

SILICON STRIP DETECTOR QUALIFICATION FOR THE CMS EXPERIMENT

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Zusammenfassung

Der CMS Detektor (Compact Muon Solenoid) ist eines von vier Experimenten, die derzeit am LHC Beschleuniger (Large Hadron Collider) am Europäischen Zentrum für Elementarteilchenphysik CERN in Genf fertiggestellt werden. Dieser Proton-Proton Beschleuniger wird einen neuen Energiebereich von bis zu 14 TeV Schwerpunktsenergie erforschen. Um eine bestmögliche Spurauflösung und eine sehr schnelle Auslese zu gewährleisten, besteht der innere Spurdetektor von CMS aus einem Silizium-Detektor mit Pixeln in den innersten Lagen, die von Streifenmodulen umgeben sind.

Die kleinsten Detektions-Einheiten des Streifen-Spurdetektors sind sogenannte Module. Sie werden auf größere Strukturen, den sogenannten *Shells* im inneren Bereich (Tracker Inner Barrel, TIB), *Rods* im äußeren Bereich (Tracker Outer Barrel, TOB), *Disks* in der inneren Endkappe (Tracker Inner Disk, TID) und *Petals* in der äußeren Endkappe (Tracker End Cap, TEC) des zentralen Spurdetektors montiert. Der gesamte Streifen-Spurdetektor umfasst eine sensitive Fläche von ungefähr 198 m^2 und besteht aus ca. 16.000 Siliziummodulen.

Bevor die Sensoren auf die entsprechenden Substrukturen montiert wurden, fand eine Qualitätsüberprüfung statt, bei der jeder einzelne Auslesekanal auf seine Funktionalität getestet wurde. Nur Module mit einer Fehlerrate von kleiner als 2 % wurden für die Integration in den Spurdetektor zugelassen. Im Fall der äußeren Endkappen fand die anschließende Petal-Montage in sechs sogenannten Petal-Integrations-Zentren (Petal Integration Centers) statt, von denen eins in Aachen errichtet wurde. Im Anschluss an die Fertigung wurde jedes Petal einem Langzeittest, bei dem alle Komponenten zum ersten Mal gemeinsam ausgelesen und bei tiefen Temperaturen betrieben wurden, unterzogen und entsprechend qualifiziert. Von 294 produzierten Petals (288 werden für die beiden Endkappen benötigt) erhielten 286 Petals die beste Qualitätsstufe. Nur etwa 1 ‰ aller TEC Auslesekanäle wurde im Einzelmodul-Test und im Petal-Langzeittest als fehlerhaft identifiziert.

Im Sommer 2006 fand der sogenannte MTCC (Magnet Test and Cosmic Challenge) in der CMS Montagehalle am CERN statt, bei dem das Experiment zum ersten Mal geschlossen und Teile aller Subsysteme gemeinsam ausgelesen wurden. Der supraleitende Solenoid-Magnet wurde bei einem Magnetfeld von bis zu 4 T betrieben und ein Bruchteil des Myon-Systems lieferte die für die Auslese aller Subdetektoren nötige Information über den Durchgang eines Myons aus der kosmischen Höhenstrahlung. Auf diese Weise konnte die Leistungsfähigkeit der beteiligten zwei Shells des TIB, vier Rods des TOB und zwei Petals der TEC (was etwa 1 % des finalen Streifen-Spurdetektors entspricht) bei verschiedenen Magnetfeldern über einen Zeitraum von ungefähr zwei Monaten und unter Verwendung von kosmischen Myon-Signalen untersucht werden.

Der letzte Test vor der Installation des Spurdetektors im CMS Experiment war der sogenannte TST (Tracker Slice Test) im Frühjahr/Sommer 2007, der in der TIF (Tracker Integration Facility) am CERN durchgeführt wurde. Nach dem Einbau aller Komponenten in den Spurdetektor wurden ungefähr 25 % der $+z$ Seite des Streifendetektors unter Verwendung von Szintillationszählern zum Nachweis kosmischer Teilchendurchgänge ausgelesen.

Insgesamt wurden etwa 5 Millionen Myon-Ereignisse bei verschiedenen Betriebsbedingungen aufgezeichnet. Diese Ereignisse wurden zusammen mit Daten von der Inbetriebnahme benutzt, um Detektor-Eigenschaften wie Ladungsverteilungen, Signal-zu-Rausch-Verhältnisse und das Streifenrauschen zu untersuchen. Außerdem wurden anhand dieser Daten fehlerhafte Kanäle identifiziert, die in der Größenordnung von einigen Promille liegen.

Die Funktionsfähigkeit des Siliziumstreifen-Spurdetektors während dieser verschiedenen Konstruktions- und Testphasen wird in der vorliegenden Arbeit diskutiert. Dabei wird ein besonderer Schwerpunkt auf die Endkappen des Spurdetektors gelegt.

Abstract

The Compact Muon Solenoid (CMS) is one of the four experiments being installed at the Large Hadron Collider (LHC) which is located at the european organization for nuclear research CERN in Geneva. This proton-proton collider will explore a new energy regime of up to 14 TeV center-of-mass energy. To provide the best spatial resolution for the particle trajectory reconstruction and a very fast readout, the inner tracking system of CMS is build up of silicon detectors with a pixel tracker in the center surrounded by a strip tracker.

The silicon strip tracker consists of so-called modules representing the smallest detection unit of the tracking device. These modules are mounted on higher-level structures called *shells* in the tracker inner barrel (TIB), *rods* in the tracker outer barrel (TOB), *disks* in the tracker inner disks (TID) and *petals* in the tracker end caps (TEC). The entire strip tracker spans an active area of about 198 m² and consists of approximately 16000 modules.

Before the silicon sensors were assembled on the respective substructures they had to pass a qualification test where each single readout channel was checked for its functionality. Only modules with a failure rate of less than 2 % were allowed to be integrated in the tracker. In case of the tracker end caps the following petal assembly took place in six so-called Petal Integration Centers whereof one was located in Aachen. Subsequent to the assembly each petal was tested and graded in a longterm test being the first time that all petal components were read out simultaneously and operated in a cold environment. Out of 294 production petals (288 are needed for the two end caps) 286 petals received the best quality grade A. Only about 1 ‰ of the TEC readout channels were flagged as faulty in the single module test and the petal longterm test.

In summer 2006 the so-called Magnet Test and Cosmic Challenge (MTCC) took place in the CMS assembly hall at CERN. It was the first time that the experiment was closed including parts of all subdetectors. The superconducting solenoid was ramped up to a magnetic field of 4 T and parts of the muon system were used to deliver a trigger for cosmic ray muons to all subdetectors. Thus, the performance of the participating two shells of the TIB, four rods of the TOB and two petals of the TEC (representing about 1 % of the final strip tracker) could be studied in different magnetic fields over a period of approximately two month using cosmic muon signals.

The last test before inserting the tracker in the CMS experiment was the Tracker Slice Test performed in spring/summer 2007 at the Tracker Integration Facility (TIF) at CERN after installing all subdetectors in the tracker support tube. Approximately 25 % of the strip tracker +z side was powered and read out using a cosmic ray trigger built up of scintillation counters. In total, about 5 million muon events were recorded under various operating conditions. These events together with results from commissioning runs were used to study the detector response like cluster charges, signal-to-noise ratios and single strip noise behaviour as well as to identify faulty channels which turned out to be in the order of a few per mille.

The performance of the silicon strip tracker during these different construction stages will be discussed in this thesis with a special emphasis on the tracker end caps.

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Chapter 1

Introduction

Already two thousand years ago scientists and philosophers have searched for the fundamental constituents of matter. The two main questions were: "What is matter made of?" and "Which forces hold it together?". Also today exactly these questions are the motivation for particle physics. Only the theories and experiments have changed. Nowadays large particle accelerators reaching enormous energies are built to take a deeper look inside matter than ever before. At the same time the detection devices have to be improved to be able to process a large amount of data with high precision.

1.1 The Standard Model of Particle Physics

The theoretical description of nature, in particular of its constituents and the interactions among them, is combined in the Standard Model of Particle Physics (SM). This framework was developed during the last century and lead to a sophisticated formalism to structure the matter and to explain its behaviour. On the one hand it is based on the fundamental fermions which build up all observed matter and on the other hand it contains the gauge bosons mediating the interactions.

The 12 elementary fermions carrying spin $\frac{1}{2}\hbar$ are divided into 6 quarks and 6 leptons (see table 1.1) and the associated antiparticles, differing only in the signs of all additive quantum numbers like the electric charge. They are classified in three generations where each generation is a heavy copy of the former one and within a generation a pair of fermions compose a left-handed weak isospin doublet. In addition, every generation consists of one (for leptons) or two (for quarks) right-handed weak isospin singlets. The heavy particles of the second and third generation are instable and decay into the first generation constituents. Thus the stable matter in the universe is made up of electrons and the corresponding neutrinos, up- and down-quarks.

The forces between the particles are mediated by gauge fields resulting in the existence of related gauge bosons with integer spin. Today there are four known interactions: the electromagnetic, the weak, the strong and the gravitational force. The corresponding bosons are listed in table 1.2. Except for the gravitation, which is not yet implemented in the SM, these interactions are well described by quantum field theories, namely Quantum Electrodynamics (QED), which is unified with the weak force in the GSW theory for electroweak interactions, and Quantum Chromodynamics (QCD).

Fermions	Generation 1	Generation 2	Generation 3	Charge		
				electrical [e]	weak	colour
Leptons	$\begin{pmatrix} \nu_e \\ e \end{pmatrix}_L$	$\begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}_L$	$\begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}_L$	0 -1	+1/2 -1/2	- -
	e_R	μ_R	τ_R	-1	0	-
Quarks	$\begin{pmatrix} u \\ d \end{pmatrix}_L$	$\begin{pmatrix} c \\ s \end{pmatrix}_L$	$\begin{pmatrix} t \\ b \end{pmatrix}_L$	+2/3 -1/3	+1/2 -1/2	<i>rgb</i> <i>rgb</i>
	u_R	c_R	t_R	+2/3	0	<i>rgb</i>
	d_R	s_R	b_R	-1/3	0	<i>rgb</i>

Table 1.1: Fundamental fermions of the Standard Model of Particle Physics. The left-handed weak isospin doublets are indicated with an L whereas the right-handed singlets are labeled with R . The weak charge is meant as the third component of the weak isospin T_3 .

One fundamental principle in modern physics on which the SM is based is the demand for local gauge invariance of the theories. This requirement leads for example in the electroweak model, which is the unification of the electromagnetic and weak interaction described by the combined symmetry group $SU(2)_L \times U(1)_Y$, to the existence of the γ , $W^\pm$ and Z^0 bosons. Although these particles have been discovered experimentally the theory is incomplete since it predicts only massless bosons which contradicts the measurements. Because of that a new complex doublet, called the Higgs field, was introduced in the SM to be able to give mass to the W and Z bosons. Since the vacuum expectation value of this field is non-vanishing the symmetry is spontaneously broken by choosing a particular phase of the ground state. Using this Higgs mechanism which predicts an additional scalar boson - the Higgs boson - the masses of the heavy gauge bosons can be created. But this particle has not been discovered yet. Excluding a low energy regime for its mass by former experiments ($m_H > 114.4 \text{ GeV}$ @ 95% confidence level [1]) and deriving an upper limit due to the requirement of unitarity ($m_H < 1 \text{ TeV}$) it is expected that the Higgs boson will be found at the Large Hadron Collider at CERN¹, if it exists.

Bosons	Interaction	Mass [GeV]	Q [e]	Spin [$\hbar$]	Range [m]
Photon γ	electromagnetic	0	0	1	∞
$W^\pm$	weak	≈ 80.4	± 1	1	$\ll 10^{-16}$
Z^0	weak	≈ 91.2	0	1	$\ll 10^{-16}$
8 Gluons g	strong	0	0	1	10^{-15}

Table 1.2: Gauge bosons of the quantum field theories in the Standard Model and some of their properties.

Apart from the minimal SM there are also further extensions in order to explain the particle masses and to unify the different interactions between them. One example is the Minimal Supersymmetric Standard Model (MSSM) where a symmetry between fermions and

¹European Organization for Nuclear Research, formerly known as **C**oncil **E**urop  enne pour la **R**echerche **N**ucl  aire

bosons is postulated leading to supersymmetric partners for each standard model particle with a spin shift of $\frac{1}{2}\hbar$. This framework provides five Higgs bosons instead of one, three of them electrically neutral (h , H and A) and two of them electrically charged ($H^\pm$). Such a theory avoids the fine tuning of the Higgs mass concerning the hierarchy problem of the electroweak, the GUT and the Planck scale. But it introduces a lot of new parameters that are not predicted by the model itself but have to be determined from measurements.

Up to the present the SM agrees very well with the experimental results. Nevertheless there are several open questions that cannot be answered by this model. For example it is unknown why there are three generations of fundamental fermions. Another problem are the 25 free parameters in the minimal SM like the fermion masses or the coupling constants which cannot be derived from the theory but have to be inserted in the framework by hand after measuring their values in experiments. In addition the unification of all four interactions affiliating them to a common symmetry is still an open issue. These examples show that the SM is not the final description of the structure of matter. It will be further tested in new collider experiments exploring an energy regime up to the TeV scale. This will allow to examine the favoured extensions and thus to evolve the Standard Model and the knowledge of nature.

1.2 The Large Hadron Collider

The Large Hadron Collider is a ring accelerator for protons located at CERN. It is the successor of the former Large Electron Positron Collider (LEP) that was shut down in 2000. In contrast to LEP where electrons and positrons were accelerated up to a center of mass energy of 208 GeV the LHC will use two proton beams with 7 TeV each. Among other things this increase of energy is due to the large proton mass. It is approximately 2000 times larger than the electron mass which causes the synchrotron radiation to be negligible. A disadvantage of the proton is its substructure resulting in an enormous QCD background of uninteresting events that have to be separated from the events under investigation and leading to an unknown center of mass energy of the hard interaction. It is less than 14 TeV.

Since the LHC is constructed in the former LEP tunnel it has also a circumference of 27 km with two separate beam pipes crossing at four interaction points. There the two proton beams collide with a center of mass energy of 14 TeV at a frequency of 40 MHz. To measure the particles originating from these collisions large detection devices are built around the intersection points covering different fields of particle physics:

- The ALICE detector (**A** **L**arge **I**on **C**ollider **E**xperiment) will focus on the study of proton-nucleus and nucleus-nucleus interactions since these particles will also be accelerated by the LHC for certain periods of the year. The aim is to investigate strongly interacting matter at very high energy densities and to produce the so-called quark-gluon plasma as it was present a few microseconds after the Big Bang [2].
- The LHC-b experiment (**L**arge **H**adron **C**ollider **b**eauty) will exploit the high $b\bar{b}$ cross section at the LHC to study CP violation in B -meson decays with high precision. In addition, rare B and τ decays will be investigated [3].
- The ATLAS (**A** **T**oroidal **L**HC **A**pparatus) and CMS (**C**ompact **M**uon **S**olenoid) detectors are multi purpose experiments to search for the Higgs boson, to test the Stan-

Standard Model and to explore new physics beyond it such as the search for supersymmetric particles [4][5].

In the basic design the protons are accelerated in 2808 bunches each containing up to 10^{11} protons with a bunch spacing of 25 ns. The acceleration is done using superconducting radio frequency cavities while the bending of the beam is made by superconducting dipole magnets with 8.4 T magnetic field strength. To provide high statistic also for events with a small cross section the LHC will reach after the initial low luminosity phase with $\mathcal{L} \approx 10^{33} \text{ cm}^{-2}\text{s}^{-1}$ its design luminosity of $10^{34} \text{ cm}^{-2}\text{s}^{-1}$. This leads for example to the production of about $10^8 t\bar{t}$ pairs per year. Thus a detailed study of top quark properties like its mass, width and couplings is possible. In addition, the large number of $b\bar{b}$ pairs allows for a precise investigation of CP violation. The huge energy range finally enables the production of new heavy particles like SUSY particles or maybe the Higgs boson as well.

1.3 The CMS Experiment

The CMS experiment is a classical multi purpose detector composed of different subsystems. It is designed for a good lepton identification and a precise measurement of all particle energies and momenta ranging from 100 GeV up to the TeV scale. The whole detector has a length of 21.6 m, a diameter of 14.6 m and a total weight of 12500 tonnes. In figure 1.1 a schematic view of the Compact Muon Solenoid is shown.

The innermost part is a silicon pixel detector to provide high resolution of the interaction vertices. It is surrounded by the silicon strip tracker that measures the trajectories of charged

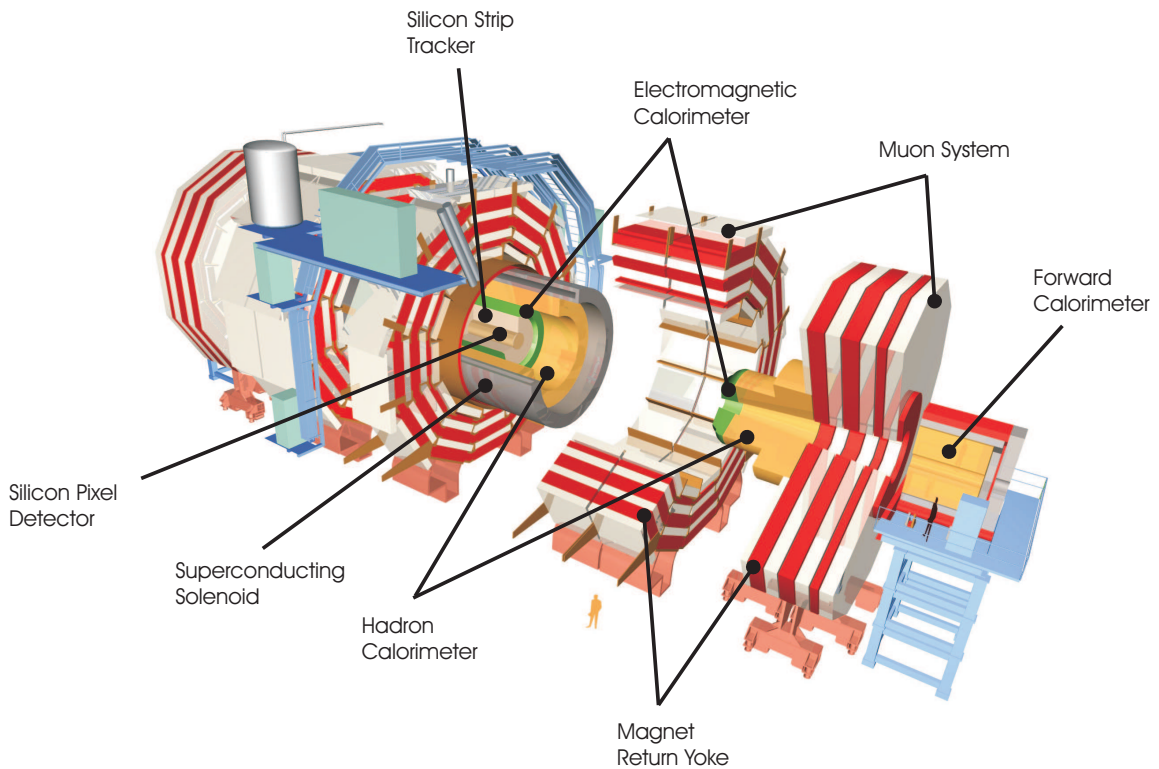


Figure 1.1: Schematic view of the CMS detector. The different subsystems are shown by colours. [6]

particles, followed by the calorimeters. The electromagnetic calorimeter determines the energy of electrons, positrons and photons by stopping them and producing an electromagnetic shower whereas hadrons are absorbed in the hadronic calorimeter. In order to identify the charge and the momentum of the particles using the track curvature in a magnetic field the previous components are installed inside a superconducting magnet. Finally, the iron return yoke of the magnet is instrumented with a muon detector system. Muons are, besides neutrinos, the only particles leaving the detector.

