure 1.5. View of the ATLAS detector. The various sub-detectors that compose it are indicated.

The Figure 1.6 shows the Cartesian coordinate system adopted in the ATLAS detector.

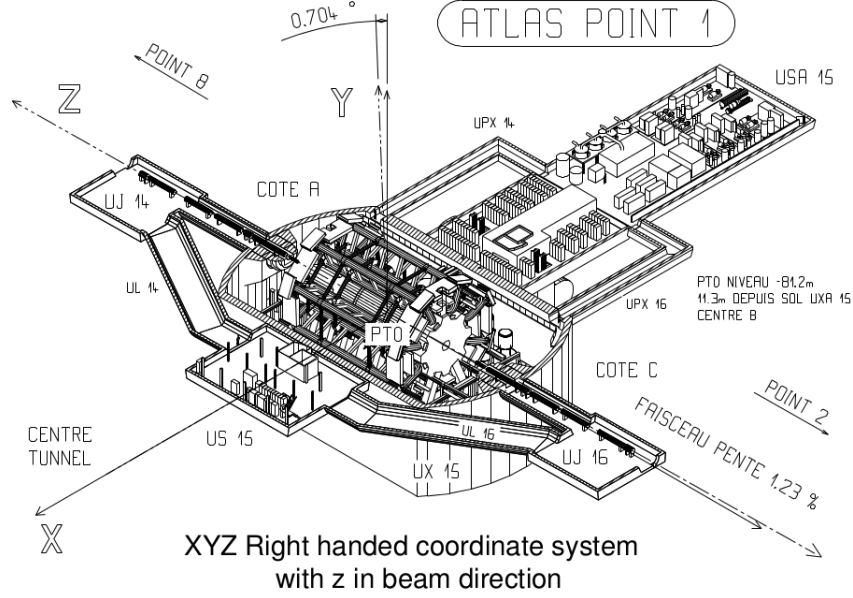


Figure 1.6. The z axis is defined long the LHC beam direction while the x axis towards the center of the LHC collision ring. The $x - z$ plane is inclined of 0.704° compared to the horizontal plane while the y axis is defined as pointing upwards, in the normal direction on the $x - z$ plane.

The nominal interaction point is defined as the origin of the coordinate system, while the beam direction defines the z axis and the $x - y$ plane is transverse to the beam direction. On the transverse plane $x - y$, the coordinate (r, ϕ) are used, where ϕ is the azimuthal angle around the z axis and r is the distance from the interaction point.

In alternative to use the polar angle θ , is usual to measured from the beam axis, the pseudorapidity which is defined as:

$$\eta = -\ln \tan \left(\frac{\theta}{2} \right) \quad (1.3)$$

This represents the limit for $m \rightarrow 0$ (with m mass of the particle) of the rapidity defined as:

$$y = -\frac{1}{2} \ln \left(\frac{E + p_z}{E - p_z} \right) \quad (1.4)$$

where p_z is the projection of the particle momentum along the beam axis; one can demonstrate that the rapidity gap Δy (or $\Delta \eta$ if the particles involved are massless) between two particles is a relativistic invariant.

In Figure 1.7 is shown the trend of the pseudorapidity with respect to the azimuthal angle from which it depends.

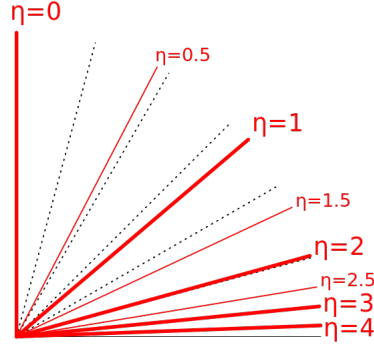


Figure 1.7. Trend of the pseudorapidity with respect to the azimuthal angle.

1.2.1 The ATLAS requirements

The ATLAS detector was designed primarily to discover or exclude the Higgs boson throughout the entire mass range allowed by the Standard Model on the various possible decay channels. The Higgs boson search foreseen by the Standard Model was therefore the benchmark for defining the performance required for ATLAS Experiment Detectors.

The best channels for its observation and the study of its properties are: in the $H \rightarrow ZZ^*$, where each of the two Z decays in a leptons pair giving rise to the $H \rightarrow ZZ^* \rightarrow l^+l^-l^+l^-$, and $H \rightarrow \gamma\gamma$.

For the observation of the Higgs boson, therefore, it was necessary to have a detector able to accurately measure charged leptons, photons but also jet and neutrinos, by missing transverse energy measurement, for the background rejection.

For this reason, the ATLAS detector was required to meet the following requirements:

- wide acceptance, close to the whole solid angle;
- great resolution for the momenta of charged particle and excellent efficiency reconstruction of tracks in the internal detector;
- hermetic calorimeters to measure missing transverse energy with a fine segmentation for the reconstruction of photons, electrons and jet;
- excellent ability to identify muons and measure their momenta in a range from a few hundred MeV s to the TeV order scale and to identify the charge of high p_T muons;
- quick trigger system, with high efficiency and good rejection of the background;
- fast and radiation resistant detector electronic read-out.

ATLAS is a multipurpose detector so, after the Higgs boson discovery, the actual goals of this detector is to measure the properties of this new particle for new Standard Mode tests but also to research new physics BSM like new massive bosons, SUSY and Dark Matter particles.

Table 1.1 shows the general performance of the various components of the ATLAS detector.

Detector component	Required resolution	η coverage	
		Measurements	Trigger
Tracking	$\sigma_{p_T}/p_T = 0.05\%/p_T \oplus 0.01\%$	± 2.5	
EM calorimetry	$\sigma_E/E = 10\%/\sqrt{E} \oplus 0.7\%$	± 3.2	± 2.5
Hadronic calorimetry (jets)			
barrel and end-cap	$\sigma_E/E = 50\%/\sqrt{E} \oplus 3\%$	± 3.2	± 3.2
forward	$\sigma_E/E = 100\%/\sqrt{E} \oplus 10\%$	$3.1 < \eta < 4.9$	$3.1 < \eta < 4.9$
Muon spectrometer	$\sigma_{p_T}/p_T = 10\%$ at $p_T = 1 \text{ TeV}$	± 2.7	± 2.4

Table 1.1. General performances of the various components of the ATLAS detector.

1.2.2 The magnetic system

The ATLAS magnet system [10] consists of three main parts:

- a central superconductive solenoid which is responsible for the axial magnetic field (2 T) of the inner tracker;
- the air-core barrel toroid;
- two air-cored end-cap toroids providing the necessary toroidal field configuration to the muon spectrometer forward regions.

The magnetic field peaks on the toroidal superconductors are 3.9 T and 4.1 T for the barrel and the end-caps and an average value of the field is approximately 0.5 T and 1 T, respectively.

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.

Photographs of the three different parts of the ATLAS magnet system are shown in Figure 1.8 while in Figure 1.9 is shown the spatial arrangement of the magnetic 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. Infact, a charged particle of charge q passing through a magnetic field $\vec{B}$ with velocity $\vec{v}$ is subject to the Lorentz Force $\vec{F}_L = q\vec{v} \times \vec{B}$ and performs an helix trajectory with a radius R on the orthogonal plane at $\vec{B}$. The formula that correlates transverse momentum to the magnetic field is:

$$p_{\perp} \text{ (GeV)} = 0.3 R(m) B(T) \quad (1.5)$$

The curvature radius and therefore the transverse momentum, can be determined by the measurement of the sagitta s (see Figure 1.10) of the track and is given, using geometrical considerations and approximating for small angles α , from the expression:

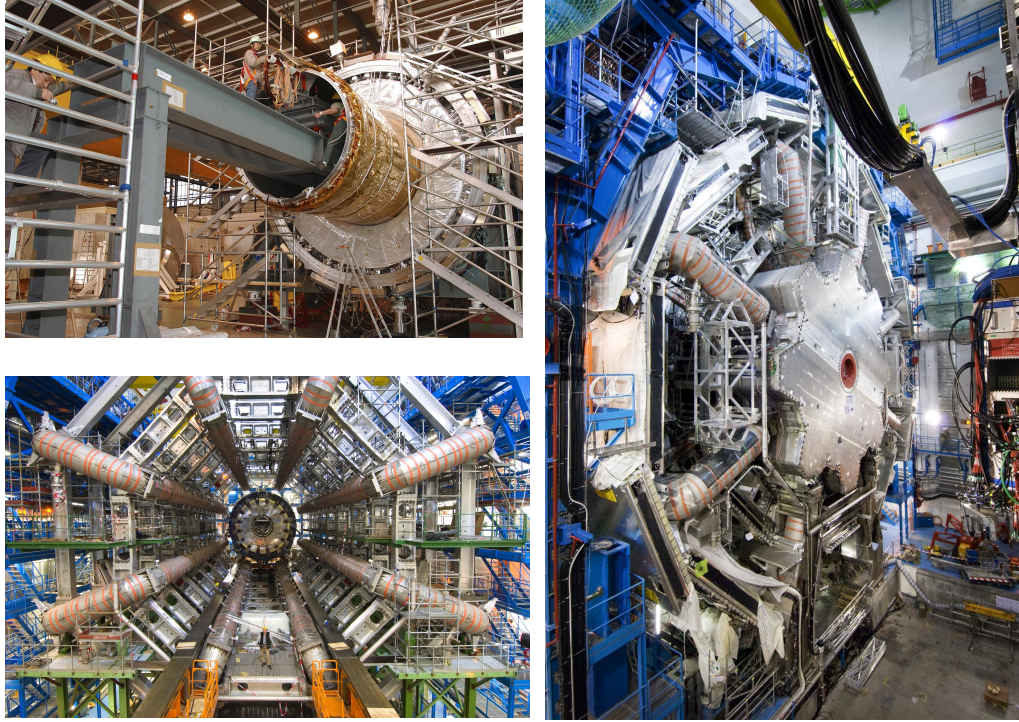


Figure 1.8. Photos of the different parts of the ATLAS magnet system during their assembly and installation in the ATLAS cavern.

Left: In the top picture, the cylindrical solenoid magnet is being inserted into the liquid argon calorimeter. 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.

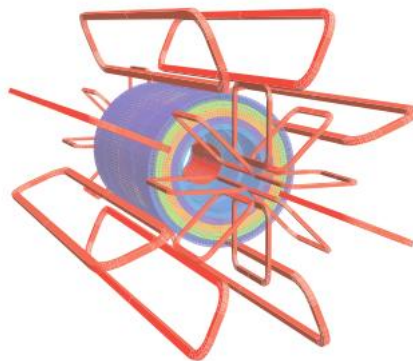


Figure 1.9. Spatial arrangement of the ATLAS magnetic system.

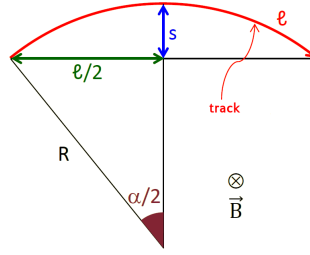


Figure 1.10. Geometrical definition of the sagitta.

$$s \cong \frac{1}{4} R \alpha^2 \quad (1.6)$$

and the expression:

$$l \cong R \cdot \alpha \quad (1.7)$$

From equation (1.6) and (1.7) the expression for the sagitta is obtained:

$$s \cong \frac{l^2}{8R} \quad (1.8)$$

Composing the equation (1.5) with (1.8), the formula for the measurement of the transverse momentum from the sagitta, given the magnetic field, is obtained:

$$p_{\perp} \text{ (GeV)} \cong 0.3 \text{ B(T)} \frac{l^2}{8s} \quad (1.9)$$

where the momentum uncertainty is related to the sagitta measurement precision.

Defining the curvature of the track as $k = \frac{1}{R} \cong 0.3 \cdot B \cdot \frac{1}{p}$ and estimating the associated uncertainty $\delta k \cong 0.3 \cdot B \cdot \frac{1}{p} \cdot \frac{\delta p}{p}$, the momentum resolution is obtain

$$\frac{\delta p_{\perp}}{p_{\perp}} \cong \frac{p_{\perp}}{0.3 \cdot B} \cdot \delta k \quad (1.10)$$

If s is measured with N equidistant points, each with an error σ_x (considering the phenomenological equation $\delta k \cong \frac{\sigma_x}{l^2} \sqrt{\frac{720}{N+4}}$) the momentum uncertainty is given by

$$\frac{\delta p_{\perp}}{p_{\perp}} \cong \frac{p_{\perp} \cdot \sigma_x}{0.3 \cdot B l^2} \sqrt{\frac{720}{N+4}} \quad (1.11)$$

In ATLAS, the z axis magnetic field (generated by the central solenoid) provides curvature of the track in the transverse plane x-y and thus allows to measure their transverse momenta. Indeed, the toroidal magnetic field (generated by the barrel/end-cap toroids) consists of circular field lines around the beams (z axis) and curves the particles in the z-y plane.

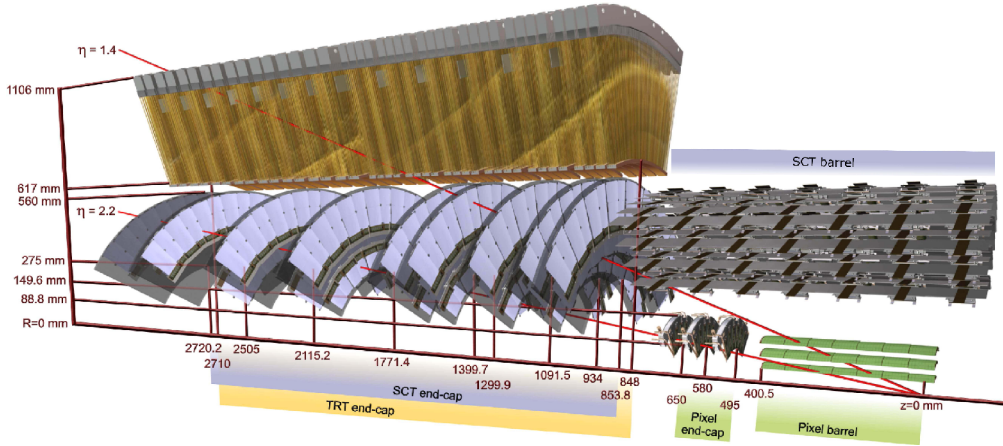


Figure 1.11. Graphical representation of the different parts composing the ID of the ATLAS experiment. The relative distances between the various elements are also noted.

1.2.3 Inner tracker

The ATLAS Inner Detector (ID) [11] is composed by 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 and 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 the 4 layer Pixel detectors followed by other 4 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. 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 Figure 1.11.

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. The intrinsic resolution of each pixel detector element, with a size of $50 \times 400 \mu\text{m}^2$, can be as good as $10 \mu\text{m}$ in the measurement of the precision coordinate ($115 \mu\text{m}$ for the perpendicular to the precision one). The slightly coarser ($80 \mu\text{m}$) SCT elements limit the SCT hit reconstruction uncertainty to $17 \mu\text{m}$ while the 4 mm diameter TRT straws provide a hit position measurement with a resolution of $130 \mu\text{m}$. 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.

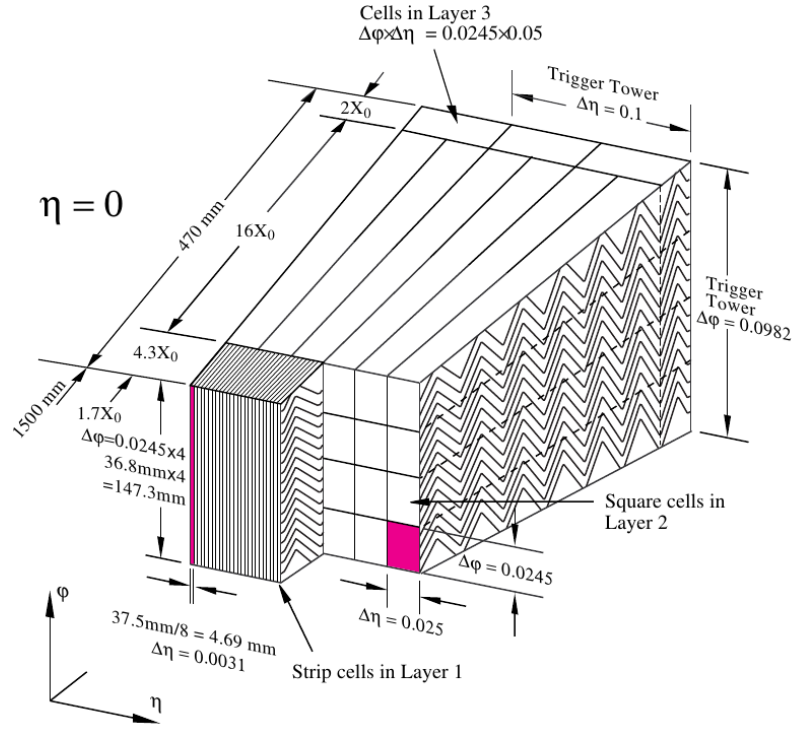


Figure 1.12. View of a barrel module of the LAr calorimeter showing cell segmentation and accordion structure.

1.2.4 Electromagnetic calorimeter

The ATLAS electromagnetic calorimeter [12] is divided into a barrel part ($|\eta| < 1.475$) and two end-cap components ($1.375 < |\eta| < 3.2$), each housed in their own cryostat.

It is a liquid Argon (LAr) detector with accordion-shaped kapton electrodes, and lead absorber plates over its full coverage. Its geometry provides a full coverage in ϕ . It is composed of two identical half cylinders in the barrel region and of two coaxial wheels in each end-cap region. Each module of both the barrel and end-cap calorimeters is characterized by three layers: the first layer is finely segmented in η to achieve an accurate position measurement, the second layer collects the largest fraction of the energy of the electromagnetic shower, and the third layer collects only the tail of the electromagnetic shower and is, therefore, less segmented in η . A schematic view of a barrel module is shown in Figure 1.12 where the different layers are clearly visible. The total active thickness is around 22 radiation lengths (X_0) in the barrel region and from 22 up to 38 X_0 in the end-cap regions.

1.2.5 Hadronic calorimeter

The ATLAS detector has an hadronic calorimeter [13] system consisting of three different types of calorimeters:

- **Tile Calorimeter:** it is a sampling calorimeter made up of steel and scintillators; it is positioned directly after the electromagnetic calorimeter and covers the

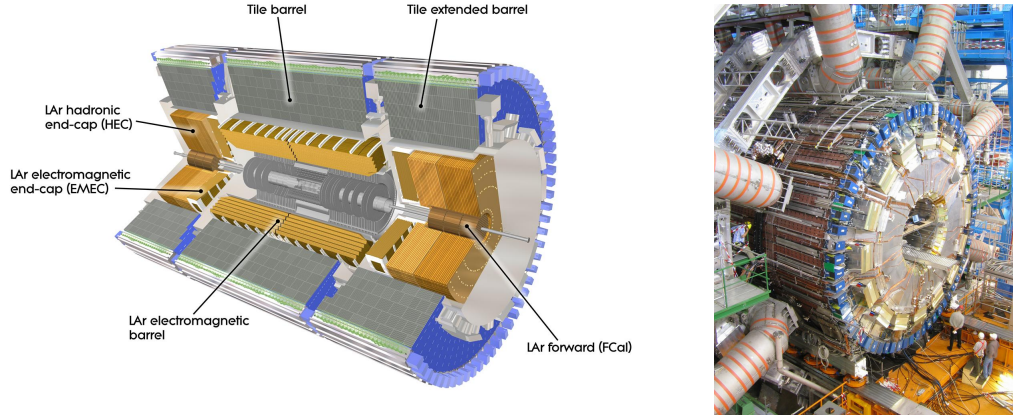


Figure 1.13. *Left:* A graphical representation of the ATLAS calorimeter section. The LAr and Tile parts are depicted along with their segmentation in barrel and end-cap calorimeters.

Right: Photograph of the barrel calorimeter inserted in the ATLAS detector. The end-cap toroid coils surrounding the calorimeter are visible. The main part of the calorimeter (Tile) is 8 m in diameter and covers 12 m along the beam axis.

region $|\eta| < 1$ in the barrel area while its extensions in the end-cap cover the region $0.8 < |\eta| < 1.7$;

- **LAr Hadronic End-cap Calorimeter (HEC):** it consists of copper planes interposed with a liquid Argon gap that constitutes the active material; it consists of two independent wheels for each end cap positioned immediately after the electromagnetic calorimeter with coverage in $|\eta|$ slightly overlapping the Tile calorimeter up to $|\eta| = 1.5$;
- **LAr Forward Calorimeter (FCal):** it is integrated into the end-cap cryostats to make its coverage homogeneous and to reduce the background to the muon spectrometer; it is about 10 lengths of interaction and consists of three modules, the first, with copper as absorber, to optimize the measurements of the electromagnetic fraction (f_{em}) and the other two, with tungsten, to measure the energy of the hadrons.

1.2.6 Muon chambers

The muon spectrometer [14] defines the overall dimensions of the ATLAS detector. It is located outside the calorimeter modules and covers the space between approximately 4.5 m and 11 m in radius and 7 m and 23 m longitudinally. It has the task of detecting charged particles out of the barrel and end-cap calorimeters and measuring their momenta and trajectories which are deflected in the magnetic field up to $|\eta| < 2.7$. It is also designed to trigger these particles in the region $|\eta| < 2.4$. The muon spectrometer structure is shown in Figure 1.14.

Destined to measure high-momentum final-state muons, among the most promising signatures of physics at the Large Hadron Collider, the ATLAS Muon Spec-

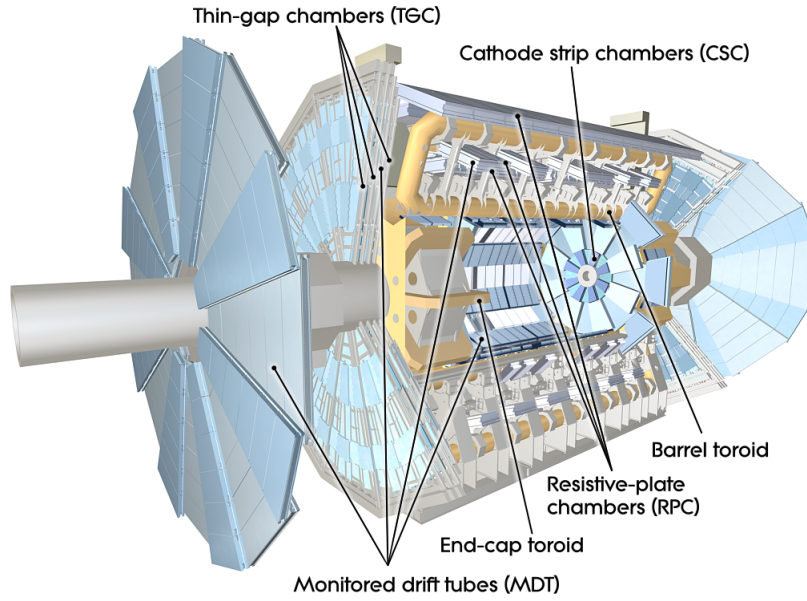


Figure 1.14. View of the ATLAS muon spectrometer.

trometer 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 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 with high accuracy.

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 bunch crossing 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 $5 - 20 \text{ mm}$ and they are also able to provide a measurement of the track along the so called second coordinate ϕ^2 .

²The so called *principal coordinate* (or first coordinate) is defined as the coordinate (or the plane) in which the particle is bent and therefore where it has the highest resolution. For example, in the internal ATLAS system (inner detector and calorimeters), the principal coordinate will be ϕ (there is an axial field) while in the muon spectrometer system, the first coordinate will be η (toroidal field).

The arrangement of the muon chambers is such that particles originating from the interaction point pass through three precision and three trigger detection layers. 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 1.15 shows a schematic representation of different sections of the ATLAS muon spectrometer.

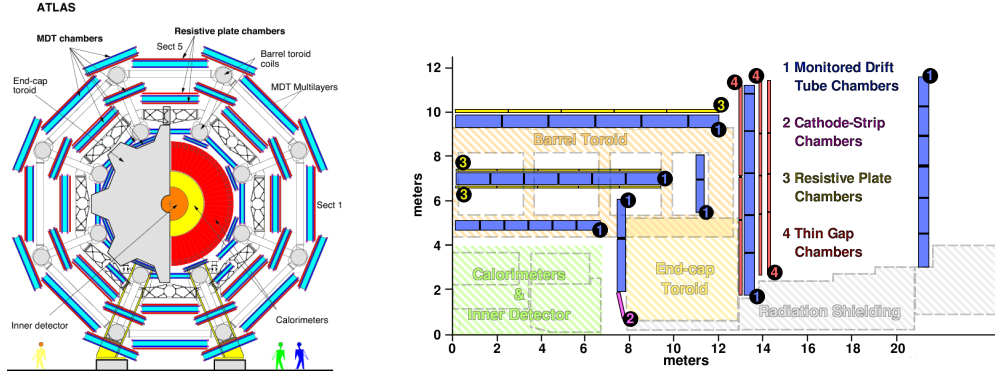


Figure 1.15. View of the ATLAS muon spectrometer components. The different layers of the four detector technologies composing the muon system are visible.

Left: Schematic view of the muon spectrometer in the x-y projection of the barrel region.

Right: A section in z-y of one quarter of the ATLAS detector for $\phi = \pi/2$ matching the position of large muon sectors.

As shown in Figure 1.15, in the end-caps, the chambers are perpendicular to the axis of the beams and positioned at increasing distances from the interaction point; they are called Small Wheel (SW), Big Wheel (BW) and Outer Wheel (OW) respectively. Only the SW is internal to the toroidal magnets and the other two are external; these three stations are used for measuring the momentum of the forward muons.

Monitored Drift Tubes (MDT)

The MDTs cover almost the full rapidity region of the ATLAS MS $|\eta| \leq 2.7$ apart from the high rapidity region of the SW where CSCs are used. The basic structure consists of two multi-layers of drift tubes separated by a support frame, as shown in Figure 1.16. 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.

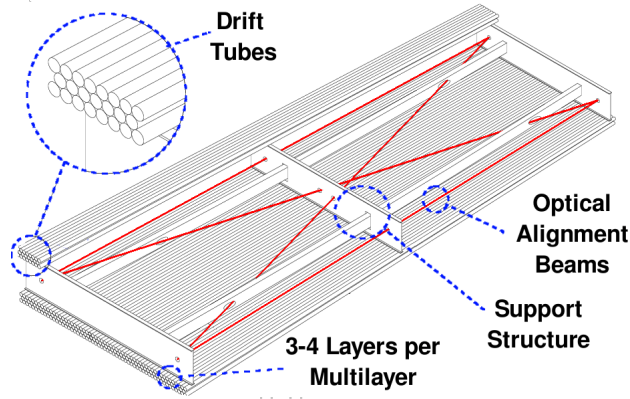


Figure 1.16. Support structure of the MDT chamber.

The elementary detection element of the ATLAS MDT chambers is a cylindrical aluminium drift tube, 30 *mm* in diameter, which encompasses a central cathode wire of 50 μm diameter kept at a nominal potential of 3080 *V*. The tubes are flushed with a non-flammable gas mixture $\text{Ar} + \text{CO}_2$ (93% – 7%) with a small amount of water vapour at a pressure of 3 *bar*.

The electric field inside the tube is proportional to the inverse of the wire distance so the electrons, produced by the ionization of the gas by the charged particle passing through it, drift towards the anode wire while the ions drift towards the cathode wall of the tube. Near the wire the field is sufficiently high to produce the avalanche multiplication of the electrons with a gain of $\sim 2 \cdot 10^4$. The signal is read on the anode wire. It is a negative signal due to the potential variation caused by the positive ions that move away from the wire.

The position of the track is determined by measuring the drift time and the use of the time space relation (*r-t* ratio) that allows the drift time to be tied to the distance from the wire. For each tube a radius of circle *r* is identified by the drift time and the track is reconstructed putting together the circles of different pipes (Figure 1.17) by making a linear fit that minimizes the residues.

The average resolution of the single tube is $\sigma_r \simeq 80 \mu\text{m}$ and the average resolution of a chamber, consisting of 3 + 3 or 4 + 4 layers of tubes, is $\sigma_r \simeq 50 \mu\text{m}$. The chambers are rectangular in the barrel and trapezoidal in the end caps. Their shapes and sizes have been chosen to optimize the solid angle coverage while simultaneously considering the magnet coils and support structures (Figure 1.16).

Cathode Strip Chambers (CSC)

The CSCs are located in the two innermost region of the end caps, the so called “Small Wheels (SW)”, covering the largest rapidity region $2 \leq |\eta| \leq 2.7$ ($\sim 7 \text{ m}$ from the interaction point) that is characterized by the highest particle flux among the muon spectrometer stations. They are operated with a gas mixture of $\text{Ar} + \text{CO}_2$ (80% – 20%) while the voltage is tuned individually per chamber layer ($\sim 1800 - 1900 \text{ V}$) in order to achieve uniform gain throughout the whole CSC system.

They are Multi-Wire Proportional Chambers with the wires serving as the detector anodes. The CSC host two cathode layers of read-out strips measuring the

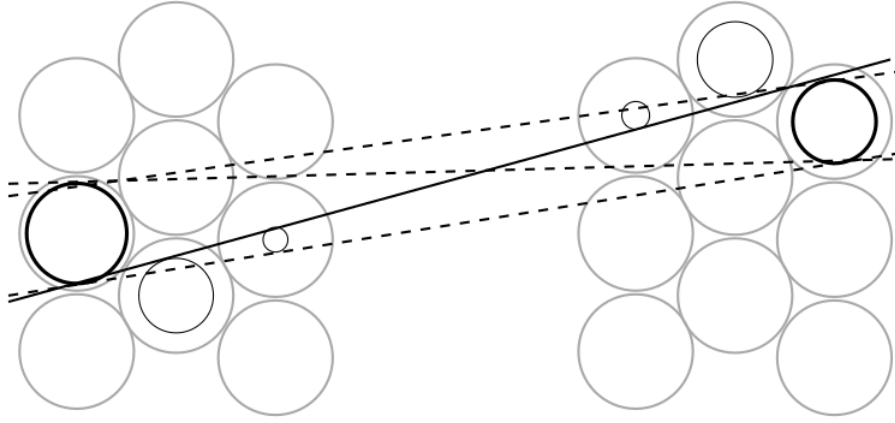


Figure 1.17. Reconstructed track with the MDTs; drift circle seeds with the four possible tangent lines are plotted and only the black line is the correct seed.

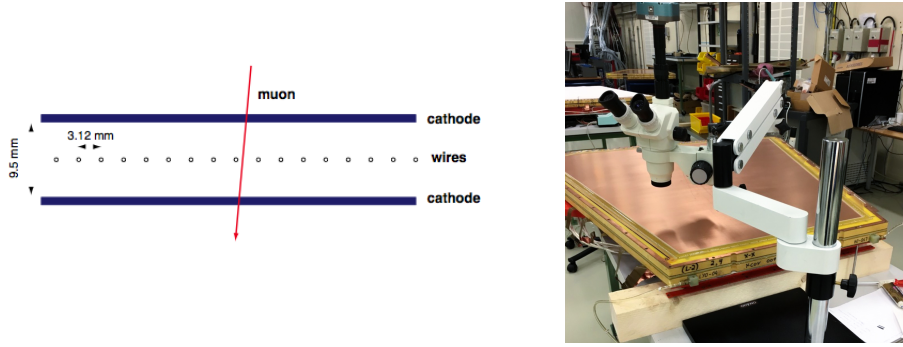


Figure 1.18. *Left:* Scheme of the Cathode Strip Chambers. *Right:* Photo of one CSC.

principal and the perpendicular to it (second) coordinates. The principal coordinate is obtained by a charge interpolation on the segmented cathode, with strips running perpendicularly with respect to the anodes ($\sigma_r \sim 60 \mu m$ for perpendicular tracks). A second layer of read-out 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 $30 ns$; this allows for efficient operation in the forward region (high background) of the muon spectrometer.

Resistive Plate Chambers (RPC)

The RPC is a parallel-plane gas detector consisting of two resistive planes, made of high resistivity plastic sheets, placed at a distance of $2 mm$ through insulating spacers. The electrical field between the planes is about $4.9 kV/mm$ and allows the formation of avalanches to the anode along the ionizing tracks. The signal is read by capacitive coupling on metal strips mounted on the outer face of the resistive plane. A RPC chamber is composed by two rectangular detectors called units (see Figure 1.19). Each unit is composed itself by two independent layers read out by two groups of orthogonal strip (η and ϕ).

The used gas is a mixture of $C_2H_2F_4$: $IsoC_4H_{10}$: SF_6 (94.7% 5% 0.3%)

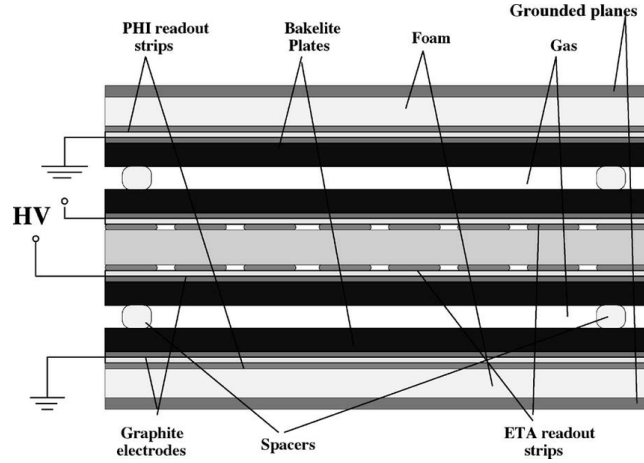


Figure 1.19. Scheme of the Resistive Plate Chambers.

which meets the demand for a relatively low working voltage, non-flammability and low cost.

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.

Moreover, being a fast detector technology the RPC are also characterized by bunch crossing identification capability. Additionally, their fast and coarse tracking can be used to identify the hits of the precision chambers that are related to the detected muon track.

Thin Gap Chambers (TGC)

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 (organized in one triplet and two doublet - see Figure 1.20 (down)), 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 read-out strips running perpendicularly to the wires. A graphical representation of a TGC chamber section is shown in Figure 1.20 (up) They are operated with a highly quenching gas mixture of $CO_2 + n - C_5H_{12}$ (55% and 45%) and a very intense electric field (3200 V) to satisfy the time, momentum, and azimuthal coordinate resolution requirements while making the performance of large surface chambers insensitive to mechanical deformations. The very good timing resolution guarantees the bunch crossing identification capability of the TGC.

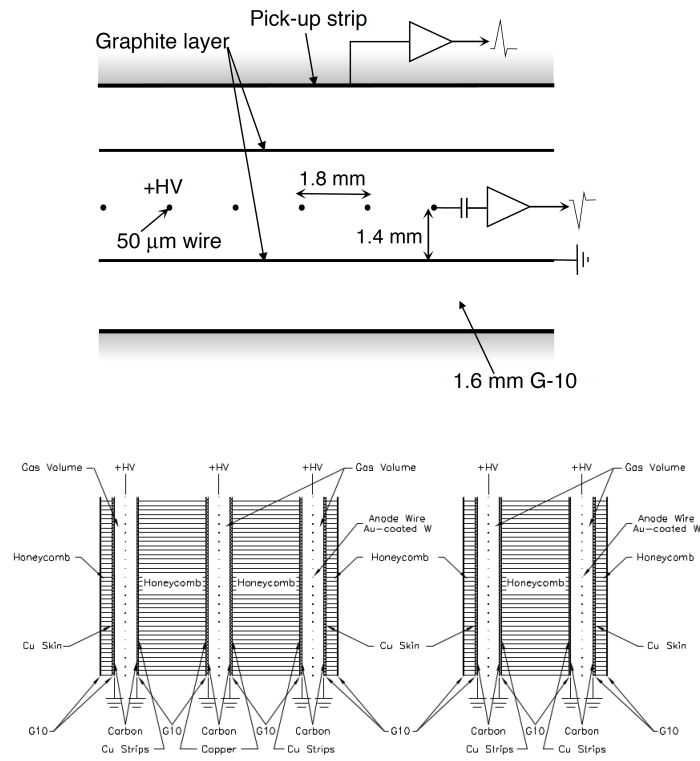


Figure 1.20. Up: Scheme of the Thin Gap Chambers.

Down: Triplet and doublet of a TGC Chamber.

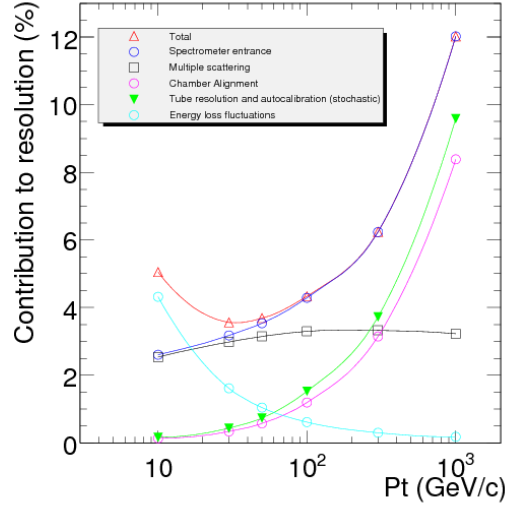


Figure 1.21. Muon spectrometer resolution as a function of muon p_T ; The various contributions are highlighted.

Spectrometer performances

For low p_T values, the dominant contributions to MS resolution are energy loss fluctuations and multiple scattering, for intermediate p_T multiple scattering is dominant, while for high p_T chambers alignment, calibration and intrinsic resolution contributions are dominant (see Figure 1.21).

The intrinsic resolution of a multiplet of three or four layers of MDT is $\sigma_x \simeq 50 \mu m$ and combining the two multilayers of a single chamber reaches $\sigma_x \simeq 35 \mu m$. For a track that crosses three MDT chambers, there is a resolution of $45 \mu m$ on the sagitta (Figure 1.22). During the construction, MDT wires have been mounted with a precision of $20 \mu m$ and the position of the chambers is continuously monitored by an optical alignment system which allows to know the relative displacements of the chambers in axial direction and radial with a precision of $30 \mu m$. These results bring the resolution of the momenta from 5% for 10 *GeV* muons, to 12% for 1 *TeV* muons.

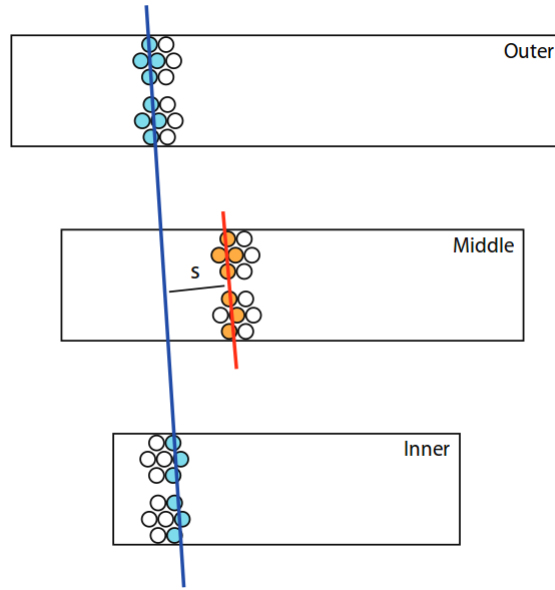


Figure 1.22. Sagitta (s) definition in the ATLAS MDT system.

Table 1.2 shows the various performances for all components of the ATLAS muon spectrometer.

Type	Function	Chamber resolution (RMS)			Measurements/track		Number of	
		z/R	ϕ	time	barrel	end-cap	chambers	channels
MDT	Tracking	$35 \mu m (z)$	—	—	20	20	1088 (1150)	339k (354k)
CSC	Tracking	$40 \mu m (R)$	5 mm	7 ns	—	4	32	30.7k
RPC	Trigger	10 mm (z)	10 mm	1.5 ns	6	—	544 (606)	359k (373k)
TGC	Trigger	2 – 6 mm (R)	3 – 7 mm	4 ns	—	9	3588	318k

Table 1.2. General performances of the various components of the ATLAS muon spectrometer.