The conditions that a detector at the Large Hadron Collider has to meet are very challenging both on the hardware side and the data acquisition side. At the interaction point of the proton-proton collisions all components are exposed to an enormous radiation. The whole detector has to be extremely radiation hard. In addition the experiment has to cope with a large amount of particles at the same time originating from the primary interaction and the pile-up events which requires a high granularity of all subdetectors. The bunch crossing time of 25 ns demands furthermore a fast readout electronics even though only events that have passed different trigger levels are completely read out.

In the following paragraphs the subsystems of the CMS detector are explained briefly from the outer to the inner parts.

The Muon System

Since muons are a clear signature for a lot of physics processes a good muon detection device is vital for every high energy physics experiment. For example the Higgs decay channel $H \rightarrow ZZ \rightarrow \mu^+\mu^-\mu^+\mu^-$ can be identified directly via the four muons.

In CMS the muon system consists in the barrel region of drift tubes (DT) covering a pseudo-rapidity up to $\eta \approx 1.3$ and providing a precise measurement in the bending plane. Because of the inhomogeneity of the magnetic field and the higher rate in the forward region the end caps are instrumented with cathode strip chambers (CSC). They have a fast response time and a fine segmentation so that a high precision is also guaranteed in this environment. In addition both barrel and end caps are equipped with resistive plate chambers (RPC) to provide a fast and highly segmented trigger.

These different detectors ensure the main purposes of the muon system that are muon identification, muon trigger and muon momentum measurement. The standalone momentum resolution $\delta p_T/p_T$ will be in the order of 8 – 15 % at 10 GeV and 20 – 40 % at 1 TeV [7]. Since the positioning of the muon system with respect to the central tracking device is measured with a laser alignment system this resolution can be improved through a track matching between the two subdetectors. Using the tracker information this will lead to a global momentum resolution in the order of 1 – 1.5 % at 10 GeV and 6 – 17 % at 1 TeV.

The Magnet

The magnet of the CMS experiment is a large superconducting solenoid with a length of 13 m and an inner radius of about 3 m. This allows to install both the inner tracking system and the calorimeters inside the magnet reducing the radiation length in front of the calorimeters and thus ensuring a more accurate energy measurement of the collision products.

With a magnetic field of 4 T parallel to the beam axis a good momentum resolution for high momentum muons is achieved up to $\eta \approx 2.5$. In addition the precise muon trigger

- based on the large magnetic field - provides an efficient first level trigger which is very important in order to reduce the large amount of data to the interesting events.

The magnetic flux is returned via a saturated iron yoke of 1.5 m thickness that is instrumented with several layers of muon chambers. During operation an energy of 2.7 GJ will be stored in the magnet [8].

The Hadron Calorimeter

The main goals of the calorimeter systems including the electromagnetic calorimeter are to identify and to measure precisely the energy of photons and electrons, to measure quark and gluon directions and energies by measuring the energy and direction of particle jets and to provide hermetic coverage to detect missing transverse energy [9].

The hadron calorimeter (HCAL) consists of an inner barrel and two endcaps which are located inside the magnet and an outer calorimeter mounted on the first muon absorber layer. It is a sampling calorimeter made of 4 mm thick plastic scintillator tiles read out using wavelength-shifting plastic fibers. The scintillators are inserted between copper absorber plates of 5 cm thickness in the barrel region and 8 cm thickness in the end caps. To extend the pseudorapidity coverage up to $3 \leq |\eta| \leq 5$ a separate forward calorimeter is installed 6 m downstream of the hadronic endcaps. The active medium is made of quartz fibers embedded in a copper absorber matrix.

The Electromagnetic Calorimeter

A scintillating crystal calorimeter with lead tungstate (PbWO_4) crystals was chosen as electromagnetic calorimeter (ECAL). Due to a small Molière radius the high density crystals allow a very compact calorimeter design. In addition it is a fast scintillator with a short radiation length. The ECAL is also divided in a barrel region where avalanche photodiodes collect the scintillation light and end caps where vacuum photodiodes are used.

Although the electromagnetic calorimeter has a rapidity coverage up to $|\eta| = 3$ a precise energy measurement is only possible in the range of $|\eta| < 2.6$. The energy resolution can be parametrized as

$$(\sigma/E)^2 = (a/\sqrt{E})^2 + (\sigma_n/E)^2 + c^2$$

where a is the stochastic term, σ_n the noise, c the constant term and E the energy in GeV. For the barrel region at small $|\eta|$ the stochastic term is about $2.7\%/\sqrt{E}$, the constant term 0.55% and the noise (low luminosity) in E_T about 155 MeV [10]. Each crystal has a cross section of about $22 \times 22 \text{ mm}^2$ and a length of about 23 cm corresponding to 26 radiation lengths.

The ECAL will play an essential role in the potential discovery of the Higgs boson. The measurement of the two-photon decay mode for $m_H \leq 150 \text{ GeV}$ or the measurements of electrons and positrons from the decays $H \rightarrow ZZ$ and $H \rightarrow WW$ for $140 \text{ GeV} \leq m_H \leq 700 \text{ GeV}$ are clear signatures for its existence.

The Tracking System

Due to the enormous particle flux close to the interaction point the tracking system as innermost detector part has to be extremely radiation hard. Silicon has been chosen to

be the best material for this environment providing at the same time very good signal performances. To reduce the radiation damage as much as possible the whole tracker will be operated at -10°C . Nevertheless the innermost layers have to be replaced after a few years of running when reasonable operation is no longer possible.

The CMS tracking system is composed of two main parts: The silicon pixel detector at short distances to the interaction point and the silicon strip detector surrounding the pixel tracker. With an active silicon surface of about 1.06 m^2 for the pixel and about 198 m^2 for the strip detector this is the largest silicon tracker ever built.

The Pixel Tracker

Because the most interesting events are supposed to contain secondary vertices like τ events or b-jets, the tracking system has to be as close as possible to the primary interaction vertex in order to provide for example a high efficient b-tagging. In this region pixel devices are needed to get a good pattern recognition with high resolution. Over the full coverage of the CMS detector the pixel system should deliver at least two hits per track (see figure 1.2) so that secondary vertices are found and long-lived particles like b- and c-quarks and τ -leptons are tagged.

The pixel tracker consists of three barrel layers and two end disks on each side of the barrel. The three barrel layers are mounted at a radial distance of about 4.4 cm, 7.3 cm and 10.2 cm to the beam pipe. The innermost layer is expected to stay operational at full LHC luminosity for at least two years. Afterwards it has to be replaced due to the high radiation dose. Along the beam pipe the pixel device has a length of approximately $-50\text{ cm} \leq z \leq 50\text{ cm}$.

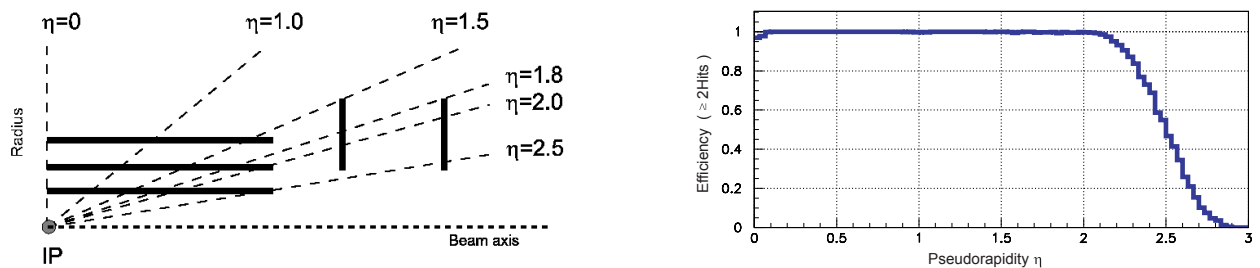


Figure 1.2: Geometrical layout of the pixel detector and hit coverage as a function of pseudorapidity. [11]

The pixel shape was chosen to be rectangular with a size of $100 \times 150\ \mu\text{m}^2$. This guarantees a good resolution in both dimensions. Moreover an analog readout is used to allow charge sharing for further increase of the hit resolution which is supposed to be $15 - 20\ \mu\text{m}$ [11].

The Silicon Strip Tracker

Analog to the pixel tracker the silicon strip tracker has a barrel and an end cap region. The barrel is subdivided into the Tracker Inner Barrel (TIB), consisting of four layers, and the Tracker Outer Barrel (TOB), which contains six layers. The barrel is closed on both sides with several disks: In the inner part with the Tracker Inner Disks (TID), a structure of three disks, and in the outer one with the Tracker End Caps (TEC), each consisting of nine disks.

The whole tracker has an outer diameter of about 2.2 m and a length of 5.5 m covering the pseudo-rapidity up to $|\eta| = 2.5$.

The active detector parts where charged particles are measured are the silicon strip modules. They consist of the sensors, the readout electronics and support structures. To simplify the assembly and the maintenance the modules are mounted on substructures called shells for the TIB, rods for the TOB and petals for the TEC. These structures that are later on assembled on the barrel and the endcaps, respectively, hold also the support cables and the cooling pipes to purge the heat from the modules. In addition, analog opto hybrids are mounted on the substructures to convert the analog electrical signal from the silicon detector to an analog optical signal. The optical readout is very fast and avoids a deterioration of electrical signals in the strong magnetic field. Furthermore the material budget is reduced by using optical fibers instead of copper cables. Photographs of the subdetectors and the corresponding substructures are shown in the appendix A.2.

Although the all silicon tracker delivers very precise track measurements one disadvantage is the material that is located in front of the calorimeters. In figure 1.3 the material budget of the tracker is shown in units of radiation length² X_0 . It has a minimum of $0.3 X_0$ at $\eta \approx 0$ and a maximum of $1.7 X_0$ at $|\eta| \approx 1.4$.

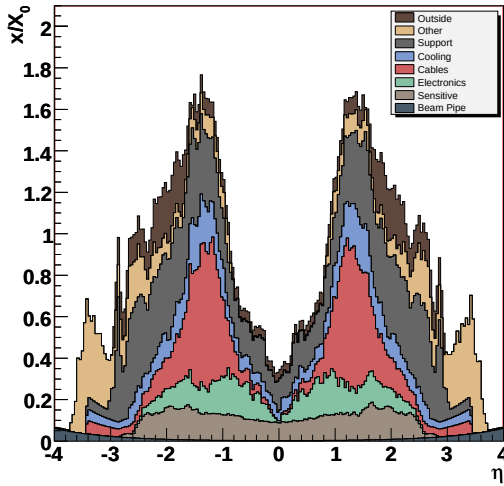


Figure 1.3: Material budget in units of radiation length as a function of pseudo-rapidity η broken down into the functional contributions. [11]

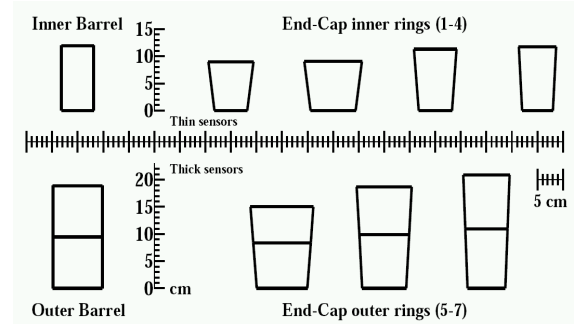


Figure 1.4: Silicon strip sensor geometries in the CMS tracker. Including stereo and alignment modules they are assembled to 15 different module types. [11]

In the barrel region the strips are parallel to the beam axis whereas in the end caps the detectors are positioned in rings (3 rings in TIB and up to 7 rings in TEC) in such a way that the strips are pointing to the beam pipe. Due to these requirements 15 different module geometries are needed resulting in rectangular detectors for the barrel and trapezoidal detectors for the end caps (see figure 1.4). The one dimensional strips allow the measurement of the particle trajectory perpendicular to the readout channels. The $r\phi$ measurements lead to a single point resolution in the order of $30\mu\text{m}$ in the TIB and $45\mu\text{m}$ in the TOB, respectively. To get 3-dimensional space points, the two innermost layers of TIB and TOB,

²The radiation length X_0 is defined as the path length after which the energy of a high energetic electron is decreased to $\frac{1}{e}$.

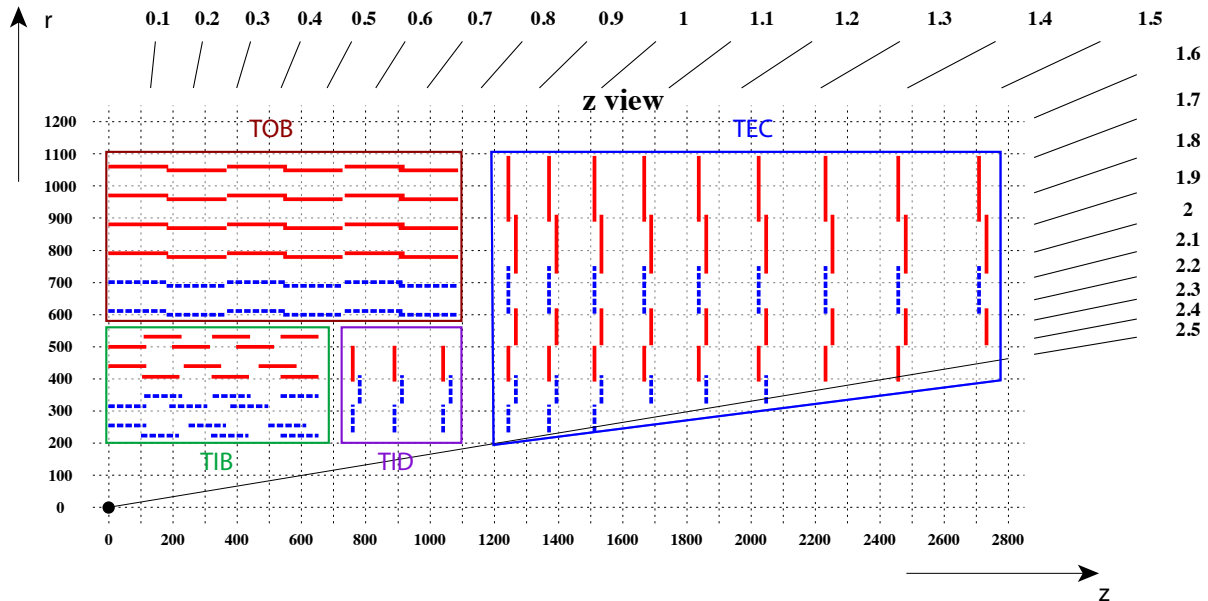


Figure 1.5: Schematic $r-z$ -view of one quarter of the silicon strip tracker. The lengths are given in mm. The pseudo-rapidity coverage ranges up to $|\eta| = 2.5$. Single sided silicon modules are indicated in red (solid lines) while double sided modules are shown in blue (dashed lines). The four subdetectors TIB, TOB, TID and TEC are indicated by different colours. [12]

the two innermost rings of TID and rings 1, 2 and 5 of TEC are additionally equipped with so-called stereo modules. The sensor on these detectors is tilted by an angle of 100 mrad (about 5.6 degree) with respect to the detector that delivers the ϕ coordinate. Stereo and phi modules are mounted back-to-back and form a double module delivering a single point resolution for the z -coordinate of $230\ \mu\text{m}$ and $530\ \mu\text{m}$ in TIB and TOB and, due to the changing pitch, a variable resolution of the r -coordinate in TID and TEC. Details concerning the different module characteristics are shown in tables A.1 and A.2. A longitudinal cut through one quarter of the strip tracker is depicted in figure 1.5. The different subdetectors as well as single and double sided modules are highlighted by colours.

As shown in figure 1.6 the tracker layout provides at least 9 hits in the silicon strip tracker up to $|\eta| < 2.3$ with at least 4 of them being two-dimensional measurements [11]. The resolution of the transverse momentum p_t , which can be measured for charged particles in a magnetic field due to the curvature of the trajectory, also benefits in the barrel region from the precise $r\phi$ measurement whereas it degrades in the end cap region because of the reduced r measurement. In figure 1.7 the transverse momentum resolution is shown for muons of different energies as a function of pseudo-rapidity.

In the pixel system the track density will be very high due to the short distance to the interaction point. In the strip tracker reaching from approximately $r = 255\text{ mm}$ to about $r = 1100\text{ mm}$ the track occupancy is smaller. For the pixel device the occupancy will be of the order of 10^{-4} per pixel and LHC bunch crossing whereas for the strip detector at an intermediate region ($20\text{ cm} < r < 55\text{ cm}$) it will be up to $2 - 3\%$ per strip and LHC bunch crossing and in the outer region of the tracker about 1% although the cell size is much larger than in the pixel system. A coarser granularity in the strip tracker is acceptable. It reduces the number of readout channels and thus the data size. In total the roughly 15000 modules add up to 9.6 million readout channels.

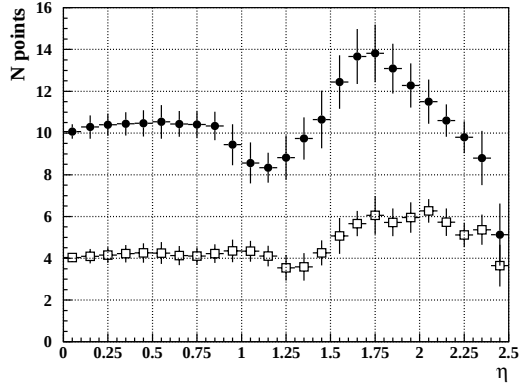


Figure 1.6: Number of measurement points in the strip tracker as a function of pseudo-rapidity η . Filled circles show the total number while open squares show the number of stereo layers. [11]

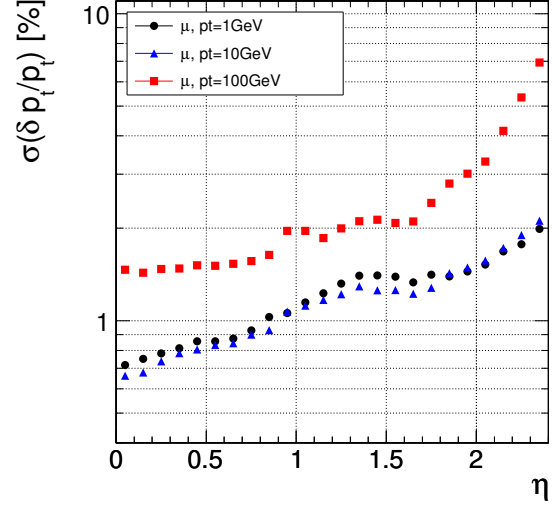


Figure 1.7: Transverse momentum resolution for single muons with transverse momenta of 1, 10 and 100 GeV. [11]

The Trigger and Data Acquisition System

At the design luminosity of $10^{34} \text{ cm}^{-2}\text{s}^{-1}$ about 10^9 interactions will occur every second. It is not possible to read out such a huge amount of data and write it to mass storage. The event rate that will be kept has to be reduced by several orders of magnitude. The CMS experiment therefore uses two levels of triggers: The level 1 trigger (L1) which is based on custom-made electronics and the high level trigger (HLT) which is a software trigger running on commercial processors [13, 14].

The L1 uses only data of coarse granularity from the calorimeters and the muon system while the other data are held in pipeline memories on the front-end electronics for about $3.2 \mu\text{s}$ until the decision of the L1 arrives. This trigger is based on the identification of muons, electrons, photons, jets and missing transverse energy. It reduces the initial event rate of 40 MHz by a factor of 1000 so that about 100 kHz are passed on to the high level trigger. At this time data of higher granularity including information from the tracking devices are analyzed to further separate interesting events from the whole data set. The processing time of the HLT is in the order of ms up to 1 s. It decreases the rate again by a factor of 1000. Since the average event size is 1 MB the final event rate of 100 Hz corresponds to a data flow of 100 MB/s that has to be stored.

Chapter 2

Single Module and Substructure Tests for the TEC

After the assembly of a single silicon strip module is finished a single module test called ARC test¹ is performed. If the module is graded well meaning it fulfills certain quality criteria it is delivered to the integration centers for integration into higher level structures like petals for the TEC or rods for the TOB. When this structure is fully equipped with modules, analog opto hybrids etc. a complete system test called Longterm test (LT test) is done. Only structures with a small error rate are allowed to be integrated in the tracker subdetectors afterwards. In this chapter the two tests are discussed briefly. For detailed information see [15] concerning the ARC test and [16] concerning the LT test, respectively.

2.1 The CMS Silicon Strip Modules

2.1.1 Interaction of Charged Particles with Matter

Due to the Coulomb interaction with the electrons of the atoms charged particles lose energy when traversing through matter. This specific energy loss $-dE$ per distance dx depends both on the characteristics of the particle and the properties of the matter. For charged, heavy particles it can be described with the Bethe-Bloch-Formula [17]:

$$-\frac{dE}{dx} = 2\pi N_0 r_e^2 m_e c^2 \rho \frac{Z}{A} \frac{z^2}{\beta^2} \left[\ln \left(\frac{2m_e \gamma^2 v^2 W_{\max}}{I^2} \right) - 2\beta^2 - \delta - 2\frac{C}{Z} \right] \quad (2.1)$$

with	N_0	Avogadro's number
	r_e	classical electron radius
	m_e	electron mass
	c	speed of light
	ρ	density of medium
	Z	atomic number of the medium
	A	atomic weight of the medium
	z	charge of a traversing particle
	$\beta = v/c$	velocity of incident particle in units of speed of light

¹APV Readout Controller test

$\gamma = 1/\sqrt{1 - \beta^2}$	Lorentz factor
$W_{\max}$	maximum energy transfer in a single collision
I	effective ionization potential averaged over all electrons
δ	density correction
C	shell correction

For low energies the specific energy loss decreases with $1/v^2$. It is independent from the mass of the incident particle and only depends on its charge and velocity. If equation 2.1 is parametrized as a function of the kinetic energy instead of the velocity of the particle, the specific energy loss also depends on its mass. Slow particles lose more energy than fast ones. At very low velocities the shell correction C is important to correct for atomic binding. If the velocity of the particle reaches the order of the speed of light c the energy loss slightly increases with increasing energy. This behaviour is dominated by the logarithmic term in equation 2.1. The density correction δ flattens the relativistic rise because the material becomes polarized. The minimum of the distribution is located at kinetic energies in the order of the rest mass of the respective particle ($\beta\gamma \approx 3$). Since the energy loss for particles with higher kinetic energies (e.g., cosmic-ray muons) is mostly close to that minimum value these particles are called minimum ionizing particles or MIPs. The Bethe-Bloch parametrization of energy loss is only valid in a certain energy range depending on the effective atomic number of the absorber and the mass of the incident particle, for example about $0.1 \leq \beta\gamma \leq 1000$ for positive muons in copper. At lower energies various corrections must be made and at higher energies radiative effects such as bremsstrahlung begin to be important. The mean

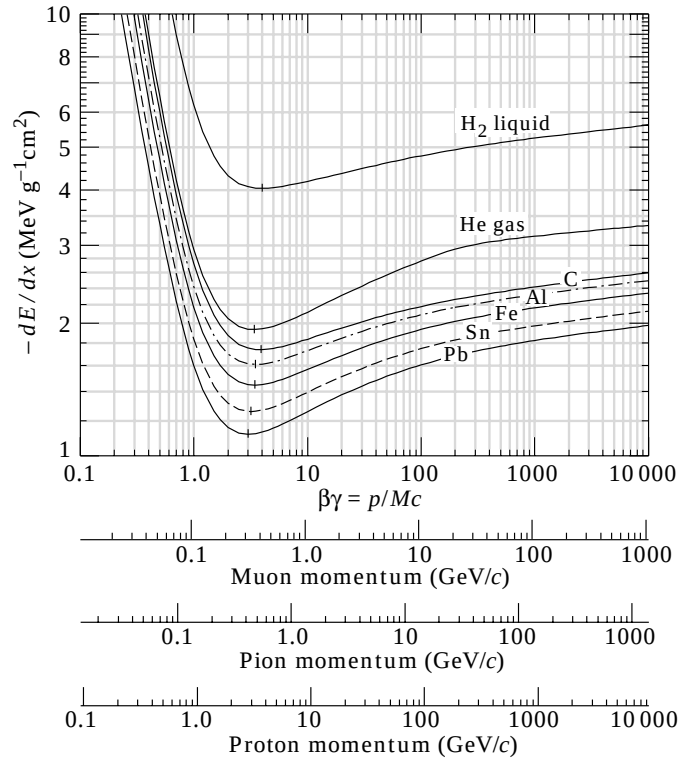


Figure 2.1: Mean energy loss rate for different absorber materials according to the Bethe-Bloch formula. The minimum of all distributions is approximately at $\beta\gamma \approx 3$. Particles with energies at this minimum are denoted as minimum ionizing particles. [18]

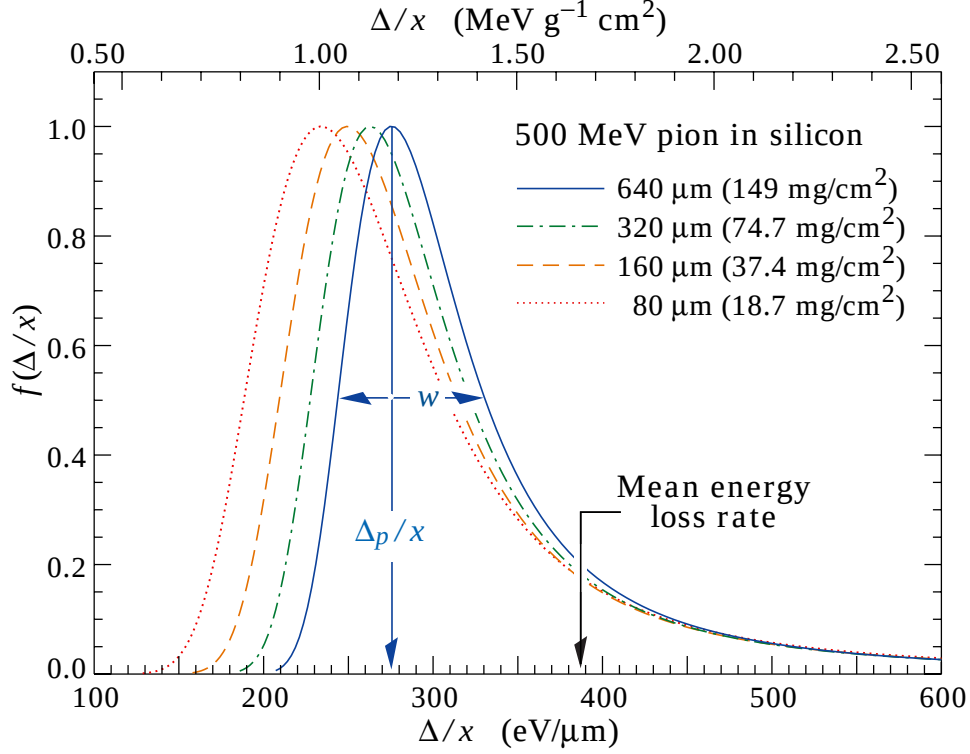


Figure 2.2: Landau distributions for 500 MeV pions in different thicknesses of silicon, normalized to unity at the most probable value Δ_p/x . [18]

energy loss rate corresponding to the Bethe-Bloch equation for different absorber materials is shown in figure 2.1.

Due to the stochastic nature of the energy loss the mean energy loss described by the Bethe-Bloch formula cannot be used to characterize the behaviour of a single particle. The probability distribution function $f(\Delta; \beta\gamma, x)$ parametrizing the energy loss Δ in a given absorber thickness x is called the Landau distribution. This distribution is shown in figure 2.2 for 500 MeV pions in different thicknesses of silicon. The most probable energy loss Δ_p is less than 70 % of the mean for a typical silicon strip detector [18]. Since the long tail of the distribution is often lost in background and is difficult to measure up to very high energy losses, the most probable value is much more relevant to detector calibration than the mean value. For thick absorbers the distribution describing the energy loss begins to approximate a Gaussian.

2.1.2 Layout and Function Principle of the CMS Silicon Strip Detectors

To illustrate the function principle of a semiconductor a simplified band scheme is used. As shown in figure 2.3(a) the semiconductor consists of two energy levels: the valence band with the highest energy E_V at its upper edge and the conduction band with the lowest energy E_C at its lower edge. In between is the Fermi energy E_F and the band gap $E_G = E_C - E_V$.

If the temperature is low there are no free electrons in the semiconductor and thus the valence electrons occupy completely the valence band whereas the conduction band remains

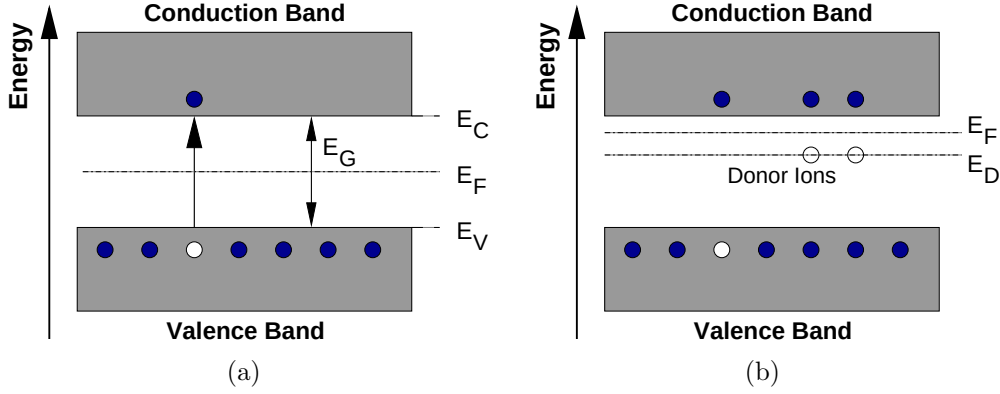


Figure 2.3: Energy band structures of (a) pure silicon and (b) n-type doped silicon. Blue circles represent electrons and white circles holes, respectively.

empty. By delivering enough energy to the bound electrons it is possible to lift them to the conduction band leaving behind a positive charged hole in the valence band. Both the unbound electrons and the holes can move and participate in the conduction process. If a charged particle crosses the semiconductor the deposited energy produces a large number of electron-hole-pairs leading to a short small power surge and thus to a signal in the presence of an electrical field.

To increase the performance of the detector the semiconductor is usually doped with foreign atoms. Therefore atoms with either one valence electron more than silicon (*n*-type doping) or one valence electron less (*p*-type doping) are incorporated in the crystal lattice. The first case leads to an excess of electrons in the conduction band (see figure 2.3(b); due to the doping a new energy level with the donor energy E_D is generated) and the second one to an excess of holes in the valence band. By contacting *n*-type and *p*-type doped silicon a diffusion of electrons in the *p*-type and of holes in the *n*-type region takes place until the increasing electrical field stops that process. Electrons and holes recombine in the neighbourhood of such a *pn*-junction. A depletion zone arises where no free charge carriers are available anymore. To increase this natural depletion zone, which is relatively small, an external reverse bias voltage is applied to the junction. The *n*-type region is connected to a positive and the *p*-type region to a negative potential. This causes both the electrons in the *n*-type and the holes in the *p*-type doping to be removed from the *pn*-junction resulting in an enlargement of the depletion zone which at the same time is the sensitive volume for particle detection.

The CMS silicon strip modules consist of different doped silicon layers in order to obtain with the applied bias voltage a large depletion area where charged particles produce electron-hole-pairs when crossing the detector. Figure 2.4 shows the schematic design of such a silicon microstrip sensor. It is mainly composed of three areas with different doping: Heavily doped p^+ -strips providing one dimensional information about the traversing particle, *n*-type silicon representing the bulk of the sensor where charge carriers are produced and a heavily doped n^+ -type region at the so-called backplane of the module. The latter ensures good ohmic contact to the aluminium coating where the positive voltage for the reverse bias is applied. The p^+ -strips are embedded in the *n*-type bulk. Several layers of isolating SiO_2 and Si_3N_4 create a dielectric for the capacitors consisting of a p^+ -strip and the aluminium strip above.

If a charged particle crosses the silicon sensor electron-hole-pairs are produced along the

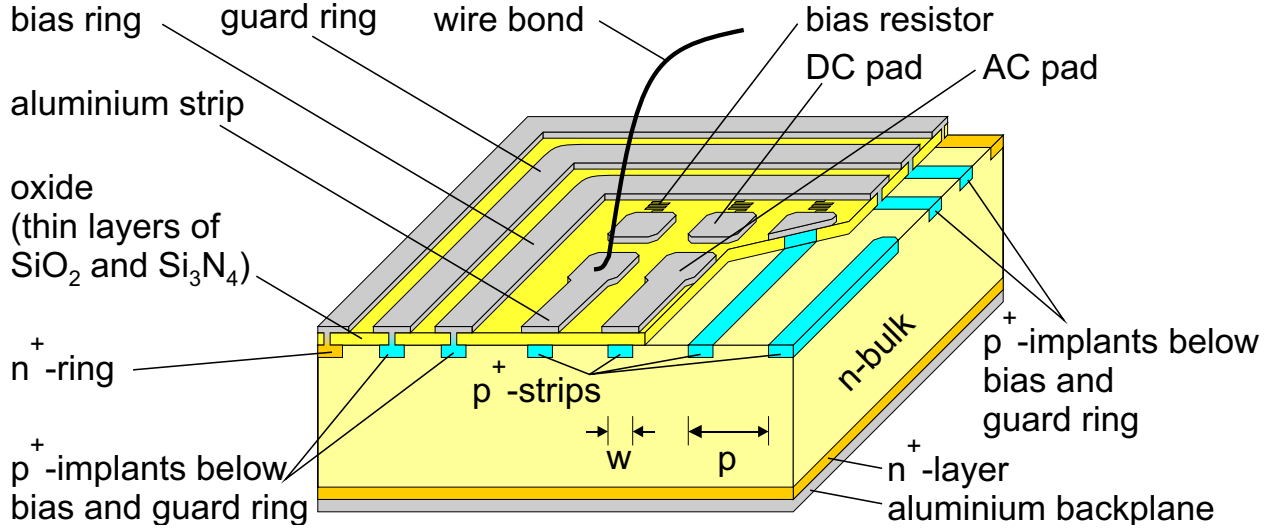


Figure 2.4: Schematic design of a CMS silicon microstrip sensor. [15]

particle trajectory within the n -type bulk. Because of the applied electrical field the electrons drift to the n^+ - and the holes to the p^+ -side with a drift time in the order of 10 ns. The resulting charge pulse in the p^+ -strips finally induces a signal in the aluminium strips that is read out by the so-called APV25-S1 chip.

The whole silicon strip module is made of several different components (see figure 2.5 for a TEC ring 6 module as example). Carbon fibre based support structures are used to carry the sensors and the front-end readout electronics. These support structures fulfill multiple requirements: The material budget is as low as possible in order to minimize the total amount of material in front of the calorimeters; it is very stiff to guarantee precise mounting of the detection device; so-called inserts provide efficient heat removal from the sensors; it is radiation hard and has approximately the same thermal expansion coefficient as silicon avoiding stress under temperature changes.

To apply the depletion voltage to the aluminium coated backplane of the sensor a capton cable is mounted on the carbon frame. Afterwards the sensors and front-end hybrids are glued to the frames using high precision assembly robots providing an accuracy in the order of $30\ \mu\text{m}$ for the sensitive coordinate. The capton cable is then connected to the backplane with conductive glue and wire bonds.

The readout chips have a distance of $44\ \mu\text{m}$ between two neighbouring readout channels at the input. This pitch varies on the sensors due to the different geometries (see tables A.1 and A.2). A pitch adapter is used to adjust the sensor and the chip pitch. This adapter and the readout chip (and also the different sensors in case of modules consisting of two silicon detectors) are electrically connected via wire bonds. The pitch adapter is followed by the front-end hybrid carrying several readout and control chips, namely:

- The APV25-S1 chip². This is the main component responsible for the data acquisition. Each APV chip is connected to 128 readout channels and samples the voltage pulses of every channel continuously every 25 ns storing the data in a 192 cells deep analogue

²APV is the abbreviation for **A**nalogue **P**ipeline **V**oltage. In the following the full name APV25-S1 will be replaced by APV for better readability.

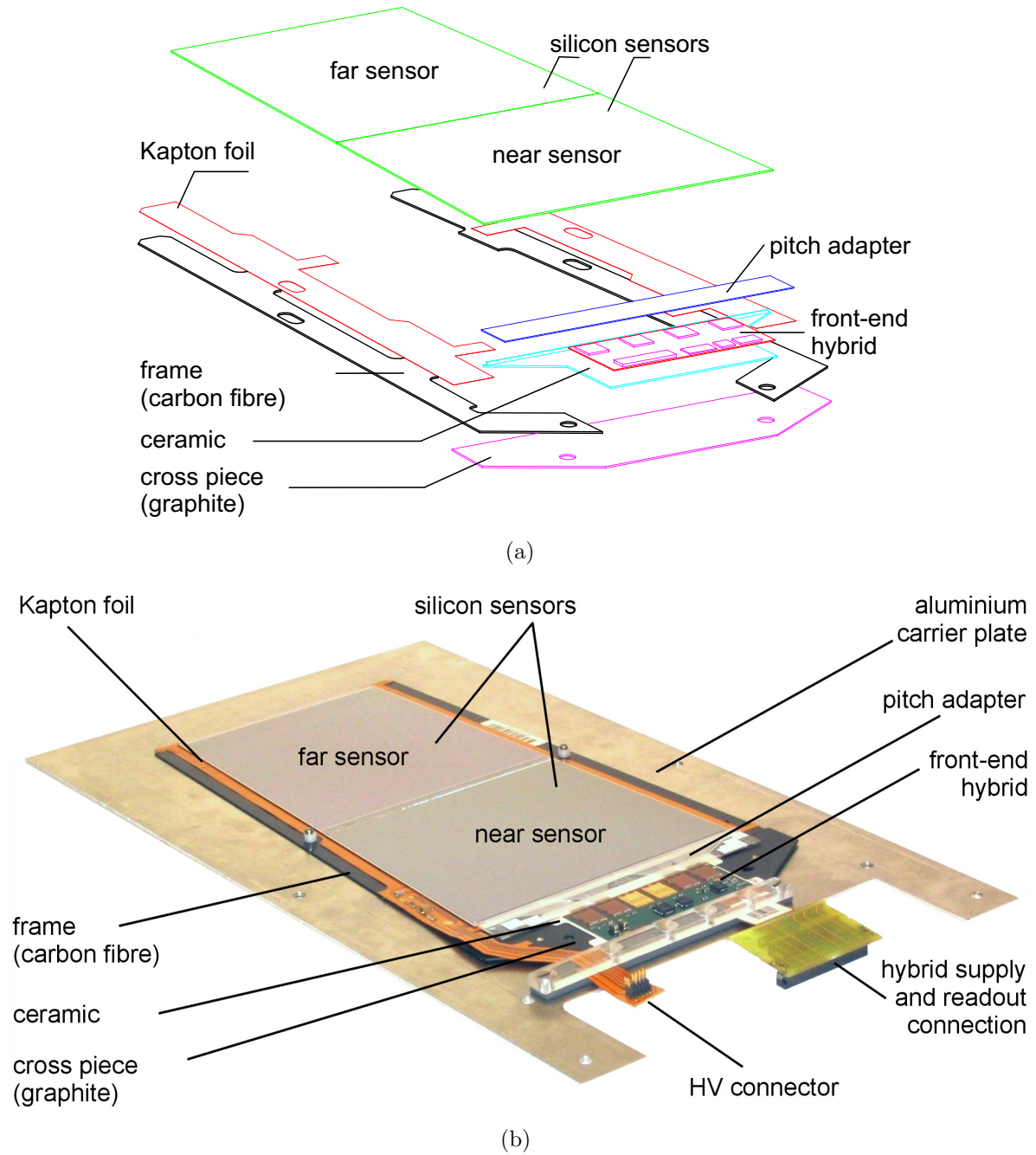


Figure 2.5: Layout of a TEC ring 6 detector. (a) Schematic exploded drawing, (b) photograph. [15]

pipeline per channel. After $4.8\mu\text{s}$ the data will be overwritten, thus requiring the arrival of a trigger signal less than $4.8\mu\text{s}$ after the event occurred. The APV has two main operation modes: The Peak Mode where the signal of one pipeline cell is read out and the Deconvolution Mode where the weighted sum of three succeeding pipeline cells is processed. The latter will be used in the high luminosity phase since it enables a shaping constant equal to the LHC clock of 25 ns whereas the Peak Mode has a shaping time of 50 ns preventing two hits within 25 ns to be disentangled. The disadvantage of the Deconvolution Mode is higher noise. Because of that the Peak Mode, where the signal-to-noise ratio is maximized, is used in case of low event rates. The signal information of all input channels are forwarded to a 128:1 multiplexer leading to only one output channel per APV.