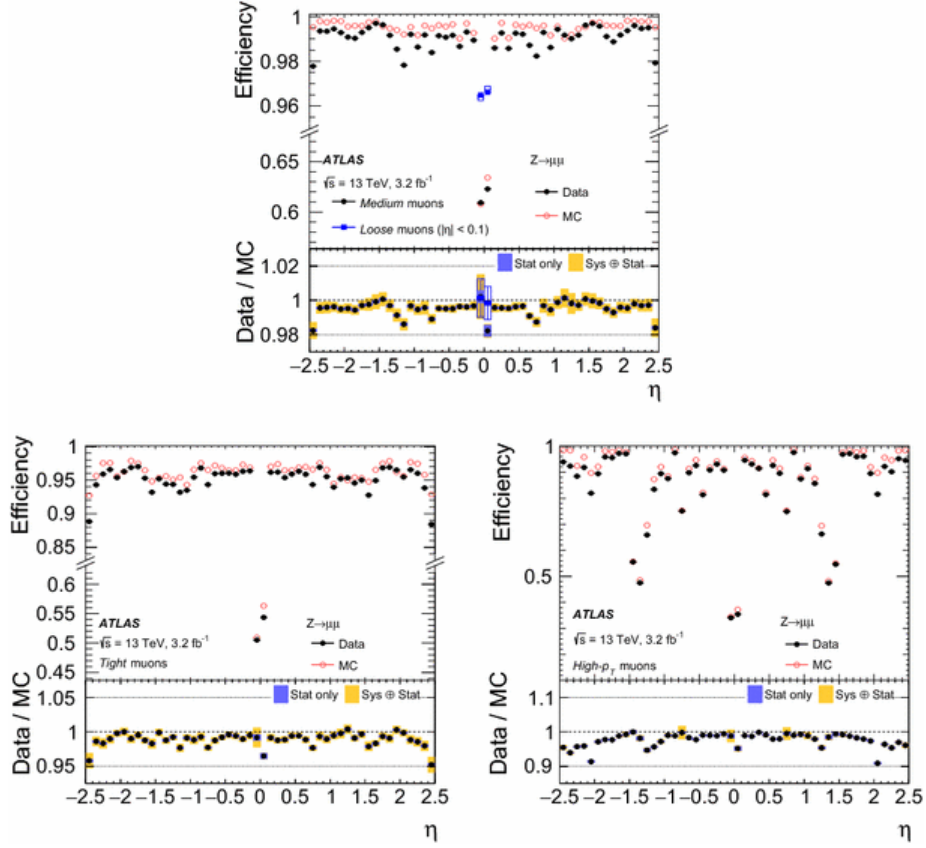


Figure 1.23. Muon reconstruction efficiency, extrapolated from the in proton–proton collision data at $\sqrt{s} = 13 \text{ TeV}$, as a function of η measured in $Z \rightarrow \mu\mu$ events for muons with $p_T > 10 \text{ GeV}$ shown for Medium (*top*), Tight (*bottom left*), and High- p_T (*bottom right*) muon selections. Panels at the bottom show the ratio between the measured and the predicted efficiencies, with statistical and systematic uncertainties.

1.2.7 The trigger system

The ATLAS trigger system [15] carries out the selection process in three stages (Figure 1.24). The Level-1 trigger works on a subset of information from the calorimeter and muon detectors. The decision to keep the data from an event is made less than $2 \mu\text{s}$ after the event occurs, and the event is then retrieved from pipelined storage buffers. Of $4 \cdot 10^7$ bunch crossings per second, less than 10^5 are kept by the Level-1 trigger.

The Level-2 trigger is a large array of custom processors that analyse in greater detail specific regions of interest identified by the Level-1 system for each event. In the mean time, the full event data is collected into buffers. A few thousand events per second pass Level-2, and have their data passed on to Level-3.

The Level-3 trigger is a large farm of CPUs which performs a detailed analysis of the full event data. About 200 events per second are left after the Level-3 analysis, and these are passed on to a data storage system for offline analysis.

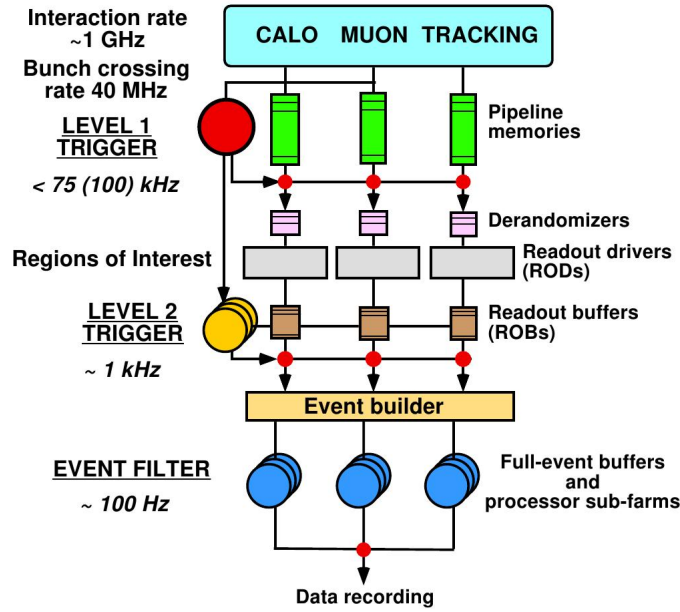


Figure 1.24. Overview of the three-step trigger architecture.

The muon trigger system

The Run II muon trigger system is divided into two levels:

- the First Level Trigger (L1), discussed above;
- the High Level Trigger (HLT) which includes the two previous high-level triggers in Run I for better sharing of resources and simplification of hardware and software.

The high level trigger, however, refines the decisions taken from the previous level by composing information from different detectors and applying additional selection criteria using software algorithms. It has a few seconds of processing time and allows to reduce the rate up to 1 kHz .

There are two different types of triggers, each with three different p_T thresholds:

- low- p_T , with 4 GeV (MU4), 6 GeV (MU6), 10 GeV (MU10) threshold;
- high- p_T , with 11 GeV (MU11), 15 GeV (MU15), 20 GeV (MU20) threshold;

The Low-Pt trigger only involves the first two RPC stations (RPC1, RPC2) that belong to the Medium Barrel, while the High-Pt trigger uses all three stations (belonging to the Internal and Medium Barrel), requesting a coincidence even on the farthest plane (Outer Barrel).

For most physics studies, the MU20 threshold that selects tracks with $p_T \geq 20\text{ GeV}$ is very important, giving a plateau efficiency of about 73%.

1.3 ATLAS upgrade

The LHC will be upgraded in several phases extending the reach of its physics program as discussed in Section 1.1.2. Already after the end of the first long shut-down (LS1) during 2013-2014 the accelerator's energy was increased at the design value of 7 TeV per beam with a luminosity of the order of $\mathcal{L} = 10^{34} \text{ cm}^{-2}\text{s}^{-1}$. With the intermediate upgrades that will follow in the next years ATLAS foresees a luminosity increase by a (safe) factor 7 with respect to the design value. In order to maintain its current excellent performance, the ATLAS detector, will need some important upgrades.

Major upgrades provided by ATLAS for the LS2 [16] are:

- the New Small Wheel (see next Chapter);
- integrating the NSW into the L1 trigger;
- new LAr calorimeter electronics for better use in the L1 trigger (to cope with the higher pile up);
- completion of the FTK (Fast tracker) with 10^9 pre-stored tracks in associated memories: match real hit pattern to stored pattern (L2 trigger).

Even during the LS3 (2022-2023) there will be other upgrades [17] of the ATLAS detector to ensure that its performance does not crawl with the installation of HL-LHC.

- the main activity will be the construction of a new inner detector for which today the collaboration is very active with R&D, prototypes and engineering work ;
- the Calorimeter read-outs will need a substantial upgrade (new photo-detector), part of it will be done in a staged way in the 2018 shut-down;
- most of the existing electronics/computing/TDAQ will need to be upgraded and modernized to face additional 8-10 years of running in extreme conditions;
- finally, also the MDT/RPC electronic will be upgraded.

Chapter 2

The New Small Wheel (NSW) Project

2.1 Present Small wheel layout

The current small wheel (SW) structure, shown in Figure 2.1, is composed by two wheels each one consisting of two parts:

- the *Detector Wheel* where the tracking detectors (MDT and CSC cameras) and the alignment system are installed; the mechanical structure consists of a massive central hub from which the various rays, all interlinked to each other like petals around the corolla of a flower, extend radially;
- the shielding (*JD shielding*), i.e. a disk-shaped structure that covers the entire surface of the SW with, in the more interior radius, a protruding cylindrical extension (plug) around the beam pipe. Trigger chambers (TGC) are located in the outer part of the discoid shield.

2.2 Limitations of the present Small Wheel

There are two fundamental aspects that must be taken into account with the instantaneous luminosity increase predicted by LHC for the ATLAS muon spectrometer.

1. The performance of muon tracking (especially in end-cap regions) worsens because of the increase in the background rate expected in the cave. Background hits in the muon spectrometer originate predominantly from low energy photons and neutrons: these particles are generated by proton collisions, synchronous with bunch crossings that mislead the ATLAS trigger (*in-time background*), or by collisions that occur one or more bunch crossings before (*out-of-time background*). Regardless of the mode of production, we refer to such particles as the *cavern background*. In order to be able to predict the rates of this background, two elements are needed: a careful measurement of the level of cavern background observed in current conditions of activity and reliable extrapolation (from Monte Carlo simulations) for higher energy and luminosity.

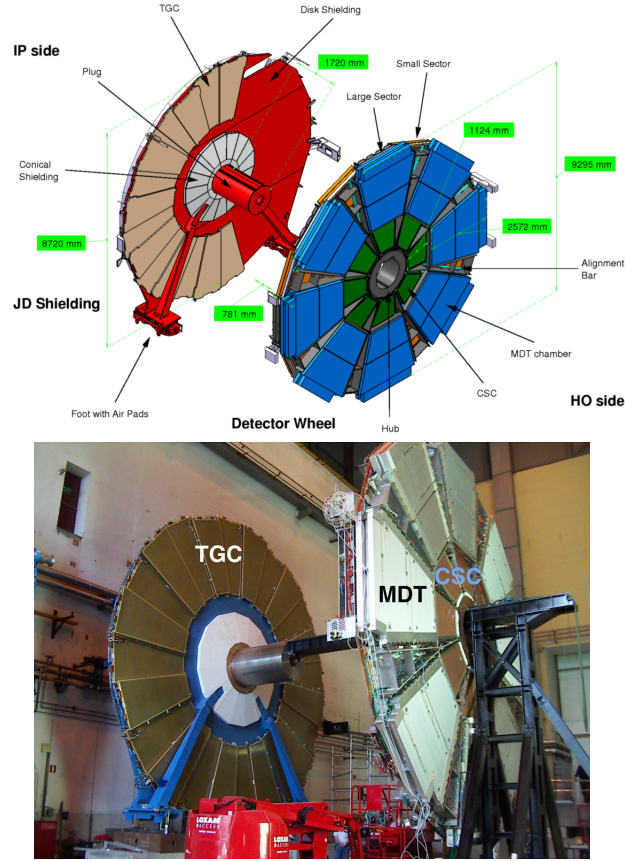


Figure 2.1. Up: Schematic structure of the actual SW.

Down: Photo of the current muon SW during its assembly phase on surface. The three different detector technologies composing the inner muon end-cap are visible.

The background hits rate is a function strongly dependent on the radial distance from the beam line and is therefore very high for detectors close to the beam pipe. By extracting the future high luminosity and high energy conditions, using the rates observed for the 2012 luminosity conditions, there is a significant degradation of performance in terms of both efficiency and resolution in the inner station of the spectrometer in the end-cap, the Small Wheel. As can be seen in Figure 2.2, the efficiency of the current MDT decreases linearly with the rate increase and a rate of 300 kHz per tube, which is the one expected for the design luminosity of $10^{34} \text{ cm}^{-2} \text{ s}^{-1}$, already has inefficiencies of about 35%, which can be retrieved at chamber level, but beyond this rate the efficiency decreases dramatically even at chamber level. Considering that the resolution of the muon momenta depends heavily on the presence of the hits in the SW, the degradation of its performance is highly detrimental to the overall performance of the detector.

2. The first level trigger rate for muons increases proportionally to instantaneous luminosity as the rate of muons and background tracks increase in turn. The first-level trigger in end-cap regions is based on track segments reconstructed

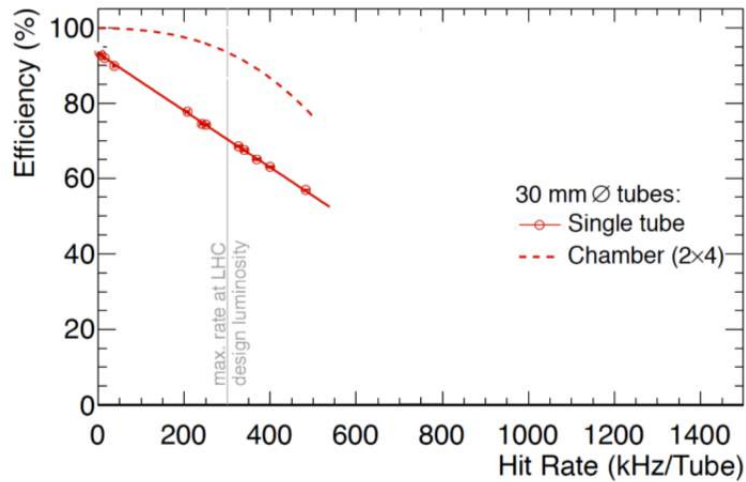


Figure 2.2. Reconstruction efficiency for a single MDT tube hit (continuous line) and segment track efficiency (dotted line) for a MDT chamber as a function of the estimated rate from data and simulations. With the expression “designed luminosity” refers to the actual instantaneous luminosity $\mathcal{L} = 1 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$.

by the TGCs. The transverse momentum of the muons is determined by the angle of the track segment with respect to the direction pointing towards the interaction point. A significant part of the end-cap trigger rate consists of background: low energy particles, mainly protons, generated inside the material between the IP and the end-cap muon station, and particles that are scattered in the material, produce false triggers by striking the trigger chambers with an angle similar to that of the real high- p_T -shaped muons, as shown in Figure 2.3. A 2012 data analysis shows that around 90% of the muon trigger in end caps are false. Consequently, the rate of the first-level trigger for muons in end-cap regions is 8 to 9 times higher than that in the barrel. In fact, as can be seen in Figure 2.4, more than 90% of the first level trigger rate for muons comes from the end caps, and most of the triggered objects are not reconstructed offline. The maximum rate allowed by the first level trigger is 100 kHz , determined by the experiment read-out system and only 20 kHz for single muon. At a luminosity of $3 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ the expected rate, extrapolated from the data with the current small wheel configuration, is 60 kHz for $p_T > 20 \text{ GeV}$ and then is three times larger than the one bearable by the read-out system. Increasing the threshold to 40 GeV reduces the rate of only a factor two, which is therefore even greater than the bearable one at the cost of a substantial loss of efficiency.

2.3 Upgrade requests

The performances of the new SW detector must be as good as those present, at both low and high luminosity. They must be able to measure the muon transverse

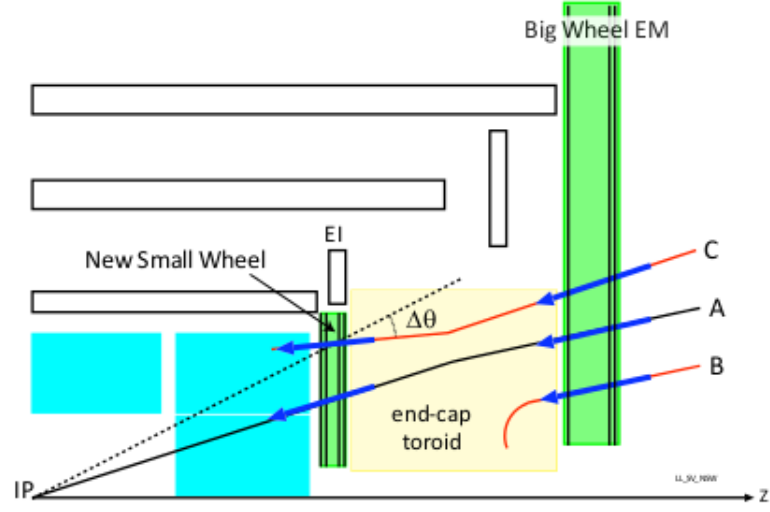


Figure 2.3. Muon trigger scheme in end-caps. The current trigger system, relying only on the Big Wheel, would accept all three tracks shown. With NSW only track A, as confirmed by the systems placed on both wheels, will be accepted. Track C will be discarded because the track in the NSW does not point in the direction of the interaction vertex and the same fate will have the track B.

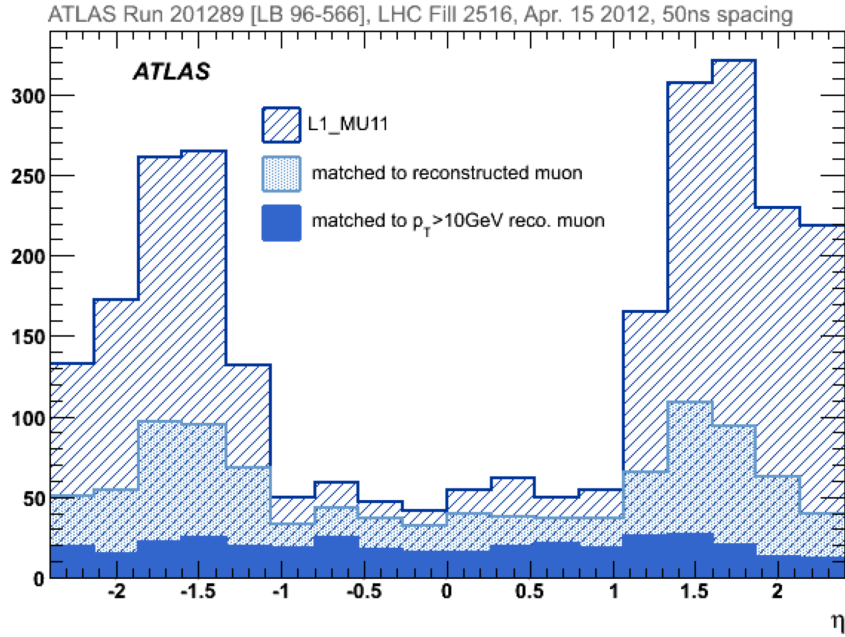


Figure 2.4. Distributions in η of muons ($p_T > 10 \text{ GeV}$) coming from the I level trigger (L1_MU11) with the subset of those for which there is a well-reconstructed track (combining information on tracks from the inner detector and the muon spectrometer for $p_T > 3 \text{ GeV}$). Finally, it is also shown the distribution of triggered muons for which there is a reconstructed muon with $p_T > 10 \text{ GeV}$.

momentum with a precision of 10% at 1 TeV for all η coverage of the SW (up to $|\eta| < 2.7$). For this reasons, these new detectors must satisfy these features:

- ability to reconstruct the tracks with a resolution of $\sim 50 \mu m$ on the bending plane to match the performance of the current MDT chambers. This will ensure that the spectrometer has a better momentum resolution of 10% at 1 TeV ; to do this, a resolution of at least 100 μm will be required for each layer of future multilayer detectors that will be installed in the New Small Wheel;
- tracking efficiency greater than 97% for muons with $p_T > 10 GeV$ (efficiency of current MDTs);
- efficiency and resolution must not degrade at high p_T ;
- capability to measure the second coordinate (ϕ) with a resolution of $\sigma \sim 1 - 2 mm$ to facilitate the reconstruction of muons.

The environment in which the NSW will work will be characterized by numerous spurious hits generated by δ rays¹, neutrons or other background particles. Also over time, the detector's activities may not work in its own way with limited possibilities to repair them. This is why a multilayered and very robust detector is required. Any new detector installed in place of the current Small Wheel must be operational for ATLAS's entire activity time and be able to accumulate up to 3000 fb^{-1} .

2.4 NSW Layout

The NSW system [18] will consist of sixteen planes of detectors arranged in two multiple layers, each comprising eight small-strip TGC (sTGC) and as many MicroMegas (MM). sTGCs are mainly used for the trigger, given their ability to identify products from single bunch crossing. The detectors are arranged (sTGC - MM - MM - sTGC) to maximize the distance between the sTGCs of the two multilayers (see Figure 2.5).

¹Electrons generated during primary ionization having such energy to produce other electron-ion pairs and generate a fake additional track in the detector.

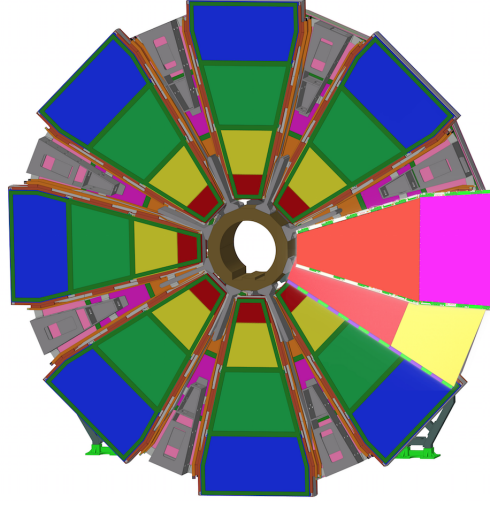


Figure 2.6. Graphical representation of an assembled NSW. Two MM sectors, one small and one large, are also shown. In reality, the MM will not be visible sitting in between the two sTGC quadruplets.

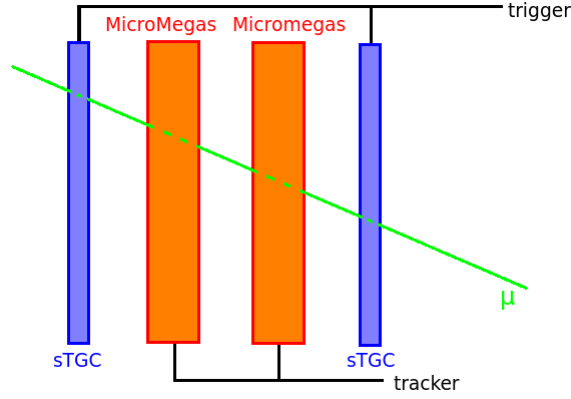


Figure 2.5. Detectors disposition in the New Small Wheel (sTGC - MM - MM - sTGC).

As the online track hits (hits collected and analysed during data capture) are reconstructed with limited accuracy, the increase in distance between sTGC(s) improves resolution in the reconstruction of the angle for online track segments. The choice of having eight planes per detector is dictated by the need to provide a robust and fully functional detection system for the entire operating period, because if some detectors may have malfunctions over the years the repair would be rather problematic. Furthermore, neutrons, background photons but also δ rays, change the number of hits compared to that of the real tracks. With eight levels of detectors the tracks will be reliably reconstructed even under these conditions.

There is also a radial segmentation of each layer in modules of different sizes and shapes. For the MM layer 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:

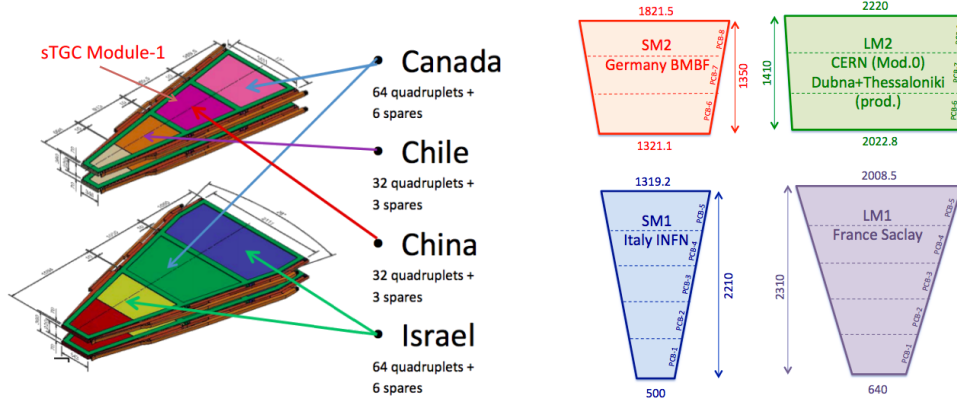


Figure 2.7. Division, among the various nations, of the construction tasks of the pieces of the various detectors (*left: sTGC; right: MM*). Italy has the task of building the Small MicroMegas sector 1 (SM1) of the MM quadruplet.

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

The detectors selected for NSW, sTGC and MM are flat geometric gas detectors. While the internal structure of the two detectors is different, the position measurement is based in both cases on precision strips printed on printed circuit boards (PCBs). To stiffen each layer of the detector without making the structure too heavy, the aluminium honeycomb panels, that have hexagonal cells structure, high stiffness and low density) are glued to the PCBs. Detector units of each detector type assembled in multiplets and generally have a trapezoidal shape.

The MM detectors, which will be discussed in detail in the next chapter, are exceptional in precision tracking due to the strip pitch ($\mathcal{O}(500 \mu m)$) and despite to the small gap gas ($5 mm$). In addition, the two technologies used in the NSWs are complementary to tracking: sTGCs can also contribute to offline precision tracking, as these chambers can measure track hits at a resolution of better than $150 \mu m$, (this value largely depends on the angle of the incident track), while MM detectors will also be used for the trigger, providing additional robustness and coverage of the device in the end caps region.

Based on the issues and needs outlined, one can define the general layout features of the NSW and its detectors:

- sTGC chambers are the primary trigger system and MM chambers are the main precision detectors;
- trigger acceptance in $1.3 < |\eta| < 2.5$;

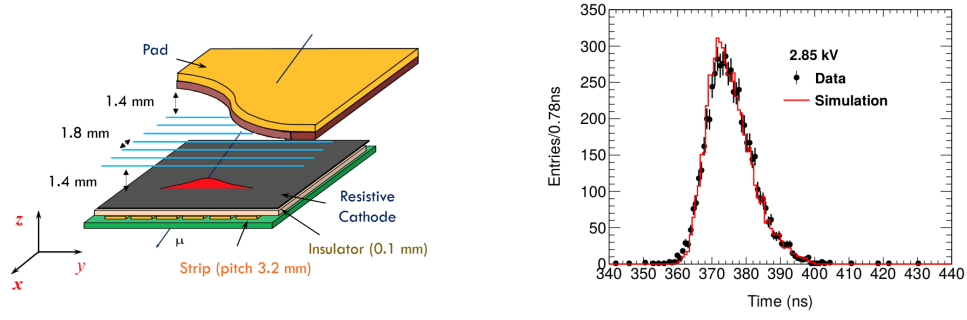


Figure 2.8. *Left:* Graphical representation of the sTGC internal structure. The signal due to the drifting of the ionization charges and their multiplication is induced on the anode wires, read-out pads and strips sitting behind the cathode planes. *Right:* Due to the thin gap and the very intense electric field applied $\sim 95\%$ of the measured drift times are confined within a 25 ns time window proving the bunch crossing identification capability of the sTGC detector.

- accuracy of precision tracking in $1.3 < |\eta| < 2.7$;
- detectors are located in eight small sectors, and as many large sectors, covering in η the corresponding MDT chambers in end-cap and outer end-cap stations;
- wheel consisting of planar detectors, unlike current CSCs that are inclined;
- a total of eight layers of sTGC detection and as many MM in each sector; the arrangement of the various layers in the direction z consists of four layers of sTGC, four MMs, an optional spacer and a supporting structure, four other layers of MM and the last four of sTGC(s);
- re-use of the current JD shielding structure.

2.5 small Thin Gap Chambers (sTGC)

The sTGC(s) are the detectors selected to perform the trigger function. Trigger detectors must provide bunch crossing identification, good timing resolution, and good angular resolution, better than 1 mrad , for online track reconstruction that translates into good spatial online resolution.

The basic structure of a sTGC is shown in Figure 2.8 (*left*). It consists of a grid of tungsten wires plated in gold, with $50\mu\text{m}$ thickness and a distance of about 1.8 mm . The cathodic planes are made of a compound of graphite and resin and on one there are the perpendicular strips on the wires while on the other there are pads that cover a large rectangular surface. The strips have a 3.2 mm pitch, much smaller than the current ATLAS TGC, so the new chambers are called “small strip” TGCs. The chamber is filled with a gas mixture of $55\% \text{ CO}_2$ and $45\% \text{ n-pentane}$, which has an electron drift velocity of about $3 \text{ cm}/\mu\text{s}$ under an electric field of 2.9 kV/cm .

The project for NSW has two quadruplets separated by 35 cm in z . Each quadruplet contains four sTGC(s), each with pads, wires and read-out strips. Pads are used to produce a coincidence of three to four to identify tracks of muons pointing roughly toward the point of interaction. They are also used to define what

the read-out strips should read to obtain a precise measurement in the bending coordinate for the online selection of muons. The azimuthal coordinate, for which a precision of about 10 mm is required, is obtained from the read-out of the wires. Charge of all strips, pads, and wires is read for offline reconstruction.

The position resolution required by the trigger has been optimized by constructing small prototype detectors and studying it according to the strip pitch, keeping the number of read-out channels at a minimum. The results of this constructive and test phase, attempting to produce a full-size quadruplet ($120 \times 70\text{ cm}^2$) so that it can be tested in an environment whose conditions better reflect those of ATLAS, led to the following results:

- despite the size of built prototypes, sTGC chambers can work smoothly, even under a γ radiation of 17 kHz/cm^2 exposure, with high efficiency for MIPs;
- using a pitch of 3.2 mm and the centroid charge centering method, the resolution in position varies from $60\text{ }\mu\text{m}$ with null incidence angles (corresponding to particles perpendicular to the read-out system) at $150\text{ }\mu\text{m}$ for angles of incidence of 30° ;
- the detection of cosmic ray muon, despite the exposure to which it has been subjected, does not show any deterioration in the efficiency of the single plane.

Regards the electronics to be associated, a new Application Specific Integrated Circuit (ASIC) named *VMM* was developed and it should be used for both sTGCs and MMs within NSWs. Both detectors require precise amplitude measurements for position determination by charge interpolation processes; in addition, in order to mitigate the deterioration of spatial resolution resulting from the use of MM in rebuilding inclined tracks, these types of detectors will operate in a mode called μTPC (discussed in detail in the next chapter), whose name derives from the track reconstruction mode based on the drift time measurement of the charge arriving on individual read-out strips, just like in a large Time Projection Chamber (TPC). In addition to the above-mentioned amplitude measurements, time measurements with a precision of 2 ns are also required, and this ASIC is able to supply both.

Chapter 3

The MicroMegas chambers

The MicroMegas (*Micro-MESh GASEous structure*) chambers are gas detectors born from the development of the wire chambers invented by G. Charpak in the '70s. It was first proposed in 1992 by Charpak and I. Giomataris to improve the spatial resolution of multiwire chambers and their ability to quickly release the detector from the positive ions generated by gas ionization at the passage of charged particles.

In Section 2.3 the requirements for the precision tracking system in the NSW has been defined. The tracking detectors should provide very good position resolution ($\sigma_x < 100 \mu m$) independent of the particle incident angle, high efficiency even at the highest background rates, and good two track separation.

3.1 The MicroMegas technology

The MicroMegas detectors [18] consist of a planar (drift) electrode, a gas gap of a few millimetres thickness acting as conversion and drift region, and a thin metallic mesh at typically $100 - 150 \mu m$ distance from the read-out electrode, creating the amplification region. A sketch of the MicroMegas operating principle is shown in Figure 3.1.

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. When a charged particle traverse the gas gap, ionizes the atoms and the electrons liberated by this ionization process drift towards the mesh. Near the mesh, the lines of force of the electric field behaves as shown in Figure 3.2 and the values of the field reached in the amplification region is 50-100 times stronger than the drifting field.

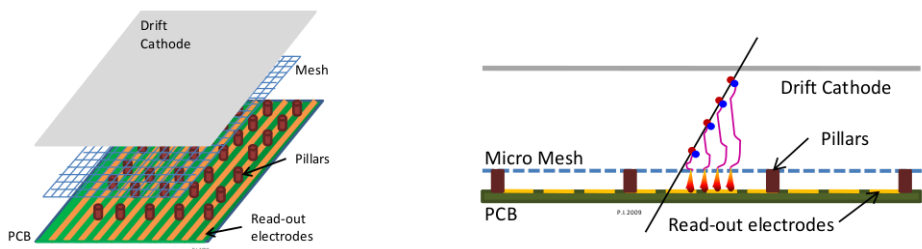


Figure 3.1. Sketch of the layout and operating principle of a MM detector.

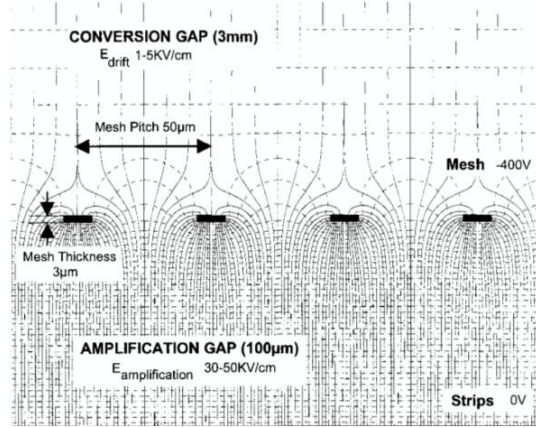


Figure 3.2. Maps of the electric field lines of a MicroMegas chamber.

The electron avalanche takes place in the thin amplification region, immediately above the read-out electrode. The drift of the electrons in the conversion gap is a relatively slow process; depending on the drift gas, the drift distance, and the drift field it typically takes several tens of nanoseconds ($v_d = 4 \div 5 \text{ cm}/\mu\text{s}$). On the other hand the amplification process happens in a fraction of a nanosecond, resulting in a fast pulse on the read-out strip.

The ions that are produced in the avalanche process move, in the opposite direction of the electrons, back to the amplification mesh. Most of the ions are produced in the last avalanche step and therefore close to the read-out strip. Given the relatively low drift velocity of the ions ($v_d \sim 4 - 5 \cdot 10^{-2} \text{ cm}/\mu\text{s}$), it takes them about 100 ns to reach the mesh, still very fast compared to other detectors. It is the fast evacuation of the positive ions which makes the MicroMegas particularly suited to operate at very high particle fluxes.

3.2 Detector gain

The electric fields in the conversion and drift zone and in the amplification zone have very different intensity (low in the drift zone and very high in the amplification zone), and are roughly uniform in both regions. Figure 3.2 shows the map of the electric field lines in a MicroMegas chamber.

Multiplication of electrons occurs in the amplification region with a high electric field between the mesh and read-out electrode. The multiplication factor M of the electrons in a gas, under a pressure P between two flat-plane electrodes at distance d , with a uniform electric field E , is described by:

$$M = e^{\alpha d} \quad (3.1)$$

where α is the Townsend coefficient, which represents the inverse of the free average path of an electron between two ionizations. A good approximation of the coefficient is given by the formula of Rose and Korff:

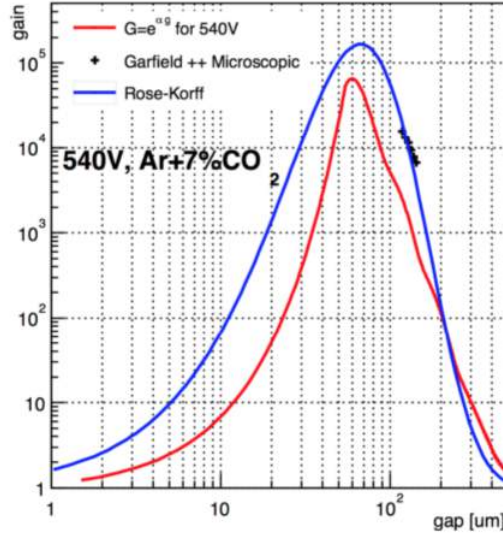


Figure 3.3. Gain as a function of the amplification gap size for a mixture of $Ar - CO_2$ at 93% – 7% with amplification voltage of 540 V. The red curve shows the course obtained from equation (3.1) while the blue curve obtained with the approximation of Rose and Korff from equation (3.2). Black dots were obtained from simulations made with GARFIELD and show the working area of the MicroMegas chambers.

$$\alpha = A \cdot P \cdot e^{\frac{-BP}{E}} \quad (3.2)$$

where A and B are two parameters that depend on the gas mixture. By substituting, in equation (3.1), the expression of the Townsend coefficient given from 3.2 and the expression of the electric field $E = V/d$, where V is the applied voltage:

$$\log M = A \cdot P \cdot d \cdot e^{\frac{-BPd}{V}} \quad (3.3)$$

Figure 3.3 shows the gain factor trend as a function of the width of the amplification gap; in the small gap region, the leading contribution is given by the linear term in d until the gain reaches the plateau in the region between 50 and 100 μm where the decreasing exponential becomes the main contribution. Black dots show the work area where the MicroMegas chambers are located, so for small increases in the size of the gap the gain decreases and viceversa increases for small reductions.

3.3 Spark-protected MicroMegas

The weak point of the MM original design was their vulnerability to sparking. Sparks occur when the total number of electrons in the avalanche reaches $\sim 10^{7 \div 8}$ (Raether limit [19]).

In order to obtain, however, high detection efficiencies for MIP muons, amplification factors of the order of 10^4 must be obtained; therefore, ionization processes that produce more than a thousand electrons (due for example to photons or neutrons or

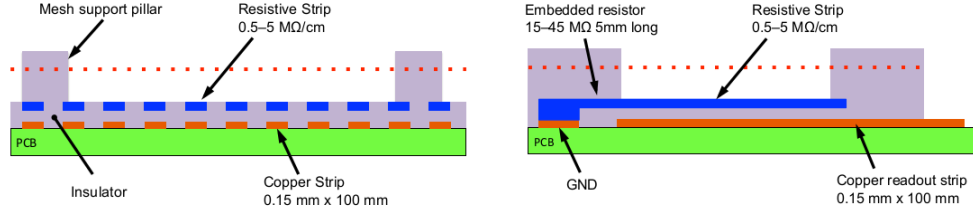


Figure 3.4. Spark protection principle.

α particles) at comparable distances to the lateral extension of an avalanche (some hundreds of μm) can produce dangerous discharges that can damage the detector or reading electronics or cause long dead times.

Therefore, since 2008, a research and development activity called Muon ATLAS MicroMegas Activity (MAMMA) [20] has been initiated; the main purpose was to address the issue of discharges and then go on to study the potential of MM technology for the NSW upgrade. The developed anti-spark protection system involves the addition of a layer of resistive strips whose resistivity should be in the order of a few tens of $M\Omega/cm$, placed on the top of a thin layer of insulating material directly above the read-out electrodes. Geometrically, resistive strips are arranged to follow the pattern of read-out strip and are electrically isolated from them; signals are induced through capacitive couplings with read-out strips that are no longer directly exposed to the charge produced in the amplification region. In case of discharges, the resistive strips are charged and, locally, the electric field falls to block the spark process. In this way the detector becomes much more “robust”.

The constructive principle just described is shown schematically in Figure 3.4. Adding this protective device, a fraction of the signal is lost but the structure can operate with a higher gain factor and have at the same time discharges whose intensity is reduced by three orders of magnitude. Therefore, all the studies of R&D for ATLAS NSW upgrades were made using resistive MM technology.

3.4 MicroMegas in the New Small Wheel

The MMs to be installed in the NSW differ from their original configuration. The first important change from the original project [21] is the application of a positive High Voltage (HV) to the resistive strips, placing the mesh at ground; this arrangement allows more stable operation of the entire detector. Moreover, the problem of any discharges is overcome thanks to the fact that the current produced in this new configuration is quickly discharged to the ground through the mesh.

One main change concerns the construction method. The first prototypes of MM has been built according to the “bulk” technology where the mesh is directly integrated in the read-out board structure. A change has been made necessary to overcome the limitations imposed by bulk technology for PCBs.

In the new scheme the mesh is part of the panel containing the cathode plane; in this way, the drift gap, being separated from the reading PCB, is no longer dependent on its size. Figure 3.5 shows a diagram of this new MM assembly method, known as

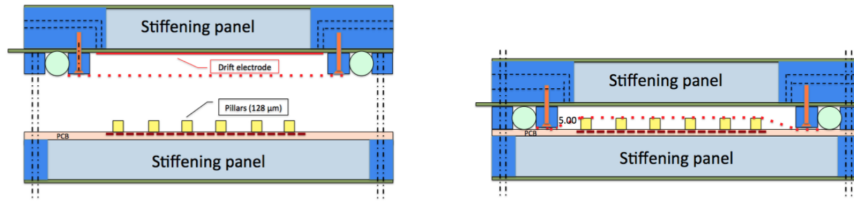


Figure 3.5. Assembly diagram of a single MM plane. *Left*: the drift and read-out panels are opened and separated, and the mesh and the mesh is integrated to the first one gluing it to an aluminium frame (mesh frame). *Right*: the drift panel is hooked to the read-out.

the “floating mesh” technique.