- The MUX chip³. In order to further combine several signal channels in the readout chain a dedicated 2:1 multiplexer chip is used multiplexing the data of a pair of APVs onto a single differential line. In addition, the signal height can be adjusted to the optimal dynamical range of the downstream laser of the analog opto hybrid.
- The TPLL chip⁴. Because the trigger and the LHC clock information are encoded into a single signal a decoding device is needed at the beginning of the readout chain to disentangle the trigger from the clock. This functionality is provided by the TPLL chip. Furthermore it compensates phase shifts in the clock originating in signal propagation delays.
- The DCU chip⁵. It is used to monitor the leakage current of the silicon sensors, the power supply voltages (1.25 V and 2.50 V) of the APVs and the temperatures of the hybrid and the sensors. In addition, each DCU has a readable identifier (the so-called DCU id) for unique assignment of each module in the tracker.

The analog data from the APV chips on the front-end hybrids are later on converted into optical signals using analog opto-hybrids (AOHs). These devices are mounted on the different tracker substructures, namely the rods (TOB), the petals (TEC), the shells (TIB) and the disks (TID), in short distance to the corresponding front-end hybrid. Every AOH consists of two or three lasers each transmitting the multiplexed signal of two APVs or 256 readout channels.

2.2 The ARC Test

The ARC system was developed by the III. Physikalisches Institut B, RWTH Aachen [19]. It provides the readout and control of single silicon strip modules via a common PC using the ARC software. During the mass production of the silicon modules for the CMS tracker this system served as test setup for the quality assurance. After its assembly each module underwent a standard test cycle containing the following procedures:

- **I-V test** to measure the leakage current at different depletion voltages.

³MUX is the abbreviation for **M**ultiplexer.

⁴TPLL is the abbreviation for **T**racke**R** **P**hase **L**ocked **L**oop.

⁵DCU is the abbreviation for **D**etector **C**ontrol **U**nit.

Grade	Rel. number of faulty channels	Leakage current per sensor at 450 V
A	$< 1\%$	$< 10\ \mu\text{A}$
A _F	$< 1\%$	$> 5 \cdot I_{\text{DB}}$ and $< 10\ \mu\text{A}$
B	$> 1\%$ and $< 2\%$	$< 10\ \mu\text{A}$
B _F	$> 1\%$ and $< 2\%$	$> 5 \cdot I_{\text{DB}}$ and $< 10\ \mu\text{A}$
C	$> 2\%$	any
C	any	$> 10\ \mu\text{A}$

Table 2.1: Quality categories for the single module test. I_{DB} is the leakage current at 450 V from the sensor database.

- **Functional test** to check the functionality of all front-end chips, the communication, low voltages and the ARC system itself.
- **Pedestal run** to calculate the mean zero signal height (pedestal) and the variance of the pedestal (noise) for each channel and synchronous noise for a group of channels (common mode).
- **Pulse shape test** to check the calibration logic of the APV and to determine the shape of the pulses.
- **Pipeline test** to find defect pipeline cells.
- **Pinhole test** to detect pinholes connecting the APV input via the aluminium strip and the p^+ -implant of that strip.

Based on the results of these tests each single readout channel was graded. The sum of all 512 or 768 results (depending on the number of strips on the detector under investigation) led to a qualification of the whole module. Only modules with less than 2 % bad channels and $10\ \mu\text{A}$ leakage current per sensor (grade A and B modules) were integrated into higher level structures. Modules failing the test were repaired if possible and tested and graded again. The different quality categories in the ARC test are shown in table 2.1. The measured data were stored in ROOT [20] files for offline analysis and the test results in xml-files. In addition, the most significant results were transferred to a central CMS tracker database. This database contains the history of all tracker components at the different integration states, for example front-end hybrids, silicon modules, petals or rods and the results of all performed qualification tests. In this way each single step can be reproduced.

Since the measurement of the leakage current or the usage of infrared light pulses for example in the pinhole test requires a dark environment the silicon detector is housed in an optically opaque test box during the whole ARC test (see figure 2.6). Because only one module is tested in that box at a time and the box itself is protected against externally induced noise, the test environment in terms of noise is very clean due to the lack of jamming sources. This allows a very precise failure detection in the ARC test.

The following defect types are distinguishable by combining the results of the different test procedures: open bonds between the pitch adapter and the sensor or between two sensors, noisy channels, short-circuited channels, pinholes, saturated channels and defect inverters of the APVs which can be used to invert the signal. The most important quantities

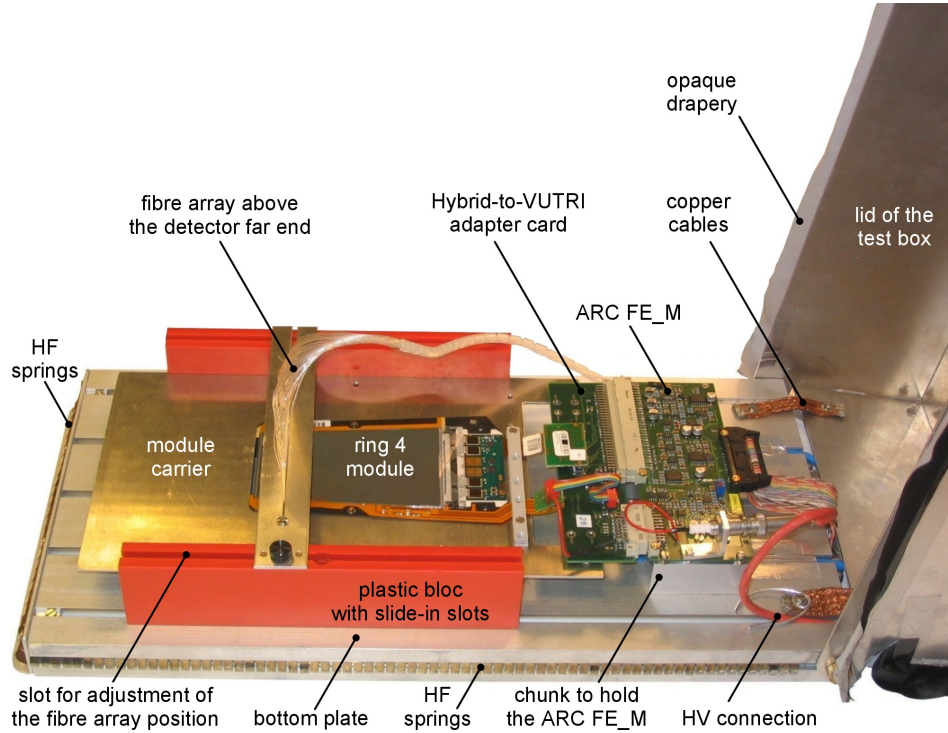


Figure 2.6: The test box used for the single module test. [15]

during the tests are briefly described in the following section. Detailed information of the ARC system and the fault finding algorithms can be found in [15].

2.2.1 Leakage Current

To study the leakage current of each module the depletion voltage is ramped from 0 V to 450 V in certain steps. At each step the leakage current is measured. It has to stay below $10 \mu\text{A}$ per sensor for all voltages applied in the range under investigation. If the current exceeds this value a second test is done using a higher current limit. If this also fails the complete ARC test is aborted. In figure 2.7 a measured I-V curve is shown. A low leakage current is important to reduce the temperature of the silicon sensors and the load of the power supplies.

2.2.2 Pedestal and Noise

The mean signal level on readout channel i that is present if no physics event was triggered, is called pedestal P_i . To distinguish it from a real physics signal originating from a passage of a charged particle through the silicon sensor the pedestal has to be measured before analyzing physics data. Therefore all channels belonging to a module are read out N times (with N in the order of 1000) with a random trigger to avoid physics signals in the events. If q_i^k is the raw data of channel i in the event k the pedestal for this channel is the raw data averaged over all events N :

$$P_i = \frac{1}{N} \cdot \sum_{k=1}^N q_i^k \quad (2.2)$$

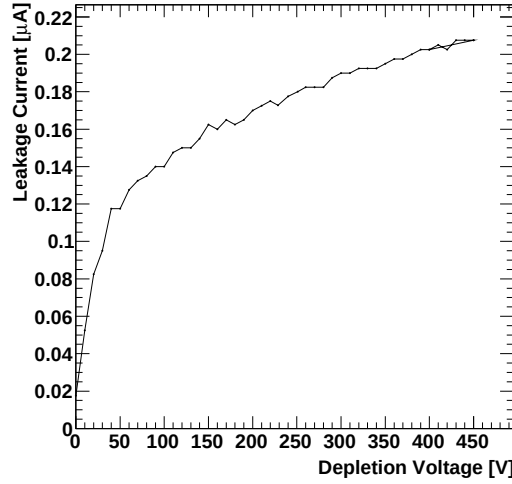


Figure 2.7: Measured I-V curve for a TEC ring 4 module.

The pedestals of a silicon module with 512 channels are shown in figure 2.8(a). It is not flat but slightly increases with increasing strip number within one APV.

Since the signal of each channel has small variations from event to event another important parameter is the noise of the channel. It delivers an estimate for the signal fluctuation and can be calculated as the standard deviation of the pedestal σ_i :

$$\sigma_i = \sqrt{\langle (q_i)^2 \rangle - \langle q_i \rangle^2} = \sqrt{\frac{1}{N-1} \sum_{k=1}^N (q_i^k - P_i)^2} \quad (2.3)$$

This variable indicates the raw noise. It is determined for each channel separately. In addition, a group of channels can show a common variation in the signal level from one event to another caused for example by fluctuations on the power supply lines. To take this so-called common mode into account for each event k the difference between the raw data and the pedestal for all 128 channels of an APV is calculated. The common mode CM^k in event k is then determined by the arithmetic mean of these deviations:

$$CM^k = \frac{1}{128} \cdot \sum_{i=1}^{128} (q_i^k - P_i) \quad (2.4)$$

Instead of calculating one common mode value for all 128 channels of an APV it is also possible to make a finer partitioning using for example four groups of 32 neighbouring channels each. This was done in the ARC test since it lead to flatter noise distributions. Furthermore bad channels have to be excluded from the common mode computation because they can influence the average deviation from the pedestal significantly. If the common mode is non-vanishing the corresponding channels have a common shift in one direction that has to be corrected in the data analysis. Thus the common mode and pedestal corrected raw data, which can be denoted as signal s_i^k , is given by:

$$s_i^k = q_i^k - CM_i^k - P_i \quad (2.5)$$

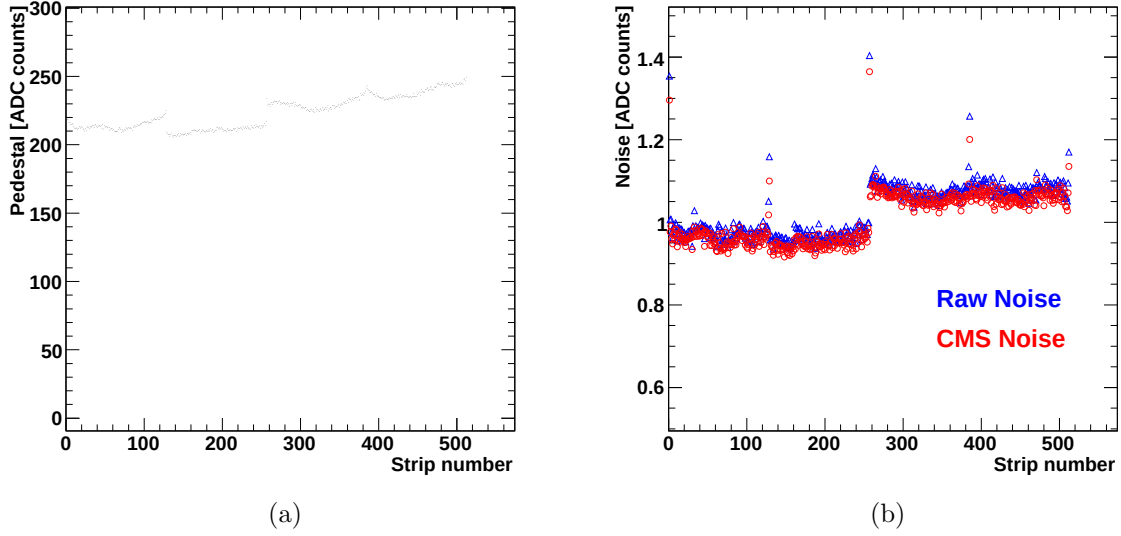


Figure 2.8: (a) A typical pedestal for a silicon module with 512 readout channels. The APV structure corresponding to a group of 128 channels is clearly visible. (b) Raw noise (in blue triangles) and common mode subtracted noise (in red circles) for the same module. In addition to the APV structure the laser structure containing 256 channels can be seen.

If this signal is triggered randomly so that there is no contribution of real physics events the common mode subtracted noise $CMSNoise_i$ can be calculated using the following equation:

$$CMSNoise_i = \sqrt{\frac{1}{N-1} \sum_{k=1}^N (s_i^k)^2} \quad (2.6)$$

Figure 2.8(b) shows the raw noise (in blue) and the common mode subtracted noise (in red) for a module with 512 channels as a function of the channel number. In this case the common mode is very small since raw noise and cms noise are nearly the same. It is visible that APV edge channels have in general a higher noise than the inner strips.

2.2.3 Tick mark

The difference between the logic 0 and the logic 1 in the APV data frame defining the sensitive range for the analogue data is given by the so-called tick mark. Its height can slightly vary from one APV to another and in addition from one laser to another since the optimal gain is set for each laser separately according to the dynamic range. This effect can be monitored by the tick mark height (see figure 2.9(a)). In order to compare the signal and the noise of channels belonging to different APVs and lasers the data have to be corrected for the actual tick mark. This can be done by normalizing the data to a common tick mark height as shown in figure 2.9(b). There the raw noise from figure 2.8(b) is normalized to a tick mark of 180 ADC counts (corresponding to the mean tick mark height in the petal longterm test) using the respective tick mark height from figure 2.9(a). This leads to a flat noise distribution where the step between laser 1 and laser 2 observed in figure 2.8(b) disappears. Since in the ARC test no optical readout was used this effect has only to be

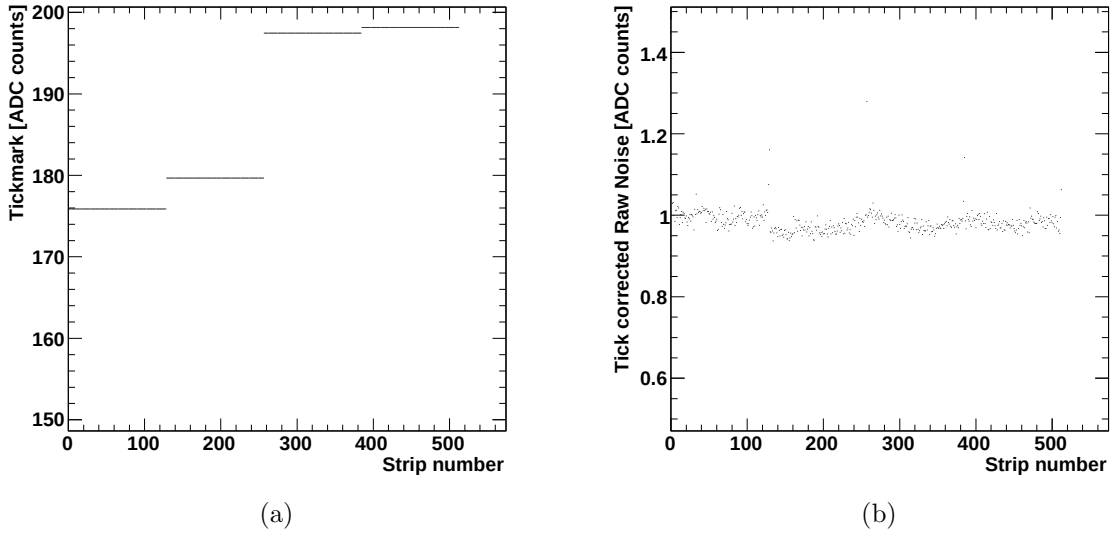


Figure 2.9: (a) Tick mark height of the four APVs belonging to the module from figure 2.8. (b) Raw noise of the same module corrected for the tick mark height by normalizing the data to a common height of 180 ADC counts (corresponding to the mean of the tick mark height distribution). The step between the two lasers seen in figure 2.8(b) has disappeared.

taken into account in the petal longterm test and the tracker commissioning described in later chapters.

2.2.4 Pulse Shape

To measure the pulse shape on a single channel the internal calibration logic of the APV can be used. It injects a δ -like charge pulse on each eighth channel so that one APV has eight

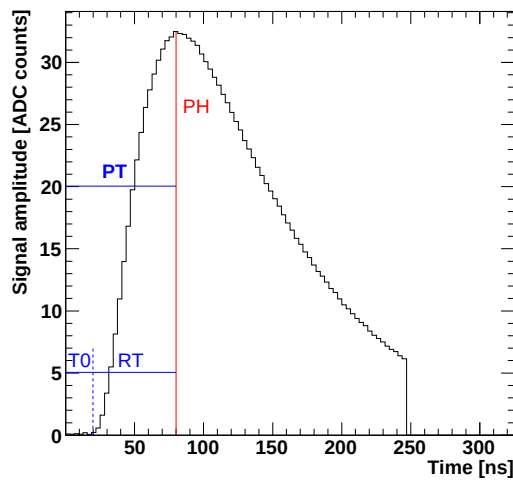


Figure 2.10: Calibration pulse shape for a single channel of an APV. The parameters describing the shape are obtained from a fit.

calibration groups. To measure the full pulse on a channel the procedure has to be repeated several times where at each step the distance between the write and the read pointer of the pipeline, the so-called latency, is changed so that the full pulse can be scanned. Since the pulse shape is very sensitive to the strip capacitance faults like open bonds or short-circuited channels can be found by analyzing the pulses. In figure 2.10 a calibration pulse for one channel of an APV is shown. It can be characterized by the following parameters: The pulse height PH which is the maximum value of the pulse; the peak time PT describing the time between the start of the measurement and the point of maximum amplitude; the rise time RT which is defined as the time between the maximum value and the intersection point of the fitted curve with the baseline and the time offset TO which arises from the difference between peak time and rise time. These parameters are derived from a fit to the pulse shape and indicate a deviation from the expected behaviour due to a fault.

2.3 ARC Test Results

In total 6544 silicon strip modules with 3,954,176 readout channels were mounted on petals for the two tracker end caps (including spare petals). The overall quality of these detectors can be seen in figure 2.11(a). Before mounting them on the petals only 5606 readout channels corresponding to about 1.4 ‰ showed a conspicuous behaviour in the ARC test. The type of fault for these channels derived from the single module test is depicted in figure 2.11(b). The most commonly occurring defects are open bonds between pitch adapter and sensor (flag-ID 2) and noisy channels (flag-ID 64). If the wire bond between the pitch adapter and the sensor is missing the channel is completely lost because it cannot be read out anymore. This is not true for noisy channels. In general they can be used for particle detection since the noise behaviour does not only depend on the channel itself but also on the environment so that it

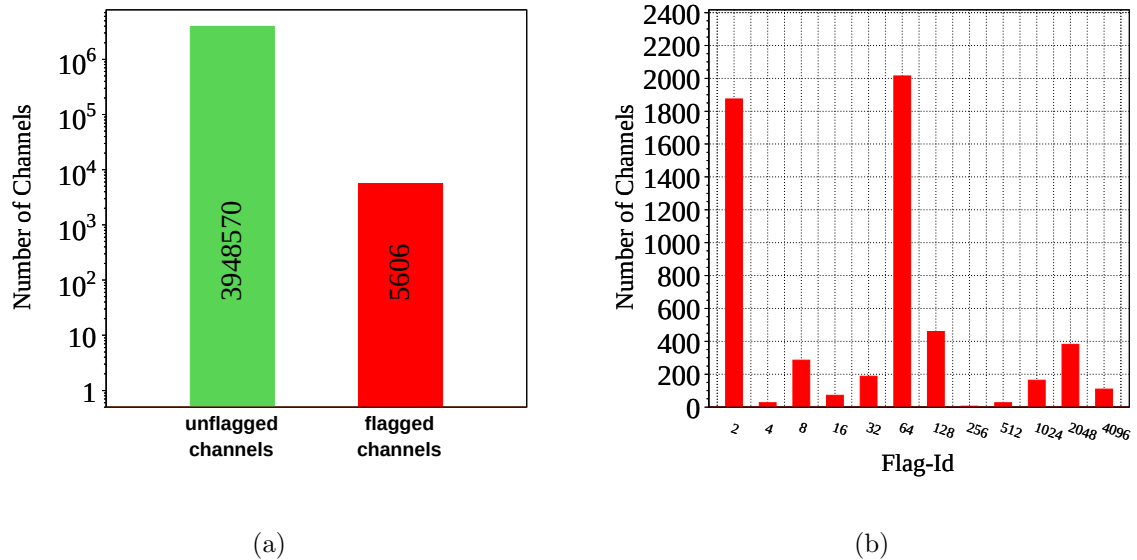


Figure 2.11: (a) Total number of good and bad readout channels on TEC modules in the ARC test. (b) Error classification of the bad channels in the ARC test. Flag-ID 2 corresponds to pitch adapter-sensor opens and flag-ID 64 to noisy channels. The meaning of the other flag-IDs is listed in table B.1.

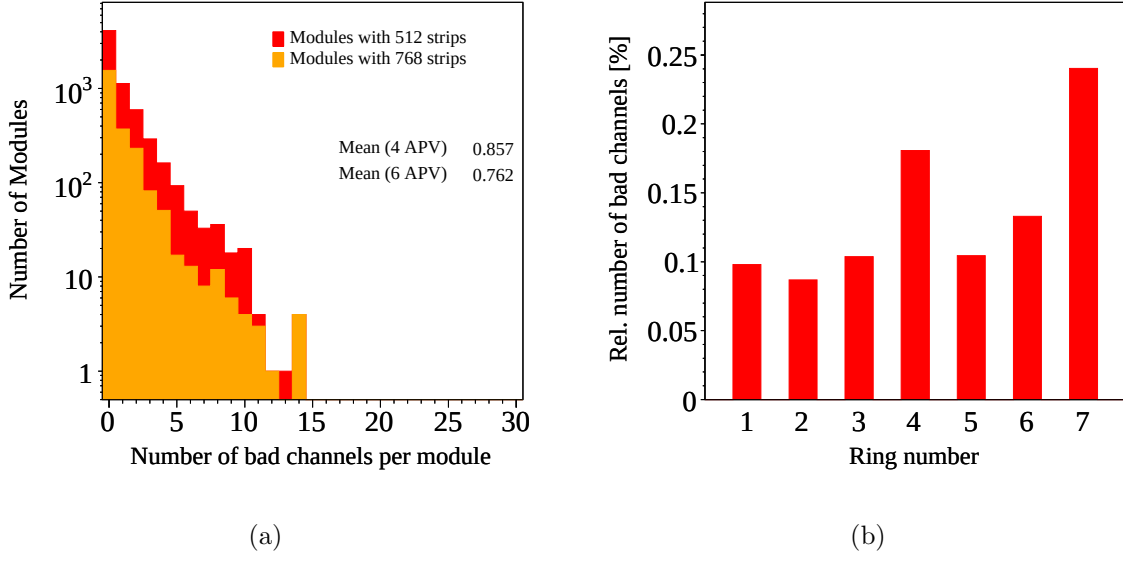


Figure 2.12: (a) Number of faulty flagged channels per TEC module. The distributions for modules with 512 strips (in red) and 768 strips (in yellow) are stacked. (b) Relative number of faulty channels per TEC ring. Since each ring consists of a different number of readout channels the absolute number of bad channels per ring is normalized to the total number of channels in that ring.

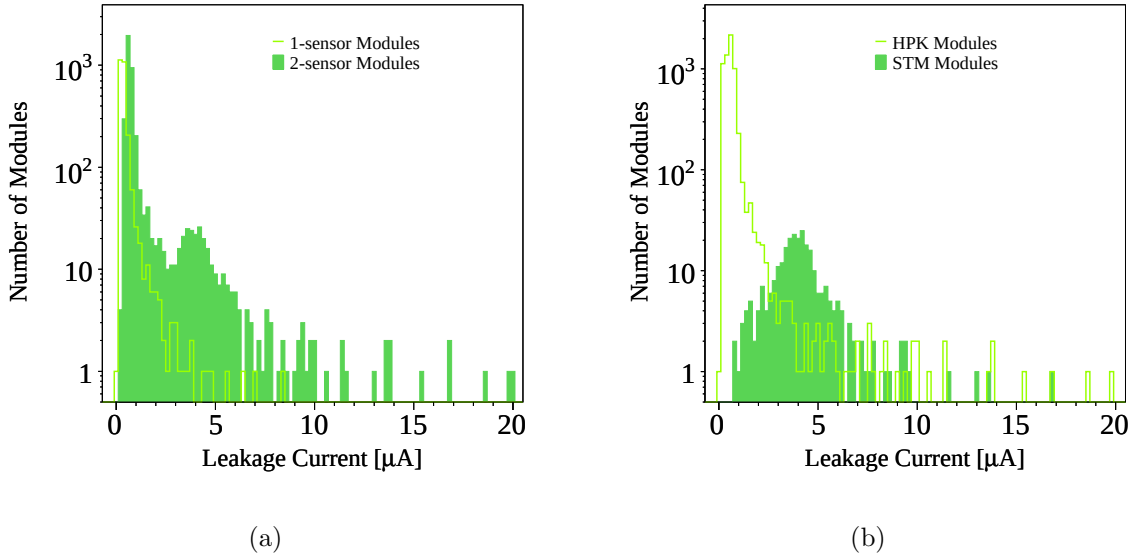


Figure 2.13: Leakage current of the TEC modules measured in the ARC test at 450 V. (a) Distributions for one-sensor modules (open histogram) and two-sensor modules (filled histogram). The leakage current is below $10 \mu\text{A}/\text{sensor}$ as required. (b) Distributions for sensors produced by HPK (open histogram) and STM (filled histogram). The leakage current is higher for STM modules but stays below $10 \mu\text{A}/\text{sensor}$.

can be different for the final tracker setup. In addition, a worse signal-to-noise ratio caused by higher noise is acceptable as long as it is high enough to distinguish between physics signals and fake signals. Thus not all strips included in the number of flagged channels are unusable for particle reconstruction.

To validate that no clustering of a large number of bad channels occurs on a single module figure 2.12(a) shows the number of flagged strips per module for all TEC modules mounted on a petal. The distribution in red represents modules with 512 readout channels whereas the one in yellow corresponds to detectors with 768 strips. The latter have never more than 14 flagged channels per module which is equal to about 1.8 % and the former do not exceed 10 faulty strips corresponding to about 1.9 %. The mean number of faulty channels per module is about 0.9 strips (0.2 %) in case of 4 APVs and 0.8 strips (0.1 %) in case of 6 APVs. The two 512-strip modules with 11 and 13 bad strips, respectively, were faulty and graded C. After a repair action they turned to be valid but the new test data are not available so these numbers are an artefact. Thus the requirement to use only modules with less than 2 % bad channels according to table 2.1 is fulfilled. In addition, the failure density with respect to the seven rings used in the tracker end caps is very small (see figure 2.12(b)). The relative number of bad channels is below 2.5 ‰ for each ring taking into account the total number of strips in the ring under investigation since all TEC rings consist of a different number of readout channels.

To ensure the proper functionality of the silicon sensors with an acceptable leakage current after several years of irradiation the initial leakage current has to be below $10\text{ }\mu\text{A}$ per sensor. Figure 2.13(a) depicts the leakage current both for one-sensor modules (open histogram) and for two-sensor modules (filled histogram) as measured in the ARC test at 450 V. As required, no module exceeds $10\text{ }\mu\text{A}$ and $20\text{ }\mu\text{A}$, respectively. The second peak for two-sensor modules around $4\text{ }\mu\text{A}$ is caused by the fact that the silicon sensors were delivered by two different producers (Hamamatsu Photonics K.K. HPK, Japan and ST Microelectronics STM, Italy) leading to different properties. HPK produced the thin⁶ sensors and parts of the thick ones while STM was responsible for the remaining thick sensors. This is reflected in figure 2.13(b). The open distribution shows the leakage current for sensors produced by HPK while the filled histogram corresponds to STM sensors. It is obvious that the second peak comes from a higher leakage current of the STM sensors with respect to the HPK ones. Nevertheless the leakage current is within the specifications so that all modules can be used for the tracker.

2.4 Layout of the Petals and the Tracker End Caps

2.4.1 The Petal Structure

To ease the handling and the maintenance of the silicon modules they are mounted on modular structures before the insertion in the tracker subdetectors. For the tracker end caps these structures are called petals because of their petal-like shape. They consist of a 10 mm NOMEX core which is covered both on the front and the back side with a 0.4 mm Carbon Fibre Composite (CFC) skin. To remove the heat produced by the electronics on each petal with a maximum heat load of about 87 W a cooling pipe made of titanium is embedded in

⁶Since the strip length and hence the noise increases with increasing ring number, the sensor thickness is extended from $320\text{ }\mu\text{m}$ (ring 1-4) to $500\text{ }\mu\text{m}$ (ring 5-7) to obtain a better signal performance for the longer modules such that the signal-to-noise ratio is still good.

the petal core. It allows to cool the silicon detectors on both sides of the petal. The modules are mounted on the petal on four points. Two of them are high precision bushings providing a mounting precision of better than $20\text{ }\mu\text{m}$ [11]. All four points serve as thermal contact between the module and the cooling pipe using aluminium inserts on which the detectors are positioned. Each petal has two cooling circuits with C_6F_{14} . In the final TEC structure four or five petals are supplied with the coolant in parallel.

The silicon modules are arranged on rings in the tracker end caps so that they form sectors on each petal. One petal carries up to seven rings where modules belonging to ring 1, 3, 5 and 7 are mounted on the front side of the petal as seen from the interaction point while rings 2, 4 and 6 are positioned on the back side. All modules are mounted in such a way that they overlap within one ring azimuthally and within adjacent rings radially. This ensures full coverage on the petal level.

Both rings 1 to 4 and rings 5 to 7 are connected to a so-called Communication and Control Unit (CCU) which is located on the back side of each petal (mounted on the Communication and Control Unit Module CCUM). They interface the LVDS token ring network used on the petal to the front-end chips delivering clock, trigger and control signals. The silicon modules and the analog opto-hybrids, converting the analog data from the APV chips into optical signals, as well as the CCUs are connected to the motherboard which is called Inter Connect Board (ICB). The ICB provides the electrical components with ground, various supply voltages and the bias voltage and transmits control signals. In addition, the analog data of the front-end hybrids are differentially transferred over a few centimeters to the AOHs. To monitor the environment inside the tracker several temperature and humidity probes are mounted on or connected to the ICB. In figure 2.14 a photograph of one side of a petal body with the assembled InterConnect Board is shown. Figure A.5 depicts a photograph of both front and back side of a fully integrated petal with silicon modules and analog opto-hybrids.

All silicon modules belonging to one petal are subdivided into three low voltage groups: the first one consists of ring 1 and 2, the second contains ring 3, 4 and 6 and LV group 3 is allocated to ring 5 and 7. For each LV group there are two high voltage channels containing up to four single HV lines each biasing one or two silicon modules.

In the tracker end caps one front and one back petal (see next section) are combined to a control ring. To ensure the functionality of this control ring each CCU can be bypassed electrically if it fails. If two consecutive CCUs are faulty the whole control ring, i.e. two petals are lost. In addition, a digital opto-hybrid (DOH) belongs to each control ring which converts electrical signals into optical ones and vice versa. It is mounted on the digital opto-hybrid module (DOHM) located on the back petal. For redundancy a second DOH is included in the DOHM.

2.4.2 The Tracker End Caps

The silicon strip tracker is closed on both sides along the beam axis by the Tracker End Caps (TECs), ranging in radial direction from $220\text{ mm} \leq r \leq 1135\text{ mm}$ and in longitudinal direction from $1240\text{ mm} \leq |z| \leq 2800\text{ mm}$ where the point of origin is in the center of the CMS experiment. Each end cap consists of nine Carbon Fibre Composite (CFC)/honeycomb structures called disks on which the petals are mounted. The advantage of the modular design is that each petal can be individually assembled in the TEC or removed from it without affecting the whole structure. In total 16 petals are mounted on each disk: eight

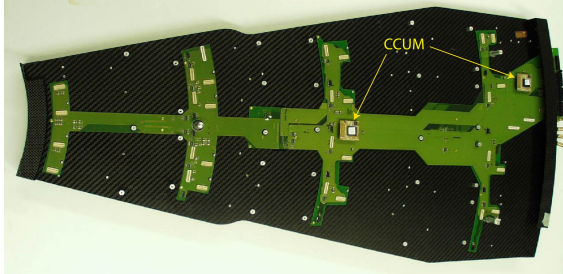


Figure 2.14: Photograph of the back side of a petal body with assembled InterConnect Board (in green). The two CCUMs are visible. [11]

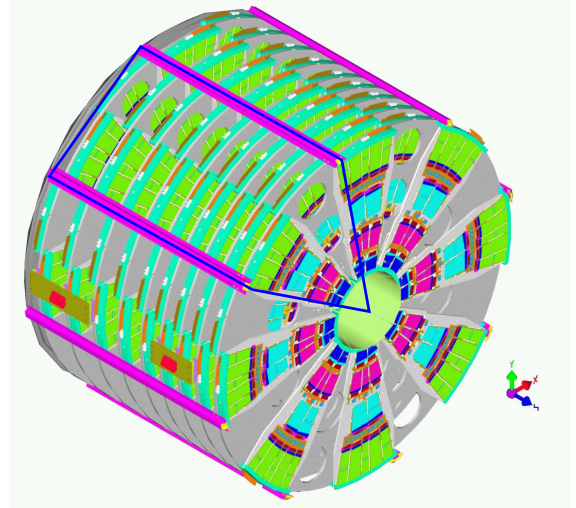


Figure 2.15: Sketch of one tracker end cap. One sector is indicated with a blue line. Modules are mounted in rings around the beam axis. [11]

on the front side as seen from the interaction point (front petals) and eight on the back side (back petals). Front and back petals are arranged in such a way that they overlap azimuthally to provide full coverage.

Along the beam axis nine front and nine back petals compose a so-called sector which contains 400 silicon modules. Eight sectors belong to each TEC and 288 petals are needed for both tracker end caps. In figure 2.15 a sketch of one TEC is shown. The blue line indicates one sector. Figure A.4 depicts two photographs of a TEC where the disc and the petal structure as well as the ring geometry are clearly visible.

The number of rings mounted on the nine disks varies from the innermost to the outermost one. Petals belonging to disks 1-3 carry all seven rings, on disks 4-6 ring 1 is missing, disks 7 and 8 do not have rings 1 and 2 and disk 9 only carries rings 4-7. For this reason both front and back petals exist in two flavours: long petals belonging to disks 1-3 and short petals mounted on disks 4-9. A summary of the TEC layout is given in table C.1.

Rings 1, 2 and 5 consist of double-sided modules where two single silicon modules are mounted back-to-back with a stereo angle of 100 mrad. This allows a space measurement both perpendicular and parallel to the strip direction.

2.5 The Petal Longterm Test

After central integration of the cooling loop, the InterConnect Board and the analog opto-hybrids including fibre routing the petal bodies were distributed to six so-called Petal Integration Centers (PICs) located in Aachen, Brussels, Karlsruhe, Louvain, Strasbourg and CERN. They were responsible for mounting the silicon modules on the petals and testing the entire structure in a dedicated test procedure. The petal assembly was done in a clean room environment. All modules were integrated on the petal mechanics and basic connectivity and communication tests were performed. The identity of all components and their position on the petal were stored in special xml-files and uploaded to the tracker database.

Parameter	Min. value	Max. value	Type of cut
Pedestal	150	400	Absolute
Normalized Noise	0.9	1.1	Percentage
Normalized Pulse Height	-20 %	+20 %	Percentage
Peak Time Average Subtracted	-15	15	Absolute

Table 2.2: Valid ranges for module test parameter values in the LT test. [16]

After the petal was fully assembled it was subjected to the petal longterm test (LT test) being the first time that all petal components were read out simultaneously and tested in a cold environment. To thermally stress both the mechanics and the electronics and to test their proper behaviour under these conditions the petal was in the course of three temperature cycles cooled down to -20°C and warmed up to room temperature. At both temperatures, after having checked the connectivity and functionality of all components, several test procedures were performed, namely:

- **Time tunes** and **Latency runs** to synchronize the signals of all modules.
- **Opto scans** to adjust the parameters of the analog opto-hybrids.
- **Pedestal runs** to calculate the pedestal, the noise and the common mode for each channel.
- **Calibration Profile runs** to determine the pulse shape for each channel using the calibration logic of the APVs.
- **I-V runs** to measure the leakage current at different depletion voltages.

Like in the ARC system the results of the different tests are combined to qualify each module separately. It is graded by using relative cuts ($\pm 10\%$) on the averaged and normalized common mode subtracted noise and on data taken with the APV internal calibration pulse logic (the normalized pulse height distribution and the peak time of the calibration pulses), see table 2.2. In addition, the tick height of each laser, the number of DAQ errors, the opto scan and low voltage connections and the pedestal amplitudes are monitored and the leakage current per sensor must stay below the given thresholds. The sum of all module grades then define the quality of the whole petal according to table 2.3. Since all tests were

Grade	Fraction of faulty channels per petal	Single module grade (worst case)	Leakage current per sensor at 450 V
A	$< 0.5\%$	A & $< 25\%$ B	$< 3\mu\text{A}$
B	$< 1\%$	A & $< 50\%$ B	$< 3\mu\text{A}$
C	$< 1.5\%$	1 C with $< 2.5\%$ bad channels rest A & B	$< 10\mu\text{A}$
D	$> 1.5\%$	any other	$> 10\mu\text{A}$

Table 2.3: Quality categories for the petal longterm test. Only petals with grade A and B are integrated in the tracker end caps.



Figure 2.16: Photograph of the petal longterm test setup in Aachen. It consists of a refrigerator, where the petal is put in, a cooling plant, a rack with the electronics and two PCs, one used for the slow control and the other one for the longterm test software.

performed several times at warm and cold operation temperatures in total three test cycles (two in warm and one in cold environment) were analyzed and used to grade the silicon modules. The final petal grade was derived in the end from the worst behaviour of each single module in one of the three cycles. The analysis package used to process the longterm data was called Defect Analyzer. Details concerning this software can be found in [21].

The measured data were stored in ROOT files for offline analysis and the test results in xml-files. If the petal passed the LT test with grade A or B it was forwarded to the tracker end cap integration. In case of grade C and D it was reworked (for example a faulty module was replaced by a new one) and the test was repeated. Finally, for good petals, the most important test results were uploaded to the central CMS tracker database.

All tests based on single readout channels were done in peak mode as well as in deconvolution mode both with inverter⁷ on and off. Only the calibration profile runs were performed exclusively in peak mode with inverter turned on. In addition, no LED array as used in the ARC system was available in the longterm setup so that specific defects like pinholes could not be spotted in the LT test.

A photograph of a typical petal longterm test setup is shown in figure 2.16. It consists of a refrigerator, a cooling plant, a rack and two computers. The refrigerator, where the petal under investigation is located, serves as passive cooling of the petal by adjusting the environment temperature. It is cycled between approximately 17°C and −25°C. It is purged with dry air to reduce the humidity, minimizing the risk of condensation on the silicon detectors. The cooling plant is connected to the cooling pipe embedded in the petal body.

⁷A unity gain inverter is included in the APV which can be switched onto the preamplifier output to invert the signal. This is included so that the shaper circuit always sees the same polarity of signal when silicon strip detectors of either polarity are used [22].