The figure shows the assembly of a single MM plane with separate drift and read-out panels (Figure 3.5 - *left*) then coupled (Figure 3.5 - *right*) together. The mesh support pillars are arranged at the top of the read-out panel. The mesh is integrated into the drift panel: it is first extended and then glued to the aluminium frame surrounding the rigid panel (stiffening panel). As shown in Figure 3.5 (*right*), once the two panels have been hooked up with a high precision mechanical process, the mesh is placed above the supporting pillars. The advantages of this new technique are above all constructive, since mesh sizes are now independent from PCBs and therefore production can take place in different places and times; the opening and cleaning operations of the detector are also facilitated.

The MM performance has been extensively studied since the beginning of the MAMMA project. The first results showed a spatial resolution of down to $40 \mu\text{m}$, well below the ATLAS requirements, employing a prototype of MM with strip pitch of $250 \mu\text{m}$ and a mixture of $\text{Ar} : \text{CF}_4 : i\text{C}_4\text{H}_{10}$ (88% 10% 2%). Nevertheless, two points must be taken into account: too fine granularity implies a high number of channels for the required electronics, resulting in increased costs, and the gas mixture must be safe from the point of view of ageing. Therefore, after testing various gas mixtures, ATLAS has opted for the reuse of the $\text{Ar} : \text{CO}_2$ (93% 7%) blend, already used in existing MDT chambers, which has proved to be suitable for meeting the operational requirements for the NSW. Finally, with regard to the read-out strips, the option of a strip pitch of $\sim 400 \mu\text{m}$ was adopted, a choice that translates into $\sim 2 \cdot 10^6$ channels of electronics for the NSW system, which, although large, is still reasonable. In summary, the main constructive and operational parameters of MM that will be used for NSWs in ATLAS are reported in Table 3.1.

3.4.1 MicroMegas layout in the New Small Wheel

The different dimensions of the MM modules (SM1, SM2, LM1, LM2) that have to be built are illustrated in Figure 2.7 (*right*). Depending on the type (large/small sector and radial position) each trapezoidal module consists of several PCBs precisely glued together. The read-out PCB will consist of $0.5 \pm 0.05 \text{ mm}$ thick PCB base material with thick copper film of $17 \mu\text{m}$ height etched via photolithography. The strip width will be $300 \pm 20 \mu\text{m}$ for all the modules with a pitch of $425 \pm 20 \mu\text{m}$ and $450 \pm 20 \mu\text{m}$ for small and large modules respectively.

Item/Parameter	Characteristics	Value
Mesh	Stainless steel separate from read-out board	325 lines/inch
Amplification gap		128 μm
Drift/conversion gap		5 mm
Resistive strips	Interconnected	$R = 10 \div 20 M\Omega cm/cm$
read-out strip pitch		0.425 $\div$ 0.445 mm
Stereo angle	4/8 layers	$\pm 1.5^\circ$
Total number of strips		2.1 M
Gas	$Ar : CO_2$	93 : 7
HV on resistive strips	positive polarity	550 V
Amplification field		40 kV/cm
Drift field		600 V/cm

Table 3.1. Main MM detector and operating parameters.

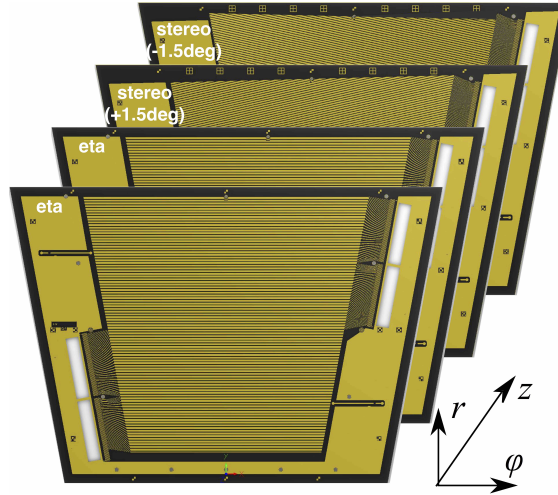


Figure 3.6. Drawings of the four different read-out PCBs that make up one MM module.

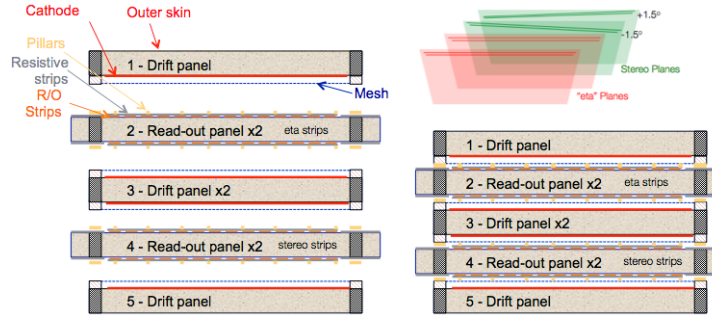


Figure 3.7. Layout of a multiplet of a MicroMegas detector consisting of three drift panels and two double-side read-out panels. The first two MM gap read the precision coordinates (η) and the second two read the second coordinates (ϕ).

The layout of the read-out PCB boards is illustrated in Figure 3.6. Each PCB comprises 1023 read-out 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 detector read-out 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 read-out 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 η strips) while the other two will have the strips tilted by a small stereo angle ($+1.5^\circ$ and -1.5° stereo strips respectively) to allow for the reconstruction of the second coordinate (ϕ).

Each MM module will combine four detection layers (equivalent to four MM gaps). A schematic view of a MicroMegas quadruplet consisting of three drift panels and two read-out panels is shown in Figure 3.7 and in Figure 3.8 (*right*).

The outer layers of one MM quadruplet are two identical one-sided drift panels¹ 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 read-out panels carry the read-out PCB on both sides. One of the two read-out panels features two parallel eta-strip read-out 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 the NSW MM detectors the connection between the read-out board and the read-out strips will be realised via the Zebra connectors [22]. To ensure a good contact between the front-end and the strips a compression bar, installed on the outer part of the drift panel, will push the read-out board (MMFE8 [23]) on the strip pattern.

3.5 Single strip response and track reconstruction

As explained in Section 3.1, the passage of a charged particle within the gas gap is revealed by collecting on the strips the ionisation charge produced. The signal of

¹Cathode PCBs have simply a thin layer of copper on the fiberglass surface.

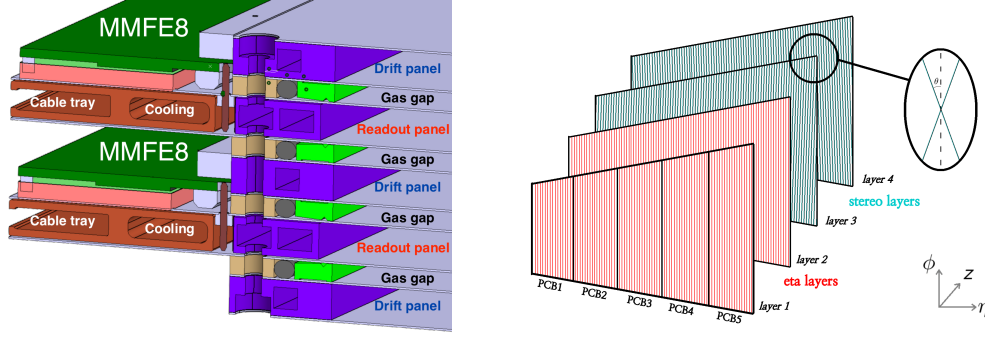


Figure 3.8. *Left:* 3D drawing of the quadruplet edge showing the guide for the alignment pin and the electronics and services placement on the read-out PCB surplus part. *Right:* Schematic view of the 4 layers of a MicroMegas multiplet. In the picture is shown the orientation of the strip of each layer.

each single strip is read-out through the APV25² read-out electronics that provides the value of the collected charge as a function of time with a sampling of 25 ns. In particular, for the MicroMegas Module 0 (SM1) cosmic ray test, it was decided to consider 18 charge sampling for a total time window of 450 ns. On the signal of the single strip, a fit is made on the rising edge with a Fermi-Dirac function:

$$f_{FD}(t) = \frac{A}{1 + e^{-\frac{t-t_{FD}}{B}}} + C \quad (3.4)$$

Where A is the charge, C is the baseline parameter and, through these two parameters, the charge from the strip $Q = A - C$ can be obtained; in addition, the signal arrival time is obtained from the floating point t_{FD} and the signal rising slope from parameter B . The time taken by the signal to pass from 5% to 95% of its amplitude is equal to $\sim 6B$ and in the MicroMegas chambers for the ATLAS experiment have a signal formation time of 100 ns (drift time of positive ions to the mesh). Figure 3.9 shows, three examples of a single strip signal with fit on the rising edge with Fermi-Dirac function.

3.5.1 Methods for reconstructing the position

Charge centroid

For each event one can have consecutive groups of strips, called clusters, and for each strip that composes the cluster the collected charge and the signal arrival time with respect to an external trigger is measured. The cluster size (strip multiplicity) depends on the inclination angle of the track: perpendicular tracks generate small clusters, while tracks with large tilt angles light up more strips.

The goal of this type of detector is to reconstruct the hits of the particles that pass through it in order to determine the momentum and the charge of the particles. For this reason, the cluster position reconstruction is an important point for the correct use of these chambers.

²Only for the SM1 prototypes the read-out electronics is the APV25 while the VMM electronics, still not available in its final version, will be the read-out of the final MM modules.

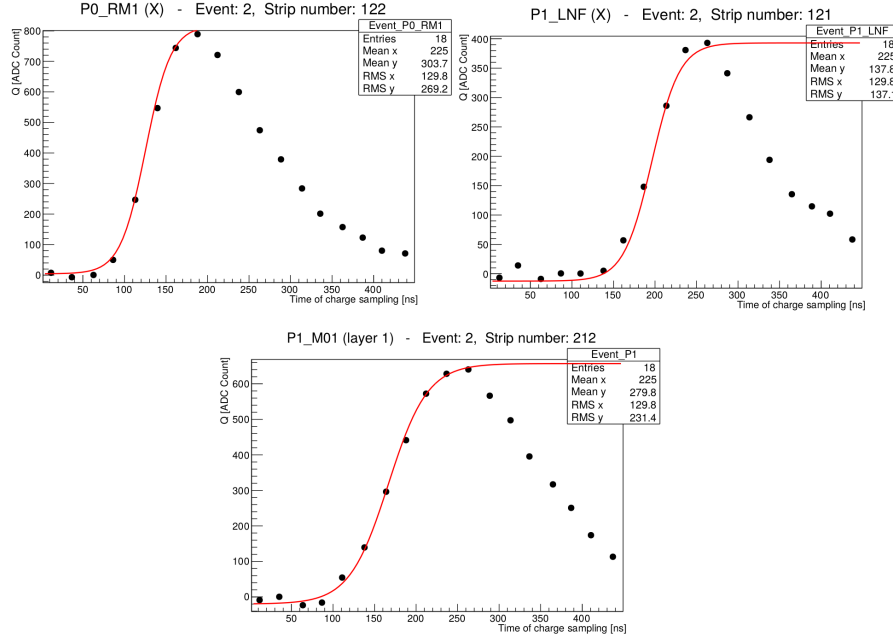


Figure 3.9. Examples of a single-strip signal read by APV25 electronics for two Tmm (see Section 5.1) MicroMegas detector ($P0_RM1$ and $P1_LNF$) and for the first layer of $SM1$ prototype. Fit to the rising part of the distribution is performed using Fermi-Dirac equation (eq. 3.4).

The simplest hit reconstruction that can be performed is by using the *centroid method*, where the hit position is calculated as the average position of strips in a cluster weighted by their charge measurements:

$$x_{centroid} = \frac{\sum_{i=1}^N q_i \cdot x_i}{\sum_{i=1}^N q_i} \quad (3.5)$$

with x_i being the positions of the strips. An example of a reconstructed cluster in a event is shown in Figure 3.10.

This method performs well for tracks approximately perpendicular to the chamber due to the reduced cluster dimension.

μ TPC

The centroid method allows only to reconstruct the interacting point of the particle through the cluster location while the μ TPC *method* allows to locally reconstruct the track within the drift gap with the measure of signal arrival times on the individual strips that composes the cluster. As shown in Figure 3.11, the x -coordinate will directly depend on the strip position while the z -coordinate is obtained from the measure of signal arrival times by the use of the drift velocity of electrons $z_i = v_{drift} \cdot t_i$.

The electron drift velocity depends on the gas mixture used and on the electric field applied. From simulations carried out with GARFIELD [24], the drift velocity as a function of the electric field applied for different gas mixtures is obtained. As shown in Figure 3.12, a drift velocity of $v_{drift} = 4.7 \text{ cm}/\mu\text{s}$ for $Ar - CO_2$ mixture

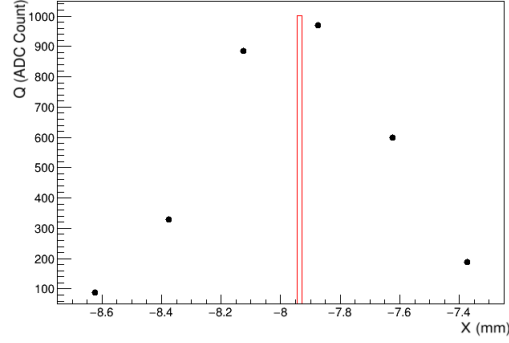


Figure 3.10. Example of a reconstructed cluster in a event: the dots are the q_i and the x_i of a single strip in a fixed x position while in red is shown the cluster x position calculated using the centroid method (eq. 3.5).

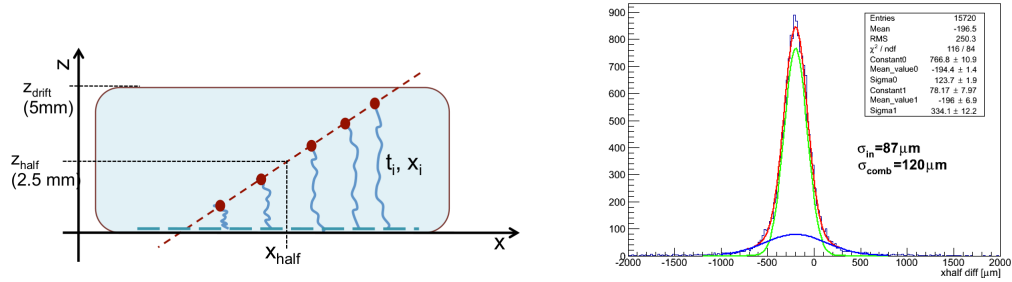


Figure 3.11. *Left:* Reconstructed track with the MM μTPC operating mode.

Right: distributions of Δx_{half} for particle with an impact angle of 30° . The distribution is fitted with a double Gaussian (red line) accounting for a *core* distribution (green line) plus tails (blue line).

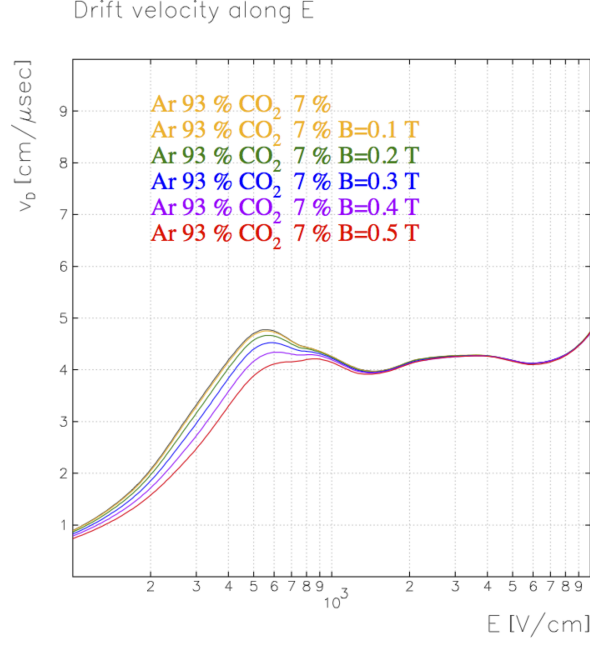


Figure 3.12. Drift velocity as a function of the electric field applied, for different gas mixtures, obtained by simulations carried out with GARFIELD. Drift velocity with magnetic field $B = 0.5 \text{ T}$ are also shown because in the NSW of the ATLAS experiment the MicroMegas chambers will have to work in the presence of a magnetic field.

(93% – 7%) with a drift electric field of 0.6 kV/cm in the absence of magnetic field is expected. We note that this value of the electric drift field is in the drift velocity plateau zone for the selected gas mixture. With this value the maximum drift time in the gap of 5 mm is of $\sim 100 \text{ ns}$.

As can be seen in Figure 3.11, once the $x - z$ coordinates from each strip within the cluster are obtained, one can reconstruct the track inside the drift gap by selecting clusters with at least three strips and making a linear fit $z = mx + q$ which allows us to obtain the angular coefficient m of the straight line and hence the inclination angle of the track $\theta = \arctan(m)$. The best measure of the position of the cluster in this case is given by the coordinate x_{half} which corresponds to the intersection between the line obtained from the fit and the line $z_{half} = 2.5 \text{ mm}$, as shown in Figure 3.11. x_{half} is obtained from the equation 3.6

$$x_{half} = \frac{z_{half} - q}{m} = \frac{2.5 \text{ mm} - q}{m} \quad (3.6)$$

where m and q are the two fit parameters.

The two reconstruction methods are complementary as the centroid method provides better spatial resolution for perpendicular tracks or for tracks with inclination angles between 0° and 10° , while the method of μTPC is ideal for tracks with incidence angles greater than 10° that light up more strips. Figure 3.13 shows the spatial resolution as a function of the incidence angle on the chamber obtained by the

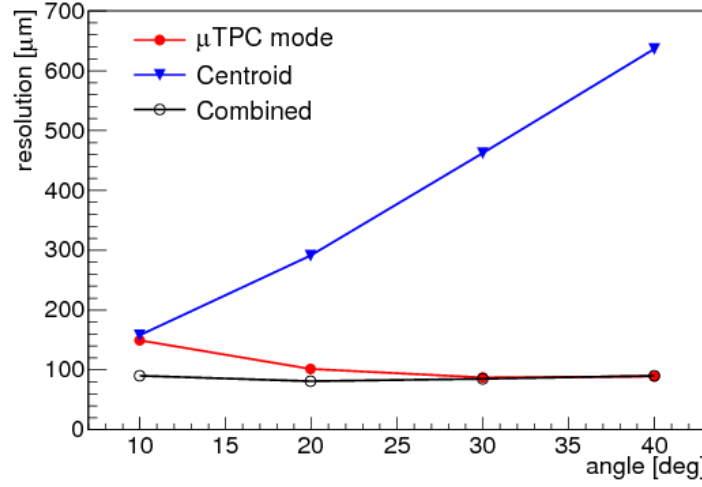


Figure 3.13. MM spatial resolution with charge centroid method (blue triangles), μ TPC method (full red circles) and the combination of the two (black open circles) as a function of the particle impact angle. The data were acquired at the SPS/H4 test beam facility with a $150 \text{ GeV}/c \mu/\pi$ beam.

centroid method, using the μ TPC method and the combination of the two methods. In the NSW of the ATLAS experiment, tracks will have incidence angles between 8° and 32° and combining the two methods a resolution of $100 \mu\text{m}$ throughout the range can be obtained.

3.5.2 Performance inside a magnetic field

The MM chambers of the NSW will operate in a magnetic field up to about 0.3 T with different orientations with respect to the chamber planes but with a sizeable component orthogonal to the MM electric field. The impact of the magnetic field on track reconstruction strongly depends on the inclination of the incident tracks. As shown in Figure 3.14, given an external magnetic field, the ionisation electrons are subject to a focusing effect (Figure 3.14, third picture) due to the Lorentz angle, thus resulting in clusters with fewer strips; in the opposite case, electrons are subject to a defocusing effect (Figure 3.14, second picture).

The degradation of the performance of the μ TPC reconstruction due to the focusing effect can be compensated by the improvement of the resolution of the centroid reconstruction in that case. A proper combination of the two reconstruction techniques allows to have a good spatial reconstruction at all angles.

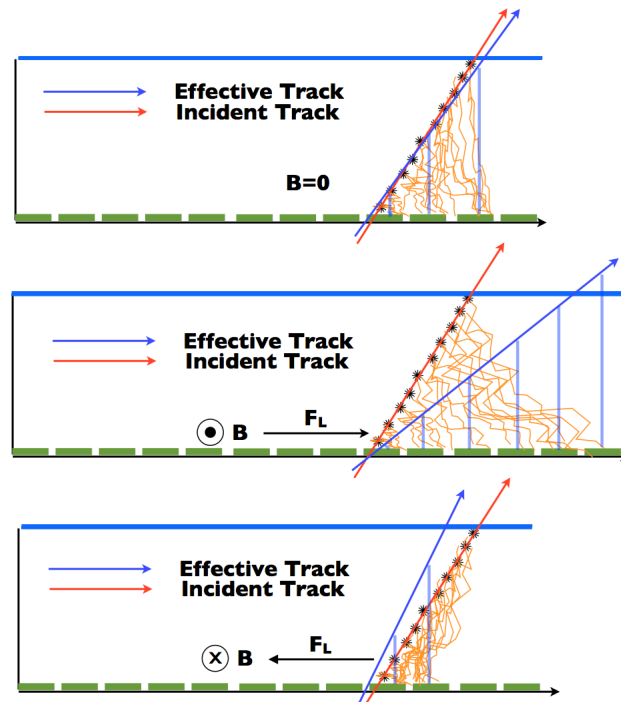


Figure 3.14. Pictorial view of the effect of the magnetic field on the drift in a MM chamber. The real track is shown in red and the reconstructed track in blue; $B = 0$ (*up*) and $B \neq 0$ (*middle* and *down*) are shown.

Chapter 4

Production quality control and construction

The INFN section of Roma1 is involved in the development and construction of MicroMegas chambers. In particular the commitment of Roma1 consists in the construction of the drift panels that make up the quadruplets that will be mounted in the ATLAS experiment.

Given the complexity of the experiment, the MM-Quadruplet and all its components, including the drift panel, will have to respect certain parameters imposed for the proper functioning of the chambers within the environment in which they will work. For this reason, quality control (QA/QC) measures on the various components that will be used for the construction and the panel itself are very important.

4.1 Drift Panel structure

Drift panels, shown in Figure 4.2, are divided into two types according to their position in the quadruplet of a MM chamber:

- outer: the two panels that, in fact, make up the outside part of the chambers and have only one face with copper;
- central: the panel that is located at the center of the quadruplet and has two faces with the copper deposited above because it is used for two different MM gaps within a quadruple.

A single panel is a sandwich of two skins glued on a stiff plane and consists of several elements that have the functions to make it work, make it durable and lightweight and attach it to others to create the complete MM module.

The “sandwich” (Figure 4.1) consists of:

- first PCB (fibreglass skin);
- aluminium honeycomb surrounded with an aluminium frame;
- second PCB.

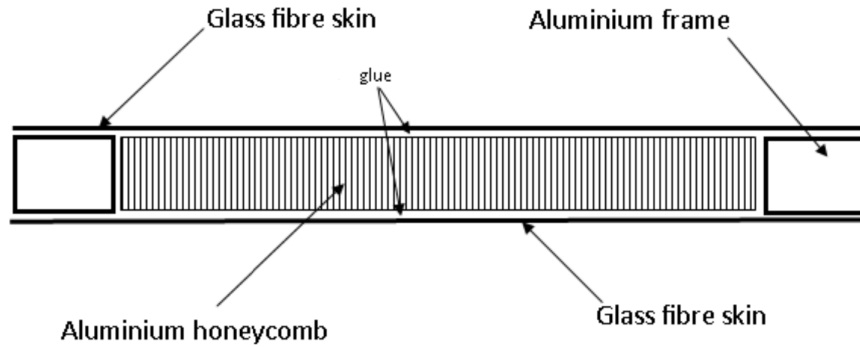


Figure 4.1. Schematic view of the MicroMegas drift panel section structure.

In case of central panel, both PCBs have the coppered layer. In case of outer panel only the front one has copper.

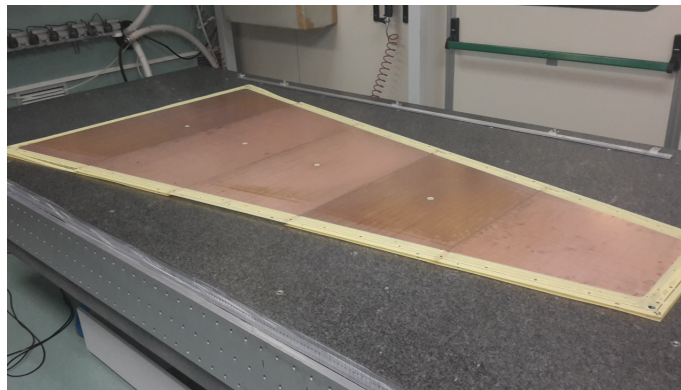


Figure 4.2. Photo of one of the central panels assembled in Roma1.

Printed Circuit Board

The basis for the operation of the drift panels are the Printed Circuit Boards (PCBs), 500 μm thick fiberglass¹ of various sizes, on which, with a lithographic techniques, a film of copper of about 17 μm is deposited, as shown in Figure 4.3.

Each single panel is composed by 10 PCBs (5 for each side) arranged as shown in Figure 2.7 (*right*) which are the “skins” of the panel.

¹The Fiberglass is a composite material made of glass fibers arranged orthogonally between two layers in an epoxy matrix, widely used as an insulator, present in many electronic devices, including household appliances and power tools.

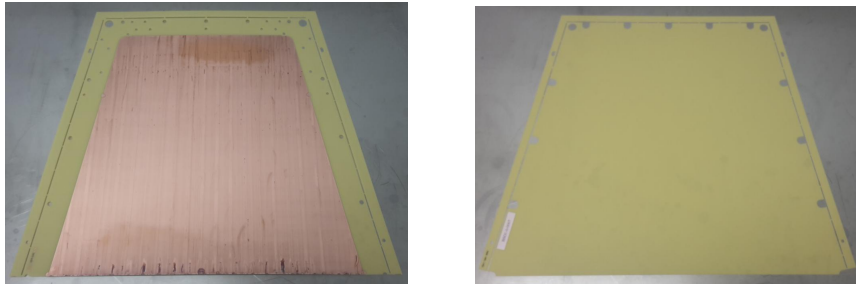


Figure 4.3. *Left:* Photo of one drift PCB (PCB 1, the smallest one) used for building SM1 drift panels. One can see the thin layer of $17\ \mu\text{m}$ copper over the yellow coat of fiberglass.
Right: Photo of one PCB (PCB 1, the smallest one) used for the outer drift panels of SM1.

Honeycomb

The internal structure of each panel is made of $10.1\ \text{mm}$ thick aluminium honeycomb sheets, shaped according to the shape of the PCB (Figure 4.4), to make the panel rigid and at the same time lightweight.



Figure 4.4. Photo of one cut aluminium honeycomb sheet.

Frame

Frames, as the honeycomb, are used to support the drift panel; each frame has several holes for the ground connections for the screwing with the rest of the Q-plet and for spacial screws used to tighten the so called Zebra connector compression bars (the method used to allow the read-out of the strips).

Each panel has 10 frame bars: 6 are along the perimeter and other 4 are transversal, as shown in Figure 4.5.

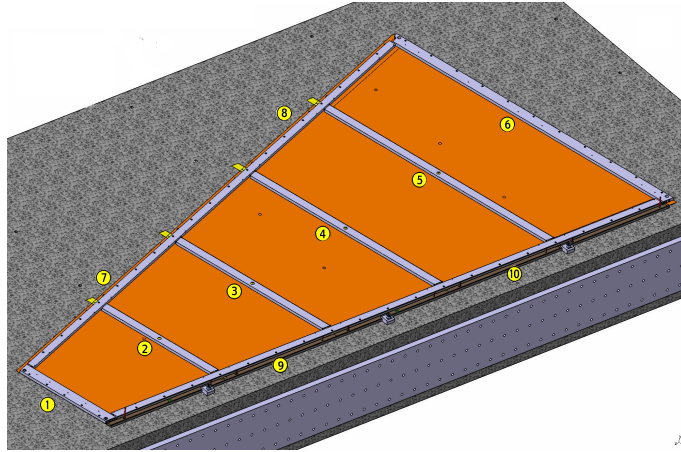


Figure 4.5. Picture of the position of the frames in each SM1 drift panel.

Interconnections

Each panel will be assembled to compose the MM module with the 4 gas gaps. To connect the various panels (drift and read-out) to each other but above all to keep the distance between them once an over pressure is created in the gaps to the gas flushing, interconnections are used that are integrated into each panel and are centred on each PCB (except for the first, the smallest, that has no interconnections). In Figure 4.6 there is a photo of one of the interconnections used for the drift panels in Roma1.

The position of the interconnections in the panel will be described in Section 4.3.



Figure 4.6. Photo of one of the interconnections used for the drift panels in Roma1.

HV connectors and Gas pipe

Other important components of each panel are the HV connectors (Figure 4.7 - *left*), mounted laterally on each panel, used to connect the 300 V to the whole coppered area of the panel to make sure that it works correctly as a cathode.

The gas pipes (Figure 4.7 - *middle*) are arranged in both bases of the trapeze and are used to enter the mixture of $Ar : CO_2$ inside each gap and to provide the exit.

In Figure 4.7 - *right*) is shown the position of the gas pipes and the HV connectors in the panel during the construction phase.



Figure 4.7. *Left:* Photo of HV connector used for the drift panels in Roma1.

Middle: Photo of the gas pipe used for the drift panels in Roma1.

Right: Zoom of the region of the first PCB during the construction phase. Is shown the position inside the panel of the honeycomb cutted sheet, the HV connectors and the gas pipes.

4.2 Components QA/QC measurements

As mentioned above, the quality control measurements are a very important procedure to make sure that the panels built with their components respect the request of the ATLAS collaboration. All measurements were done by randomly selecting a sample of about 10% of the entire production.

4.2.1 Frames

The thickness of the frame bars were measured in Pavia before their machining, that is before the holes needed to attach the mesh on the drift panels are drilled. These measurements were done in two different ways:

- the ON/OFF system which directly measured the thickness through a comparator (Figure 4.8 - *left*);
- the laser system (Figure 4.8 - *right*).



Figure 4.8. Photo of the two measurement systems: *left* is shown the ON/OFF system while *right* is show the laser system [27].

The Laser system is the device that we intend to use for bar QA/QC. We additionally used ON/OFF system to check the absolute calibration of the laser measurements system. In Figure 4.9 the thickness measurements done with the laser system are shown for each frame bars type. All measurements are within specification apart for type 4 bars.

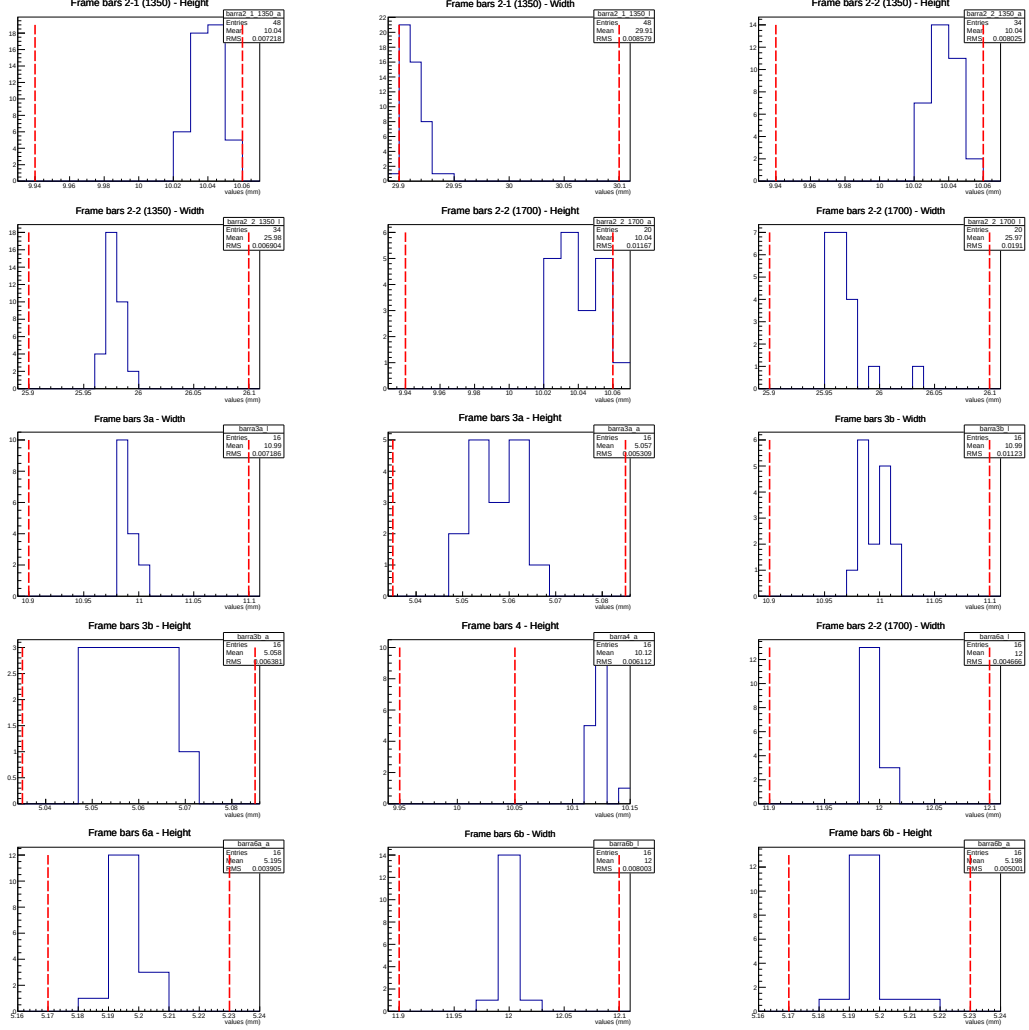


Figure 4.9. In each plot, the measurements of the bar thickness done, with the laser system, for each frame bars type are shown. It is possible to see, between the two red lines, the tolerances region imposed by the ATLAS collaboration. For type 4 bars, measurements are out of nominal range.

For type 4 bars, the measurements were repeated with the ON/OFF system and all measurements were compatible within tolerance ranges. This has led to the suspect that there could be a systemic error, for the measurements done with the laser, due to the work piece width, which is, for type 4 bars about twice as large as the other pieces.

It has been verified that a systematic error is actually present in the laser measurements when increasing the piece width. Figure 4.11 (*left*) shows the difference

between the measured height and its nominal value as a function of the nominal width of all the bars. Making a linear fit ($y = p1 \cdot x + p0$), it comes out that the slope is not compatible with zero ($p1 = (2.386 \pm 0.033) \cdot 10^{-3}$). On the other hand, by doing the same kind of measurements for calibrated bars, no mis-calibration in the laser system measurements is observed. Infact, for the fit of the calibrated bars, the slope is compatible with zero ($p1 = (3.5 \pm 5.4) \cdot 10^{-4}$), as shown in Figure 4.11 (*right*).



Figure 4.10. Transversal section of the frame bars (*left*) and of the calibrated bars (*right*).

The conclusion is that even type 4 bars are within the nominal values, the systematic error must be due to the particular shape (Figure 4.10) of these bars. Bars type 4 can be used for the construction of new SM1 drift panels.

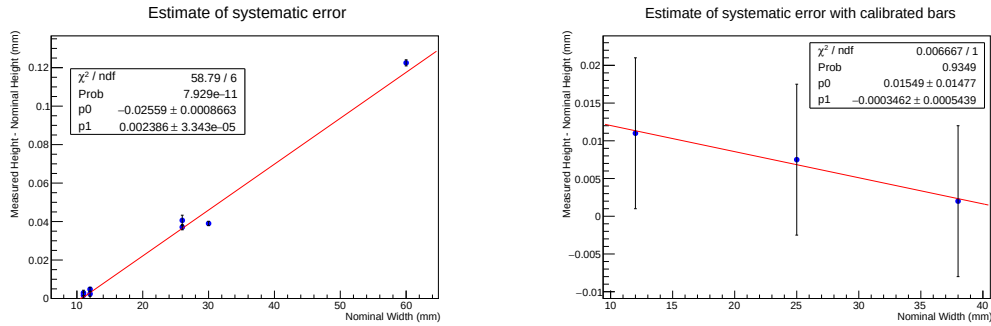


Figure 4.11. Difference between measured width and nominal height as a function of the nominal height for the SM1 frame bars measured in Pavia (*left*) and some calibrated bars also measured with the same method in Pavia (*right*). The error bars are the RMS of the measurements done. A systematic error is observed in the frame bars measurements.

4.2.2 PCB

The PCB thickness was measured in Roma1 INFN section with the Limbo system that is composed by 10 comparators that measure the difference between the plane and the surface where the sensors are laying, as shown in Figure 4.12 (*left*).

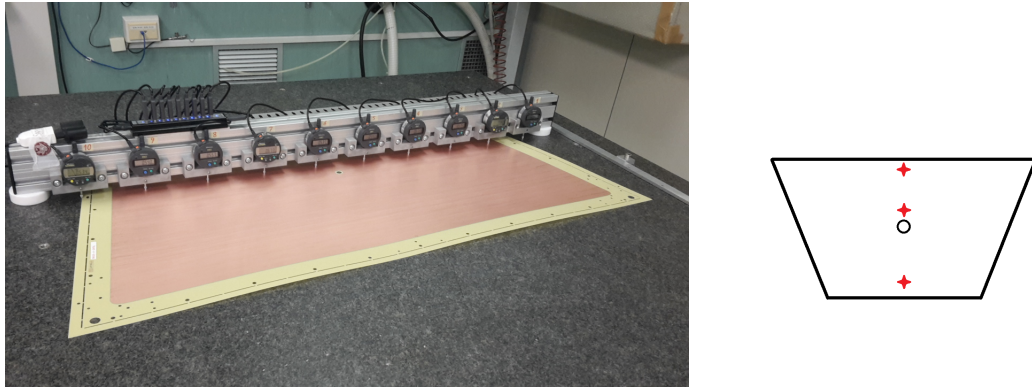


Figure 4.12. *Left:* Photo of Limbo measure system during a PCB thickness measurement. *Right:* Schematic picture of how the thickness measurements of each PCB are taken.

Due to the flexibility of the boards it has been necessary to put weights near the measurement point; only three/four measurements (the value read by the central comparator) were taken for each PCB, as shown in Figure 4.12 (*right*).

In Figure 4.13 are reported, for each type of PCB, the measured thickness values of the selected PCB sample for the *board small drift* (BSD) and the *board small outer* (BSO) (*up*) and its differences between nominal values (*down*).

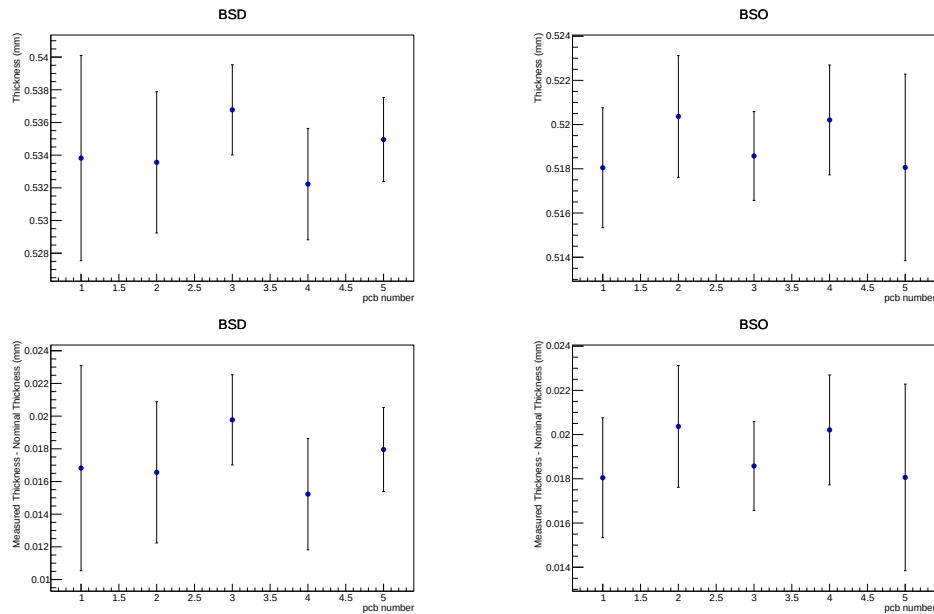


Figure 4.13. *Up:* Average thickness for the BSD and BSO PCB sample. *Down:* Differences between the measured thickness and the nominal thickness for each type of PCB. The error bars are the RMS of the measurements done.