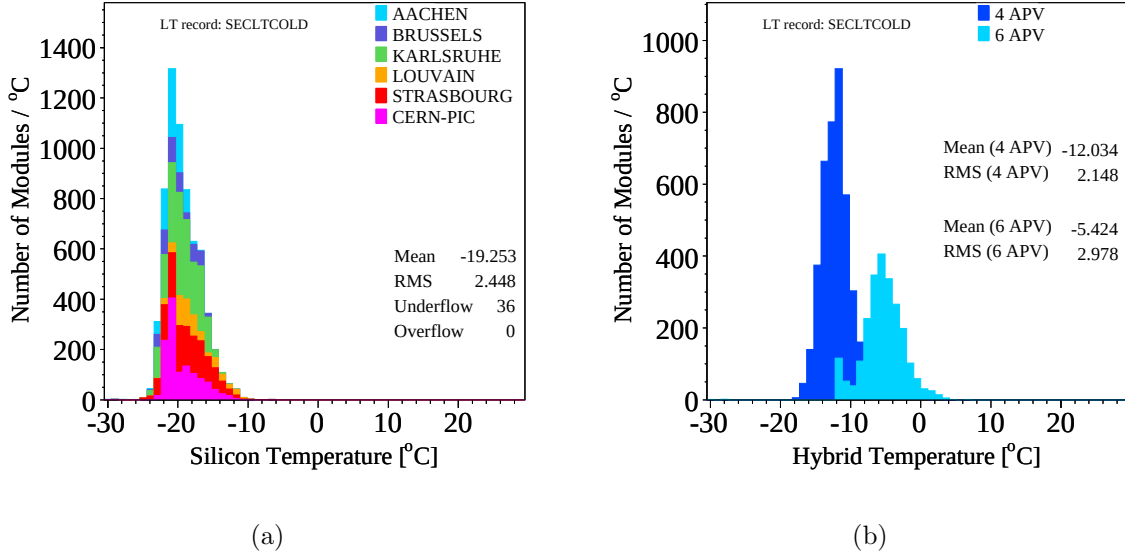


Figure 2.17: Temperatures of the silicon modules during the cold cycle of the petal longterm test as measured with the DCU. (a) Temperature of the silicon sensors broken down to the six petal integration centers. All values are below the required -10°C . (b) Temperature of the hybrids broken down to the number of APVs carried. The more chips are mounted the more heat is produced.

The coolant C_6F_{14} is supplied at 17°C and -25°C during the temperature cycles. It removes the heat from the electronics. The combination of the refrigerator and the cooling plant leads to a silicon sensor temperature below -10°C during the cold cycle of the test. This is important because the tracker will be operated at a temperature of about -10°C in the final setup so that the proper functionality of all components has to be validated at these temperatures. Figure 2.17(a) shows the silicon temperature of all modules mounted on grade A and B petals in the cold test measured with the DCU. The temperature stays well below -10°C for all detectors and all six petal integration centers so that the requirement of testing below this temperature threshold is fulfilled. In figure 2.17(b) the hybrid temperature for the same class of modules is depicted, again measured with the DCU. Since the hybrid with its readout and control chips is the part of the silicon module where the largest amount of heat is produced the temperature is significantly higher than for the silicon sensors as expected. Furthermore a clear difference between modules with 512 readout channels corresponding to 4 APV chips and those with 768 strips corresponding to 6 APV chips is visible. The more chips are used the more heat is produced on the hybrids ($\sim 2.5 \text{ mW/readout channel}$).

The rack contains the power supplies for low and high voltage, an interlock box and the electronics needed for the readout of the silicon modules. The slow control related components like power supplies, the fridge and the cooling plant are controlled by one of the two PCs which is connected to the interlock box. If a problem occurs the system is shut down by sending kill signals to the low and high voltage power supplies, the fridge and the cooling plant. In addition, a door switch is installed to avoid damage by an accidental opening of the fridge door during the test and an auxiliary panic button provides an immediate shut down in case of emergency.

The second PC is used for the data acquisition housing a Trigger Sequencer Card (TSC) to deliver clock and trigger, a Front End Controller (FEC) and a Front End Driver (FED).

Furthermore it provides a software to run a complete longterm test scenario including the thermal cycles and the different test procedures. A whole longterm test took about 30 to 40 hours per petal.

2.6 Petal Longterm Test Results

A new data format was created to store the most important test information for all of the roughly 4,000,000 readout channels used in the two tracker end caps in one location. It is composed of a ROOT tree consisting of about 200 branches where each branch holds the information of all strips concerning one particular parameter. For example the exact position of a single channel in the tracker (module, ring, petal, disc, sector, TEC) can be delivered, the raw noise as well as the common mode subtracted noise in all four APV readout modes is stored for each strip and the final flag obtained in the longterm test can be accessed. In addition, the leakage current and the flag-Id arising from the single module test are received from the tracker database and matched to the corresponding channels in the LT test. This allows to easily compare the results of different procedures or test centers, to investigate the overall quality of all readout channels with respect to a specific parameter and to monitor the development of each single strip from the behaviour in the ARC test to the longterm test.

Out of 294 production petals usable for the tracker end cap integration (288 petals are needed, the rest is spare) 286 petals received grade A. The remaining eight petals were qualified manually (they were set to grade B_M) because of corrupted integration data. Figure 2.18(a) shows the overall quality of the single readout channels corresponding to the 294 production petals. Only 1.2 ‰ of the strips got a faulty flag in the petal longterm test which is comparable to the ARC result and emphasizes the very high quality of the petals and the silicon modules.

As already mentioned some procedures used in the ARC test were not available in the LT test. In addition, the test environment was much more complicated compared to the single module test. In the ARC system one detector was placed in a dedicated test box well shielded from noise sources whereas in the LT setup some tens of modules mounted on a petal were operated and read out at the same time. Therefore the fault identification is not so detailed like in the ARC test as shown in figure 2.18(b). Most flags assigned to bad channels are likely open bonds between pitch adapter and sensor (flag-ID 4), noisy channels (flag-ID 64) and unidentified problems (flag-ID 1024). Defects like pinholes or open bonds between two sensors are not detected as such. Nevertheless channels that were found to be conspicuous only in the ARC test and not in the LT test (see figure 2.19) are mostly identified as noisy channels so that real defects were spotted both in the single module and the petal longterm test (except faults occurring during the petal integration that could not be detected in the ARC test). Thus a more reliable estimation of a lower bound of real faults, independent from the performed test, is given by the number of channels that are tagged as faulty both in the ARC and the longterm test, which is about 0.9 ‰. The small amount of channels flagged either only in the ARC or only in the LT test is caused by different test procedures and analysis algorithms that are performed in the two setups. During the ARC test for example, the noise behaviour of each strip is extracted from a single pedestal run while in the longterm test the results of several pedestal runs are combined. This procedure reduces the impact of random noise that is induced for example by the setup itself. Because

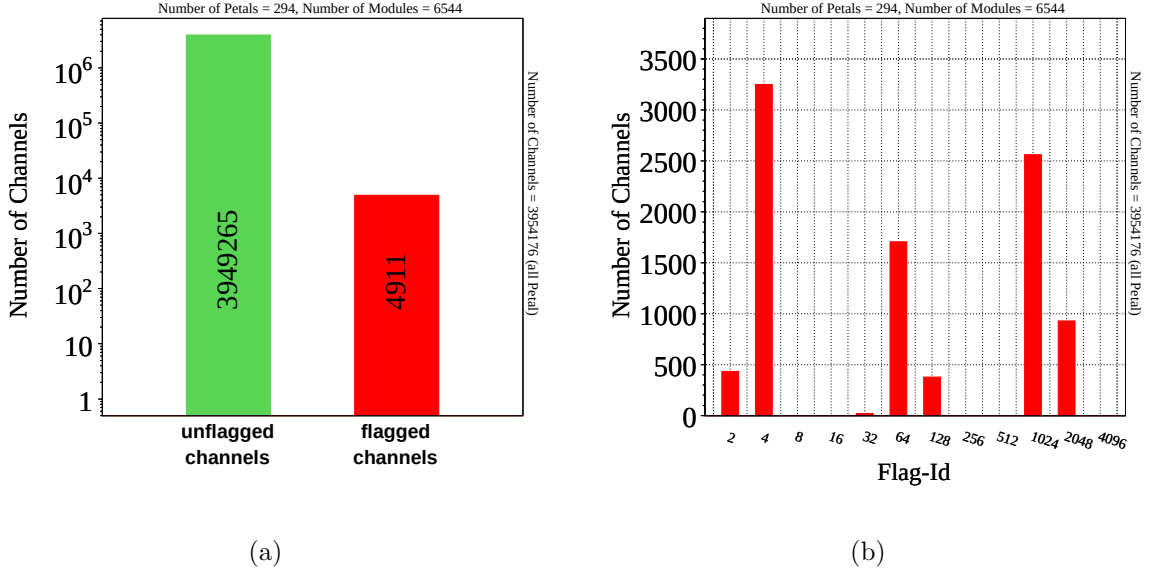


Figure 2.18: (a) Total number of good and bad readout channels on TEC modules in the LT test. (b) Error classification of the bad channels in the LT test. Flag-ID 4 corresponds to likely pitch adapter-sensor opens, flag-ID 64 to noisy channels and flag-ID 1024 to unidentified problems. The meaning of the other flag-IDs is listed in table B.1.

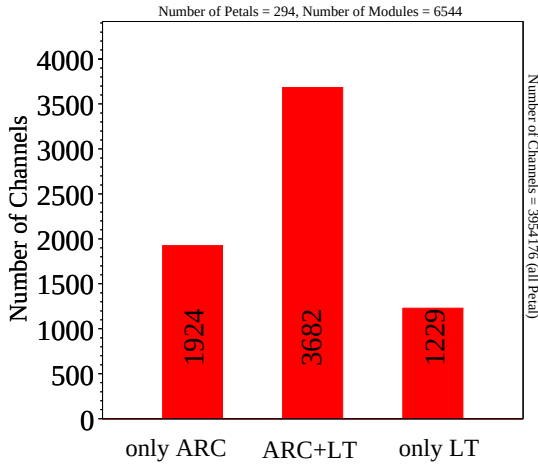


Figure 2.19: Comparison of bad channels identified in the ARC and the LT test.

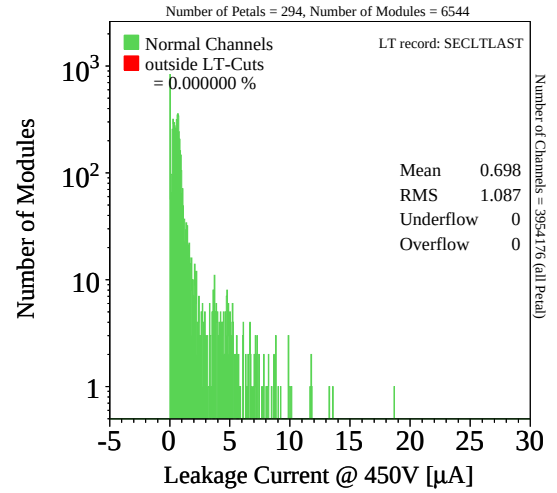


Figure 2.20: Leakage current of the TEC modules measured in the LT test. No module exceeds 10 μ A/sensor.

of that the number of faulty channels is slightly lower although the petal test is the more complicated environment for failure detection.

Figure 2.20 depicts the leakage current per module measured in the petal longterm test at 450 V. Since this setup does not provide a separate HV line for each single module but several detectors share one line it is not possible to disentangle the current contributions from the modules belonging to the same line. Instead the total leakage current of such a group of detectors is divided by the number of corresponding modules and this average is assigned to all of them. Taking this into account no sensor exceeds the limit of $10 \mu\text{A}/\text{sensor}$.

Based on the selection criteria as defined in table 2.2 figure 2.21 shows example distributions for one out of four APV readout modes (peak mode inverter on) and one out of three temperature cycles (SECLTLAST, the last test cycle performed at room temperature). All figures contain the full set of readout channels corresponding to all modules on all production petals.

Figure 2.21(a) depicts the pedestal distribution for normal channels in green and for those outside the LT cuts in red. About 99.8 % of the strips are within the required range. Since the pedestal height can be adjusted by tuning the APV settings a low or high pedestal value is no problem and therefore does not enter the grading. In figure 2.21(b) the common mode subtracted and normalized noise behaviour can be seen. The noise should stay below a certain cut value because high noise can fake physics signals and thus complicate the track reconstruction in the experiment. On the other hand very low noise points to a defect on the readout channel like an open bond between two sensors or between the pitch adapter and the sensor. In this case the strip is partially or completely lost for the track reconstruction. In the distribution the contribution of the outermost channels of each APV (these are the channels 1, 2, 127 and 128) to the group of strips outside the $\pm 10\%$ cut is shown separately (blue line) because it is a known behaviour of the chip that these strips show a tendency to higher noise values. As expected the majority of channels conspicuous for high noise with respect to the average are APV edge strips. Therefore special cuts are applied and the channels are treated as good if they are only odd in noise. In total about 0.9 % of the edge channels and 0.2 % of the inner strips are beyond the given thresholds.

In addition, both the pulse height and the peak time of the calibration pulse injected by the APV chip itself indicate a possible failure of the corresponding channel. An open bond for example leads to a reduction of the capacitance connected to the APV input. This causes the peak time to be decreased whereas the height of the measured signal increases. In case of a short-circuited channel the pulse height is in contrast reduced. Figure 2.21(c) shows the normalized pulse height distribution and figure 2.21(d) the average subtracted peak time for all channels, respectively. In both distributions only 1.1 ‰ and 0.3 ‰ of the strips violate the criteria, respectively.

All the tests shown in figure 2.21 were also done for the other APV modes (peak mode inverter off, deconvolution mode inverter on, deconvolution mode inverter off), except for the calibration pulse procedures which were only performed in peak mode inverter on, and both during the first thermal cycle at room temperature and the cold cycle at -20°C . The results are similar to the example distributions shown here. All plots concerning the different APV modes and test cycles are given in appendix D.

In figure 2.22 the distribution of tick mark heights measured in the longterm test is depicted. Figure 2.22(a) shows the tick height in SECLTLAST for each APV individually because the tick marks for two consecutive APVs sharing the same laser can slightly differ. The large number of tick marks below the required threshold of 100 ADC counts is caused

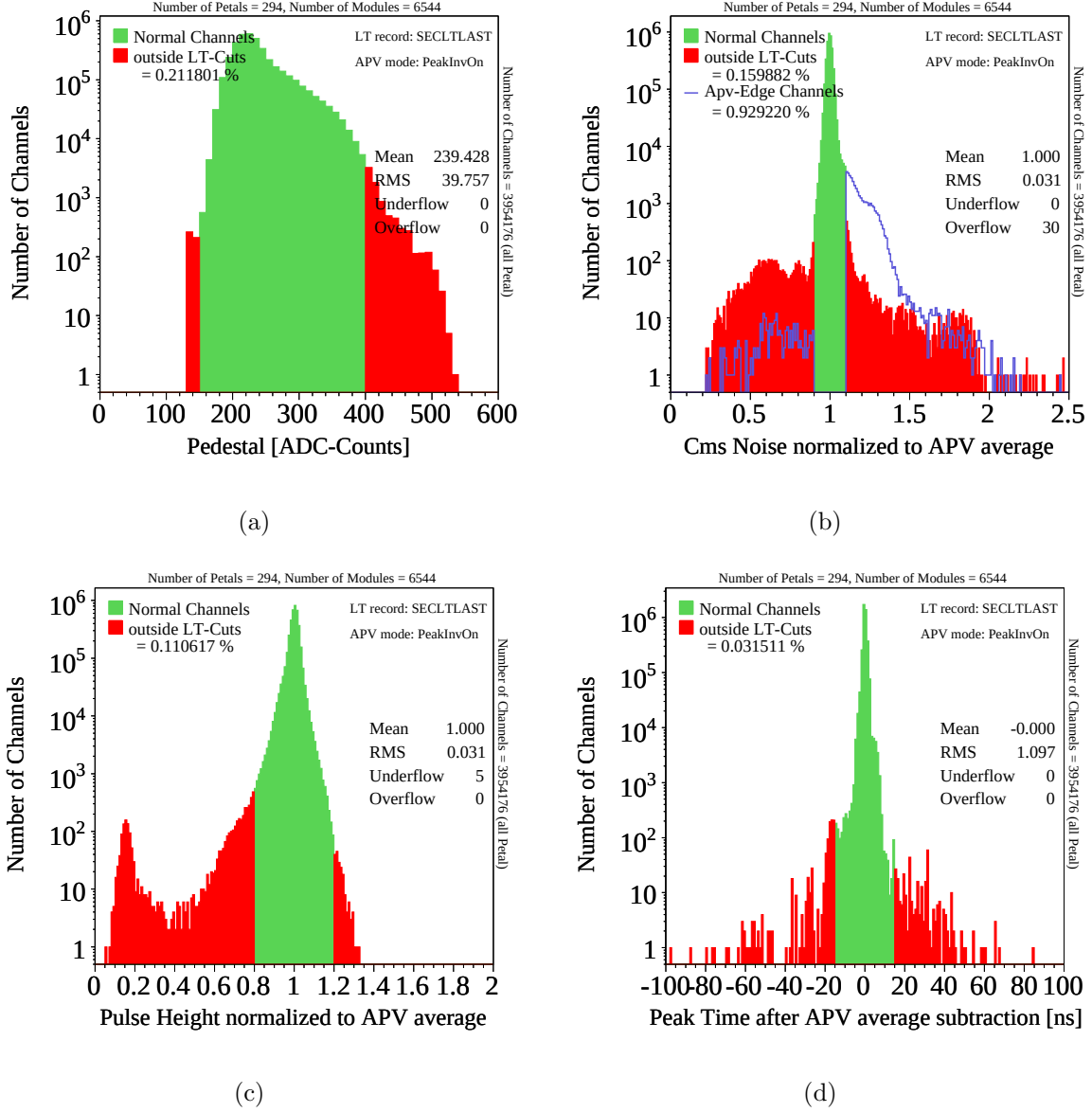


Figure 2.21: Selection criteria as used in the LT test. The distributions show the behaviour of all readout channels belonging to production petals during the last test cycle at room temperature (SECLTLAST) in peak mode with inverter on (PeakInvOn). Normal channels are labeled in green while strips outside the required ranges are marked in red. The fraction of cut channels is given. The same tests were done in the other APV modes (deconvolution, inverter on/off), except for procedures including the calibration pulse, and during the first thermal cycle at room temperature as well as in the cold environment. The results look similar to the examples shown here. The full set of plots is given in appendix D. (a) Pedestal distribution. (b) Common mode subtracted and normalized noise. In addition, APV edge channels (strip numbers 1, 2, 127 and 128) are shown separately (blue line) because in general they have higher noise and are therefore specially treated in the qualification. (c) Normalized pulse height of the injected calibration pulse. (d) Average subtracted peak time of the injected calibration pulse.