As shown in Figure 4.13 (*down*), the average thickness of each type of PCB are slightly larger than the nominal values ($15 - 20 \mu m$) but are still within the bounds of tolerance. To ensure that there is no offset in the measurements, a recalibration

of the Limbo is made using calibrated bars of 0.060 mm , 1.000 mm , 2.000 mm , 3.000 mm , 5.000 mm and 6.000 mm . Ten measurements for each bar (using all calipers) are done and the results are shown in Figure 4.14.

No significant offset in the previous measurements is observed.

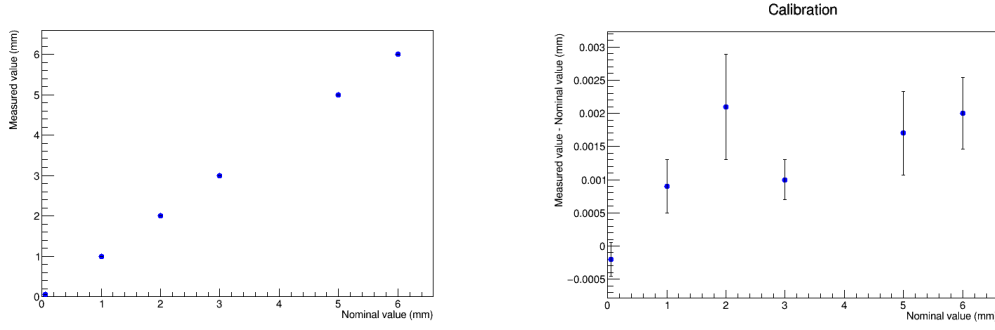


Figure 4.14. *Left:* Measured value as a function of the Nominal values of the calibrated bars. Each measurement is done by using all calipers of the Limbo; the associated error are smallest than the blue point.

Right: Differences between the measured value and the nominal value for each type of calibrated bars. The error bars are the RMS of the measurements done.

4.2.3 Interconnections set 1 (built in South Africa)

The interconnections were measured in Frascati INFN section (LNF) by the Metrology Service using the Quadra Chek 200 [25].

In Figure 4.15 the measured quantities of each interconnection type are shown and in Figure 4.16 the results of all measurements are shown. All values are within the set tolerances.

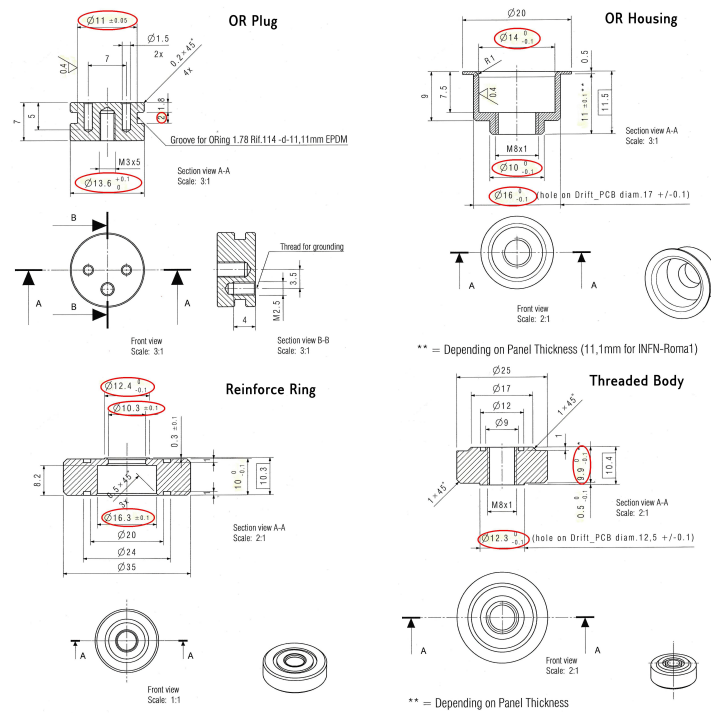


Figure 4.15. Project design of the interconnections. In red are highlighted the measured quantities.

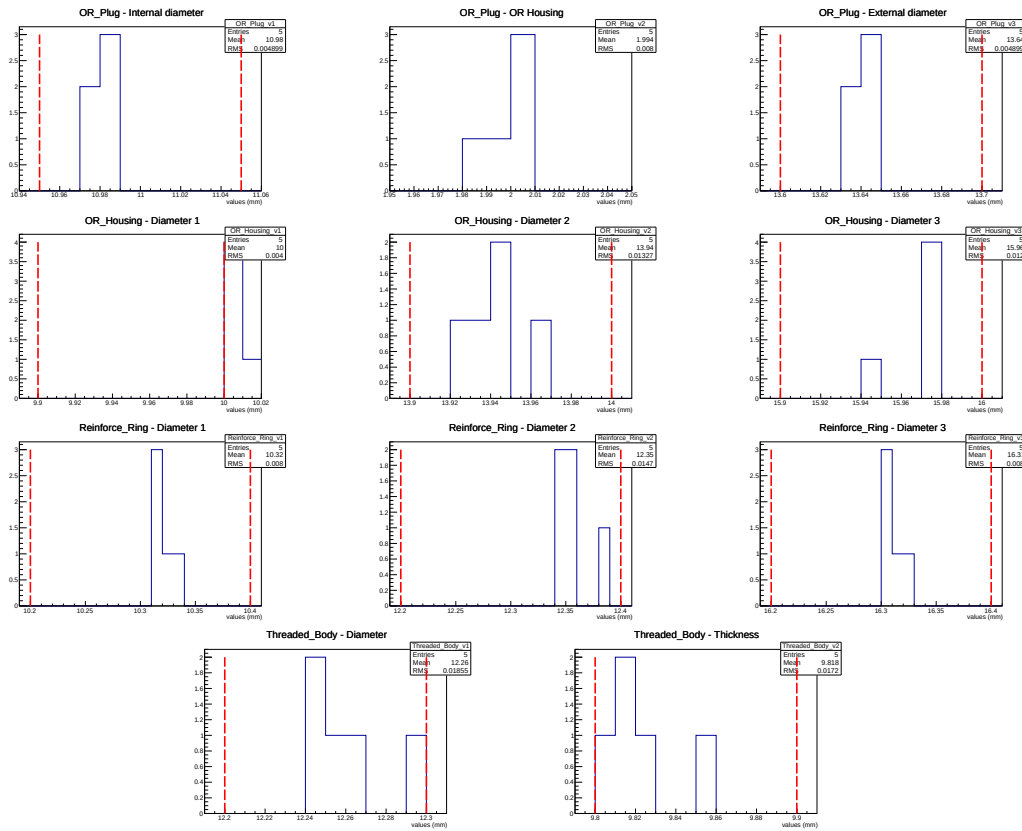


Figure 4.16. Measurements made for each values of each interconnection type. It is possible to see, between the two red lines, the tolerances region imposed by the ATLAS collaboration.

4.2.4 Interconnections set 2 (built in MBC Company)

The MBC Company interconnections were measured at MBC Company by the INFN technicians using the Mitutoyo IP67 digital caliper.

In Figure 4.17 the measured quantities of each interconnection type are shown and in Figure 4.18 and 4.19 the results of all measurements are shown. All values are within the set tolerances.

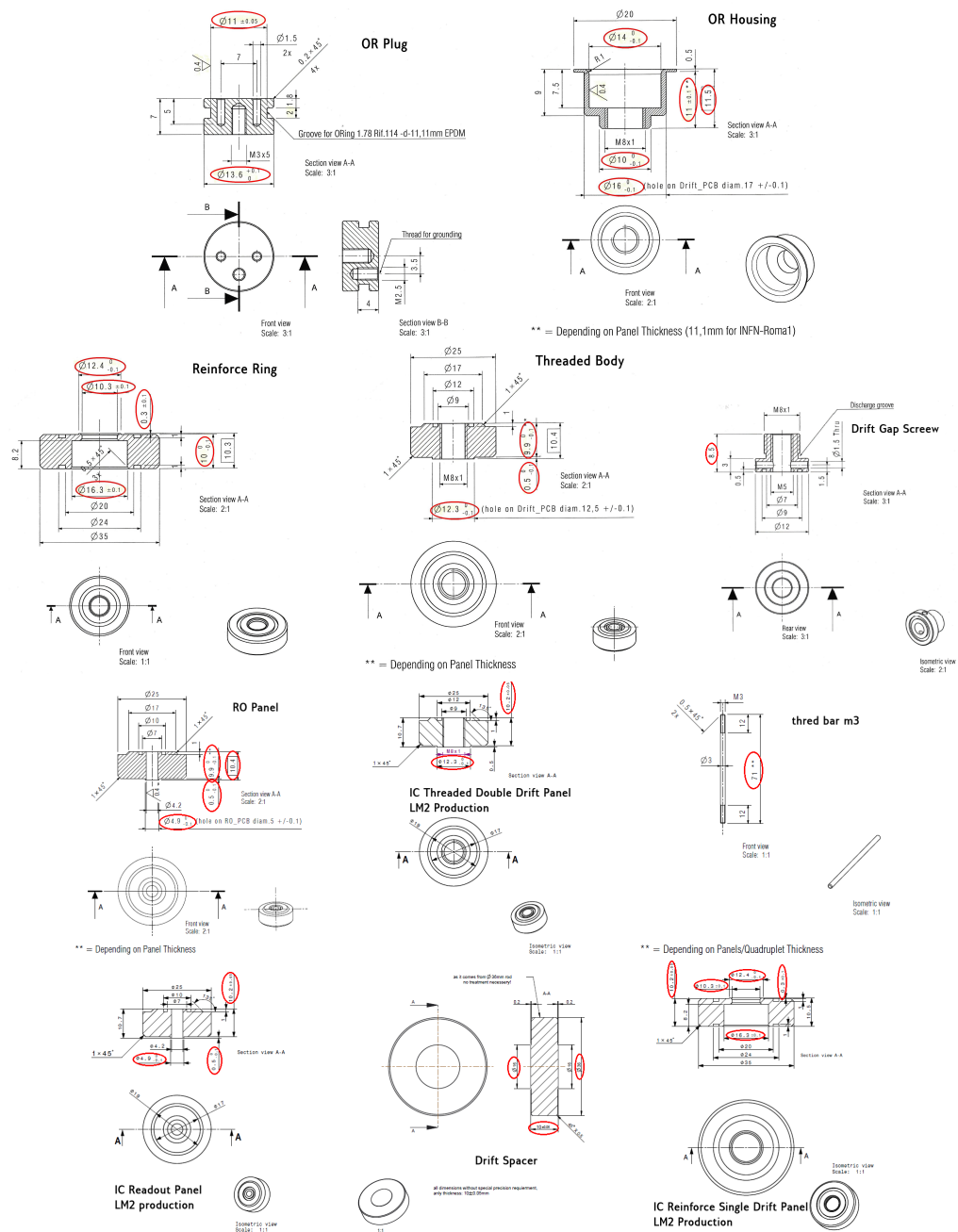


Figure 4.17. Project design of the interconnections. In red are highlighted the measured quantities.

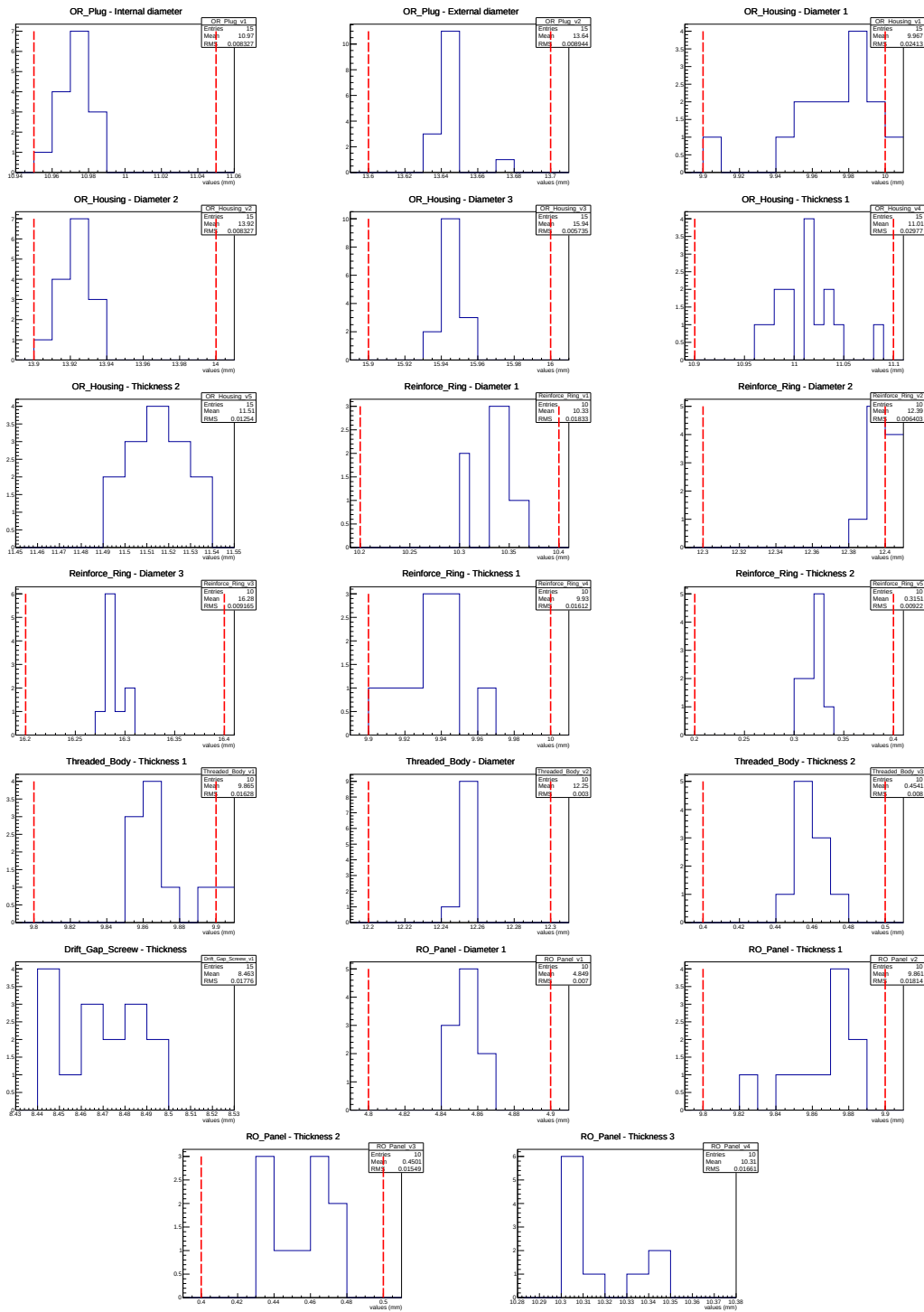


Figure 4.18. Measurements made for each values of each interconnection type. It is possible to see, between the two red lines, the tolerances region imposed by the ATLAS collaboration.

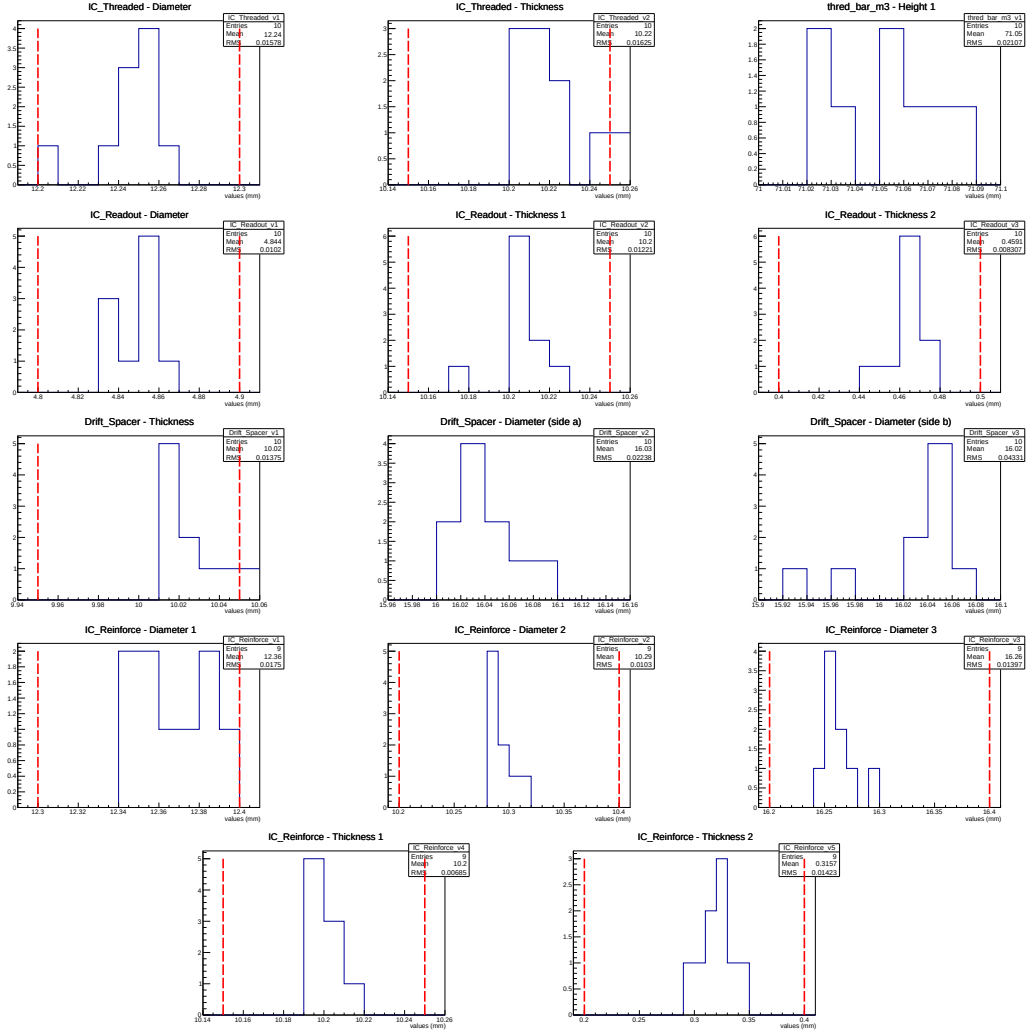


Figure 4.19. Measurements made for each values of each interconnection type. It is possible to see, between the two red lines, the tolerances region imposed by the ATLAS collaboration.

All interconnections (samples from production in South Africa and in MBC company) are within tolerances.

4.2.5 Honeycomb

The honeycomb thickness (nominal value: $10.1 \pm 0.06 \text{ mm}$) was measured in Roma1 INFN section with the Mitutoyo Linear Height 600 [26] that is composed by one comparator that measures the difference between the plane and the surface where the sensor is laying, as shown in Figure 4.20 (*left*). Over the honeycomb cut sheet some weights (lead) have been placed to prevent a bending of the sheet which could affect the thickness measurements.

In Figure 4.21 and 4.22 are reported, for each type of cut honeycomb, the measured thickness values. These honeycombs were later used for the construction of two drift panels.

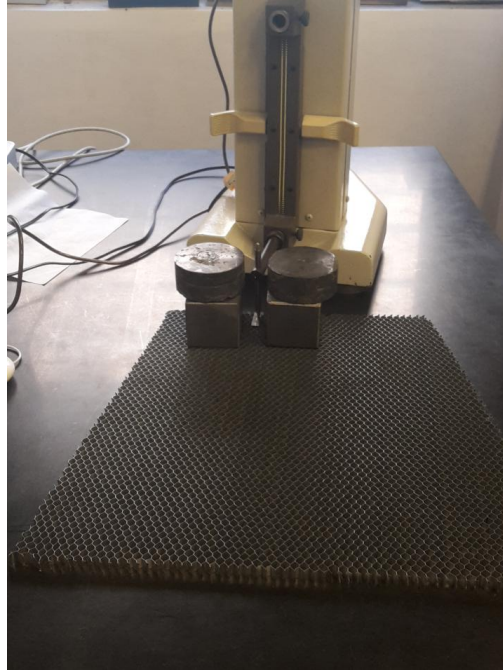


Figure 4.20. Photo of Mitutoyo Linear Height 600 during a honeycomb thickness measurement. Over the honeycomb cut sheet have been placed some weights (lead) to prevent the bending of the sheet.

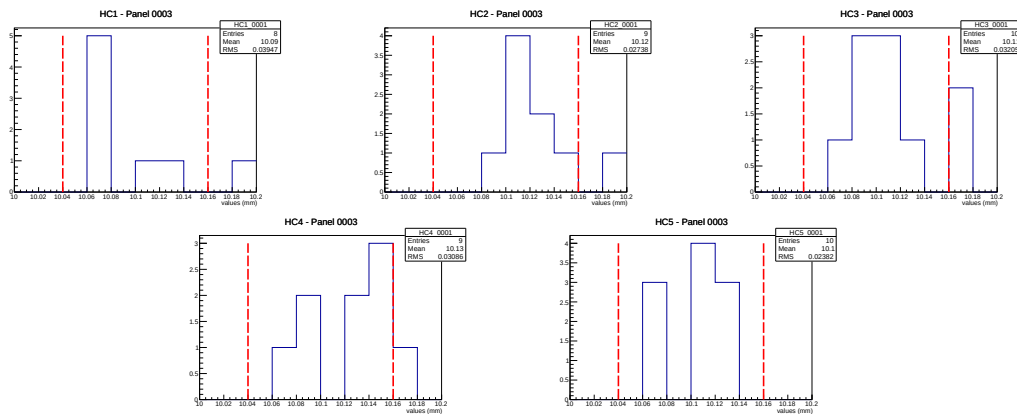


Figure 4.21. Measured thickness for each type of honeycomb which was used for the construction of the drift panel 3.

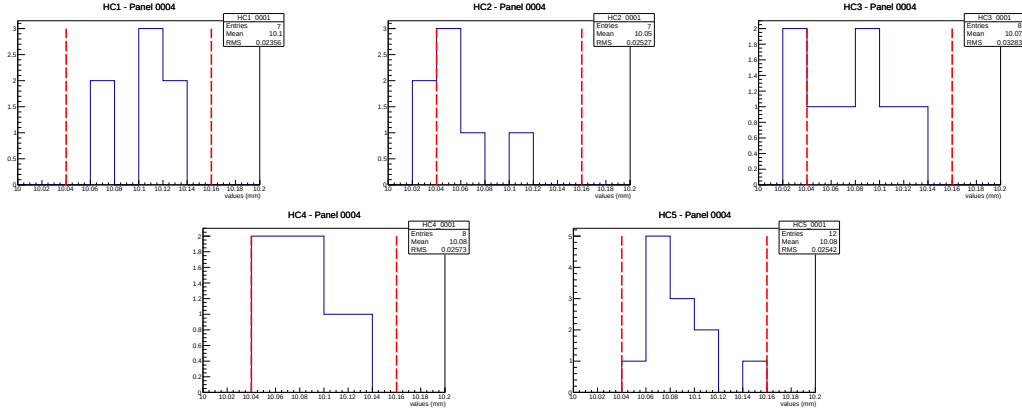


Figure 4.22. Measured thickness for each type of honeycomb which was used for the construction of the drift panel 4.

4.3 Drift Panel construction

The drift panels of the SM1 modules are assembled using the *vacuum bag method* which will be discussed in this section.

The construction procedure of the drift panels is designed to build a drift panel in one day and therefore, considering that the used glue (Araldite 2011) begins to dry after 80/90 minutes in contact with air and takes few hours for complete its gluing action, all the actions are done in 1-2 hours and then 24 hours are left for complete glue curing. This requires a good organization for the time optimization. Furthermore, to be sure that there are no impurities (especially dust) that can enter in the panel and damage its operation, all the construction procedure takes place in a *clean room*.

Inside the clean room there is a granite table (its planarity was previously measured and it is below $10 \mu m$) that needs to be cleaned before each operation to ensure the construction of a perfectly planar panel (the ATLAS requirement is a thickness $RMS < 37 \mu m$).

Precision is the key for building a good panel infact all machining is done prior to panel assembly. An aluminium bar, with several removable precision pins, is mounted on the granite table and will be used as a guide for the PCBs placement and it is also necessary to ensure that the PCBs are aligned.

The first step consists in distributing the glue on the PCBs with a special gluing machine equipped with a mechanical arm, as shown in Figure 4.23, before transferring them to the granite table.

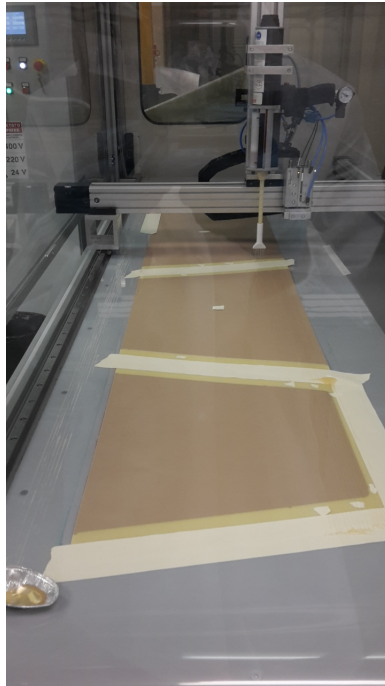


Figure 4.23. Photo of the gluing machine during the type 1, 2 and 3 PCB bonding step. To prevent that the glue being deposited in the PCB holes, these are covered with tape.

The precision holes of the biggest PCB (the type 5) are aligned with respect to the aluminium bar holes and are fixed using two precision pins. The remaining four PCBs are then aligned relative to the biggest and to the aluminium bar in the same way. In addition, a strip of kapton is fixed at the ends of two nearby PCBs in order to set better the distance between the PCBs (and to avoid their overlapping) and to avoid gas leaking in the regions between the PCBs, as shown in Figure 4.24.

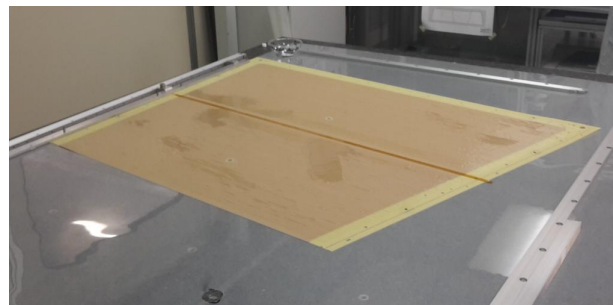


Figure 4.24. Photo of type 5 and 4 PCBs placed on the granite plane fixed to the aluminium bar with the precision pins. A strip of kapton on these PCBs is fixed as shown.

The honeycomb and the frame bars are placed on the glued PCB and aligned relative to the PCBs using pins in other holes as shown in Figure 4.25 and 4.26.

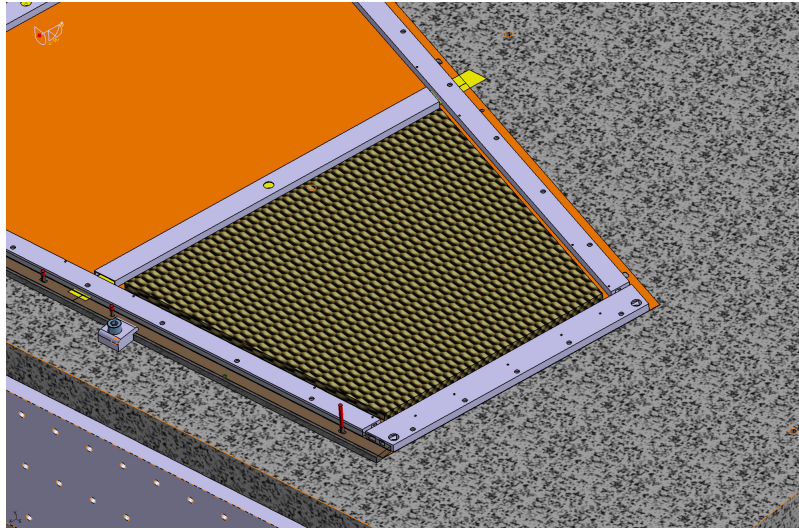


Figure 4.25. Schematization of the position of the honeycomb on the PCBs [27].

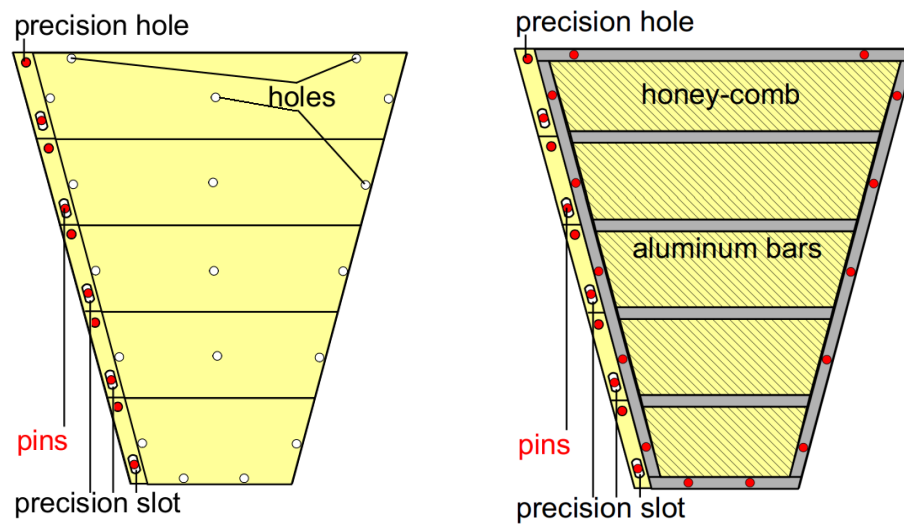


Figure 4.26. Scheme of the PCBs, honeycomb and frame bars position during a panel assembling.

Interconnections, HV connectors and gas pipes are positioned after, as shown in Figure 4.27. In addition, during the construction, the honeycomb sheets are electrically connected to the frames for subsequently grounding them.

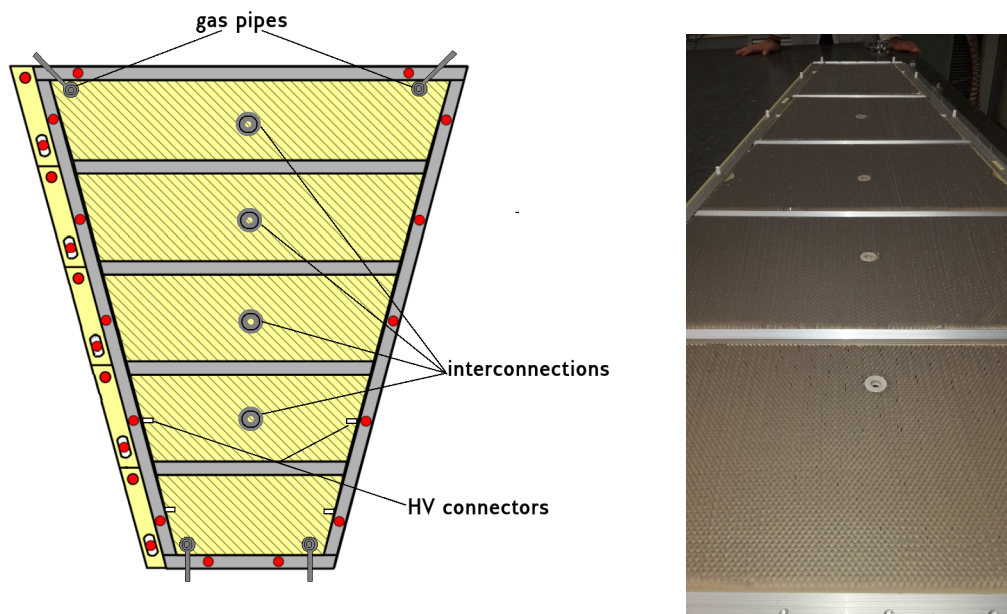


Figure 4.27. Scheme of the interconnections, HV connectors and gas pipes position during a panel assembling.

The second layer of PCBs is then placed on top for closing the panel. On the upper PCBs, is positioned a mask (see Figure 4.28), then a vacuum bag covers the sandwich and the air is pumped out, pressing the components against the granite table, as shown in Figure 4.29.

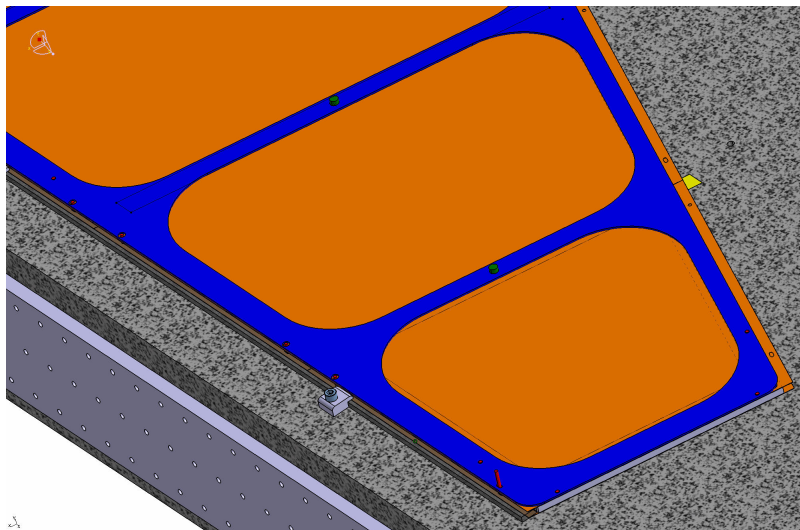


Figure 4.28. Schematization of the position of the mask on the upper PCBs for pressing the panel [27].

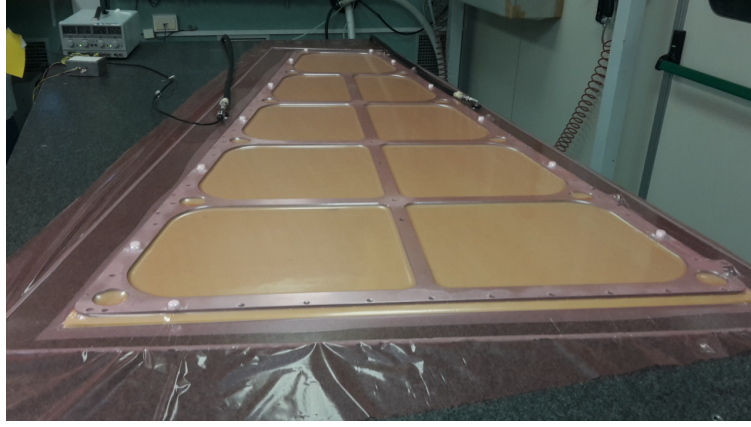


Figure 4.29. Photo of one drift panel after its assembly. The mask and the vacuum bag are shown in this photo.

4.4 Drift panels QA/QC

The drift panels quality control measurements are very important to ensure that they work properly.

These measurements are based on the control of the planarity of the panel and its dark current (HV test).

4.4.1 Planarity measurements

The ATLAS request for the drift panel planarity are an $\text{RMS} < 37 \mu\text{m}$ and a difference between the maximum and the minimum value $220 \mu\text{m}$. The thickness measurements are made using the Limbo (Figure 4.12) of the Roma1 INFN section. For each panel a grid $10 \times 14 \text{ cm}^2$ of measurements (~ 130 points per face) is done on the x-y plane (which corresponds to the granite plane on which the panel is located) using the 10 limbo comparators that will measure the panel height (thickness).

For the outer panels, the “in side” represents the coppered side while for the central panels, the “A side” and the “B side” are the two coppered side. Figures 4.30 - 4.37 present the results of the planarity measurements for the eight panels built so far. In each plot is shown the raw thickness distribution of the two sides of the panels (*up*) and the bi-dimensional plot of the panels (*middle - up*) where the colors represent the thickness of each measured point.

Furthermore, in the same figures distributions of residuals obtained with respect to the “best plane” ($f(x, y) = a \cdot x + b \cdot y + c$) where c corresponds the fitted thickness and a and b correspond to the inclination of the panel) are shown (*middle-down* and *down*).

The Table give the results in terms of RMS and max-min average thickness.

Outer panel *no.* 1

	Side in	Side out
raw thickness	11.21 mm	11.17 mm
raw RMS	41 μm	60 μm
max-min raw	203 μm	266 μm
fitted thickness	11.21 mm	11.17 mm
fitted RMS	38 μm	59 μm
max-min after fit	208 μm	281 μm

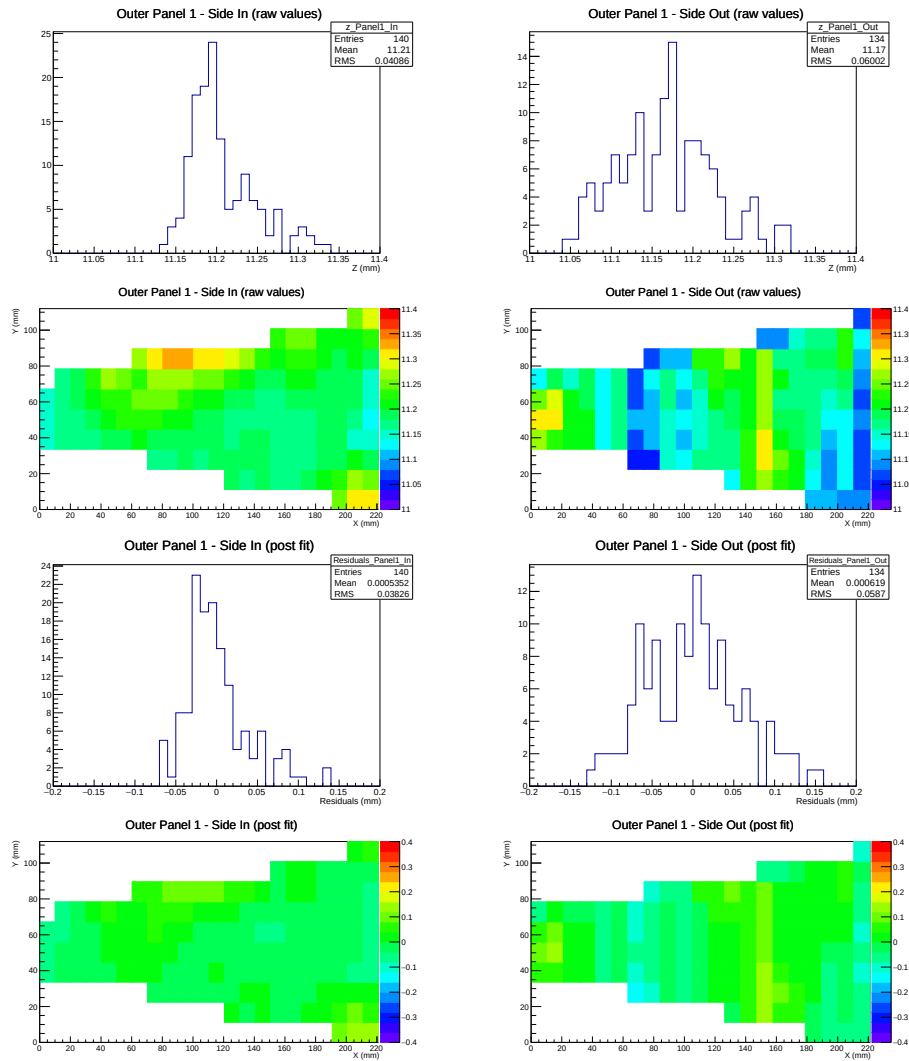


Figure 4.30. *Left:* Side in - *Right:* Side out. *Up:* raw thickness distribution of the two side of the outer panel *no.* 1. *Middle- up:* Bi-dimensional plot of the outer panel *no.* 1; coloured is represented the thickness (in mm) of the measured point. *Middle - down:* residual thickness distribution of the two side of the outer panel *no.* 1. *Down:* Bi-dimensional plot of the outer panel *no.* 1; coloured is represented the residual value (in mm) of the measured point.

Outer panel *no. 2*

	Side in	Side out
raw thickness	11.22 mm	11.17 mm
raw RMS	27 μm	50 μm
max-min raw	132 μm	243 μm
fitted thickness	11.22 mm	11.17 mm
fitted RMS	25 μm	49 μm
max-min after fit	133 μm	247 μm

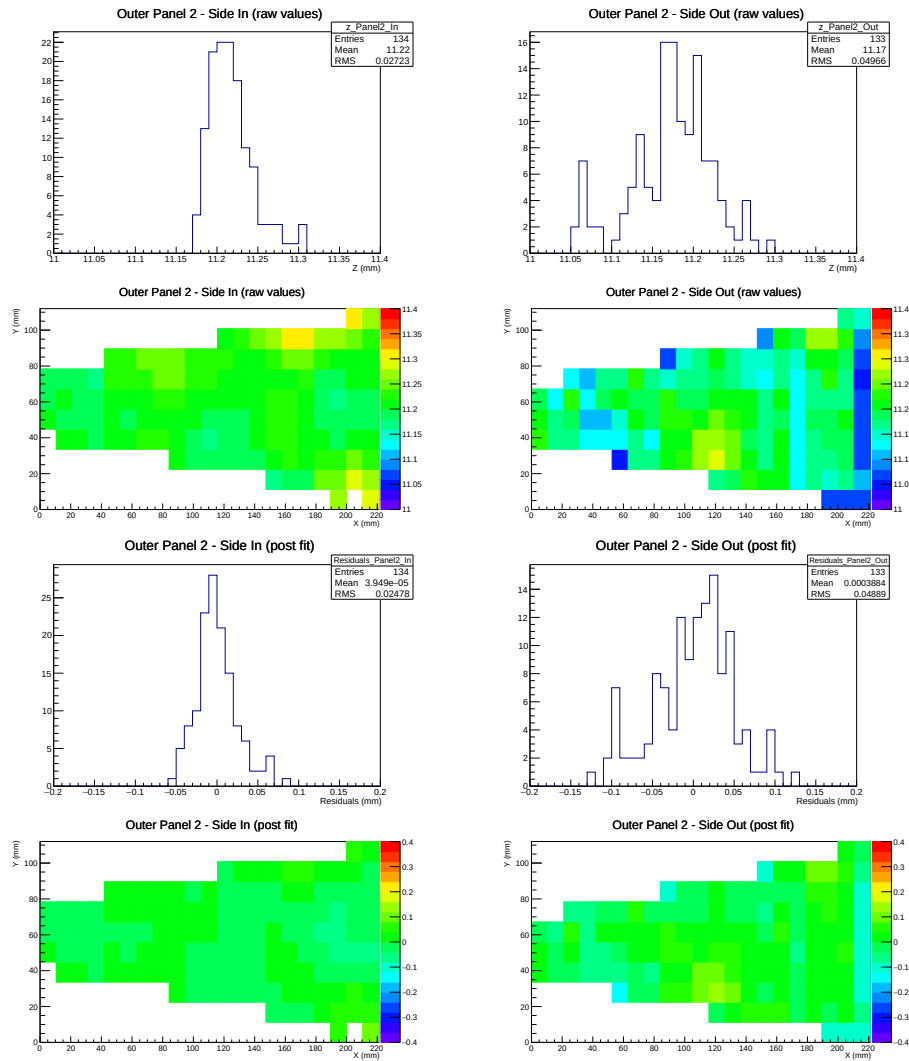


Figure 4.31. *Left: Side in - Right: Side out. Up: raw thickness distribution of the two side of the outer panel no. 2. Middle- up: Bi-dimensional plot of the outer panel no. 2; coloured is represented the thickness (in mm) of the measured point. Middle - down: residual thickness distribution of the two side of the outer panel no. 2. Down: Bi-dimensional plot of the outer panel no. 2; coloured is represented the residual value (in mm) of the measured point.*

Outer panel *no.* 3

	Side in	Side out
raw thickness	11.23 mm	11.18 mm
raw RMS	36 μm	32 μm
max-min raw	199 μm	159 μm
fitted thickness	11.23 mm	11.18 mm
fitted RMS	34 μm	31 μm
max-min after fit	250 μm	160 μm

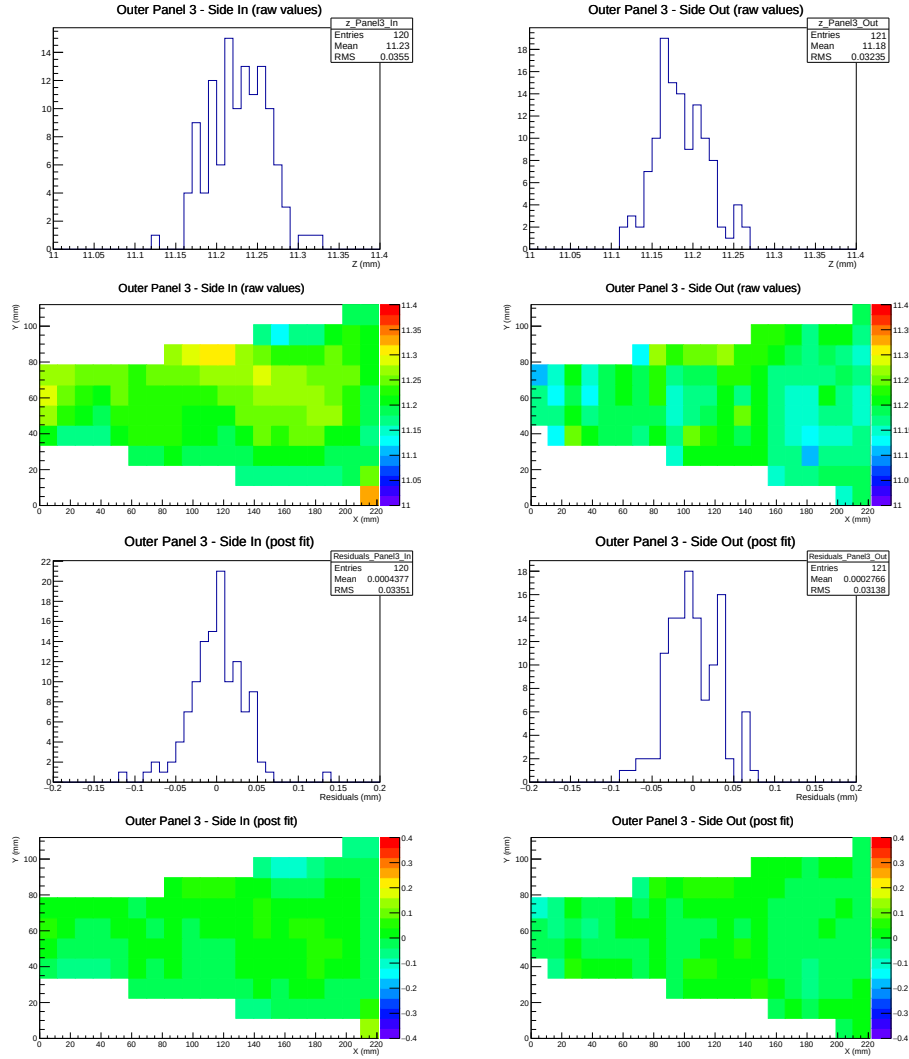


Figure 4.32. *Left:* Side in - *Right:* Side out. *Up:* raw thickness distribution of the two side of the outer panel *no.* 3. *Middle- up:* Bi-dimensional plot of the outer panel *no.* 3; coloured is represented the thickness (in mm) of the measured point. *Middle - down:* residual thickness distribution of the two side of the outer panel *no.* 3. *Down:* Bi-dimensional plot of the outer panel *no.* 3; coloured is represented the residual value (in mm) of the measured point.

Outer panel *no.* 4

	Side in	Side out
raw thickness	11.19 <i>mm</i>	11.13 <i>mm</i>
raw RMS	31 μm	39 μm
max-min raw	161 μm	193 μm
fitted thickness	11.19 <i>mm</i>	11.13 <i>mm</i>
fitted RMS	30 μm	36 μm
max-min after fit	297 μm	338 μm

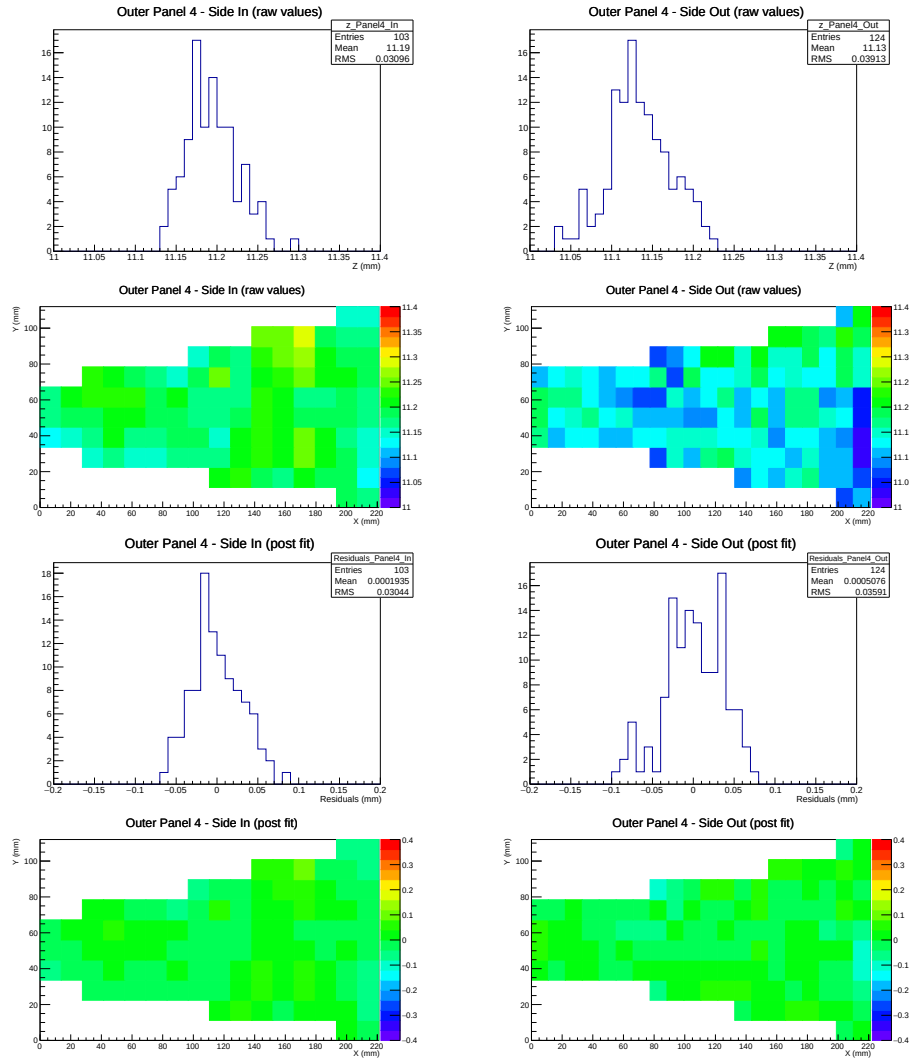


Figure 4.33. *Left: Side in - Right: Side out. Up: raw thickness distribution of the two side of the outer panel no. 4. Middle- up: Bi-dimensional plot of the outer panel no. 4; coloured is represented the thickness (in mm) of the measured point. Middle - down: residual thickness distribution of the two side of the outer panel no. 4. Down: Bi-dimensional plot of the outer panel no. 4; coloured is represented the residual value (in mm) of the measured point.*

Outer panel *no. 5*

	Side in	Side out
raw thickness	11.20 mm	11.18 mm
raw RMS	34 μm	40 μm
max-min raw	205 μm	232 μm
fitted thickness	11.20 mm	11.18 mm
fitted RMS	34 μm	40 μm
max-min after fit	206 μm	238 μm

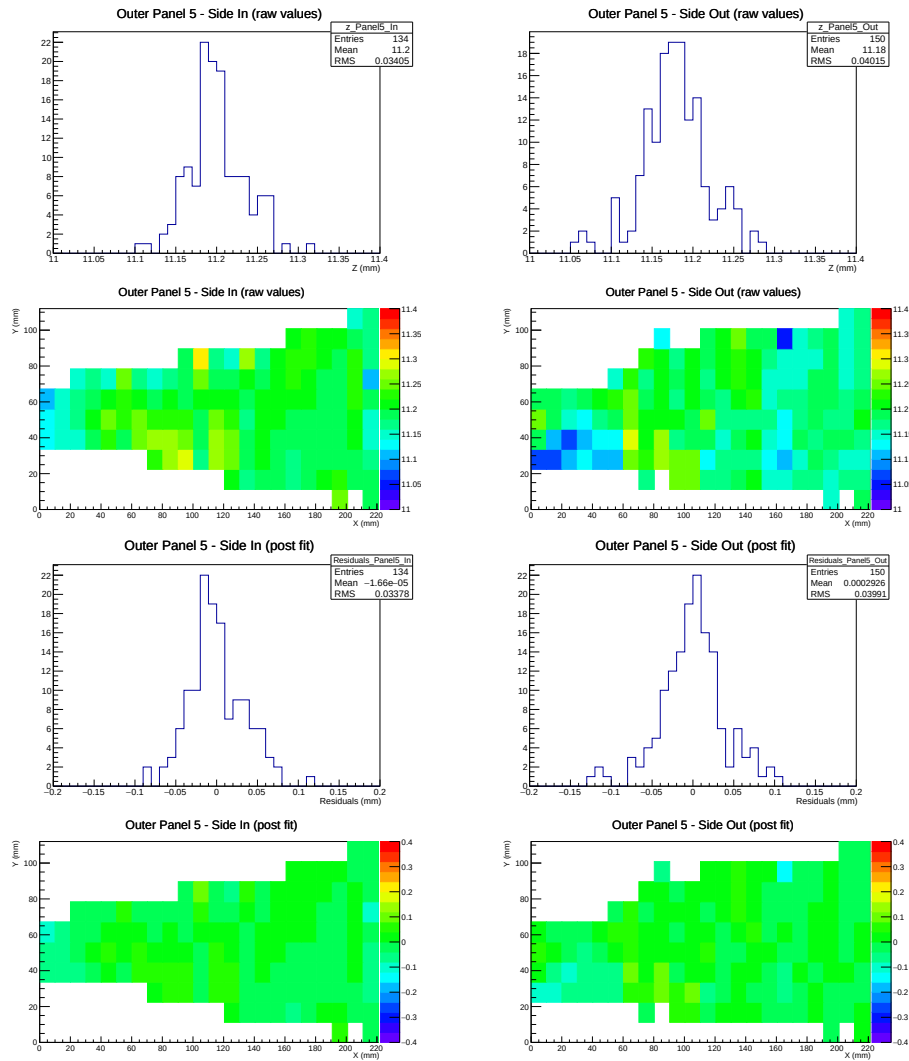


Figure 4.34. *Left:* Side in - *Right:* Side out. *Up:* raw thickness distribution of the two side of the outer panel *no. 5*. *Middle- up:* Bi-dimensional plot of the outer panel *no. 5*; coloured is represented the thickness (in mm) of the measured point. *Middle - down:* residual thickness distribution of the two side of the outer panel *no. 5*. *Down:* Bi-dimensional plot of the outer panel *no. 5*; coloured is represented the residual value (in mm) of the measured point.

Outer panel *no. 6*

	Side in	Side out
raw thickness	11.19 <i>mm</i>	11.29 <i>mm</i>
raw RMS	29 μm	47 μm
max-min raw	135 μm	236 μm
fitted thickness	11.19 <i>mm</i>	11.29 <i>mm</i>
fitted RMS	28 μm	44 μm
max-min after fit	151 μm	208 μm

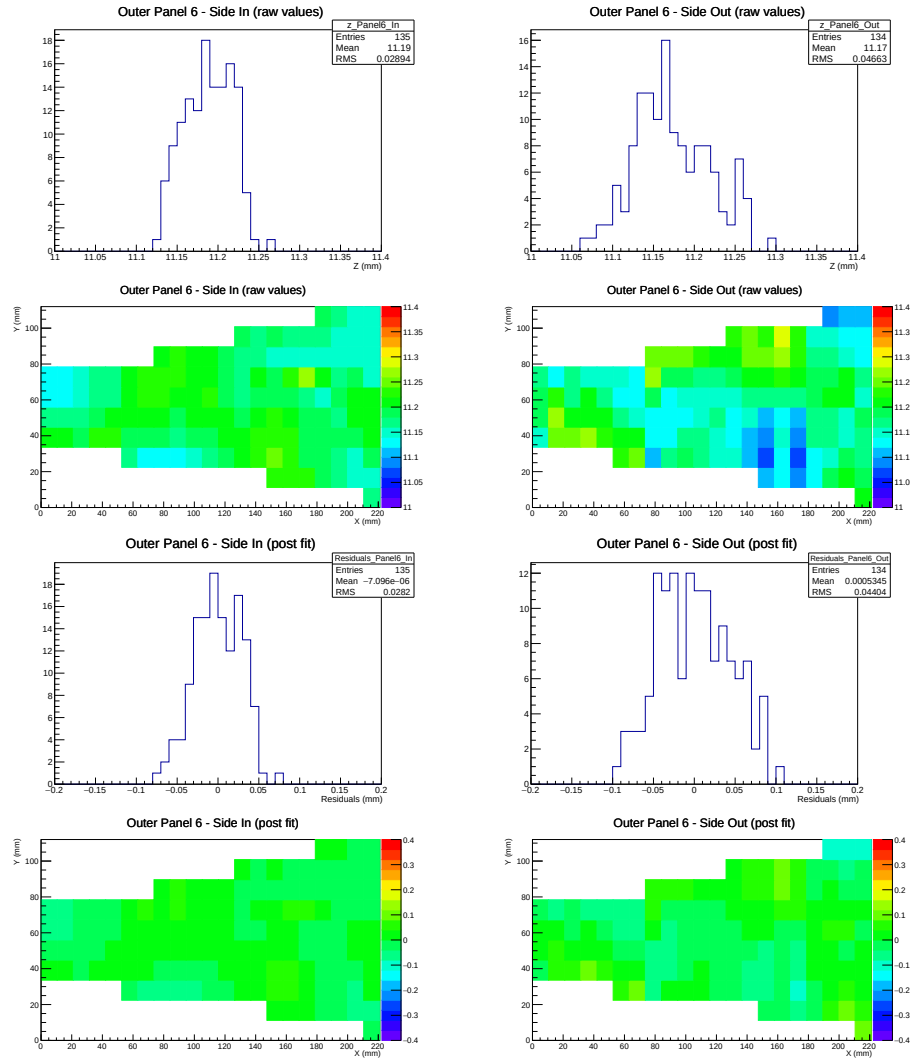


Figure 4.35. *Left: Side in - Right: Side out. Up: raw thickness distribution of the two side of the outer panel no. 6. Middle- up: Bi-dimensional plot of the outer panel no. 6; coloured is represented the thickness (in mm) of the measured point. Middle - down: residual thickness distribution of the two side of the outer panel no. 6. Down: Bi-dimensional plot of the outer panel no. 6; coloured is represented the residual value (in mm) of the measured point.*

Central panel *no.* 1

	Side A	Side B
raw thickness	11.18 <i>mm</i>	11.20 <i>mm</i>
raw RMS	42 μm	56 μm
max-min raw	266 μm	295 μm
fitted thickness	11.18 <i>mm</i>	11.20 <i>mm</i>
fitted RMS	37 μm	42 μm
max-min after fit	215 μm	251 μm

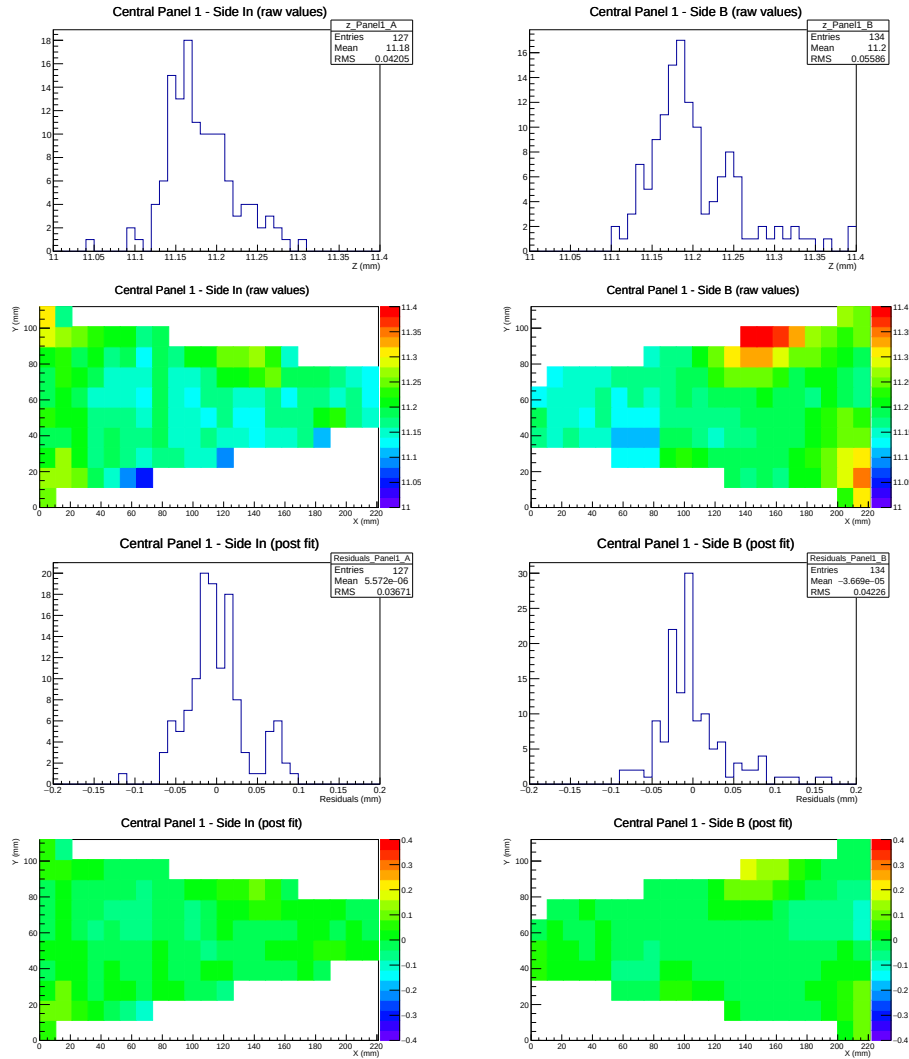


Figure 4.36. *Left:* Side A - *Right:* Side B. *Up:* raw thickness distribution of the two side of the central panel *no.* 1. *Middle- up:* Bi-dimensional plot of the central panel *no.* 1; coloured is represented the thickness (in *mm*) of the measured point. *Middle - down:* residual thickness distribution of the two side of the central panel *no.* 1. *Down:* Bi-dimensional plot of the central panel *no.* 1; coloured is represented the residual value (in *mm*) of the measured point.

Central panel *no. 2*

	Side A	Side B
raw thickness	11.23 mm	11.21 mm
raw RMS	27 μm	46 μm
max-min raw	114 μm	221 μm
fitted thickness	11.23 mm	11.21 mm
fitted RMS	26 μm	43 μm
max-min after fit	114 μm	220 μm

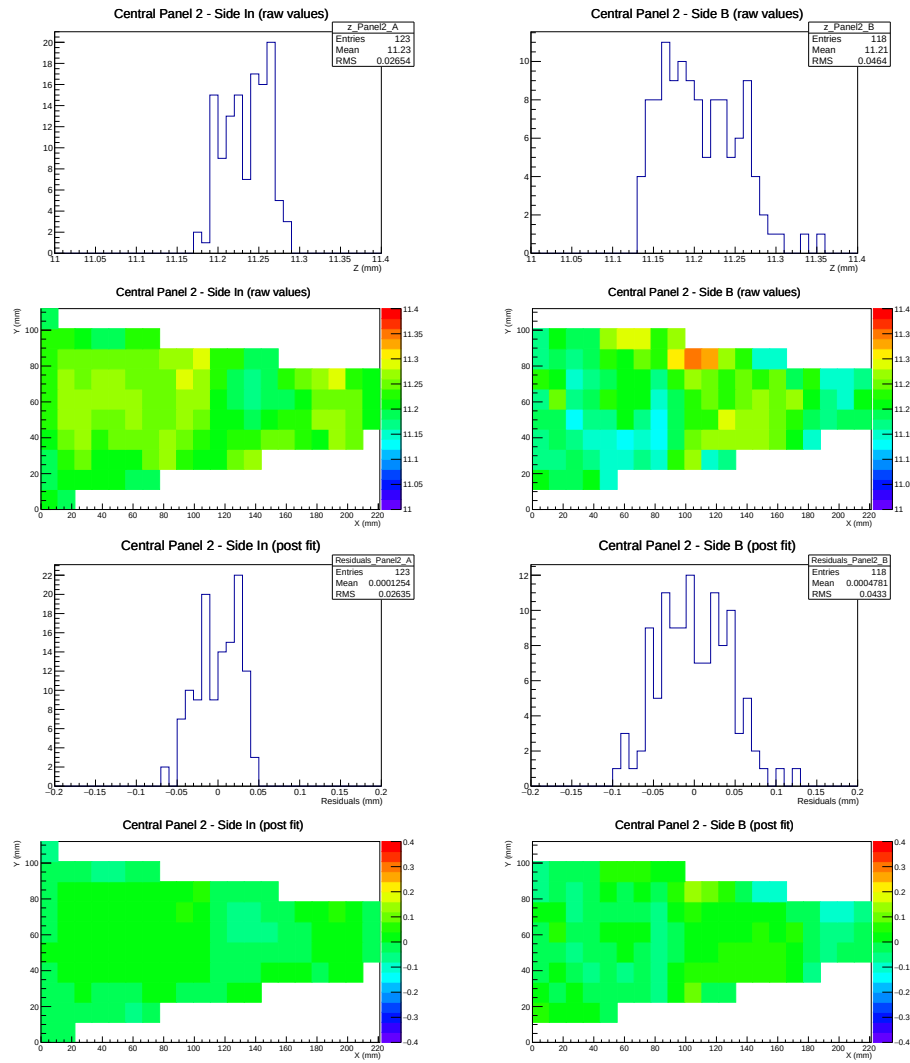


Figure 4.37. *Left: Side A - Right: Side B. Up: raw thickness distribution of the two side of the central panel no. 2. Middle- up: Bi-dimensional plot of the central panel no. 2; coloured is represented the thickness (in mm) of the measured point. Middle - down: residual thickness distribution of the two side of the central panel no. 2. Down: Bi-dimensional plot of the central panel no. 2; coloured is represented the residual value (in mm) of the measured point.*

4.4.2 Drift panel thickness

The drift panel thickness is determined mainly by the thickness of the honeycomb. As shown in Figure 4.38, a correlation between drift panels thickness and honeycomb thickness, with small fluctuations, is observed. This observation confirms that the construction method developed in Roma1 implies that the panel thickness depends on the thickness of the materials used, mainly on the honeycomb thickness, the other factors only marginally affect it.

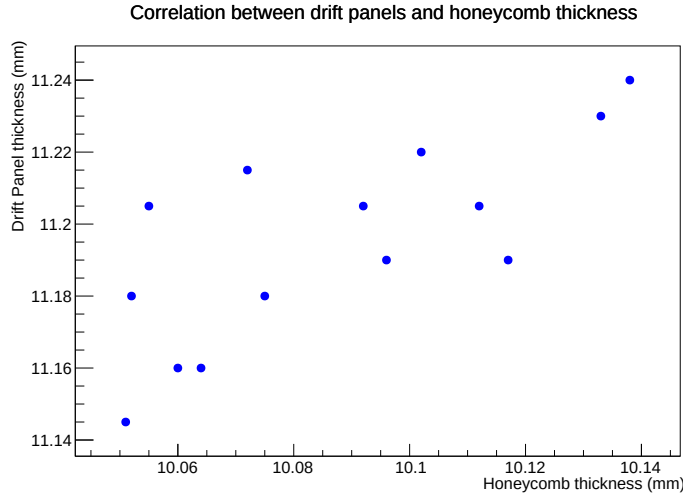


Figure 4.38. Correlation between drift panels and honeycomb thickness. The measurements of the drift panels thickness built so far are used.

4.4.3 HV test

The ATLAS request for the dark current is a value of order or below few nA . These measurements are done by connecting the coppered side of each PCB to each others and then connecting them to a generator of tension set to 1000 V as shown in Figure 4.39. The ground is connected to the honeycomb through one of the frame bar holes.

The measured dark current of panels shows a decrease after HV connection according to the typical capacitor expression $i(t) = \frac{V_0}{R} e^{-\frac{t}{\tau}}$ with $\tau = RC$ where R and C are respectively the resistance and the capacitance of the panel, until each panel has a current less than 5 nA (as required by ATLAS) after about an hour or less.

Only for the measurements of two panels (outer no. 6 and central no. 2), measured when high humidity (about 60-70%) in the clean room was present, the dark current was higher (order of 300 – 400 nA) than the specifications. The same measurements made at a humidity of 40% shows dark current values of the order of 10 nA , so there seems to be a correlation between measured current and humidity. This feature of the panels is subject to interest and will be further investigated in future.

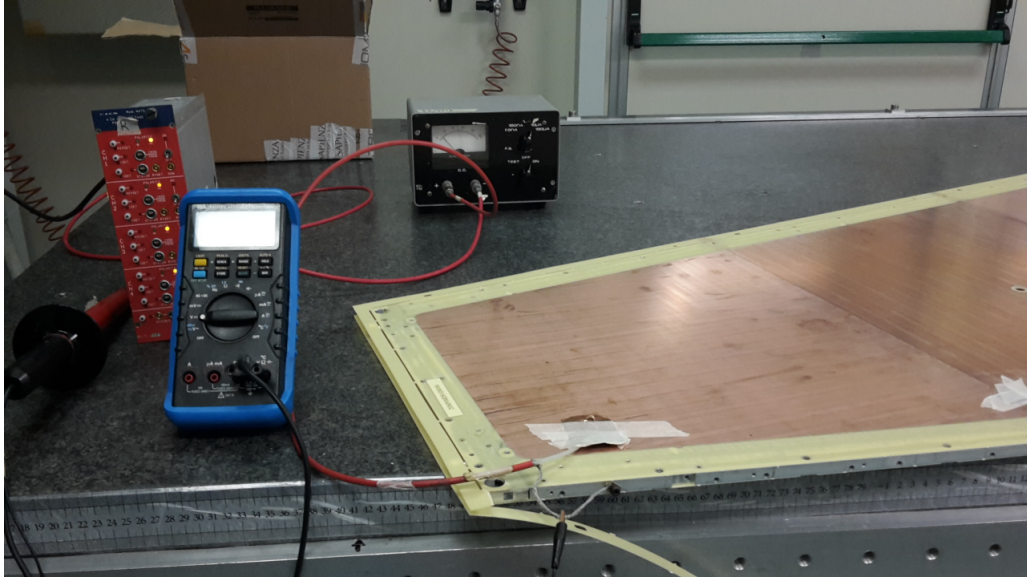


Figure 4.39. Photo of one of the assembled drift panel during the HV test. The cable that connect the panel to the generator and also the ground connection on the lateral side of the panel are shown.

4.4.4 Conclusions

The most important side for each panel is the coppered one, therefore the “side in” of the outer panels and both the side of the central panels because it is within the quadruplet and its imperfection could cause a malfunction to the MicroMegas gap.

All the panels built so far in Roma1 respect the RMS and MAX-MIN specifications required by ATLAS even if small imperfections are present (in particular on the not coppered side), especially on planarity measurements (RMS) but which are still acceptable. HV tests have been largely overcome by all built drift panels even if the dependence of the dark current as a function of the humidity has to be investigated.

Chapter 5

Cosmic Ray Stand @LNF

A dedicated Cosmic Ray Stand (CRS) is installed in the LNF of INFN. As shown in Figure 5.1, it is composed by three planes of scintillators used for the trigger signal and six planes of MDT tubes for the tracking. The total active area of the CRS is about 10 m^2 .

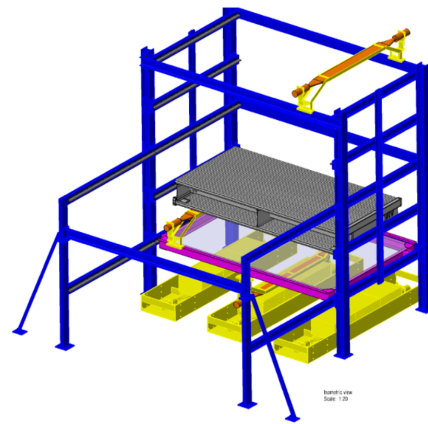


Figure 5.1. *Left:* Photo of the CRS @LNF. It is composed by three MDT plane and three plane of plastic scintillator.

Right: A sketch of the CRS structure @LNF. The instrumented MDT chamber is moved to the upper rails and in its place is a table upon which detectors under test will be placed. The table is able to roll on the rails to make easy the positioning of detectors.

The above setup will be used to study the performances of all production Q-plets that will be assembled and then mounted on the ATLAS detector. However, the first CRS tests on SM1 Module 0 described in this thesis have been made with a different setup, as shown in Figure 5.2 and described below (*from the top to the bottom*):

- **plastic scintillator** ($14 \times 11 \text{ cm}^2$) connected with a silicon photomultiplier (SiPM), supplied with a voltage of 66.4 V , which give the trigger signal;
- two **Tmm chambers** (described in Section 5.1) supplied with a voltage of 300 V (for the drift) and $550 - 555 \text{ V}$ (for the read-out) which are called respectively (from the top) *P0_RM1* and *P1_LNF*;

- the **SM1 Module 0**, with only 1 PCB (the first) instrumented for all 4 layers;
- another **plastic scintillator** ($14 \times 11 \text{ cm}^2$) connected with a silicon photo-multiplier, supplied with a voltage of 66 V, which give the trigger signal;

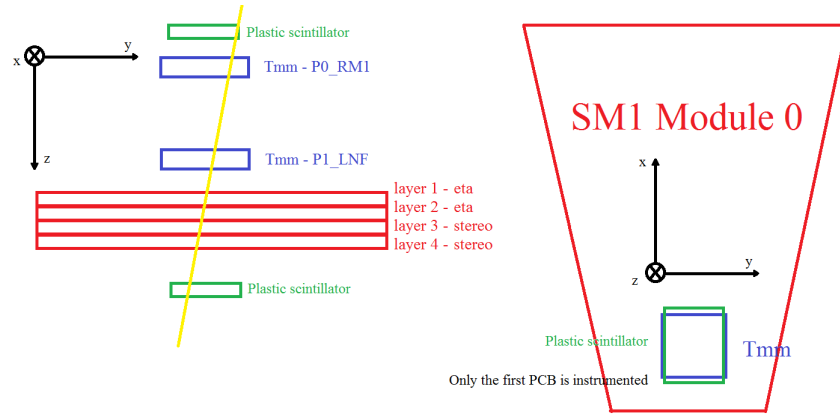


Figure 5.2. *Up:* A sketch of the CRS setup with all components. It also shows the used coordinate system.

Down: Photo of the used CRS @LNF with the two scintillator, Tmm chambers and the SM1 Module 0.

The position along the vertical axis (z) are described in the Table 5.1.

Chamber	z – position (mm)
1 st SiPM	0
P0_RM1	20.0
P1_LNF	170.0
layer 1 (<i>eta</i>)	214.5
layer 2 (<i>eta</i>)	230.5
layer 3 (<i>stereo</i>)	246.5
layer 4 (<i>stereo</i>)	262.5
2 nd SiPM	272.5

Table 5.1. The position along the vertical axis (z) of all components of the CRS @LNF.

In this setup, the signals of the two SiPM, are sent to a NIM discriminator, with a threshold set at 20 *mV* (more than one SiPM photoelectron), and subsequently to a coincidence module to do the AND of the two input signals. The exit signal is synchronized with an external clock before and then sent to the SRS on which the corresponding FECs for the read-out of the SM1 and the two Tmms are mounted.

The data come out of the acquisition system, in the form of a ROOT tree and are labelled according to the name of the detector from which they come from (*P0_RM1*, *P1_LNF* and *PX_M01* where X is the number of the layer of the module 0). Data includes the charge, the time and all the other informations that are used by the reconstruction software.

5.1 Tmm chambers

The Tmm chambers (T means a type of prototype while mm means MicroMegs) are bulk¹ resistive MM with 10 *cm* $\times$ 10 *cm* active area, with strips 150 μm wide with a pitch of 250 μm . The resistive strips follow the read-out strips (labelled as X strips) geometry with resistivity of 40 $M\Omega/cm$. The second coordinate (Y , orthogonal to the first) is read-out by another group of strips between resistive strips and X strips. In Figure 5.3 the scheme of the Tmm strips is shown.

The support pillars have a diameter of 300 μm and a pitch of 2.5 *mm*. In Figure 5.4 a picture of the Tmms used at LNF is shown.

These chambers have a gas gap of 5 *mm* and a nominal height pillars of 128 μm ; they are also filled with a gas mixture of $Ar : CO_2$ (93 : 7) with a flow rate of 1.5 *l/h*.

As discussed before, in Section 3.5, the output of the APV25 is a charge sampling of the signal of each strip. For the data analysis is necessary to define a strip selection procedure in order to remove the strips affected by cross-talk effects and not consider them during the cluster reconstruction process.

¹In the “bulk chambers”, as described in Chapter 3, the mesh is embedded directly into the read-out structure during the construction phase, unlike the chambers constructed with the “floating mesh” technique in which it is supported on the pillars.

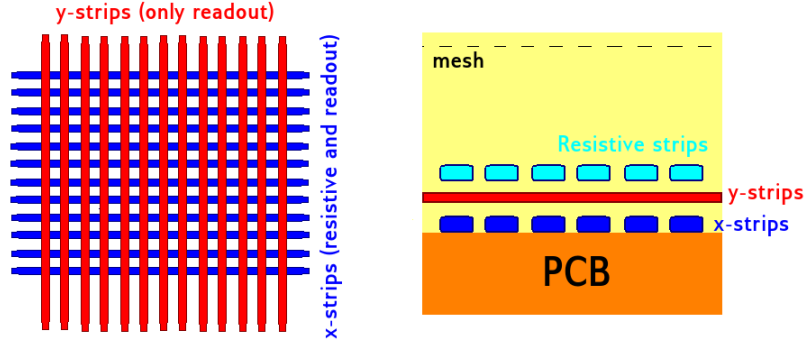


Figure 5.3. Scheme of the position of the resistive and read-out strips inside a Tmm chamber.

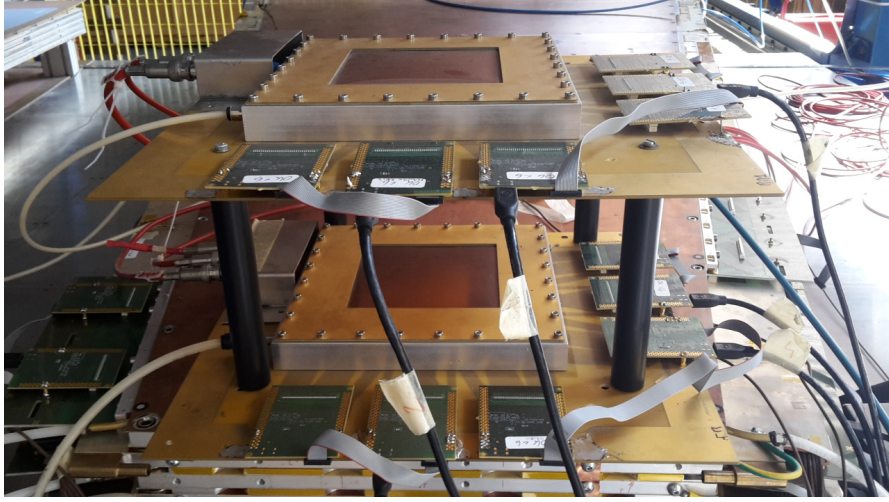


Figure 5.4. Photo of the Tmm used in the CRS. Each Tmm side (X and Y) is equipped with three APV25 (each APV has 128 channels) to read all the 360 strips of the chamber.