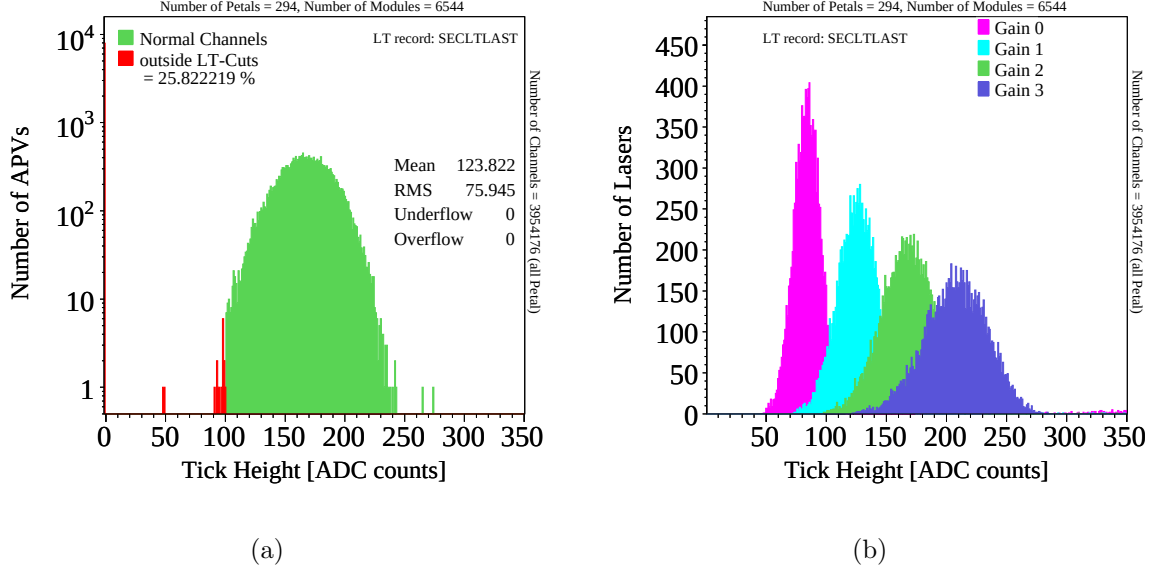


Figure 2.22: Tick mark height measured in the petal longterm test. (a) Tick mark distribution at the optimal gain value as it was used during the whole test. The large number of tick marks outside the cut (< 100 ADC counts) is caused by the fact that the tick mark data was corrupted for a large number of petals. (b) Tick mark distribution with respect to the four gain settings that can be chosen for each laser. During the gain scan all gain values are tested and the optimal one is used for the further test procedures.

by corrupted tick mark data. The lasers themselves worked well during the tests but the data stored for offline analysis were faulty. Because of that the tick height information was set to -1 for these lasers (therefore they are not visible in the distribution) leading to the large fraction of failing lasers indicating the missing of proper test data. Since the tick mark height does not intervene in the grading (a low tick height can be recovered in most of the cases by fiber cleaning) and due to the lack of time the affected petals were not retested to get the missing information.

In figure 2.22(b) the tick height is shown with respect to the four gain settings adjustable for each laser. During the gain scan the functionality of each setting is checked measuring the difference between one gain and the other. As shown in the figure a clear increase of the tick mark is visible with increasing gain. After the gain scan is performed a fixed value of the gain setting is used for the further tests reflecting the optimal value with respect to the dynamic range of the laser.

In addition to the gain also the bias of the AOH lasers is optimized in opto scan runs by measuring the APV tick mark. This ensures the best separation of the logic 0 and the logic 1. A schematic view of the laser parameters *gain* and *bias* is given in figure 2.23. The different coloured lines represent the logic 0 (solid) and the logic 1 (dashed) for the different gain settings. The corresponding arrows indicate the height of the tick mark for the respective setting. For a given gain the bias current is then adjusted such that the distance between the tick base and the tick top is maximal but not saturated, for instance. The tick marks shown in figure 2.22 are always the tick heights measured at the best bias setting.

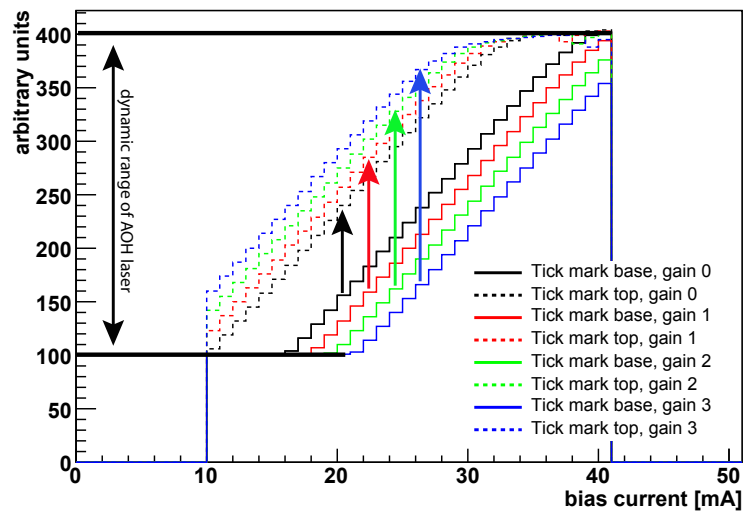


Figure 2.23: Schematic view of the tick mark height (indicated by the four arrows) for different gain settings as a function of the bias current of the respective laser. [23]

Chapter 3

The Magnet Test and Cosmic Challenge

In summer 2006 the first test of the CMS experiment including parts of all subdetectors called Magnet Test and Cosmic Challenge (MTCC) was performed. It took place in the surface hall at point 5, the interaction point where CMS will be located during LHC operation. Parts of the muon system were used to deliver a trigger for cosmic ray muons to all subdetectors. The superconducting solenoid was ramped up to the nominal magnetic field of 4 T so that data could be taken with different magnetic field configurations. This chapter concentrates on the tracker performance, especially the tracker end cap, at the MTCC. Additional information concerning the tracker operation can be found in [24].

3.1 The Setup

The MTCC took place in two consecutive phases. In phase I a fraction of all subdetectors excluding the tracker pixel system was operated in the presence of a magnetic field of up to 4 T (corresponding to a current of approximately 19000 A) and read out using the general CMS data acquisition system. In the second phase the innermost parts of this setup, namely the tracker and electromagnetic calorimeter devices, were removed to be able to map the magnetic field inside and outside the superconducting solenoid with high precision. Because of that only the MTCC phase I could be used to investigate the tracker performance and thus only this phase will be described here.

The setup shown in figure 3.1 contained the following subsystems representing several percent of the final CMS experiment:

- Parts of the tracker inner barrel, outer barrel and end caps, in total about 1 % of the full tracker (details concerning the tracker setup are described in the next section).
- Two super modules of the electromagnetic calorimeter, corresponding to about 5 % of the final ECAL.
- 15 wedges of the hadron calorimeter, representing about 10 % of the final HCAL.
- The superconducting solenoid as it will be used in the final experiment.

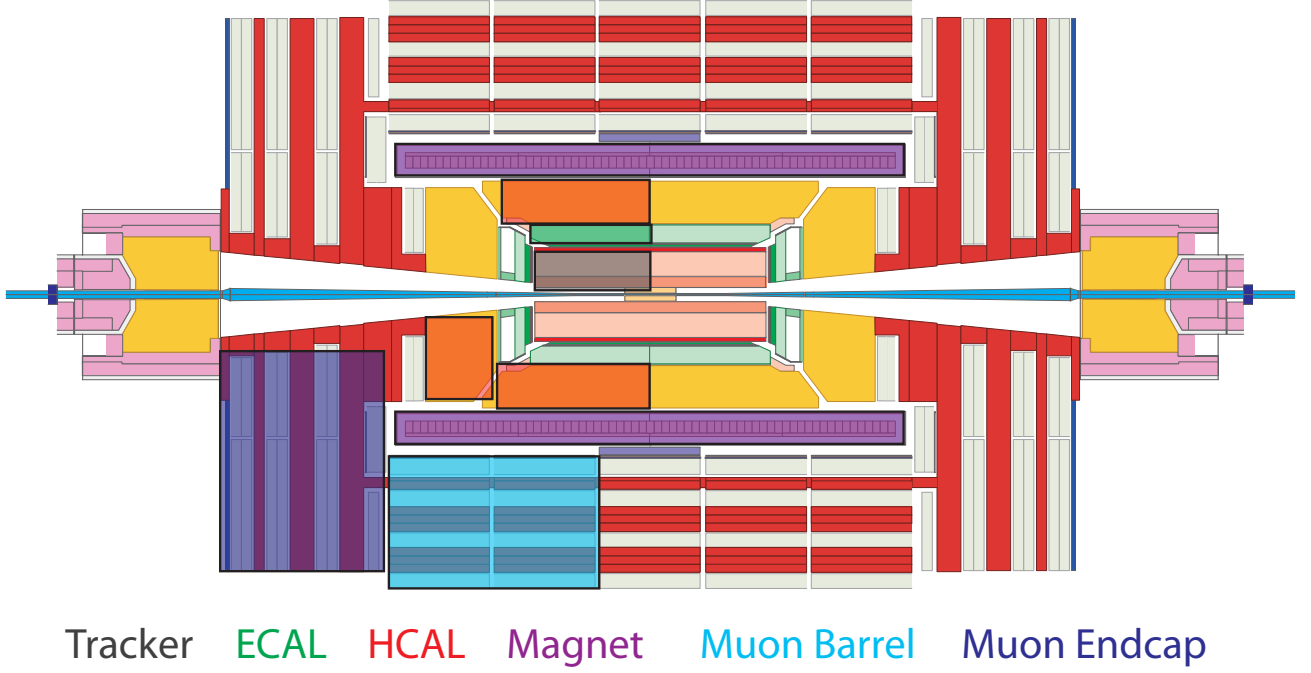


Figure 3.1: Schematic view of the CMS experiment. The detector parts used in the MTCC phase I are highlighted.

- Parts of the muon barrel region in wheels YB+1 and YB+2, corresponding to about 5 % of the final system (details concerning the muon system setup are described in section 3.2).
- Parts of one of the two muon end caps, corresponding to about 6.6 % of the final system (details concerning the muon system setup are described in section 3.2).

The safety of all detector components was ensured using the global Detector Control System (DCS) where the Tracker Control System (TCS) was embedded in. It had to control the power supplies and 40 environmental sensors monitoring the temperature and humidity. In case of high temperatures, cooling system failures or global Detector Safety System warnings the power supplies could be interlocked and switched off.

The Tracker Contribution

The tracker part installed in the MTCC represented approximately 1 % of the readout channels in the final silicon strip tracker and had an active silicon surface of about 0.75 m^2 . Three out of the four strip tracker subsystems, namely the inner barrel, the outer barrel and the end cap contributed to this setup. Modules of the tracker inner disks were not present in the test. Figure 3.2 shows an IGUANA¹ visualization of the MTCC tracker installation.

In the inner barrel part in total 75 silicon modules were mounted on two prototype shells corresponding to layer 2 and layer 3 of the final TIB structure. Layer 2 was equipped with 15 double-sided modules while layer 3 housed 45 single-sided modules.

¹IGUANA is the abbreviation for **I**nteractive **G**raphics for **U**ser **A**NALysis. It is a modular C++ toolkit for interactive visualization.

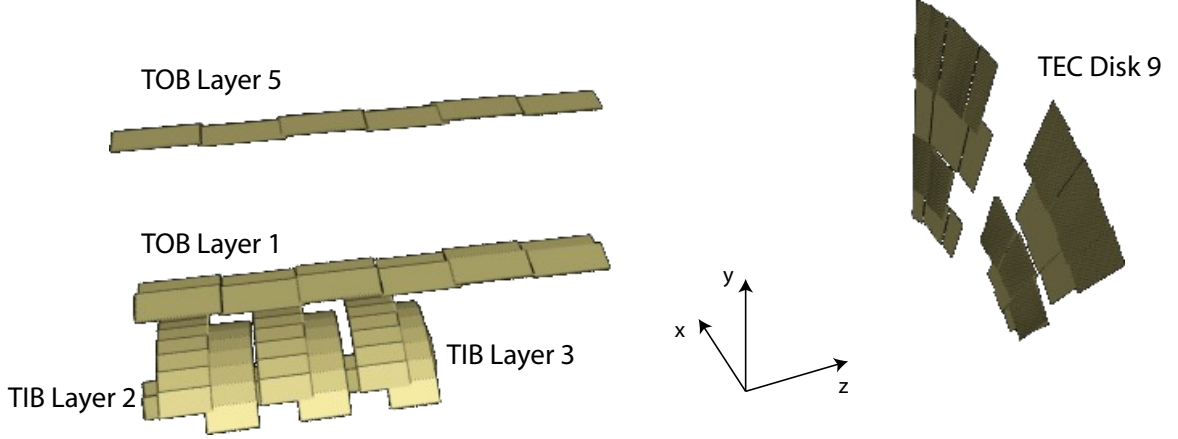


Figure 3.2: An IGUANA visualization of the tracker setup in the MTCC phase I. The two layers (1 and 5) of the TOB, the two layers (2 and 3) of the TIB and the two disk 9 petals of the TEC are visible. The geometrical arrangement represents the real construction. The silicon modules are mounted radially around the beam axis which is positioned in the horizontal plane (along z).

The outer barrel fraction consisted of four rods with 24 silicon detectors in total. Two of the rods were positioned in layer 1 with respect to the entire TOB and the remaining two formed a part of layer 5. Six single-sided modules belonged to each rod both in layer 1 and in layer 5.

The TEC structure contained two disk 9 petals, one front- and one back-petal. Since both petals were fully equipped (disk 9 petals are housing ring 4, ring 5, ring 6 and ring 7 modules) in total 34 silicon detectors represented the tracker end cap region. Their position with respect to the final TEC geometry was exact in r and ϕ and shifted by 10 mm in z .

The whole structure as described above was inserted into a prototype of the tracker support tube with the same dimensions as the final one. All silicon modules and the corresponding electronics were cooled using the integrated cooling pipes flushed with cooling liquid of about 18°C. Dry air was passed through the support tube to prevent condensation.

3.2 The Trigger

The main part of the cosmic trigger during the MTCC was the muon system. The CMS wheel YB+1 (this is the first wheel in $+z$ direction) was instrumented with one sector (sector 10) while in wheel YB+2 two sectors (sector 10 and sector 11) were read out (see figure 3.3(a)). These three sectors consisted in total of 14 drifttube chambers (DTs) and 23 resistive plate chambers (RPCs) and covered a ϕ angle of about 60° in YB+2 and about 30° in YB+1, respectively.

In addition to the muon barrel system one of the two muon end caps (the one on the $+z$ side) was partially instrumented with cathode strip chambers (CSCs). 36 CSCs were distributed among the three innermost disks of the muon end cap covering 60° in ϕ as shown in figure 3.3(b).

When a muon passed this setup the Level-1 trigger signal was processed by a central system which sent a global trigger to all participating subdetectors. In order to read out the



Figure 3.3: The muon detectors used in the MTCC as cosmic trigger. (a) Barrel wheels YB+1 with sector 10 and YB+2 with sectors 10 and 11 equipped with DT chambers and RPCs, covering a ϕ angle of about 30° and 60° , respectively (in blue). (b) Muon end cap disks ME1, ME2 and ME3 partially instrumented with CSCs covering a ϕ angle of about 60° (in green). The detectors mounted on ME4 did not participate in the MTCC.

correct pipeline cells of the APVs where the signal amplitude is at a maximum the latency between the event and the corresponding incoming trigger signal had to be adjusted. This was done measuring the signal height in the silicon strip detectors for different latency values and choosing the one where the signal performance was best. Nevertheless one has to take into account that in contrast to the final experiment with a well defined LHC clock the cosmic muons are randomly distributed within one clock cycle and because of that it is not possible to trigger the data readout always at the maximum signal height.

Since on the one hand all muon chambers were located below the tracker part so that no coincidence between chambers above and below the tracker was possible leading to a large geometrical acceptance of the trigger and on the other hand the dimensions of the muon system were larger than the ones of the tracker setup a large number of events were triggered where no signal in the tracker could be found. Therefore a special trigger configuration was available to increase the number of events with a muon passing through the tracker. The following list gives an overview of the trigger signals used as input for the Level-1 trigger system limited to the most important ones from tracker point of view:

- DT inclusive trigger where at least two chambers in the same wheel and sector with track segments are required.
- DT pointing trigger which is the same as the inclusive one but in addition with constraints on the η region of the track segments so that they are pointing to the center of the detector.
- CSC trigger where at least one track segment is required in any chamber with hits in at least 4 out of 6 layers.
- RPC trigger where hits in 5 out of 6 planes are required either in wheel YB+1 (RPC1) or in wheel YB+2 (RPC2) or in any of the two wheels but pointing to the center of the detector (RPCTB).

- HCAL trigger where a coincidence of signals from the upper and the lower part of the operated hadron barrel detector is required.

Since the usage of the drifttube and resistive plate chamber pointing triggers allowed to roughly estimate the direction of the muon it was possible to select event candidates with tracks crossing the tracker region. Nevertheless the fraction of events where a track could be reconstructed in the tracker requiring at least three hits in this subdetector was very small (about 2.3 ‰ for DT pointing and about 1.2 ‰ for RPC pointing trigger [24]).

3.3 Data Acquisition

Because of the low trigger rate the APVs were operated in peak mode. Prior to the global cosmic runs dedicated calibration runs had to be performed using a local data acquisition system. These commissioning tasks included connection scans, timing adjustment, optical gain adjustment and pedestal and noise computation for each readout channel. The latter task was done in dedicated pedestal runs taken before a cosmic run where the tracker was read out several thousand times with a random trigger. Pedestal and noise values calculated using these runs were then uploaded to the tracker online configuration database to configure the readout electronics, namely the Front End Drivers (FEDs). In addition, these information were transferred to an offline database to be available for offline reconstruction.

The tracker FEDs, where the analogue signals of all channels arrive and the analogue to digital conversion takes place, can be operated in four different modes:

- Virgin Raw: In this mode the FED performs no processing and only formats the raw detector data. It is used for detector commissioning and, for example, pedestal measurements.
- Zero-Suppressed: This is the default mode for proton-proton collisions. The raw data are pedestal and common-mode subtracted (using the previously uploaded pedestal and noise values for each channel) before identifying channels above a given signal-to-noise threshold. During the MTCC this threshold was set to 2 for signals in consecutive strips and to 5 for isolated hits. Only useful signal information above these thresholds is transmitted for further processing.
- Processed Raw: The data are pedestal subtracted and reordered to reflect the detector strip ordering but they are not zero-suppressed.
- Scope Mode: In this mode the FED simply captures the APV data stream observed within a given time window.

The most important operation modes are Virgin Raw and Zero-Suppressed. Most of the cosmic runs during the MTCC were performed in zero suppression. After writing the data to disk they were transferred from the so-called CERN Tier-0² center to the FNAL Tier-1 center at Fermilab using the final CMS computing tools. There the initial reconstruction was performed and the output files were transferred back to CERN and stored in CASTOR².

²For a detailed description of the LHC Computing Model see [25].

3.4 Data Reconstruction

The data reconstruction and analysis are performed within the CMS software framework CMSSW. It provides a large number of plug-in modules that can be adapted to raw data or higher-level reconstructed data as input. The modules to be executed and the order of execution are defined in a job configuration file. Each single event is read in, the corresponding data are processed and the output of the reconstruction step is added to the event. In addition to reconstruction modules called event data producers, there exist event data filters and event data analyzers. Filter modules are used to select events with respect to special criteria so that only these events are passed to the further processing. Finally, analyzer modules are plug-ins to interpret the reconstructed data according to physics characteristics. All different kinds of plug-ins can be developed by the user and incorporated in CMSSW. Nevertheless the common reconstruction steps are performed using predefined framework modules where individual parameters can be set by the user.

Starting from raw data received from the FEDs the following reconstruction chain is necessary to finally get reconstructed tracks belonging to particles that passed the tracker:

1. Digis: These are the pedestal-subtracted and zero-suppressed ADC counts of the single readout channels.
2. Cluster: These are consecutive strips with signals above user-defined thresholds. The absolute value of the threshold depends on the noise of the strip under investigation. The center-of-gravity of the charge distribution in the cluster gives a first approximation of the location where the particle crossed the detector.
3. RecHits: The reconstructed hit is an estimated position and error of the charged particle crossing. With respect to the cluster the RecHit position is corrected for the lorentz shift which is a deviation of the produced charge carriers inside a magnetic field leading to a shifted measurement of the crossing point.
4. Tracks: RecHits that are found to be compatible with a particle trajectory are combined to a reconstructed track. The track is described by a collection of the corresponding hits and by five so-called perigee³ parameters parametrizing the trajectory.

In addition to the event data themselves so-called non-event data are essential for the reconstruction. Among these there are for example the cabling information of all silicon detectors to know which module is located at which position, the pedestal and noise values of all readout channels to perform offline zero-suppression if needed and to run the clustering algorithm and alignment constants to correct the detector positions for misalignment. These information are stored in an offline database to which CMSSW provides an interface so that each plug-in can retrieve the needed values.