Cross-talk consists in charge induction between a hit strip (with non zero charge) and a not hit strip (or with less charge collection); thus modifying the structure of the hit map of the strips and consequently also the cluster structure.

To eliminate this effect a correction algorithm was developed by the collaboration. This algorithm subtracts charge from the cross-talk strips and adds it to the charge of the strips to which it belongs. To eliminate even noisy strips or residual cross-talk, it is necessary to apply a cut on strip charge using a threshold ($Q > 40 \text{ ADC Counts}$).

In this analysis, a *cluster* is defined as a group of consecutive strips with no more than a hole allowed between them. The total charge of a cluster is the sum of the charges of the strips which compose the cluster:

$$Q_{cluster} = \sum^N Q_{strip} \quad (5.1)$$

it depends on the operating characteristics of the chamber, as described by the

formula:

$$Q_{cluster} = (1 - A) \cdot N_e \cdot q_e \cdot G \cdot T \quad (5.2)$$

where:

- N_e is the *number of first and second ionisation electrons*;
- q_e is the *electron charge*;
- G is the *gain* of the chamber;
- T is the *transparency*, which is the probability that an electron from ionization passes through the mesh;
- A is the *attachment factor*, which is the probability that an ionization electron is absorbed by the gas.

Another characteristic value is the average number of strips per cluster which varies depending on the inclination of the track, in fact, a particle that crosses the detector at a certain angle will light more strips with respect to a perpendicular particle. The reason is that the angled track will have more extended ionization inside the chamber, as can be seen in Figure 5.5.

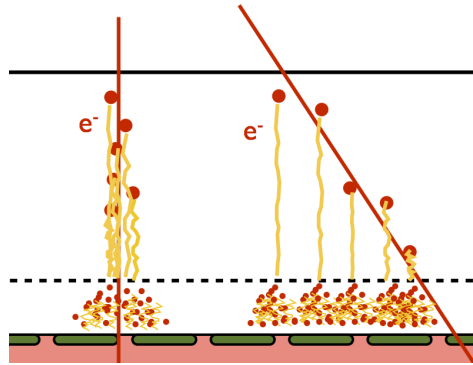


Figure 5.5. A sketch of two tracks in comparison; the left particle cross perpendicularly the MM while the right particle has an angles different from zero. The angled particle light more strips than the perpendicular.

The average value of the number of clusters per event is important to understand when a chamber is noisy and when it is inefficient. In fact, the passage of a particle should match only one cluster in each chamber; if there are more than one it is a symptom of a noisy chamber or a crosstalk effect. If it is zero it means that the chamber is not efficient.

The presence of more than one cluster may also be due to a cluster splitting effect, that is, a single cluster that is reconstructed as two, for example due to a malfunctioning strip.

Power supply and gas flow rate are important parameters to be set before the data taking to ensure proper operation of the MicroMegas chambers. In particular, for the Tmm chambers, a drift supply voltage of 300 V was used, while for the

read-out (also called amplification voltage) was 555 V; gas flushing is not particularly important in the Tmm, as they are small MM, but this is not true for Module 0.

5.1.1 Tmm event display

To figure out the causes of some problems, it is useful to see what is happening event by event through the event display: the plot of the charge and the time for each strip of each detector.

In Figure 5.6 an example of a standard event is shown where the passage of a muon (selected through the Tmm chambers using the event selection described above) produces a signal in the 2 Tmms. Clearly the cluster in the X and Y views are completely different. The propagation of charge along the resistive strips induces a signal on a large number of Y strip. Indeed, as can be seen in the plotted event, the Y clusters in the Tmms are longer than the corresponding cluster. Even the strip times are affected by this moving of the charges along the resistive strips and the Y strips, which are distant to the interaction point of the particle, have greater times. This effect produces the time parabolic figure in the plot for Y strips.

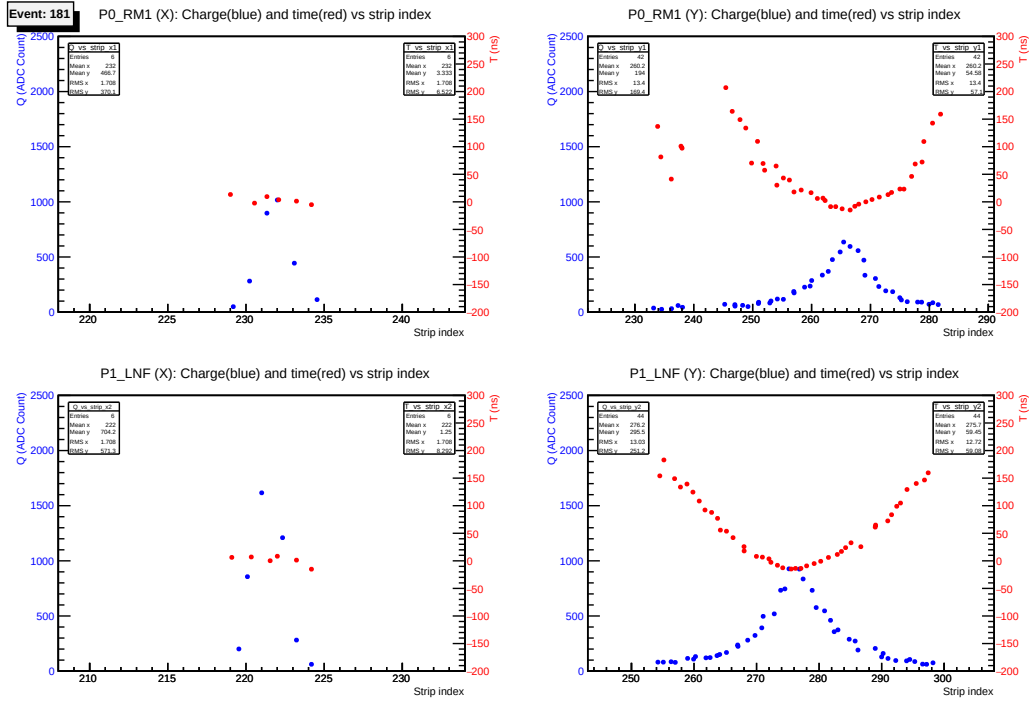


Figure 5.6. Standard event with a cosmic muon passing through the Tmms. *Up* the P0_RM1 and *down* the P1_LNF; *right*: X coordinate - *left*: Y coordinate). In *blue* is shown the charge (*left scale*) while in *red* is shown the time (*right scale*) for each single strip.

5.1.2 Basic raw distributions

Below, the Tmms characteristic distributions for each coordinate are shown; in all figures the distribution of the two chambers are shown for both views:

- strips hit map, (Figure 5.7) shows that there are several inefficient or even “dead” strip regions;
- strip charge collected (Figure 5.8). It has a bump around the $1800 \div 2000$ *ADC Counts* due to the saturation of the read-out electronics;
- strip time of the signal (obtained from the Fermi-Dirac fit) (Figure 5.9) which extends for $\sim 100 \div 120$ *ns* according to the simulations. Indeed, the electrons drift velocity obtained from the simulated data (GARFIELD) is $47 \mu\text{m}/\text{ns}$, which, considering the drift gap of 5 mm , leads to a maximum drift time of $\sim 105 \text{ ns}$. For the *Y* strip the distribution is quite different because they are coupled capacitively with the resistive strips and they see the motion of the charge along the resistive strips. This effect produces a tail in the distribution due to the greater time of the *Y* strips which are distant from the particle interaction point.

For these distributions, a first “light” selection was made in which both Tmms (with both coordinates) are required to have at least one cluster, consisting of more than three strips, in the event.

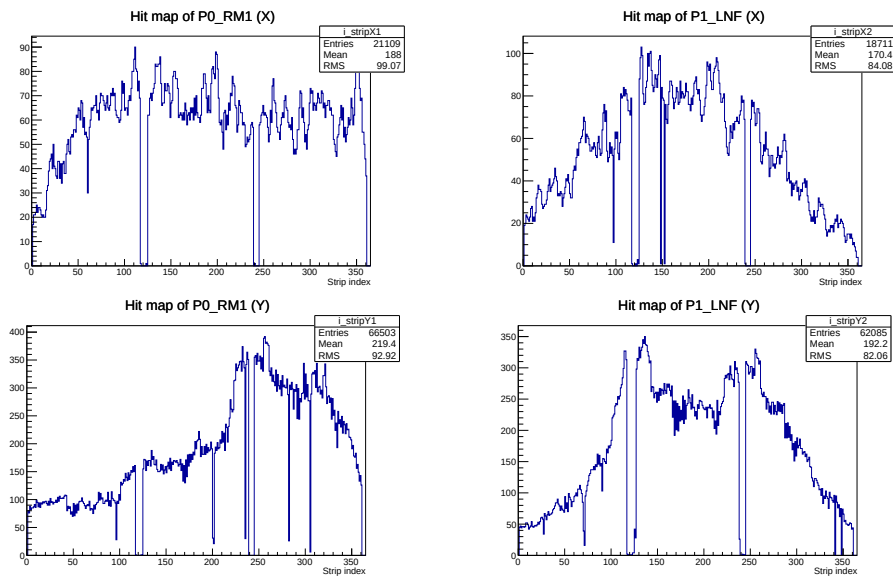


Figure 5.7. Hit map of each coordinate for each Tmms. There are some inefficient strip in each Tmm.

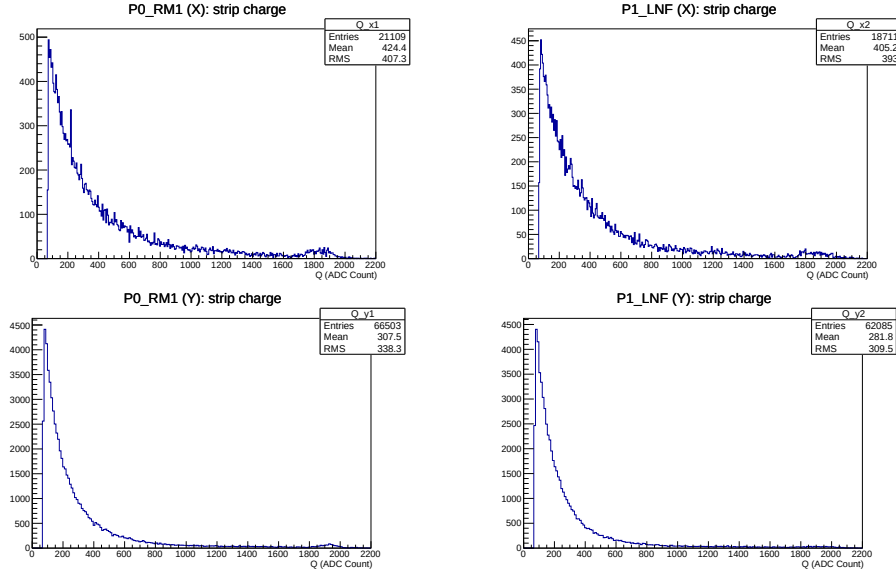


Figure 5.8. Strip collected charge of each coordinate for each Tmms. The curve has a bump around the $1800 \div 2000$ *ADC Counts* due to the saturation of the strips.

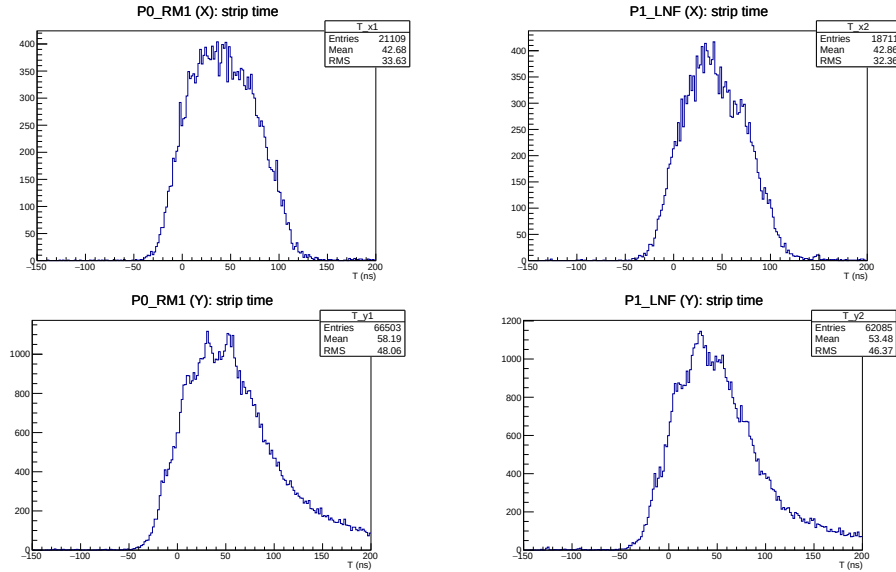


Figure 5.9. Time of each strip obtained from the Fermi-Dirac fit. The tail of the y-strip distributions is due to the movement of the electrons along the resistive strips that induce a signal with greater time on the y strips which are away from the particle interaction point.

With the same selection, the distribution of cluster charge (Figure 5.10), the earliest time of the strip which composes the cluster (Figure 5.11), the number of cluster per event (Figure 5.13), the strip multiplicity (Figure 5.12) and the position of the cluster obtained using the centroid method (Figure 5.14) are obtained.

As stated before, the Y strips are coupled capacitively with the read-out strip

and this affects the Y type cluster distributions; as can be seen from Figure 5.12, the number of strips which composes a cluster is greater and characterized by a completely different distribution in the Y-coordinate. Moreover the early time of the clusters has a tail at higher times (Figure 5.11).

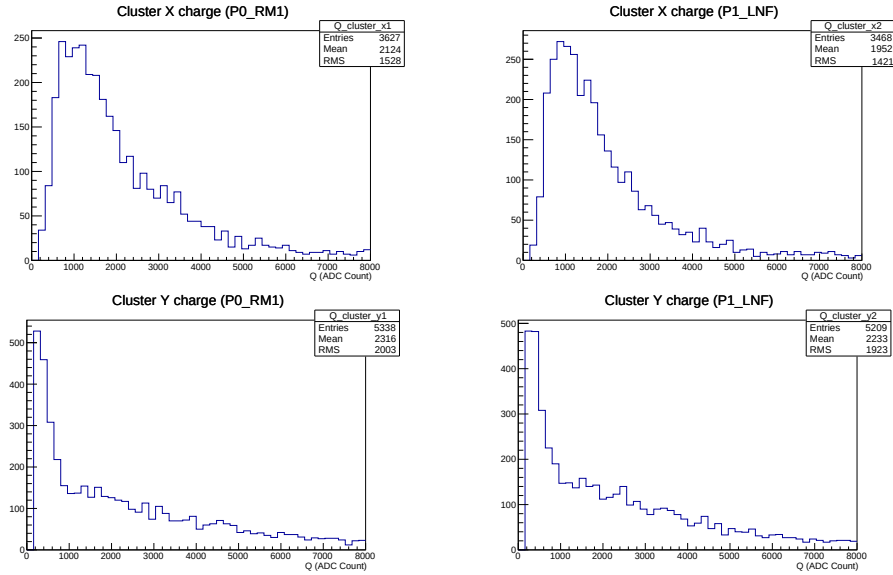


Figure 5.10. Cluster collected charge of each coordinate for each Tmm. For the X coordinate the curve is described by a typical Landau distribution For the Y the effect of the low charge strips in the cluster tail is evident.

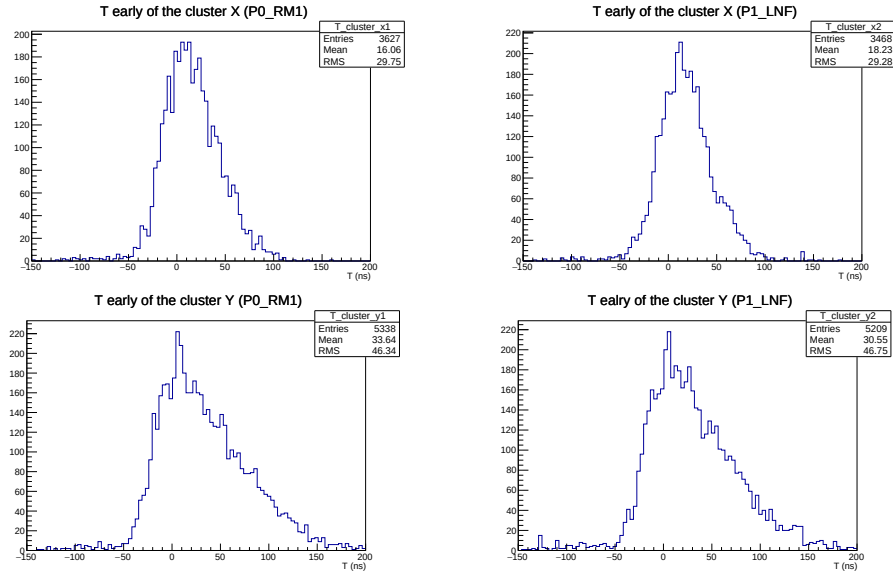


Figure 5.11. Early time of the cluster strips which means the arrival time of the particle. The tail distribution of the early time for the y-cluster depends directly from the time distribution of the y-strips.

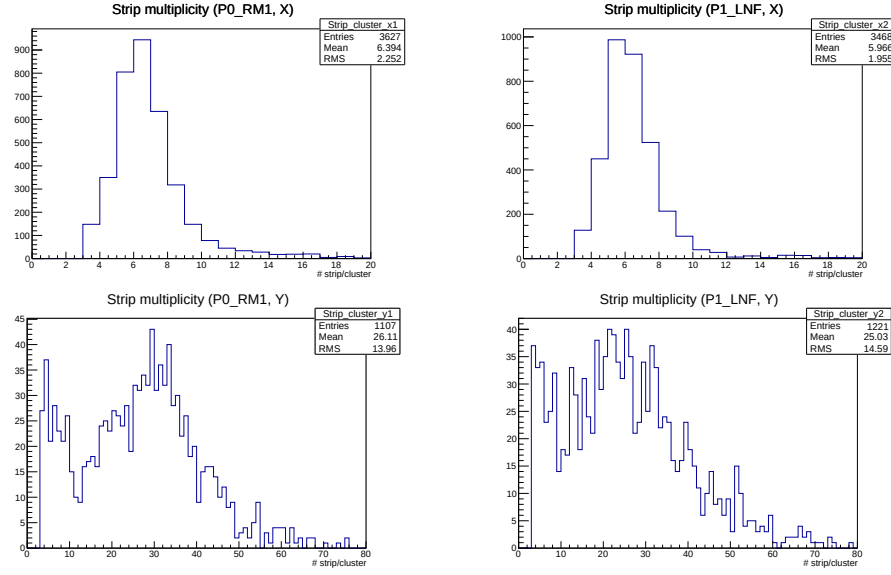


Figure 5.12. Strip multiplicity of the cluster for each coordinate for each Tmm. The average number of strip is about 6 for the x coordinate and 15 for the y coordinate because the y-strips read the movement of the charge along the resistive strips; this motion lights a greater number of strips and the strip multiplicity is affected by this phenomenon.

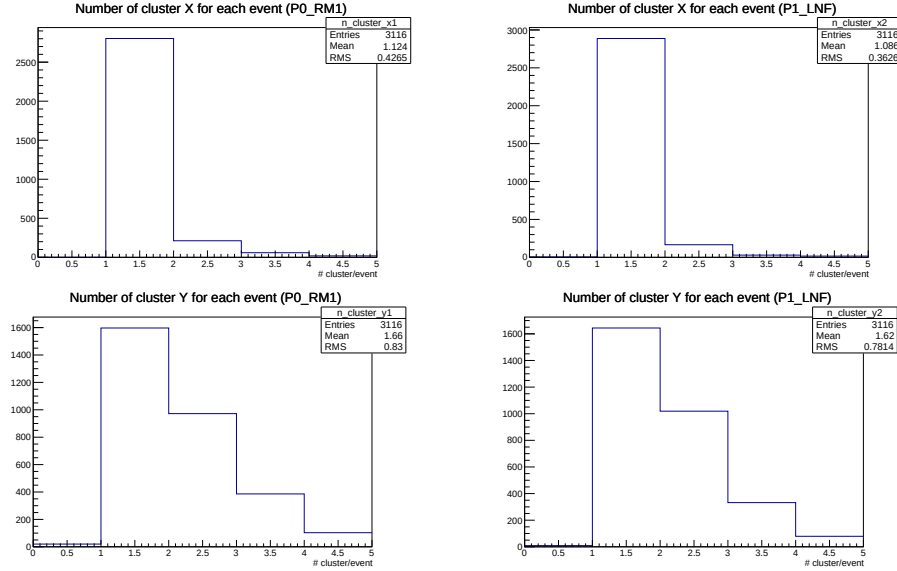


Figure 5.13. Number of cluster per event for each coordinate for each Tmm. The average number of cluster per event in the x coordinate is one (di-muon events are not so frequent) while the average number for the y coordinate is higher because the clusters are longer and it is more probable that there are one or more dead strips that induce the reconstruction software to create two different clusters (despite they are generated by the passage of the same particle).

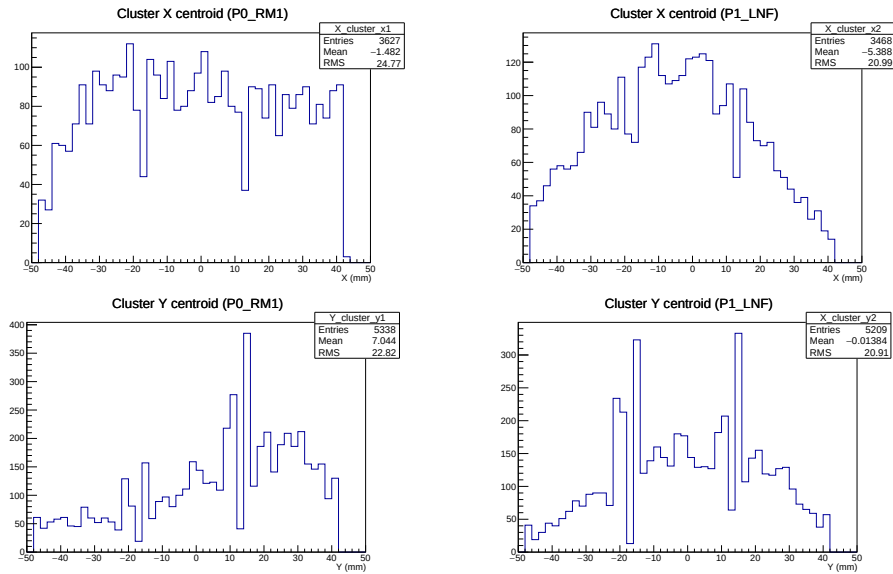


Figure 5.14. Position of the centroid of the cluster for each coordinate for each Tmm.

5.1.3 Event selection

For a proper study of Tmm and SM1 Module 0 performances, a track sample whose behaviour is perfectly known is required.

In particular, for the studies of the Tmm efficiencies, only the events labelled as “good events” are used that is events in which are present, for each coordinate and for each Tmm, a “good cluster”; in addition, a cut on the cluster charge ($Q > 100 \text{ ADC Counts}$) is applied and the early time must be included in a window 250 ns wide.

This selection is valid both on the Tmm chamber clusters and on the SM1 Module 0 clusters.

In addition, in order to obtain the resolution and software efficiency of Module 0, it is required that there is only one cluster in the X coordinate of the Tmms (parallel to the strips of Module 0). This additional request is needed to have no ambiguity on the cluster to be used for reconstruction and to have a single well-defined track.

5.1.4 Tmm hardware Efficiency and Electronic Efficiency

A study of the Tmm efficiencies is reported in this section.

Hardware efficiency

A control sample of tracks is selected based on one of the Tmm chamber. Then the hardware efficiency of the other chamber is defined as the fraction of events where there is at least one hit in the analysed chamber compared to the total number of selected events.

The efficiencies for four different definitions of hit were calculated:

- *strip*: at least one strip, in any position, with a charge greater than 40 *ADC Counts*;

- *strip (cuts)*: at least one strip, in any position, with a charge greater than 80 *ADC Counts* and its time within a selected range of 250 *ns*;
- *cluster*: at least one cluster, in any position, composed at least by two strips;
- *cluster (cuts)*: at least one cluster, in any position, composed at least by three strips and having a early time within a selected range of 250 *ns*.

	<i>P0_RM1 (X)</i>	<i>P1_LNF (X)</i>	<i>P0_RM1 (Y)</i>	<i>P1_LNF (Y)</i>
<i>strip</i>	94.4%	93.2%	94.4%	90.6%
<i>strip (cuts)</i>	93.0%	99.7%	93.1%	87.3%
<i>cluster</i>	93.4%	90.3%	93.5%	88.2%
<i>cluster (cuts)</i>	91.9%	85.7%	91.8%	83.6%

Table 5.2. Hardware efficiencies for each coordinate for each Tmm. The obtained values are lower than expected. This could be due to the many dead strips present in both Tmms.

Electronic efficiency

A particle that has been detected by one of the two coordinates (X, for example) must necessarily be passed to the detector. By selecting the control sample using the opposite Tmm chamber and the other coordinate of the analysed chamber, the electronic efficiency can be defined as the number of events with an hit in the Y-coordinate with respect to the total number of control sample events.

The efficiencies for two different definitions of hit were calculated:

- *strip*: at least one strip, in any position, with a charge greater than 40 *ADC Counts*;
- *strip (cuts)*: at least one strip, in any position, with a charge greater than 80 *ADC Counts* and its time within a selected range of 250 *ns*.

	<i>P0_RM1 (X)</i>	<i>P1_LNF (X)</i>	<i>P0_RM1 (Y)</i>	<i>P1_LNF (Y)</i>
<i>strip</i>	99.6%	99.5%	99.4%	99.4%
<i>strip (cuts)</i>	99.5%	99.3%	99.4%	98.5%

Table 5.3. Electronic efficiencies for each coordinate for each Tmm.

5.2 Analysis of the Module 0 the cosmic rays

The SM1 Module 0 had been already tested on pion beam at CERN (June 2016) and its performances are well known. However, the following analysis, which was developed on this first big MM prototype, will primarily serve to validate the methods to measure the performances of all subsequent (32) quadruplets that will be built by the Italian MM collaboration and subsequently mounted on the ATLAS NSW.

In this analysis, for the study of the efficiency of Module 0, it was chosen to use a slightly higher supply voltage than the working point (about 570 V) found during test beam.

Therefore, the drift panel power supply voltage was set to 300 V, while the read-out panel was brought to a voltage of 600 V for layer 1,2 and 3 and 585 V for layer 4 which had issues with HV. Gas flushing was instead 25 l/h.

Each layer (1024 strips instrumenting the first PCB) is equipped with APV25 reading cards that have a 128-channel reading chip. However, as this is not the final electronics that will be used in ATLAS (VMMs are still under testing), interface cards, for the reading of the quadruplet signals using the APV25, have been developed.

There are two types of interface cards which are used at the CRS:

- *CERN interface card* (in Figure 5.15 - *up*) which is equipped with four APV25 and read 512 channels for a total of 512 strips;
- *INFN interface card* (in Figure 5.15 - *down*) which is equipped with two APV25 and read 256 channels for a total of 512 strips in which each channel is connected, through the OR logic operation, with to two different strips according to a well-defined logic.

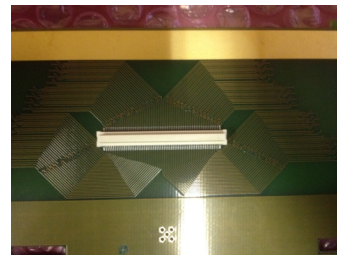


Figure 5.15. *Up:* Photo front and back side of the CERN interface card. Each card connects 512 strips to the 512 channels of four APV25.
Down: Photo of the INFN interface card with one APV25 connected to it. In the figure at right is shown a zoom of the tracks of each channel.

Such a logic is better defined in Table 5.4 where the pairs of strip read-out through each single APV25 channel are shown. The remaining 64 APV25 channels follow the same logic, so strips that follow a “straight” path are those included in the intervals $33 \div 96$ and $161 \div 224$.

By using the INFN interface cards, a lower number of APV25 can be used to read all the quadruplet strips (1024 strip x 5 PCB x 4 layers) and this will reduce the amount of electronics needed for the test.

At software level, during the signal reconstruction, the channel hit is duplicated and assigned to the two corresponding strips (respecting the values given in Table 5.4). On the other hand, during the cluster reconstruction, no duplication problem is present due to the structure of the INFN interface cards: for example, a particle that releases a charge in strips number 42-43-44-45 will be reconstruct as a cluster; the duplicated signals will be, instead, on strips number 103-107-111-100, respectively, which, being not consecutive, will not make a cluster.

<i>Strip 1 no.</i>	<i>Strip 2 no.</i>		<i>Strip 1 no.</i>	<i>Strip 2 no.</i>		<i>Strip 1 no.</i>	<i>Strip 2 no.</i>
33	97		55	122		76	15
34	101		56	126		77	4
35	105		57	115		78	8
36	109		58	119		79	12
37	98		59	123		80	16
38	102		60	127		81	17
39	106		61	116		82	21
40	110		62	120		83	25
41	99		63	124		84	29
42	103		64	128		85	18
43	107		65	1		86	22
44	111		66	5		87	26
45	100		67	9		88	30
46	104		68	13		89	19
47	108		69	2		90	23
48	112		70	6		91	27
49	113		71	10		92	31
50	117		72	14		93	20
51	121		73	3		94	24
52	125		74	7		95	28
53	114		75	11		96	32
54	118						

Table 5.4. In each row of the table, the numbers of the two strips that are read from the same channel of the APV25 are write. In the column labelled as “*strip no. 1*” the strip number with a “straight” path is written. Only with a 8 strip cluster, it can form an additional “shadow” cluster but its length will be only of 3 strips.

A large amount of data was taken which can not be used to study the performance of Module 0 but served to the fine-tuning of the data acquisition system. The

following analyses are related only to two particular runs:

- *run 275*: layer 1 instrumented with the CERN interface card while layer 2,3 and 4 instrumented with the INFN interface card;
- *run 280*: layer 2 instrumented with the CERN interface card while layer 1,3 and 4 instrumented with the INFN interface card.

5.2.1 Basic raw SM1 Mod.0 distributions (run 275 - run 280)

The basic raw distributions for the strips of two layers of the SM1 Module 0 are shown below. Only the plot of layer 1 (run 275) and layer 2 (run 280) were reported because the others seem to be dominated by a contribution of electronic noise and still have to be studied.

- strips hit map, in Figure 5.16, show for the layer 1 (*left*) and layer 2 (*right*) the profile of the active Tmm region (strip no. $200 \div 400$);
- strip charge collected (Figure 5.17). Again, as for the Tmms, the distributions has a bump around the $1800 \div 2000$ *ADC Counts* due to the saturation of the read-out electronics;
- strip time of the signal (obtained from the Fermi-Dirac fit) (Figure 5.18) which extends for $\sim 100 \div 120$ *ns* according to the expectations. Indeed, the electrons drift velocity obtained from the simulated data (GARFIELD) is $47 \mu\text{m}/\text{ns}$, which, considering the drift gap of 5 mm , leads to a maximum drift time of $\sim 105 \text{ ns}$.

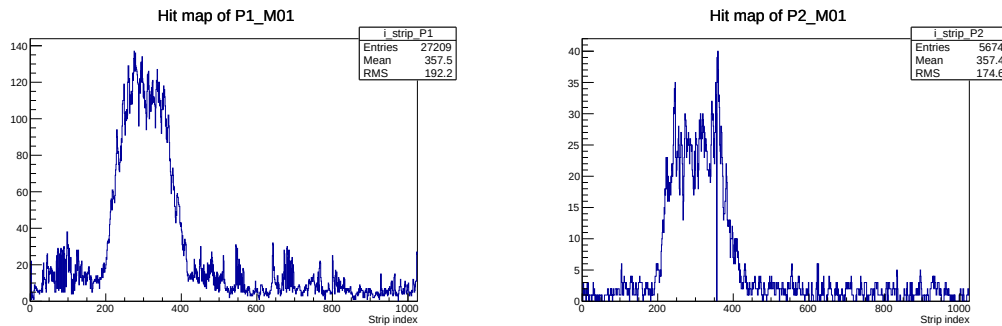


Figure 5.16. Hit map of SM1 Module 0 layers 1 and 2; it is shown the profile of the active Tmm region (strip no. $200 \div 400$).

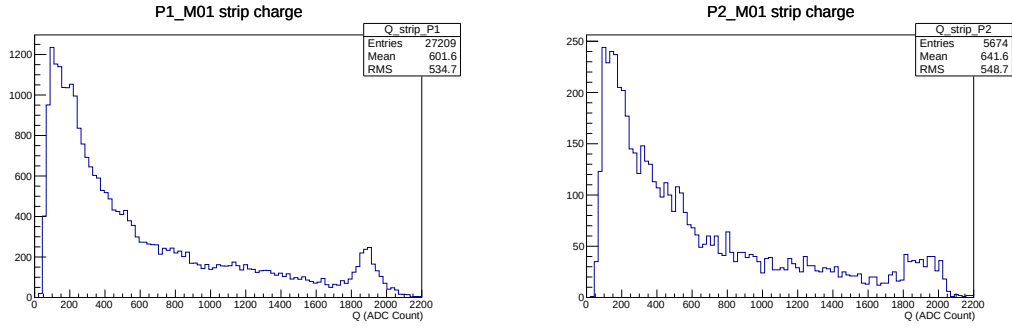


Figure 5.17. Distribution of the strip collected charge for SM1 Module 0 layers 1 and 2. The curve has a bump around the $1800 \div 2000$ *ADC Counts* due to the saturation of the strips.

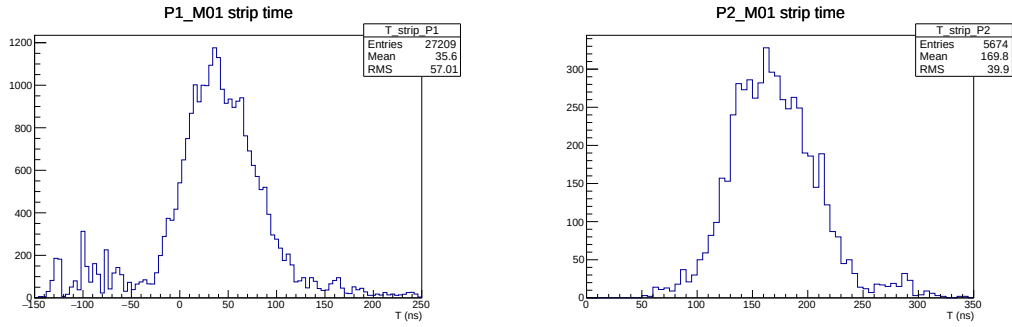


Figure 5.18. Distribution of the time of each strip obtained from the Fermi-Dirac fit.

- In Figure 5.19 are shown the cluster charge distribution;
- in Figure 5.20 are shown the early time of the cluster strips;
- in Figure 5.21 are shown the distribution of the strip multiplicity of each cluster; the distributions are peaked at about 5 strips and this is the mean value;
- as discussed before, the distribution of the number of clusters per event (Figure 5.22) is important to understand when a chamber is noisy; as expected, the distribution for layers 1 and 2 are peaked at a value of one cluster per event with few entries in 0 (inefficiency) and in 2 or more (events with more than one particle such as electromagnetic showers or di-muon events);
- in Figure 5.23 are shown the distribution of the position of each cluster obtained with the method of the centroid (eq. 3.5); these distributions mirror, of course, the layer hit map.

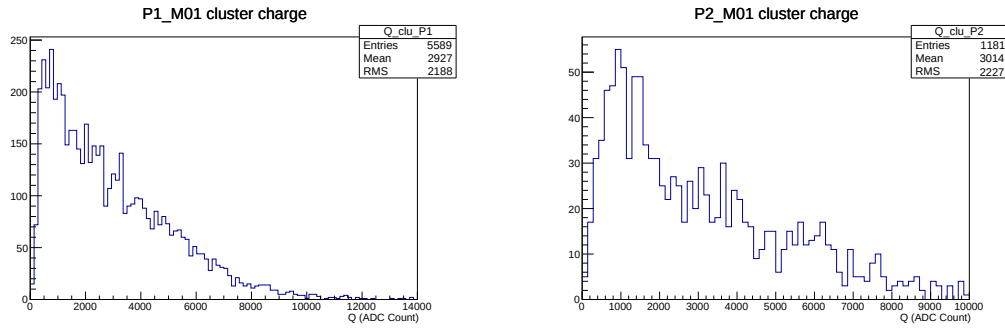


Figure 5.19. Distribution of the cluster collected charge of SM1 Module 0 layers 1 and 2.

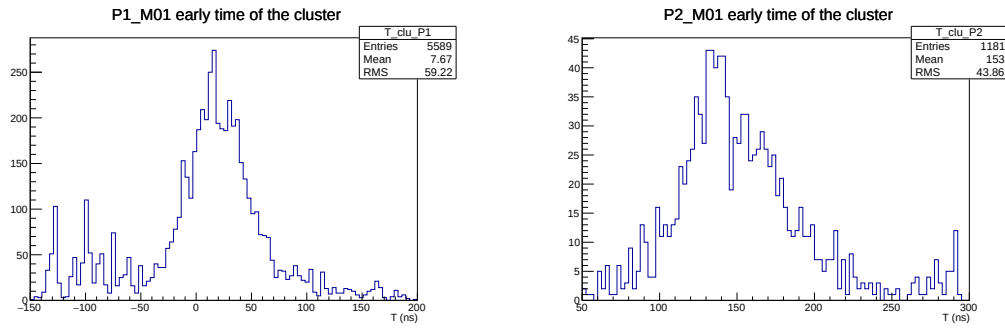


Figure 5.20. Distribution of the early time of the cluster strips which means the arrival time of the particle.

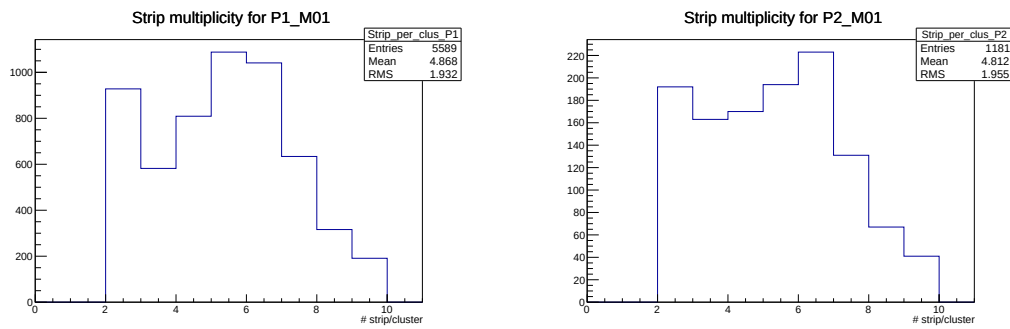


Figure 5.21. Strip multiplicity of the cluster for SM1 Module 0 layers 1 and 2.

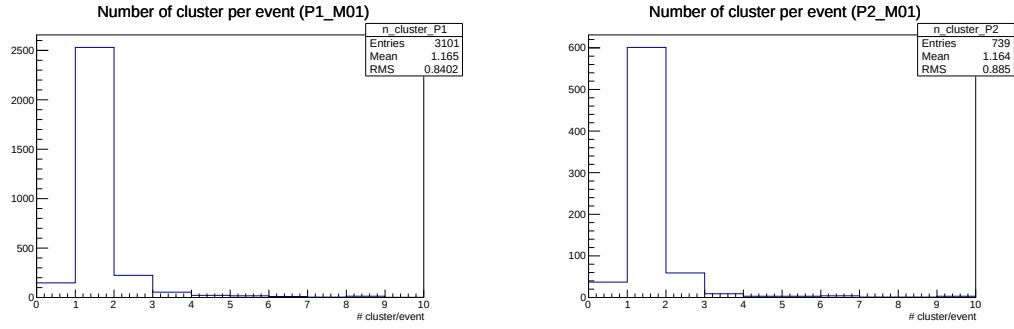


Figure 5.22. Number of cluster per event for SM1 Module 0 layers 1 and 2.

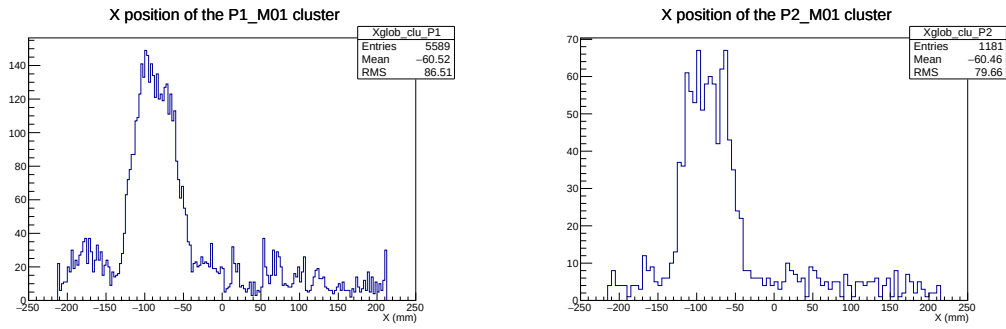


Figure 5.23. Position of the centroid of the cluster for SM1 Module 0 layers 1 and 2.

5.2.2 Module 0 event display

Particularly interesting events are shown in Figure 5.24 where all Module 0 layers saw the particle that crossed them. The muon angle using the four layer clusters can be obtained (it must be considered that layers 3 and 4 have a stereo view so the strip index does not directly represent the global spatial coordinate but is inclined relative to it and this causes the shift of the cluster to the left for layer 3 and to the right for layer 4).

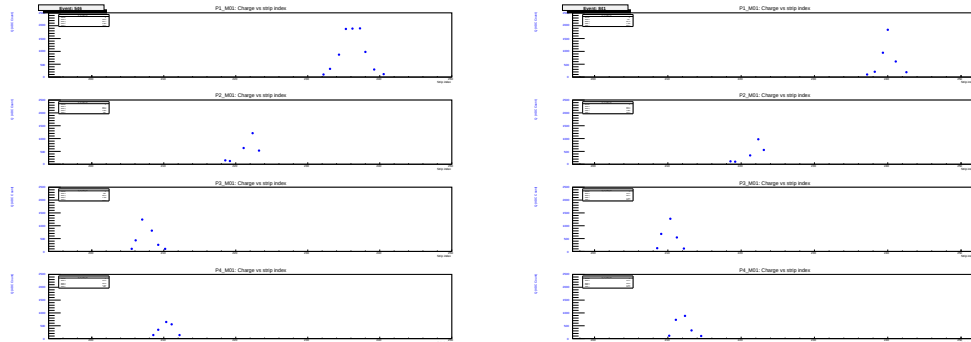


Figure 5.24. Standard events with a cosmic muon passing through all the four layers. The angle of the particle can be easily understood.

5.2.3 Hardware efficiency

As defined previously, the hardware efficiency is the fraction of events where there is at least one hit in the analysed chamber compared to the total number of selected events.

This kind of efficiency is the most basic analysis that can be made and helps to figure out if, in general, the chamber is working properly.

In this case, a hit means:

- at least one **strip** anywhere in the chamber, without any further requests (Figure 5.25-5.26, *down, left*);
- at least one **strip** with a charge $Q > 80 \text{ ADC Counts}$ and a Fermi-Dirac slope included in the range $5 \div 59 \text{ ns}$ (Figure 5.25-5.26, *down, right*).
- at least one **cluster** composed at least by two strips, anywhere in the chamber (Figure 5.25-5.26, *up, left*);
- at least one **cluster** having a charge $Q > 100 \text{ ADC Counts}$ and composed at least by two strips, anywhere in the chamber (Figure 5.25-5.26, *up, right*);

Each efficiency was also calculated by varying the control sample, as shown in Figure 5.25-5.26:

- *2 chambers*: there is a “good cluster” in at least two coordinates (of the four possible, 2 for each Tmm);
- *3 chambers*: there is a “good cluster” in at least three coordinates (of the four possible, 2 for each Tmm);
- *4 chambers*: there is a “good cluster” in each coordinate for each Tmm;
- *5 chambers*: there is a “good cluster” in each coordinate for each Tmm and also in the first layer of the Module 0 (this request varies for the calculation of the layer 1 hardware efficiency; in this case, layer 2 together with Tmm are used for the control sample).

Run 275

In Figure 5.25 the layer 1 hardware efficiencies calculated in the run 275 are shown.

The efficiency is almost constant at a value greater than 99.5%, as well as when changing the method and changing the control sample. Some points are without the error bars because the calculated efficiency is exactly 100%; in this case it can be assumed that the value 100% is an upper limit of the layer efficiency.

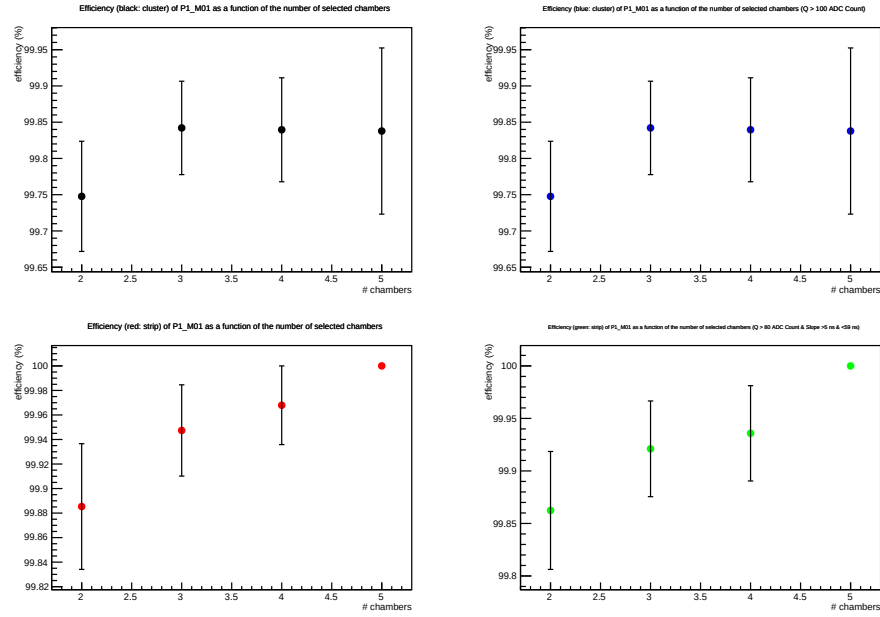


Figure 5.25. Layer 1 hardware efficiency, in the run 275, calculated with 4 different methods each depending on the number of detectors used to select the control sample.

Run 280

In Figure 5.26 are shown the layer 2 hardware efficiencies calculated in the run 280.

Layer two is now equipped with the CERN interface card and its efficiency increase until a value greater than 99%;

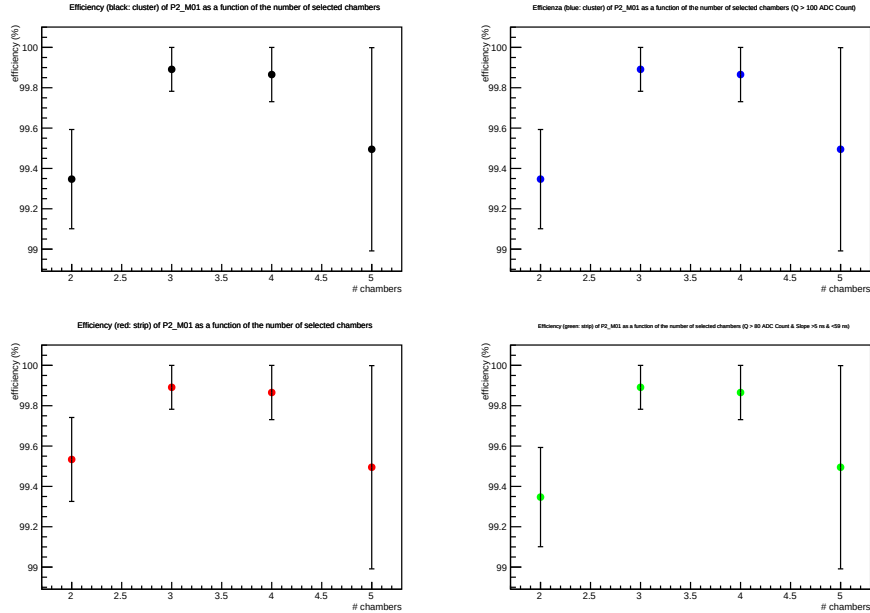


Figure 5.26. Layer 2 hardware efficiency, in the run 280, calculated with 4 different methods each depending on the number of detectors used to select the control sample.

As shown from the Figure 5.25-5.26, the hardware efficiencies do not depend on the selecting methods of the control sample and on the selected hit. The efficiencies of the two layers (layers 1 and 2) are over 99%, as expected, using the CERN interface cards.

5.2.4 Software efficiency

Hardware efficiency doesn't take into account when the measured hit is. Therefore we can define a software efficiency as the fraction of events in which is present at least one cluster in the analysed layer with the position in the range $x_{ext} \pm 5 \text{ mm}$ as illustrated in Figure 5.27, x_{ext} being the extrapolated position. It is particular interesting to measure the software efficiency as a function of x_{ext} . The choice of $\pm 5 \text{ mm}$ will be motivated in next paragraph.

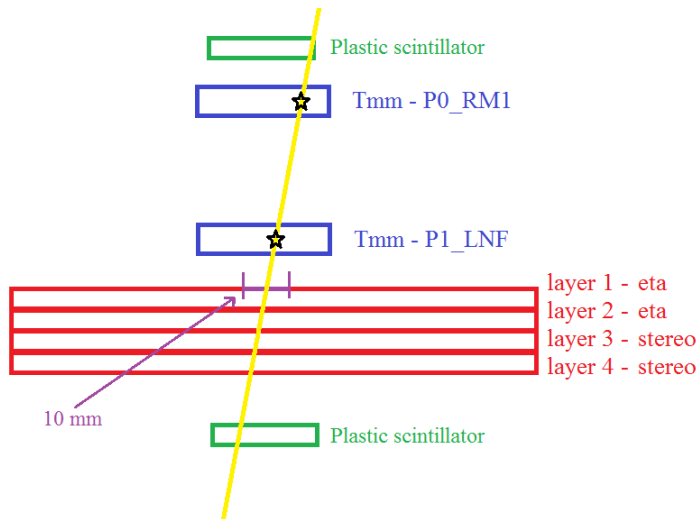


Figure 5.27. A sketch of the procedure to calculate the software efficiency.

The software efficiency is calculated only for layer 1 (*run 275*) and for the layer 2 (*run 280*).

Run 275

In Figure 5.28 is shown the software 1D efficiency of the layer 1. It is almost constant (always with a value greater than the 96%) in the 10 cm wide analysed region (between $-160 \div -60 \text{ mm}$).

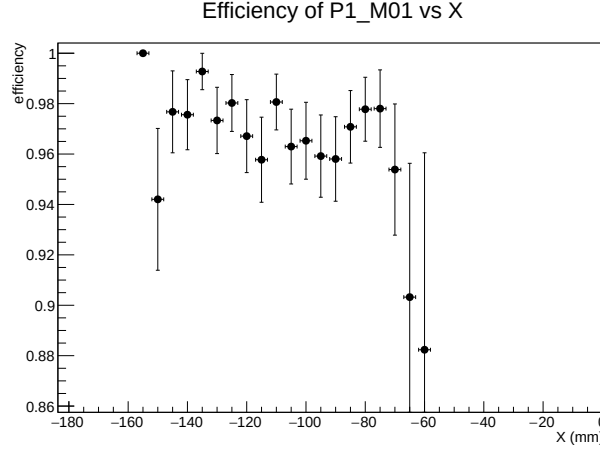


Figure 5.28. Efficiency of the first layer of the SM1 Module 0 as a function of X .

The overall efficiency obtained for the first layer is $96.59 \pm 0.38\%$.

Since the Tmm telescope provides a 2D reconstruction (X and Y views), it is also possible to obtain a 2D efficiency map. Therefore, the software 2D efficiency is defined as the ratio between the event where there is at least one “good cluster” in the analysed layer compared to the total number of selected events in a particular x - y region.

As shown in Figure 5.29, the efficiency of layer 1 is constant with only few points below 70% (but not significant due to the low statistic); in the same figure, software 2D efficiencies for layers 2 and 3, instrumented with INFN cards, are also reported. In these two cases it is evident that for half of the region there is no efficiency at all. The situation for the fourth layer is different because the signals are completely dominated by noise. These results are now under scrutiny to solve the problem.

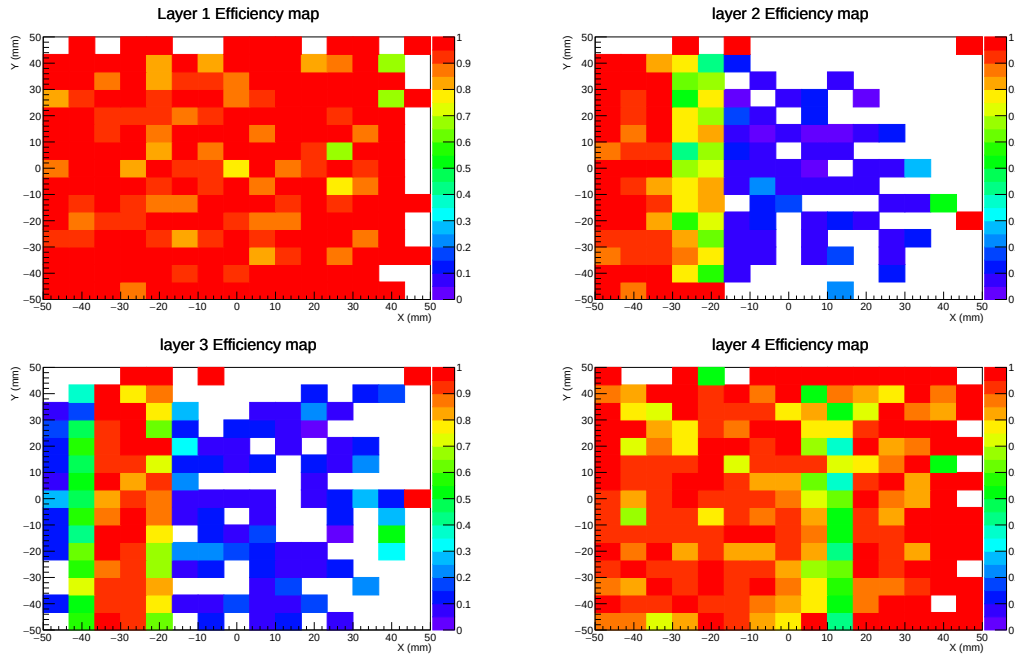


Figure 5.29. Software 2D efficiency for the layer 1 (*up - left*), layer 2 (*up - right*), layer 3 (*down - left*) and layer 4 (*down - right*).

The charge response map of layer 1 in *run 275* is shown in Figure 5.30 in each x-y region. The average charge for the tracks passing in the region is shown.

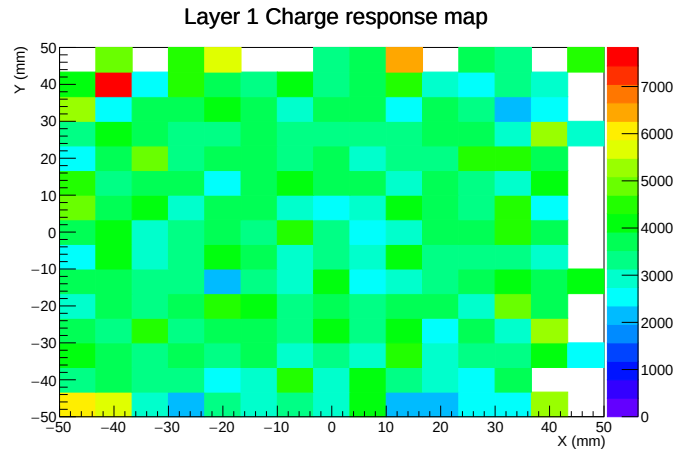


Figure 5.30. Charge response map of the first layer of the SM1 Module 0.

It can be useful to estimate the fluctuation of the charge response of the layer 1. It is shown in Figure 5.31 which is an unidimensional histogram filled with the bin content of the 2D histograms of the charge response map. Fitting a gaussian curve, the percentage variation of the uniformity charge response of the layer 1 can be obtained: it turns out that the RMS fluctuation of the charge response of layer 1 in the analyzed region is $\sim 18\%$.

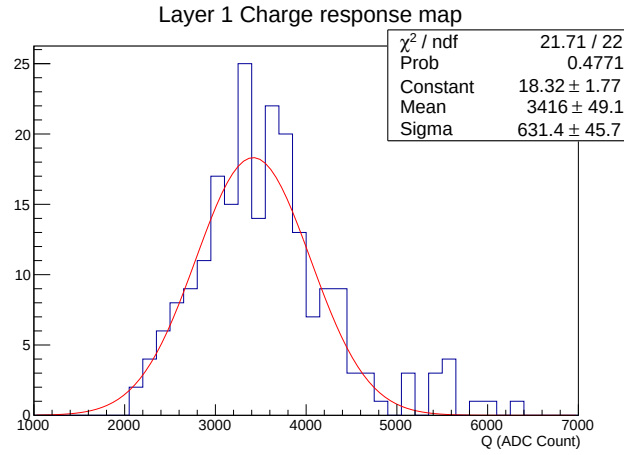


Figure 5.31. Charge response of the first layer of the SM1 Module 0 which is uniform at 18%.

Run 280

In Figure 5.32 is shown the software 1D efficiency of the layer 2. It is almost constant (always with a value greater than the 95%) in the 10 cm of analysed region (between $-160 \div -60$ mm).

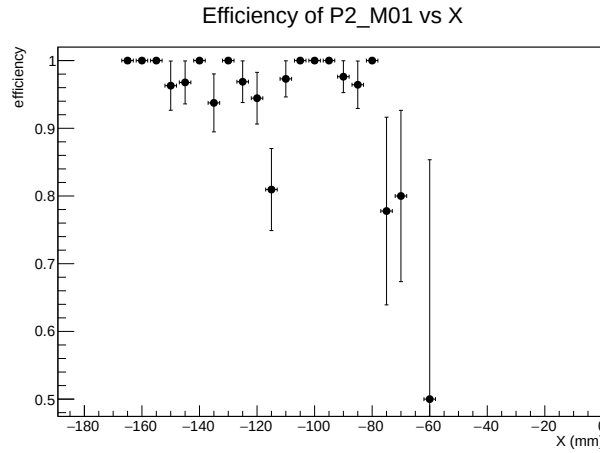


Figure 5.32. Efficiency of the second layer of the SM1 Module 0 as a function of X.

The overall efficiency obtained for the second layer is $94.40 \pm 0.99\%$.

Due to the low statistics, 2D efficiency map for the second layer have not been plotted.

5.2.5 Resolution studies

The best way to get the resolution of each single layer would be the use of collinear orthogonal tracks at high energy in a test beam. The energy of the cosmic muons is variable and not so high and therefore multiple scattering is not negligible and gives considerable contribution to the resolution.

Selecting events with single clusters in the tracking chambers (Tmm), the centroid position of the clusters are determined and the line passing for these two points can be reconstruct ($x = m \cdot z + q$).

Extrapolating, then, the expected value (x_{ext}) at the layer height z (vertical coordinate) the distribution of the differences (or residues) between the x read from the chamber and the x_{ext} can be constructed. The resulting distribution will be gaussian and, fitting it, the σ_{res} can be obtained and it will be equal to:

$$\sigma_{res}^2 = \sigma_x^2 + \sigma_{ext}^2 + \sigma_{MS}^2 \quad (5.3)$$

where σ_x is the layer resolution, σ_{ext} is the error due to the extrapolation and $\sigma_{MS} \sim R \cdot \langle \theta_{MS} \rangle$ is the multiple scattering contribution, where R is the distances between the $P1_LNF$ and the analysed layer and $\langle \theta_{MS} \rangle$ is described by the formula

$$\langle \theta_{MS} \rangle = \frac{0.0136}{p_T [GeV]} \cdot \sqrt{\frac{x}{X_0}} \cdot \left(1 + 0.038 \ln \left(\frac{x}{X_0} \right) \right) \quad (5.4)$$

So, in order to extract σ_x from the measured σ_{res} one has to estimate and subtract σ_{ext} and σ_{MS} .

Only the residuals of layer 1 (*run 275*) and layer 2 (*run 280*) could be analysed because, in these two run, these layers are not equipped with the INFN interface cards that seem to have problems.

The difference $x_{ext} - x$ depends also on possible misalignment or rotation between the telescope system and the Module 0 system, as shown in Figure 5.33.

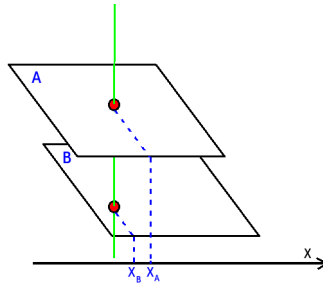


Figure 5.33. Illustration of how a misalignment on the x axis of two chambers for a straight particle results in a difference in the position of the centroids of the same track.

Run 275

In Figure 5.34 the distribution of the selected layer 1 cluster position (*left*) and the x_{ext} distribution (*right*) are shown; both distributions are about 10 cm wide, i.e. the width of the Tmm active region.

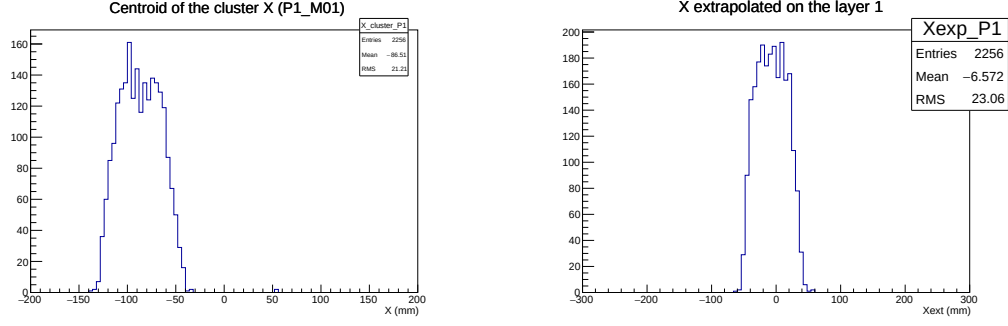


Figure 5.34. *Left:* distribution of the selected layer 1 cluster position; *right:* extrapolated position distribution on the first layer.

In Figure 5.35 (*left*) it is possible to see the linear dependence of x_{ext} on the layer 1 X distribution.

In Figure 5.35 (*right*) is shown the residuals as a function of the x_{ext} . A linear fit is done to evaluate the value of the offset and the rotation of the chambers in the x-y plane. The results for the first layer is an offset of 81 *cm* and a x-y rotation of $\sim 6^\circ$.

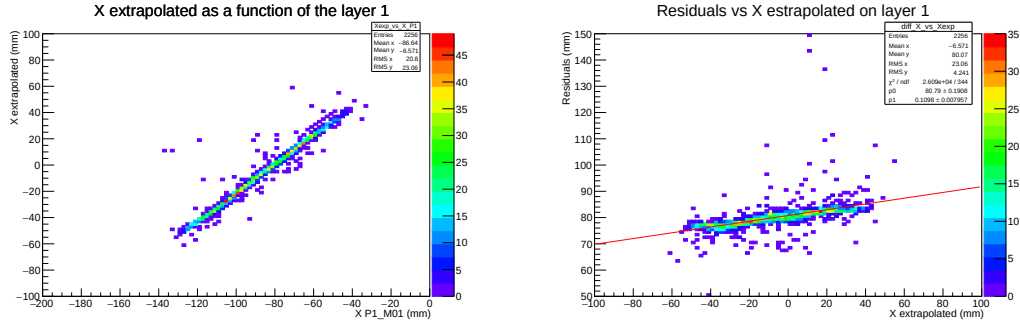


Figure 5.35. *Left:* x_{ext} using the Tmm chambers as a function of the layer 1 cluster centroid. *right:* offset (or residuals) of layer 1 as a function of the x_{ext} . There is a linear dependence of the offset from the extrapolated position which mean a rotation between the layer and the Tmm chambers in the x-y plane.

In Figure 5.36 the distribution of the residuals of the first layer after the rotation correction is shown. A gaussian curve is fitted and a width $\sigma_x = 1.0$ *mm* is obtained.

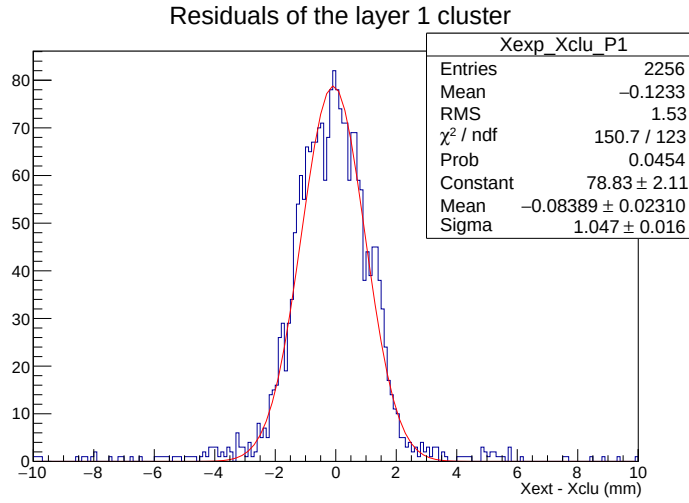


Figure 5.36. Residuals of the first layer after the rotation correction.

Knowing that the resolution of the layers obtained with a beam analysis is $\sim 100 \mu\text{m}$, it can be concluded that this residual value obtained is dominated by the error on the extrapolation of the track and by the error due to the multiple scattering.

The contribution due to the error committed during the extrapolation can be estimated knowing the distances between the two plastic scintillator ($d = 323 \text{ mm}$), the side of their active region ($l = 110 \text{ mm}$), the angular distribution of the cosmic rays ($\propto \cos^2(\theta)$) and then its variance in this experimental setup

$$\sigma_\theta^2 = \int_{\theta_{\min} = -\text{atan}(l/d) = -19^\circ}^{\theta_{\max} = \text{atan}(l/d) = 19^\circ} \theta^2 \cdot \cos^2(\theta) d\theta = 0.15 \text{ rad}^2 \quad (5.5)$$

$\langle x_{P0_RM1} - x_{P1_LNF} \rangle = \tan(\langle \theta \rangle) \cdot d' = \tan(\sigma_\theta) \cdot d' \simeq 22.6 \text{ mm}$ can be estimated, where $d' = 150 \text{ mm}$ is the distances between the two Tmms.

Assuming $\sigma \sim 100 \mu\text{m}$ the resolution of the two Tmms, using $\langle x_{P0_RM1} - x_{P1_LNF} \rangle$ in the propagation formula and considering an uncertainty of $\sim 1 \text{ mm}$ for the σ_z , the $\sigma_{ext} \simeq 100 \div 200 \mu\text{m}$ can be estimated.

Using the equation 5.3, it can be assumed that multiple scattering is the main contribution of σ_{ext} and can be described also by the equation $\sigma_{MS} \simeq R \cdot \langle \theta_{MS} \rangle$. Considering $5 \div 6 \text{ mm}$ of fiberglass ($X_0 = 160 \text{ mm}$), $\sim 1 \text{ mm}$ of aluminium ($X_0 = 8.90 \text{ cm}$) and a distance between the $P1_LNF$ Tmm and the first layer equal to $R = 4,2 \text{ cm}$, the average muons momentum $\langle p \rangle$ can be obtained using the equation 5.4: $\langle p \rangle \simeq 100 \div 200 \text{ MeV}$.

This value seems to be reasonable since there is no absorber (lead, for example) in the experimental setup that would raise the threshold of the momentum of the particles selected by the scintillators.

Run 280

In Figure 5.37 the distributions of the selected layer 2 cluster position (*left*) and the x_{ext} distribution (*right*) are shown; both distributions are about 10 cm wide, i.e.

the width of the Tmm active region.

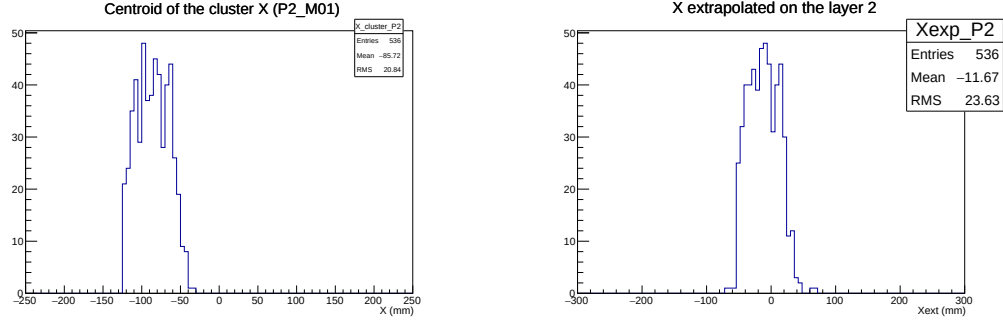


Figure 5.37. *Left:* distribution of the selected layer 2 cluster position;
right: extrapolated position distribution on the second layer.

In Figure 5.38 (*left*) is possible to see the linear dependence from the x_{ext} and the layer 2 X distribution of the cluster centroid.

In Figure 5.38 (*right*) is shown the residuals as a function of the x_{ext} on which a line fit was made to evaluate the value of the offset and the rotation of the chambers in the x-y plane. The results for the first layer is an offset of 75 cm and a x-y rotation of $\sim 6^\circ$.

It is interesting to note that the two layers are rotated by the same amount as the plane identified by the two Tmms which means that there is no rotation between the layer 1 and 2.

The differences between the two fit slope ((110 ± 9) mrad for the first layer and (116 ± 9) mrad for the second layer) is compatible with 0 at ~ 6 mrad level ($\delta\theta_{12} = (6 \pm 13)$ mrad). With higher statistics the sensibility to investigate on a possible strip rotation will increase.

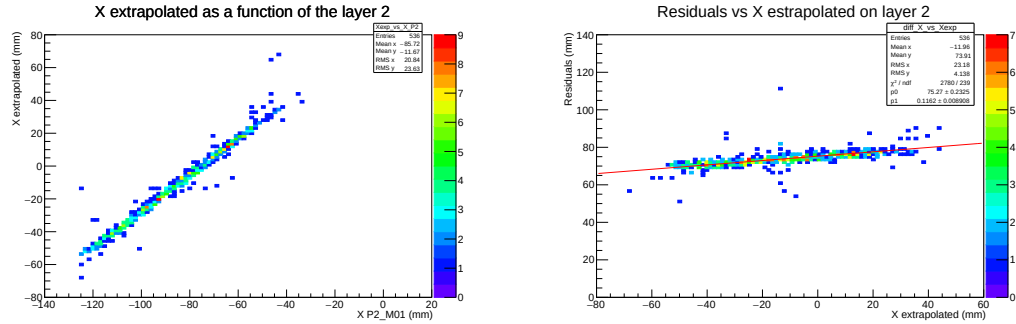


Figure 5.38. *Left:* x_{ext} using the Tmm chambers as a function of the layer 2 x distribution of the cluster centroid.
right: offset (or residuals) of layer 2 as a function of the x_{ext} . There is a linear dependence of the offset from the extrapolated position which mean a rotation between the layer and the Tmm chambers in the x-y plane.

In Figure 5.39 is shown the residuals of the second layer after the rotation correction. As gaussian curve is fitted and the $\sigma_x = 1.3$ mm is obtained.

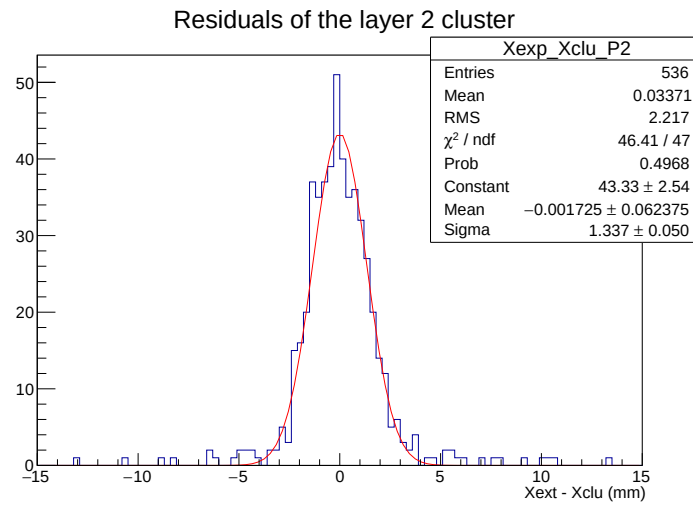


Figure 5.39. Residuals of the second layer after the rotation correction.

Chapter 6

First results from SM2 test beam

As already done for the SM1 Module 0, SM2 Module 0, built in Germany, was also brought to CERN for a test beam.

6.1 Experimental setup

The layout of the SM2 test beam done during August 2017 is shown in Figure 6.1.

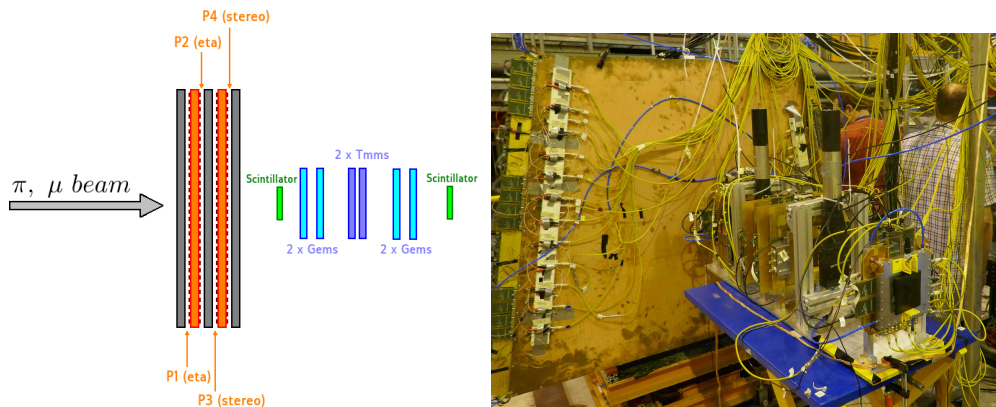


Figure 6.1. Experimental layout of the SM2 test beam. Along the z axis: SM2 chamber, scintillator, 2 two-dimensional GEMs, 2 two-dimensional Tmms, 2 other two-dimensional GEMs and the second scintillator.

The coordinate system is defined as follows: the z -axis is along the beam direction, the vertical direction is the y axis, along which the precision coordinate of the chambers is read-out and the one orthogonal to it is the x axis.

During this test beam, SM2 was positioned on a movable table for horizontal (along eta strips) and vertical (perpendicular to eta strips) translation; an aluminium frame for fixation and tilting of the module was used.

The SM2 chamber collected data with the beam impinging at different position (Figure 6.2), with different values of amplification ($575 \div 615$ V) and drift voltages (from 100 V to 350 V) and inclination angles with respect to the incident particles

beam $\alpha = 0^\circ, 20^\circ, 30^\circ$ for the μTPC studies.

All Tmm and GEM chambers are at angles $\alpha = 0^\circ$ and can be used as a telescope for tracking and selecting events.

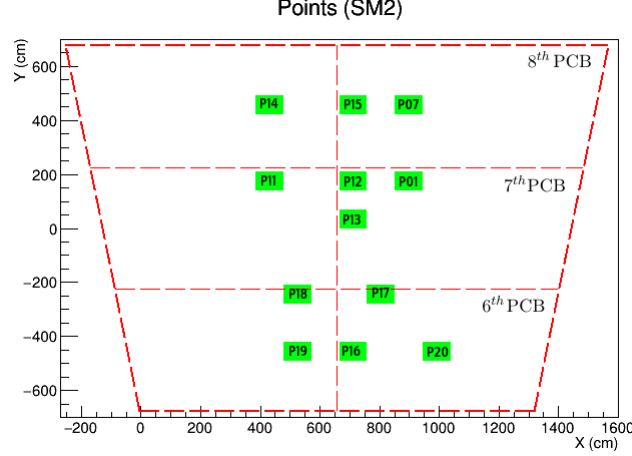


Figure 6.2. Sketch of the SM2 Module, where the position of the impinging beam are shown. Also defined are the 3 PCBs of the SM2 chamber.

6.2 Beam profile

The beam used is one of the transfer lines of the CERN SPS, the H8 line [28], composed by 180 GeV pions and muons with a spot size of $5 \times 5 \text{ cm}^2$.

In Figure 6.3 the 2D beam profile is shown obtained using the two-dimensional read-out of each telescope chamber. The GEM2 and GEM4 seems not to work properly and it will not be used in the analysis.

6.3 Event selection

As discussed in section 5.1.3, for a proper study of the SM2 Module 0 performances, a track sample whose behaviour is well known is required.

In particular, for these studies, only the events labelled as “good event” are used that is events with a “good cluster” (defined in Section 5.1.3) in at least 5 coordinates of the GEM and Tmm chambers; in addition, a cut on the cluster charge ($Q > 65 \text{ ADC Counts}$ for the Tmms and $Q > 70 \text{ ADC Counts}$ for the GEMs) is applied and the early time of the Tmms must be included in a window 200 ns wide. This selection is valid both on the Tmm chamber clusters and on the SM2 Module 0 clusters.

In addition, in order to obtain the resolution of Module 0, it is required that there is only one cluster in the Y coordinate in the analysed layers. This additional request is needed to have no ambiguity on the cluster to be used for reconstruction and to have a single well-defined track.

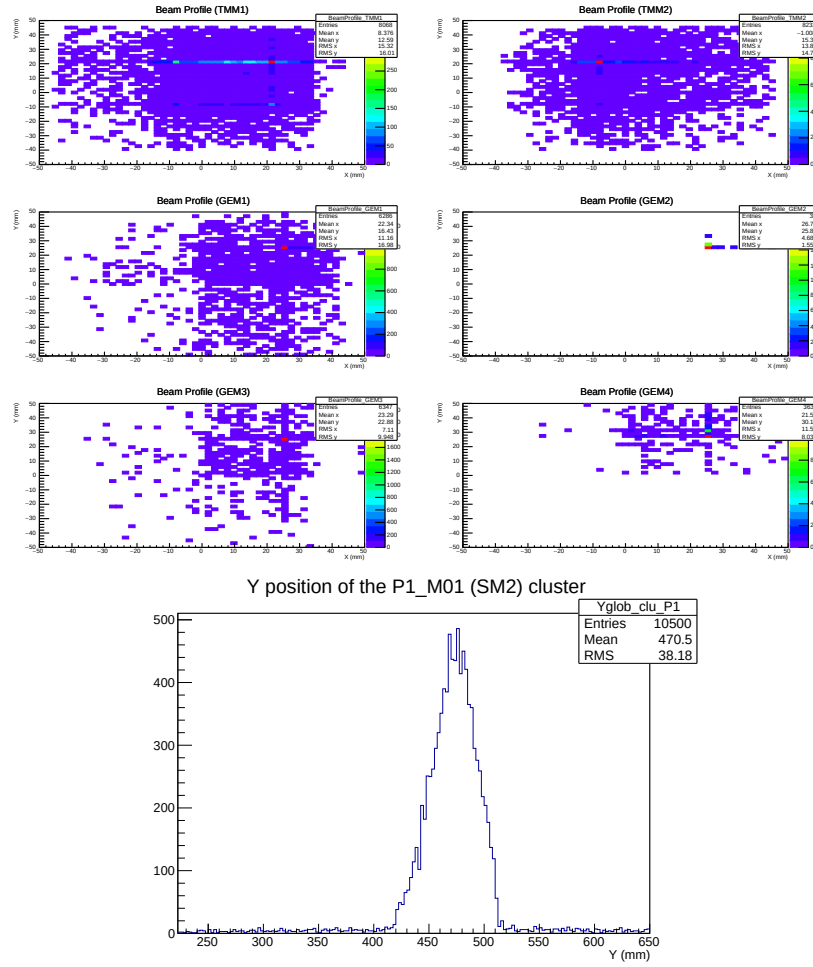


Figure 6.3. *Up:* 2D beam profile of the telescope chambers. The GEM2 and GEM4 seems not to work properly;
down: 1D beam profile of the first (eta) layer of the SM2 Mod.0.

6.4 Basic raw SM2 Mod.0 distributions (P16)

The basic raw distributions for the strips of the SM2 Module 0 are shown below. All the distribution are obtained using runs at 0° inclination and an amplification voltage of $610 - 610 - 595 - 585$ V respectively for each layer.

- strips hit map, (Figure 6.4), for each layer the profile of the beam (strip no. $400 \div 600$); layer 3 (*down-left*) seems to have some “dead” strips in the region between the strip no. 440 and no. 490; there are also some noisy strips in all layers;
- strip collected charge (Figure 6.5). The distributions have a bump around the $1200 \div 1400$ *ADC Counts* due to saturation; it is different from SM1 that has a read-out electronics with a wider dynamical range;
- strip time of the signal (obtained from the Fermi-Dirac fit) (Figure 6.6) which

extends for $\sim 100 \div 120$ ns according to the simulations.

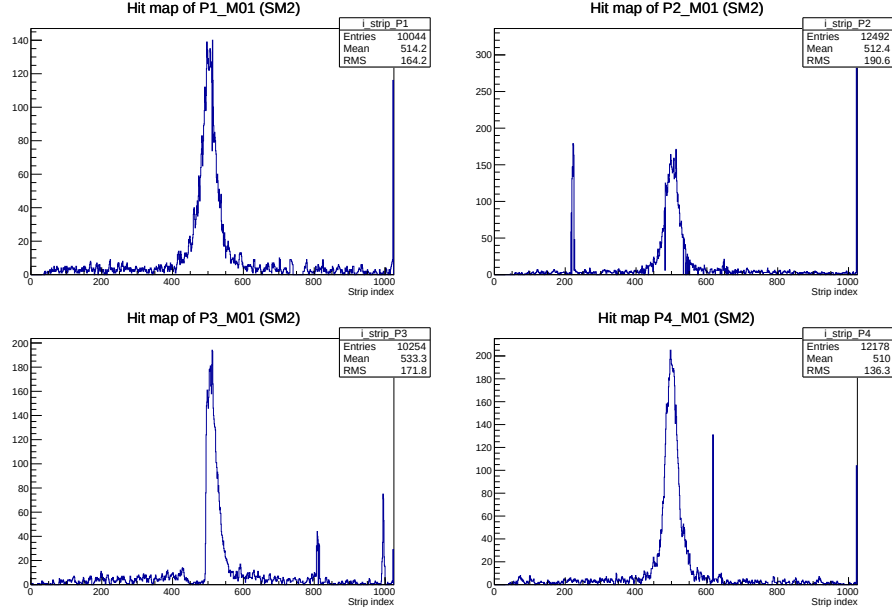


Figure 6.4. Hit map of SM2 Module 0 for each layers; it is shown the profile of the beam (strip no. $400 \div 600$).

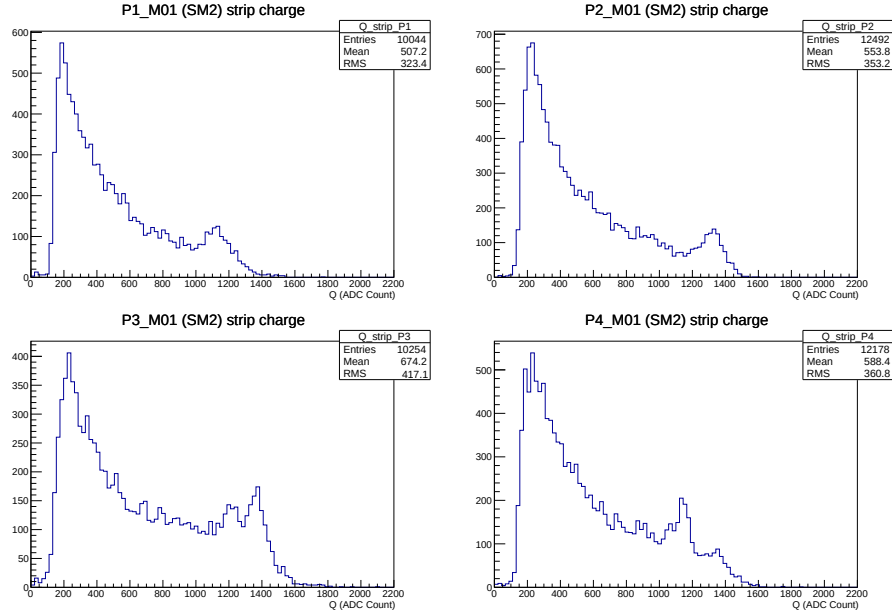


Figure 6.5. Distributions of the strip collected charge for SM2 Module 0 layers. The curve has a bump around the $1200 \div 1400$ ADC Counts due to the saturation of the strips.

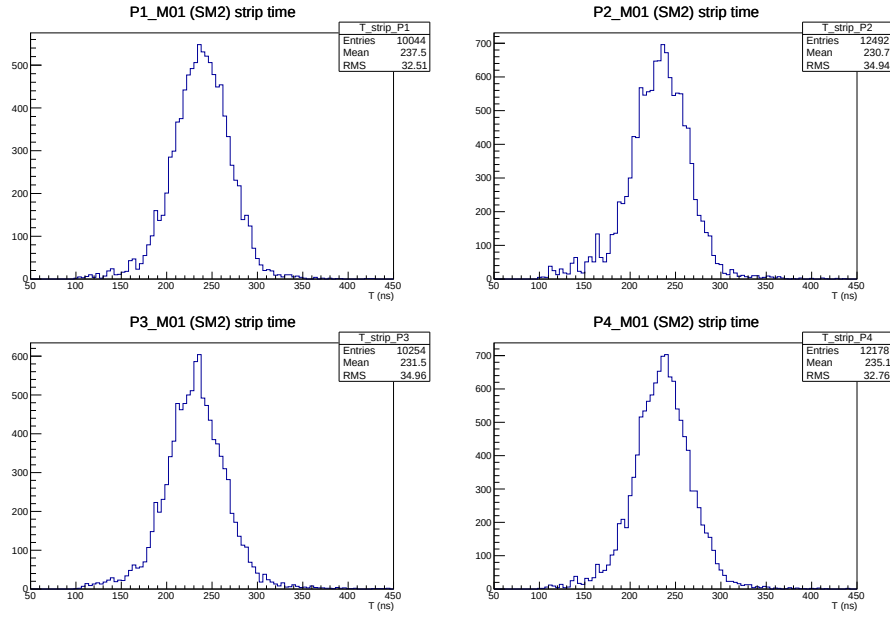


Figure 6.6. Distributions of the time of each strip obtained from the Fermi-Dirac fit.

- the cluster charge distribution (Figure 6.7);
- the early time of the cluster strips (Figure 6.8);
- the distribution of the strip multiplicity of each cluster; the distributions are peaked at about 3/4 strips and this is the mean value (Figure 6.9);
- the position of each cluster obtained with the method of the centroid (eq. 3.5); these distributions mirror, of course, the layer hit map (Figure 6.10).

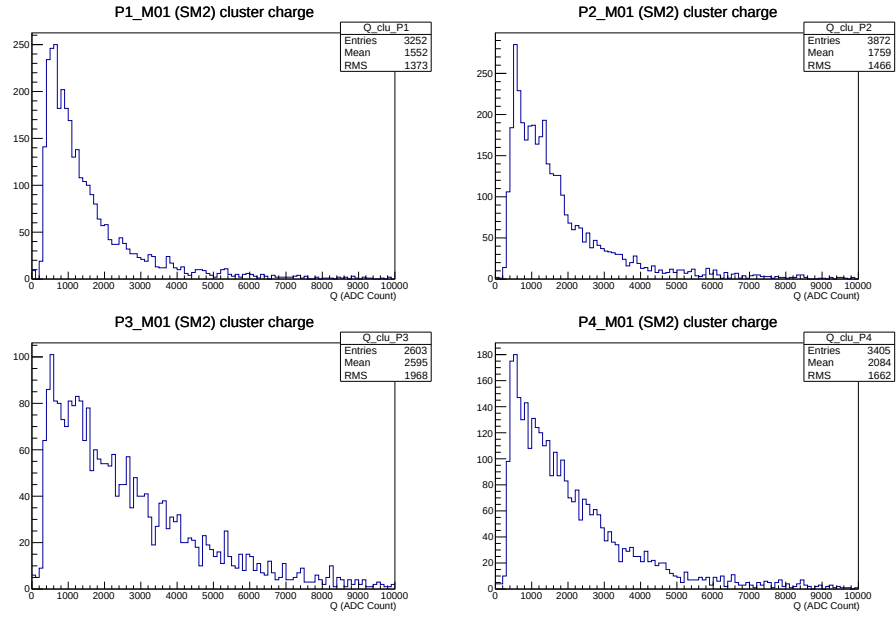


Figure 6.7. Distributions of the cluster collected charge of each SM2 Module 0 layers.

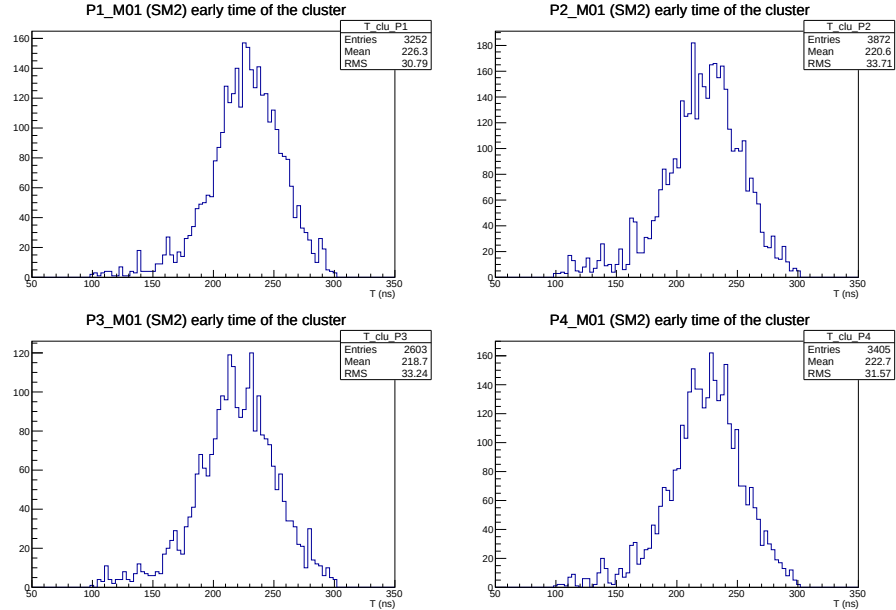


Figure 6.8. Distributions of the early time of the cluster strips which means the arrival time of the particle.

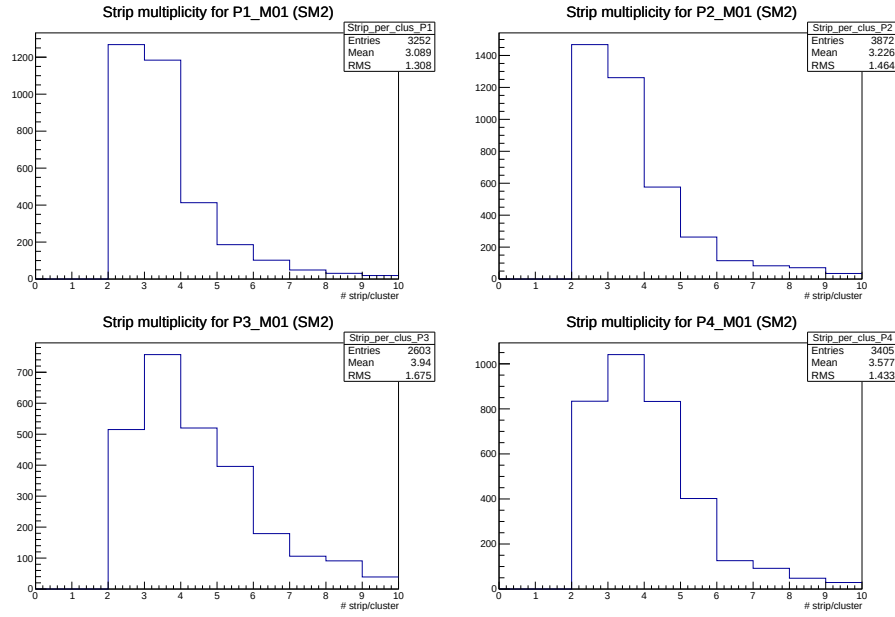


Figure 6.9. Distributions of the strip multiplicity of the cluster for each SM2 Module 0 layers.

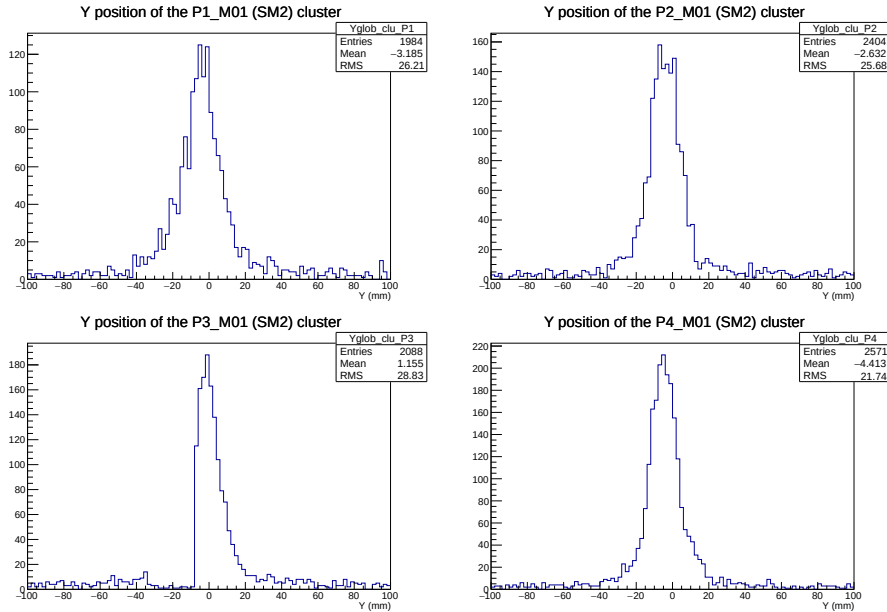


Figure 6.10. Distributions of the position of the centroid of the cluster for each SM2 Module 0 layers.

6.5 Preliminary data analysis

6.5.1 Uniformity response studies

One of the analyses done on SM2 Module 0 involves the study of the uniformity of the response of each single layer.

Using the typical distributions of each single layer for each run, the average value (the value provided by ROOT for the histogram considered) of each distribution was obtained and then are used to draw the 2D maps of the single layer responses.

In particular, the 2D maps shown below are:

- the cluster average charge which is extremely sensitive to small changes of the amplification voltage because the gain increases as a function of the V_{amp} ;
 - *layer 1* (Figure 6.11 - *up, left*) the charge response is quite uniform in the 7th and 8th PCBs while in the 6th there are some problems (e.g. internal discharges), which cause a lower effective amplification voltage respect the applied voltage, causing malfunction of the layer;
 - *layer 2* (Figure 6.11 - *up, right*) the behaviour is similar to the first layer but in the last two PCB the charge is slightly bigger; the same problem of layer 1 is in the 6th PCB with lower charge values;
 - *layer 3* (Figure 6.11 - *down, left*) the behaviour of this layer can not be studied altogether because during the run on 7th and 8th PCBs the amplification voltage on the 3rd panel was setted to 605 V while during the run on the 6th PCB, the amplification voltage is setted to 595 V. Analysing separately the points where the layer 3 is supplied at the same voltage, it can be concluded that its response is quite uniform;
 - *layer 4* (Figure 6.11 - *down, right*) the behaviour of the fourth layer is not entirely clear. The amplification voltage is different between the run on the 7th and 8th PCBs (595 V) and the 6th PCB (585 V); even considering separately the two groups of point in which the SM2 was supplied with the same amplification voltage, the charge response is not uniform;
- the distribution of the cluster early times that should not depend on the amplification voltage:
 - *layer 1* (Figure 6.12 - *up, left*) the cluster early time is uniform within 10% for the first layer;
 - *layer 2, 3, 4* the cluster early time distributions for this layers are similar to the first layer distribution with an uniformity less than the 10%;
- the strips multiplicity of the cluster which has a slight increase as the amplification voltage increases. This can be explained by the fact that increasing the amplification voltage some strips, which were below their detection charge threshold, go above the threshold. This results in a greater number of strips belonging to the cluster:

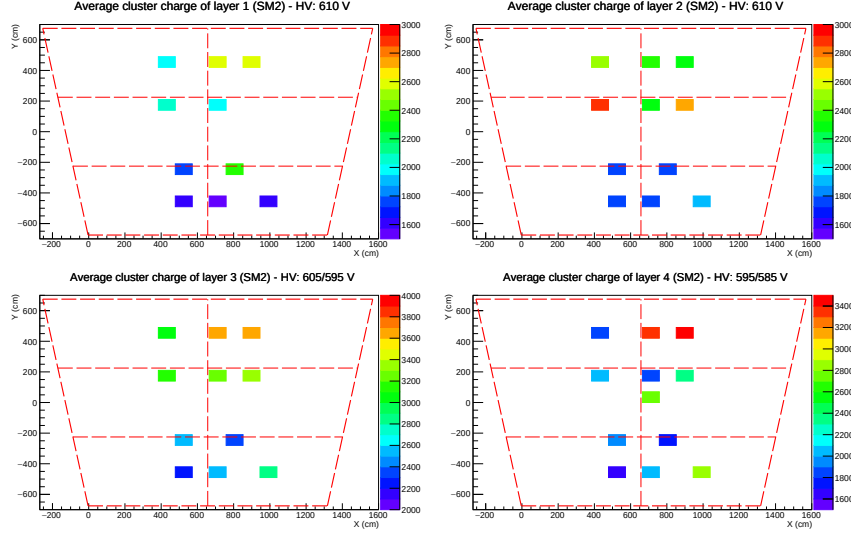


Figure 6.11. Charge response of each layer for each analysed point on SM2. The 6th PCB is the smallest one while the 7th is in the middle and 8th is on the top.

- *layer 1* (Figure 6.13 - *up, left*) the strip multiplicity is uniform within $20 \div 25$ % for the first layer with slightly lower values for the points on the 6th PCB;
- *layer 2* (Figure 6.13 - *up, right*) the behaviour of the strip multiplicity distribution for the second layer is similar to the first layer;
- *layer 3* (Figure 6.13 - *down, left*) despite the lower amplification voltage on the 6th PCB, the strip multiplicity distribution of the third layer is uniform at 20 %;
- *layer 4* (Figure 6.13 - *down, right*) the behaviour of the strip multiplicity distribution for the fourth layer is similar to the third layer except for the upper points on the 8th PCB where the strip multiplicity reach values around 4.4; this may be due to excessive electronic noise that light more strips and increases the size of the clusters.

6.5.2 Resolution of eta layers

In order to get the resolution of each layer can be used the telescope chambers (as explained for SM1 Module 0 in Section 5.2.5) to extrapolate the particle track and to compare the position measured by the layer with the expected position obtained from the extrapolation.

However, it is possible to obtain a first estimate of the resolution using only the individual layers by measuring the width of the distribution of the variable:

$$\delta_x = \frac{x_{layer\ 1} - x_{layer\ 2}}{\sqrt{2}} \quad (6.1)$$

Assuming that tracks used are all parallel, and that the two layers have the same resolution σ_x , the $\sigma(\delta x)$ is a good estimate of σ_x .

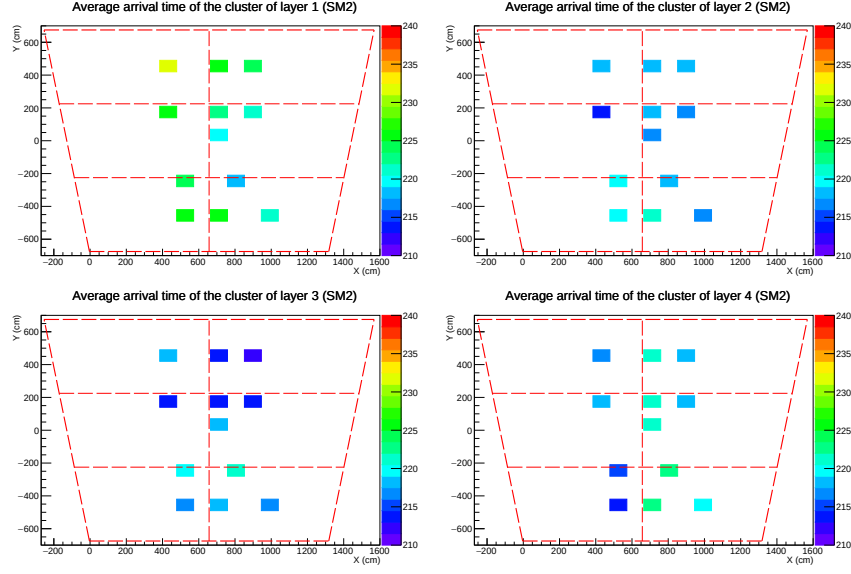


Figure 6.12. Distribution of the cluster early time for each layer.

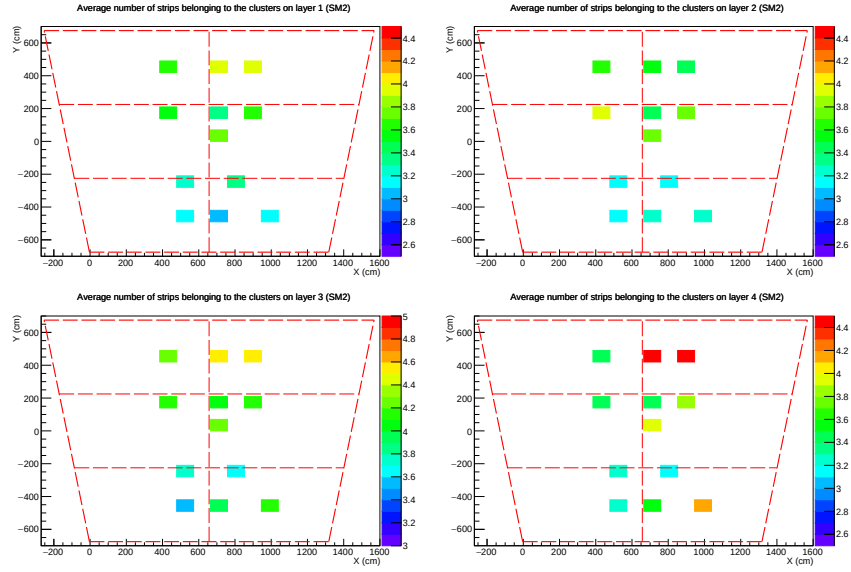


Figure 6.13. Distribution of the strip multiplicity for each layer.

In order to get $\sigma(\delta x)$, the obtained distributions are described by a bi-gaussian fit (to include the distribution tails in the fit):

$$f(\delta x) = A \cdot e^{-\frac{1}{2} \frac{(\delta x - \mu)^2}{\sigma_{core}^2}} + B \cdot e^{-\frac{1}{2} \frac{(\delta x - \mu)^2}{\sigma_{tail}^2}} \quad (6.2)$$

where A and B are the heights of the two gaussians, μ is the central value of the two gaussians corresponding to the average displacement between the two layers, while σ_{core} and σ_{tail} are respectively the width of the core-gaussian and the weight-gaussian.

Using the scan in position in the x-y plane, a spatial resolution measurement can be obtained for different beam impact point to find out if there are particular trends as a function of the impact beam point along the Module 0. For this analysis events where there is only one cluster in the first two layers are taken into account.

Figure 6.14 shows the distributions δx for the different positions in the x-y plane.

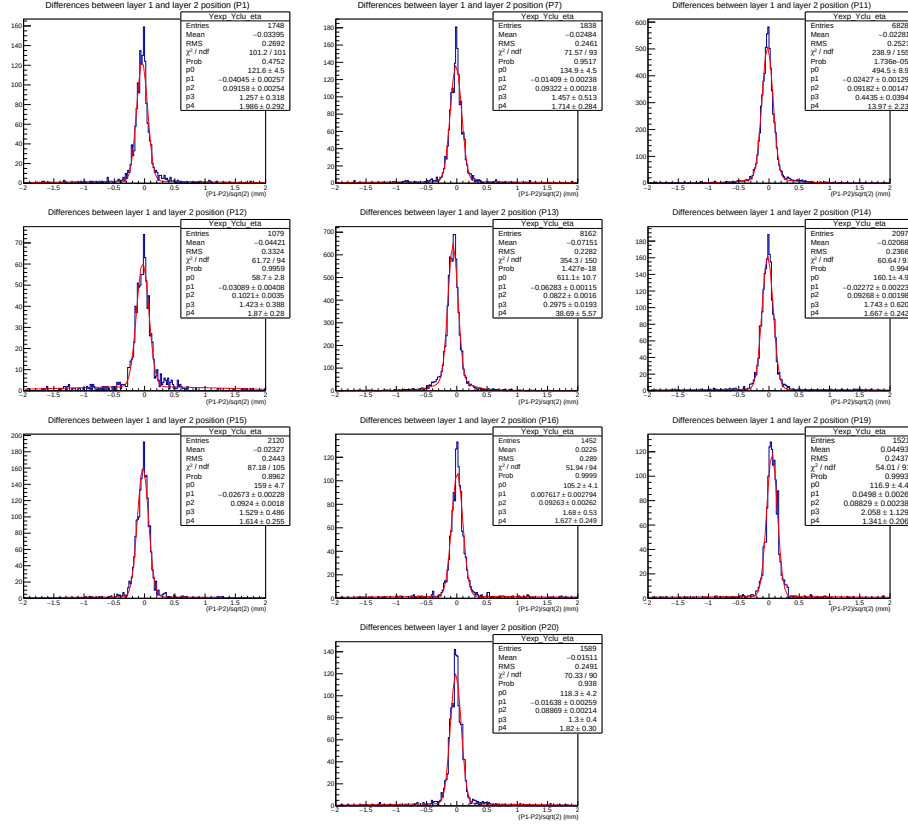


Figure 6.14. Distributions of the differences between the first and the second layer coordinate for different position on the SM2 Module 0. A double-gaussian fit (equation 6.2) is overimposed.

The resolutions σ_{core} obtained as a function of the position are shown in Figure 6.15. Only for one point (P12) the resolution is above $100\mu m$. From these, an estimate of the average resolution on the position of the two eta layers can be obtain:

$$\sigma_{layer\ 1} = \sigma_{layer\ 2} = 90.4 \pm 0.4\ \mu m$$

and it is within the ATLAS requirements.

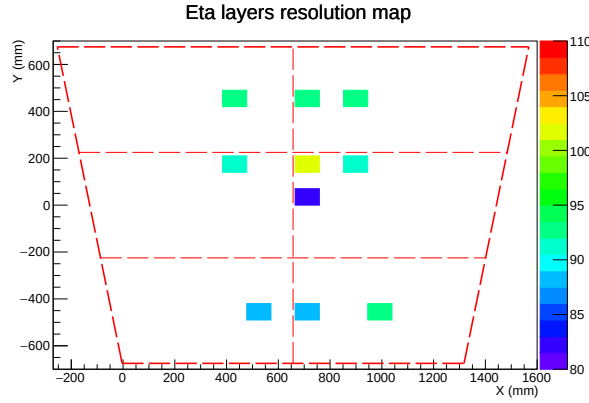


Figure 6.15. Resolution map of the eta layers.

6.6 Resolution stereo layers

Using the scan in position in the x-y plane, as before, the spatial resolution of the stereo layers can also be obtained. Knowing that the tilt angle of the stereo strips of Module 0 is $\pm 1.5^\circ$, a measurement of the first (η , equation 6.3) and the second coordinate (ϕ , equation 6.4) can be obtain [29].

$$\eta = \frac{x_{\text{layer } 3} + x_{\text{layer } 4}}{2 \cdot \cos(\theta)} \quad (6.3)$$

$$\phi = \frac{x_{\text{layer } 3} - x_{\text{layer } 4}}{2 \cdot \sin(\theta)} \quad (6.4)$$

For this analysis events where there is only one cluster in the first layer and in the two stereo layers are taken into account.

Figure 6.16 shows the distributions of differences between the centroid in the first layer and the η coordinate reconstructed by the stereo layers normalized by a factor $\sqrt{2}$ for the different positions in the x-y plane.

The resolutions obtained as a function of the position are shown in Figure 6.17; only two position (P12 and P01) have a resolution worse than the $100 \mu m$ required by ATLAS. From these, an estimate of the average resolution on the position of the two stereo layers can be obtained:

$$\sigma_{\text{stereo}} = 92.4 \pm 0.7 \mu m$$

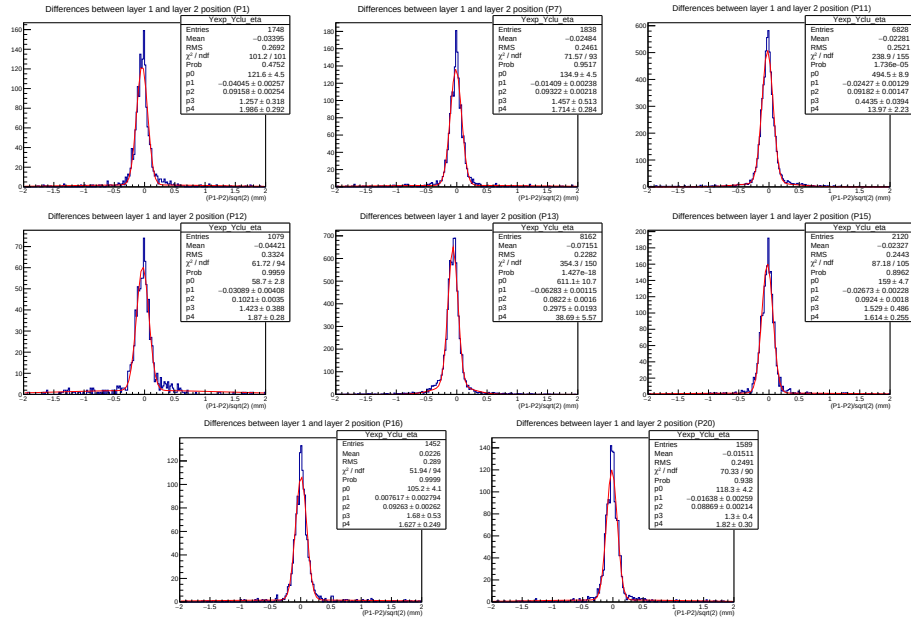


Figure 6.16. Distribution of the differences between the first layer and the η coordinate reconstructed by the stereo layers coordinate for different position on the SM2 Module 0.

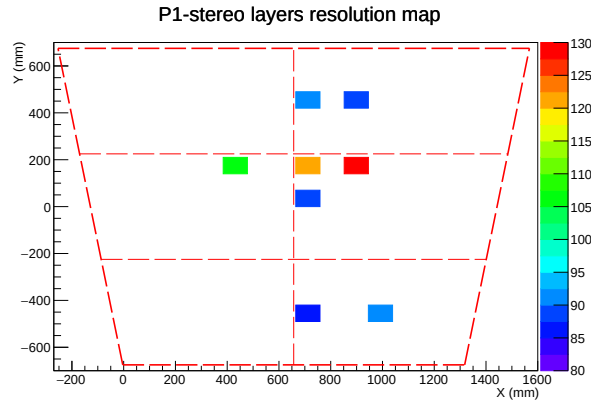


Figure 6.17. Resolution map of the P1-stereo layers.

Conclusions

In this thesis, a study of the construction and quality control of drift panels and the performance of the first prototypes of the MicroMegas chambers for the New Small Wheel of the ATLAS Experiment at LHC is presented.

The procedure for building drift panels of the SM1 quadruplets has been described together with all the quality control measurements on mechanical parameters (thickness and planarity measurements) and electrical (dark current measurements) that have been done to determine if the built panels are within the ATLAS requirements.

It was found that the panels have been constructed respecting the thickness and planarity limits even if they exhibit minor acceptable imperfections, particularly in the “*outer*” side which are less important because they correspond to the external side of the quadruplet. High voltage tests were also carried out supplying the panels with a voltage of 500 V and verifying that the dark current in each panel was less than 5 nA; it was noted also a change in the value of the current as a function of the air humidity but this dependence is still being studied.

The analysis on the cosmic ray data taken at the Frascati cosmic ray test stand that will be done to validate all the SM1 quadruplets once they will be produced has been defined. In particular, the intrinsic chamber characteristics (time, charge and multiplicity of strips and clusters) have been studied to verify the correct functioning of Module 0. Problems have been found in the use of special interface cards produced at Frascati; then the efficiency in a small region ($10 \times 10 \text{ cm}^2$) of the first PCB was studied for the first two layers, achieving values greater than 99%.

Finally, the resolution of the first SM2 MicroMegas prototype is studied using the CERN SPS muon/pion beam obtaining position resolutions for the two layers eta ($\sigma_\eta(x) \simeq 90 \text{ }\mu\text{m}$) and of the stereo layer ($\sigma_{stereo}(x) \simeq 92 \text{ }\mu\text{m}$), which are lower than the ATLAS experiment requests. The uniformity of the responses of the individual layers is also studied as a function of the beam impact point.

Conclusioni

In questo lavoro di tesi sono stati studiati alcuni aspetti legati alla costruzione ed al quality control dei pannelli di drift e alle prestazioni dei primi prototipi delle camere MicroMegas per la New Small Wheel dell'esperimento ATLAS a LHC.

Si è descritto il procedimento di costruzione dei pannelli di drift per i quadrupletti di SM1 e le misure di quality control sui parametri meccanici (misure di spessore e planarità) ed elettrici (misure di correnti parassite) per determinare se i pannelli rispettano le richieste dettate dall'esperimento ATLAS.

Si è ricavato che i pannelli sono stati costruiti rispettando i limiti di spessore e di planarità dettati da ATLAS anche se presentano piccole imperfezioni, soprattutto nelle facce “outer” che corrispondono alla parte esterna dei quadrupletti. Inoltre sono stati effettuati dei test dell'alta tensione portando i pannelli ad un voltaggio di 500 V e andando a verificare che la corrente parassita in ogni pannello sia minore di 5 nA; è stata notata anche una variazione del valore della corrente in funzione dell'umidità dell'aria ma questa dipendenza è ancora in fase di studio.

Sono state definite le tipologie di analisi che saranno effettuate sui dati del Cosmic Ray Stand di Frascati che saranno usate per validare tutti i quadrupletti SM1 una volta che saranno prodotti. In particolare, sono stati studiati gli andamenti delle grandezze caratteristiche intrinseche della camera (tempi, carica e molteplicità delle strip e dei cluster) per verificare il corretto funzionamento del Modulo 0, riscontrando problemi nell'utilizzo delle schede di interfaccia INFN costruite a Frascati; si è studiata quindi l'efficienza in una piccola regione ($10 \times 10 \text{ cm}^2$) del primo PCB per i primi due layer ottenendo valori superiori al 99%.

Infine si è studiata la risoluzione del primo prototipo di camera MicroMegas SM2 utilizzando il fascio di muoni/pioni dell'SPS del CERN ricavando le risoluzioni sulla posizione per i due layer eta ($\sigma_\eta(x) \simeq 90 \mu\text{m}$) e dei layer stereo ($\sigma_{\text{stereo}}(x) \simeq 92 \mu\text{m}$) le quali sono inferiori alle richieste dell'esperimento ATLAS. Sono state studiate anche le uniformità delle risposte dei singoli layer al variare del punto d'impatto del fascio.

Bibliography

- [1] L. Evans and P. Bryant, “*LHC Machine*”, JINST **3** (2008) S08001;
- [2] ATLAS Collaboration, “*The ATLAS Experiment at the CERN Large Hadron Collider*”, JINST **3** (2008) S08003;
- [3] S. Chatrchyan *et al.* [CMS Collaboration], “*The CMS Experiment at the CERN LHC*”, JINST **3** (2008) S08004;
- [4] K. Aamodt *et al.* [ALICE Collaboration], “*The ALICE experiment at the CERN LHC*”, JINST **3** (2008) S08002;
- [5] A. A. Alves, Jr. *et al.* [LHCb Collaboration], “*The LHCb Detector at the LHC*”, JINST **3** (2008) S08005;
- [6] ATLAS Collaboration, “*Observation of a New Particle in the Search for the Standard Model Higgs Boson with the ATLAS Detector at the LHC*”, Phys.Lett. B716 (2012) 1-29, CERN-PH-EP-2012-218, arXiv:1207.7214;
- [7] ATLAS Collaboration, “*Observation of a Centrality-Dependent Dijet Asymmetry in Lead-Lead Collisions at $\sqrt{s_{NN}} = 2.76$ TeV with the ATLAS Detector at the LHC*”, Phys.Rev.Lett.105:252303 2010, arXiv:1011.6182v2 [hep-ex] 30 Nov 2010;
- [8] LHCb collaboration, “*Observation of J/ψ resonances consistent with pentaquark states in $\Lambda_b^0 \rightarrow J/\psi K^- p$ decays*”, Phys. Rev. Lett. 115 072001 (2015), arXiv:1507.03414v2 [hep-ex] 25 Jul 2015;
- [9] L. Rossi and O. Brüning, “*High Luminosity Large Hadron Collider, A description for the European Strategy Preparatory Group*”, Tech. Rep. CERN-ATS-2012-236, CERN, Geneva, Aug, 2012;
- [10] ATLAS Magnet Project Collaboration, “*ATLAS Magnet System: Technical Design Report*”, CERN-LHCC-97-018. CERN, Geneva, 1997;
- [11] ATLAS Inner Detector Community, “*ATLAS Inner Detector: Technical Design Report*”, CERN-LHCC-97-016. CERN, Geneva, 1997;
- [12] ATLAS LARG Unit, “*ATLAS LAr Calorimeter: Technical Design Report*”, CERN-LHCC-96-041. CERN, Geneva, 1996;
- [13] ATLAS/Tile Calorimeter Collaboration, “*ATLAS Tile Calorimeter: Technical Design Report*”, CERN-LHCC-96-042. CERN, Geneva, 1996;

- [14] ATLAS Muon Collaboration, “*ATLAS Muon Spectrometer: Technical Design Report*”, CERN-LHCC-97-022. CERN, Geneva, 1997;
- [15] ATLAS Collaboration, “*ATLAS first level trigger: Technical design report*”, CERN-LHCC-98-14, ATLAS-TDR-12;
- [16] ATLAS Collaboration, “*Letter of Intent for the Phase-II Upgrade of the ATLAS Experiment*”, CERN-LHCC-2012-022. LHCC-1-020, Geneva, Dec, 2012;
- [17] Wolfram Zeuner, “*LS2 and LS3: The Largest Challenges as Known Today*”, ECFA High Luminosity LHC Experiments Workshop 2014;
- [18] ATLAS Collaboration, “*ATLAS New Small Wheel: Technical Design Report*”, Technical Design Report ATLAS. CERN-LHCC-2013-006. CERN, Geneva, 2013;
- [19] H. Raether, “*Entwicklung der Elektronen in den Funkenkanal*”, Z. Phys. 112 (1939) p.464;
- [20] J. Wotschack *et al.*, “*The development of large-area Micromegas detectors for the ATLAS Upgrade*”, Mod.Phys.Lett. A28 (2013) 1340020;
- [21] M. Iodice [ATLAS Muon Collaboration], “*Micromegas detectors for the Muon Spectrometer upgrade of the ATLAS experiment*”, JINST **10** (2015) no.02, C02026;
- [22] ZEBRA Elastomeric Connectors,
<http://www.fujipoly.com/usa/products/zebra-elastomeric-connectors/> .
- [23] MMFE-8 Specification,
<https://indico.cern.ch/event/354058/session/0/contribution/5> .
- [24] Garfield, a drift-chamber simulation program,
<http://lambda.phys.tohoku.ac.jp/kobayash/seminar/files/cern/garfield.pdf> .
- [25] Quadra-Chek 200 - User’s Guide,
http://www.inspectionengineering.com/Images/qc200_manual_eng.pdf .
- [26] Mitutoyo Linear Height 600,
<http://www.mitutoyo.com/wp-content/uploads/2016/09/D-section-Digimatic-Height-Gages.pdf> .
- [27] A. Zullo, “*SM1 drift panel assembly*”.
- [28] I. Efthymiopoulos, “*The SPS North Area Beams, Introduction to H8 Beam Line*”, 23 March 2006.
- [29] T. Alexopoulos *et al.* “*Stereo Information in Micromegas Detectors*” ATL-MUON-INT-2015-005. July 31, 2015.