The first module in the reconstruction chain unpacks the raw data received from the FEDs and reorders them by grouping digis belonging to the same silicon detector together. Each digi has an identifier that associates it with a silicon module on a dedicated position in

³The perigee parameters are the helix parametrization in a frame where the z axis is parallel to the magnetic field. The five parameters are with respect to a reference point: transverse distance of the point of closest approach, longitudinal distance of the point of closest approach, polar and azimuthal angle of the momentum at the point of closest approach and the charge over momentum magnitude.

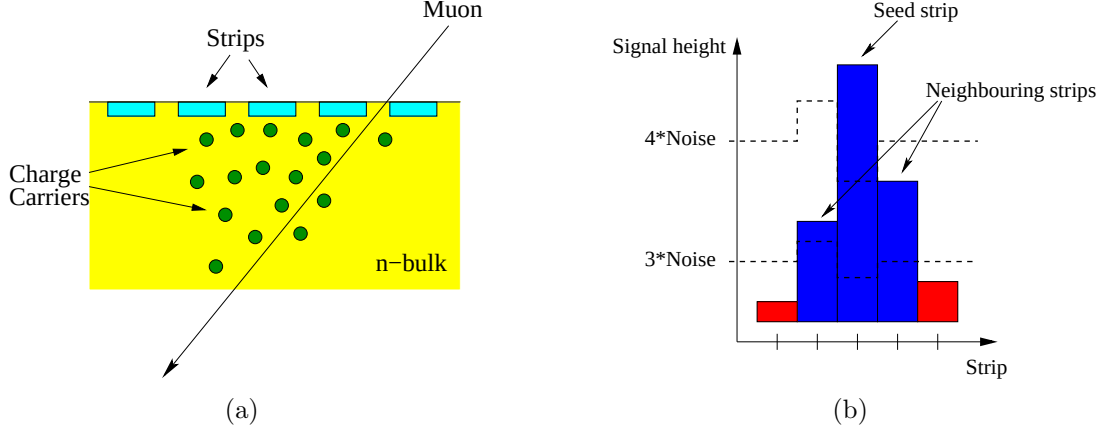


Figure 3.4: Principle of the cluster finding algorithm. (a) Simplified cross-section of a part of a silicon strip detector. Shown is the crossing of a muon that produces charge carriers along its way in the n -type bulk. The charges drift to the strips and induce a signal that indicates the passage of the particle. (b) Signal height of the respective strips. The signals on the seed strip and the two neighbouring channels are above the required thresholds so that they form a cluster (in blue). The next-to neighbours (in red) are below the threshold and do not contribute to the cluster. The cluster threshold, which is the third requirement besides the seed and the neighbour threshold, is not shown.

the tracker. To do this assignment a matching between the detector position and the corresponding FED channel is performed automatically by the tracker commissioning software in special runs. The results are written to the database which provides the cabling information to the plug-in.

In the second step, the cluster finding, the signal height of all digis is scanned using three different signal-to-noise (S/N) thresholds set by the user (see figure 3.4). The first one searches for a seed strip identified by a signal amplitude that exceeds the noise of the corresponding strip by a certain factor (at the MTCC this threshold was set to $(S/N)_s > 4$). If a seed is found the neighbouring channels are added to the cluster if their signal with respect to their noise is above $(S/N)_n > 3$. Finally, the total cluster charge has to be five times greater than the quadratic sum of the individual strip noises belonging to the cluster ($(S/N)_c > 5$). The cluster position is determined by calculating the center-of-gravity of the charge distribution since the signal height of a strip is a measure for the amount of charge drifted to the respective electrode. By weighting the signals arising from charge sharing the spatial resolution can be improved to values below the geometrical resolution of $\text{pitch}/\sqrt{12}$.

After clusterization every cluster is associated with a reconstructed hit owing its position to the cluster centroid. In case of a magnetic field the RecHit position is additionally corrected for the Lorentz shift. Depending on the track reconstruction algorithm the RecHits of a double sided silicon detector are combined to a so-called matched RecHit so that a 2-dimensional track point can be used for the trajectory fitting.

Since the tracker end cap contribution to the MTCC with two petals arranged side by side was not sufficient to be able to reconstruct tracks passing through the petals the principle of track reconstruction is only mentioned briefly. It will be described in more detail in chapter 4 dealing with the so-called tracker slice test. The track reconstruction algorithms consist of three basic steps:

- Seed creation: A minimal set of RecHits is searched that can be compatible with a particle trajectory, the so-called track seed. The seed provides a first approximation of the track parameters.
- Pattern recognition: For all RecHits compatible with a particle trajectory a collection is created. Starting from each track seed the estimated trajectory state is propagated to the layers that have not contributed to the seed creation considering the bending in a magnetic field, the energy loss due to the interaction with the material and the multiple scattering. If a RecHit is compatible with the predicted track position it is added to the respective RecHit collection, a new track candidate is created and the trajectory state is updated and propagated to the next layer. This procedure is continued until the last layer is reached or a stopping condition is fulfilled, for example if no compatible hit is found in a certain number of consecutive layers.
- Track fitting: In the last step the track is fitted and the final track parameters are smoothened. To get the best estimate for the reconstructed track the Kalman filter is applied both from outside in and from inside out and the results are combined. In addition, the RecHits are updated using the information of the track incident angle on the corresponding surface. Only the track parameters at the innermost and outermost layers are stored in the event.

3.5 Simulation of the MTCC Setup

To be able to compare the data measured at the MTCC with MonteCarlo events two different data sets were simulated using the MTCC geometry, one corresponding to a magnetic field of 0 T and the other one assuming $B = 4$ T. Since in the MTCC only cosmic muons could be studied the particle generation in the simulation was done using the Cosmic Muon Generator CMSCGEN [26] which is based on CORSIKA [27], a program for the simulation of extensive air showers.

The muons are generated at a flat surface reflecting the cosmic muon properties at a certain altitude. Afterwards they are extrapolated as a straight line to the CMS surface without any energy loss. Starting from the generated vertices located on this surface they are propagated through the MTCC setup until they reach a target region. Only muons crossing this target region are then selected and passed on to the rest of the simulation chain. To increase the efficiency of reconstructed tracks in the tracker with respect to the generated particles different target regions and event filters were used for the B field on and off samples.

In case of zero magnetic field the muon is propagated as a straight line to a small cylindrical surface reflecting the MTCC tracker setup. Only muons that cross this surface are retained and passed to the simulation. After that, a filter is applied requiring at least one simulated hit in the tracker and passing these events to the subsequent analysis.

For $B = 4$ T the target region has to be increased because the bending of the trajectory is not considered by the straight line propagation. In order to prevent an inefficiency due to the Lorentz force curvature inside the CMS volume and a bias in the transverse momentum distribution of the accepted muons the target radius is enlarged to the outer radius of the CMS detector. Additional event filters applied before and after the simulation then select those muons that make a certain signal in the MTCC tracker setup.

It should be mentioned that, although the majority of the cosmic runs with magnetic field on was performed at $B = 3.8$ T (see section 3.6), the simulation for non-zero B field was done using $B = 4$ T. This is due to the fact that the CMS magnetic field in the CMS software was parametrized only for this field configuration. Because of the non-trivial behaviour of the B field in the muon detector region it was not possible to simply rescale it.

In addition, a simulation of the various trigger configurations described in section 3.2 was not available. Instead the events used for tracker studies were selected in the simulation as explained above.

3.6 Event Selection

Since the geometrical acceptance of the triggering muon system was much larger than the one of the tracker setup it was expected that most of the triggered events would not contain a particle crossing the tracker volume. Because of that it was important to select events with respect to physical requirements from the tracker point of view in order to produce optimal data samples containing muons hitting the tracker for further analysis. Otherwise the majority of the data would have been background due to the electronics noise. In table 3.1 a summary of the most important cosmic runs used for the analysis is shown. The largest amount of runs was performed with B field off and $B = 3.8$ T, respectively. A smaller fraction was recorded using the nominal magnetic field of 4 T.

In the barrel region in total four overlapping layers (two from the TIB and two from the TOB) were present. Because of that a particle passing through the barrel volume is expected to produce hits in several layers. A simple event selection algorithm was used for TIB and TOB events requiring clusters in at least three out of the four different layers. In addition, the clusters had to exceed a cluster charge threshold of 25 ADC counts to be considered. The result of this selection is depicted in the last column of table 3.1. Only a very small number compared to the total number of triggered events satisfied the cuts.

Unfortunately the TEC contribution to the MTCC tracker was not optimal to detect cosmic muons. First of all, the petals were mounted vertically (as they are in the final TEC structure) so that cosmics going from top to bottom could only be measured with a relatively large inclination angle. Furthermore the two petals were arranged side by side leading to only one sensitive layer in the end cap region. Finally, there was no geometrical overlap (taking also into account the triggering muon detectors) between the barrel layers and the end cap inhibiting muons crossing the petals and the barrel layers at the same time. Because of that it was not possible to reconstruct particle tracks traversing the petals due

B Field [T]	#Runs	#Events	#Filtered Events (TEC)	#Filtered Events (TIB+TOB)
0.0	43	11 266 803	238 400	6 825
3.8	38	13 765 676	252 146	3 953
4.0	4	1 715 550	30 721	688

Table 3.1: Overview of the MTCC data samples used for the analysis. The number of filtered events for the TEC is larger than the one for the TIB and TOB since the selection algorithm for the TEC had to be looser.

to the lack of measurement points and the algorithm used for the TIB and TOB requiring several hits in different layers could not be adapted to the TEC part. Instead, to reduce the total number of events also for the TEC analysis, a separate data sample selecting only events where at least one cluster is reconstructed in any of the petal modules was created. With this selection in place the number of events that were suitable for a dedicated TEC analysis was reduced by roughly 98% compared to all events taken (see fourth column of table 3.1). All other cuts on the TEC data are performed later in the analysis.

3.7 Tracker Performance

In this section the performance of the tracker end cap part in the MTCC is discussed. Different aspects like the noise behaviour of the silicon modules and the reconstructed cluster properties, for example the charge and the signal-to-noise ratio, will be analyzed. Results concerning the TIB and the TOB performance can be found in [24].

3.7.1 Global and Local Coordinate Systems

In this thesis two different coordinate systems are used. On the one hand the global CMS reference frame to show the position of objects or calculate parameters with respect to the whole CMS detector and on the other hand the local reference frame belonging to each single silicon strip module in order to analyze properties relative to this surface.

The global CMS coordinate system is depicted in figure 3.5(a). It is a right-handed reference frame with its origin in the center of the CMS detector. The x axis lies in the horizontal plane pointing to the center of the LHC ring. The y axis is vertically oriented pointing upwards and the z axis is parallel to the beam in counter-clockwise direction. The azimuthal angle ϕ is measured starting from the x axis towards the y axis and covers the interval from 0° to 180° and from 0° to -180° , respectively. The polar angle θ is defined by the opening angle of a cone around the positive z axis. It spans an interval from 0° to 180° .

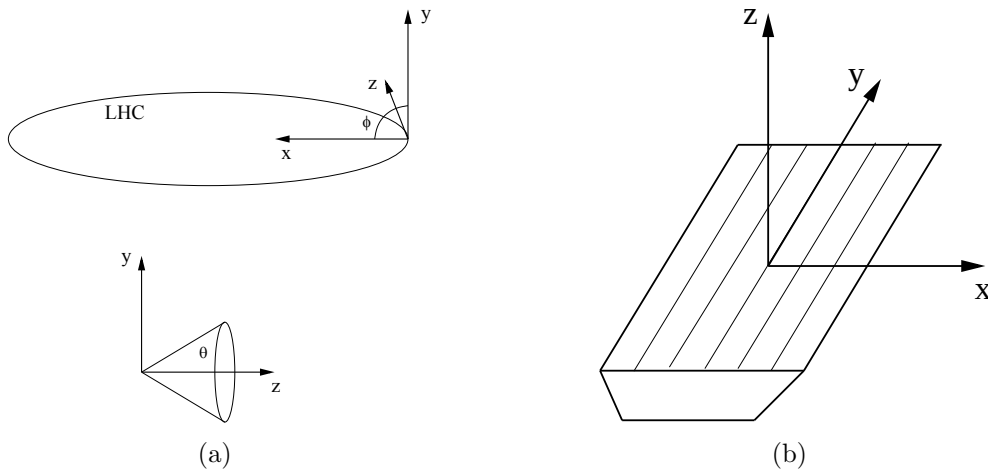


Figure 3.5: Definition of the two reference frames used in this thesis. (a) The global CMS coordinate system. (b) The local coordinate system of a single silicon strip module.

Using this polar angle the pseudo-rapidity η is calculated as $\eta = -\ln(\tan(\theta/2))$ and ranges from $-\infty$ to $+\infty$.

The local reference frame of a single silicon strip module is shown in figure 3.5(b). It is also a right-handed coordinate system with the origin positioned in the center of the active silicon surface. The x axis is perpendicular to the strips within the module plane pointing to rising strip numbers. For modules with constant pitch between neighbouring channels (TIB and TOB) this is the sensitive coordinate that can be precisely measured. This is not true for sensors with trapezoidal geometry (TID and TEC) since this axis is no longer perpendicular to all strips. The y axis is in case of rectangular modules the one that lies in the sensor plane and is parallel to the readout channels in the direction pointing away from the module hybrid. Again, for trapezoidal detectors the strips are not parallel to the y axis. Finally, the z axis is perpendicular to the module surface.

3.7.2 Noise Studies

To study the noise behaviour of the 34 TEC modules in the MTCC three different pedestal runs, taken during a period of approximately one month and using different magnetic fields, are used to calculate the single strip noise whereas one time synchronisation scan run provides the information of the tick mark height and thus the optical gain of each laser mounted on the analog opto hybrids. The pedestal runs were performed in peak mode (which corresponds to the mode used in the cosmic runs) and consisted of about 2000 triggers each. Table 3.2 summarizes the commissioning runs used in the following analysis. It should be mentioned that the modules and petals operated in the MTCC are not mounted on the final TEC structures. They were only used for test purpose and therefore modules of lower grade than the ones mounted on the production petals were installed. Nevertheless, these modules and petals were also extensively tested in the ARC test and the petal longterm test, respectively.

3.7.2.1 Noise Performance

Using the tick mark height information it is possible to calibrate the noise with respect to the optical gain which allows to compare the noise values between strips belonging to different lasers. The observed noise is normalized to a tick mark height of 600 ADC counts. Figure 3.6(a) shows a typical noise profile of one MTCC TEC module with 768 readout channels. The solid line corresponds to the uncalibrated noise whereas the dotted distribution represents the tick height normalized noise. As expected, the laser structure disappears after calibration (see also section 2.2.3).

Using this method the calibrated noise has been calculated for all strips of the two petals present in the MTCC. In figure 3.7 the results achieved with pedestal run 20314 (which will be used in the following as reference run) and the timing run are shown compared to the

Run	20268	20314	20388	20422
Type	Timing	Pedestal	Pedestal	Pedestal
Date	Aug. 6th	Aug. 8th	Aug. 18th	Aug. 26th
B Field [T]	0	0	0	2.0

Table 3.2: Overview of the MTCC timing and pedestal runs used for the analysis.

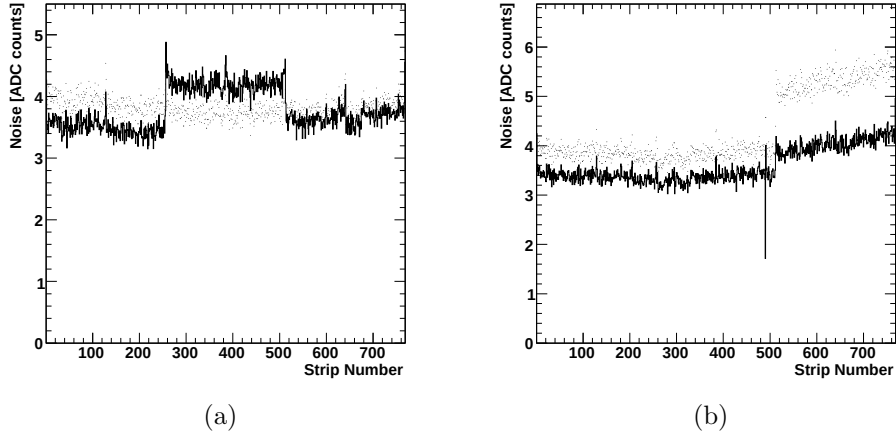


Figure 3.6: Tick mark height calibrated (dotted) and uncalibrated (solid) noise of two ring 5 modules on the front petal. (a) Module on position 2. The laser structure disappears after calibration. (b) Module on position 3. The noise increases for the third laser after calibration.

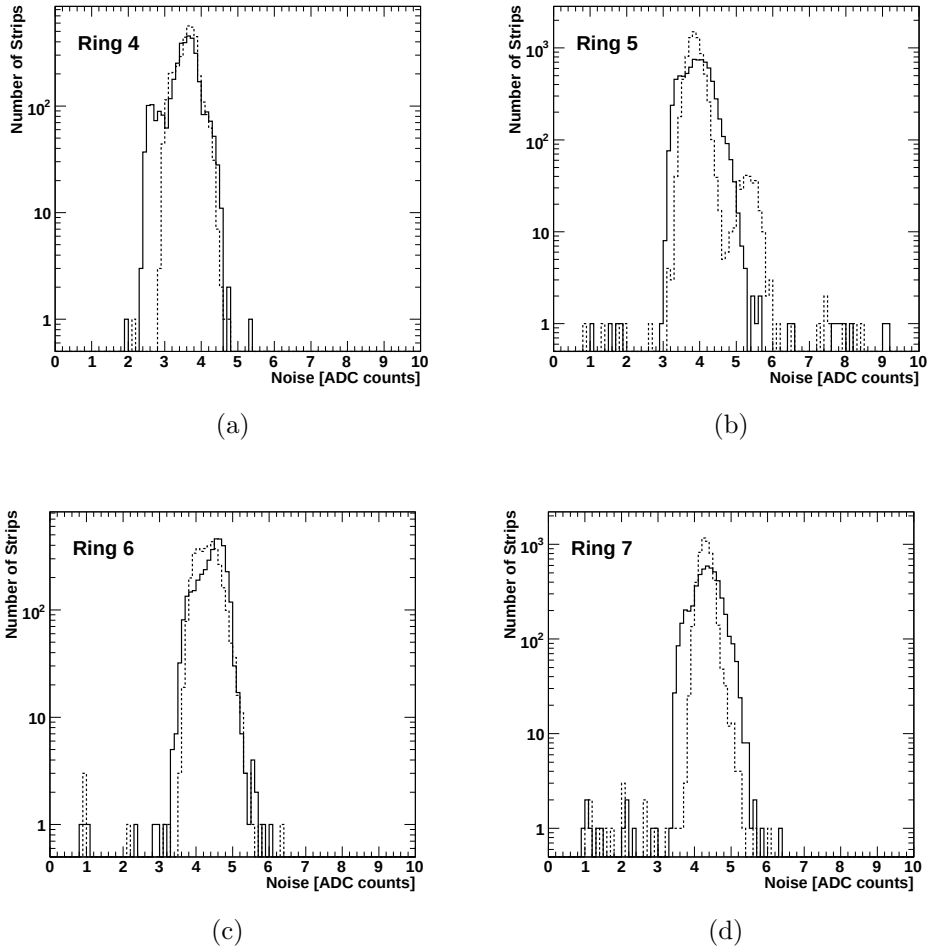


Figure 3.7: Tick mark height calibrated (dotted) and uncalibrated (solid) noise of (a) ring 4, (b) ring 5, (c) ring 6 and (d) ring 7 modules. The width of the distributions becomes smaller after applying the calibration.

uncalibrated values. Since the noise should increase with increasing strip length from ring 4 to ring 7 due to the larger capacitance connected to the APV input, the distributions are shown individually for each ring. As expected, a slope from ring 4 to ring 7 can be observed.

In general, the width of the noise distributions is reduced when applying the calibration to the laser gains. But for ring 5 modules the calibration leads to a second peak at higher noise values. This behaviour originates from a single module which is mounted on position 5.3 on the front petal. The increase is also visible in figure 3.6(b) where the noise increases after calibration for the third laser (which corresponds to channels 513 up to 768). It is attributed to fluctuations of the tick mark for this laser during the timing run. The same effect is also observed for one TIB module (see [24]).

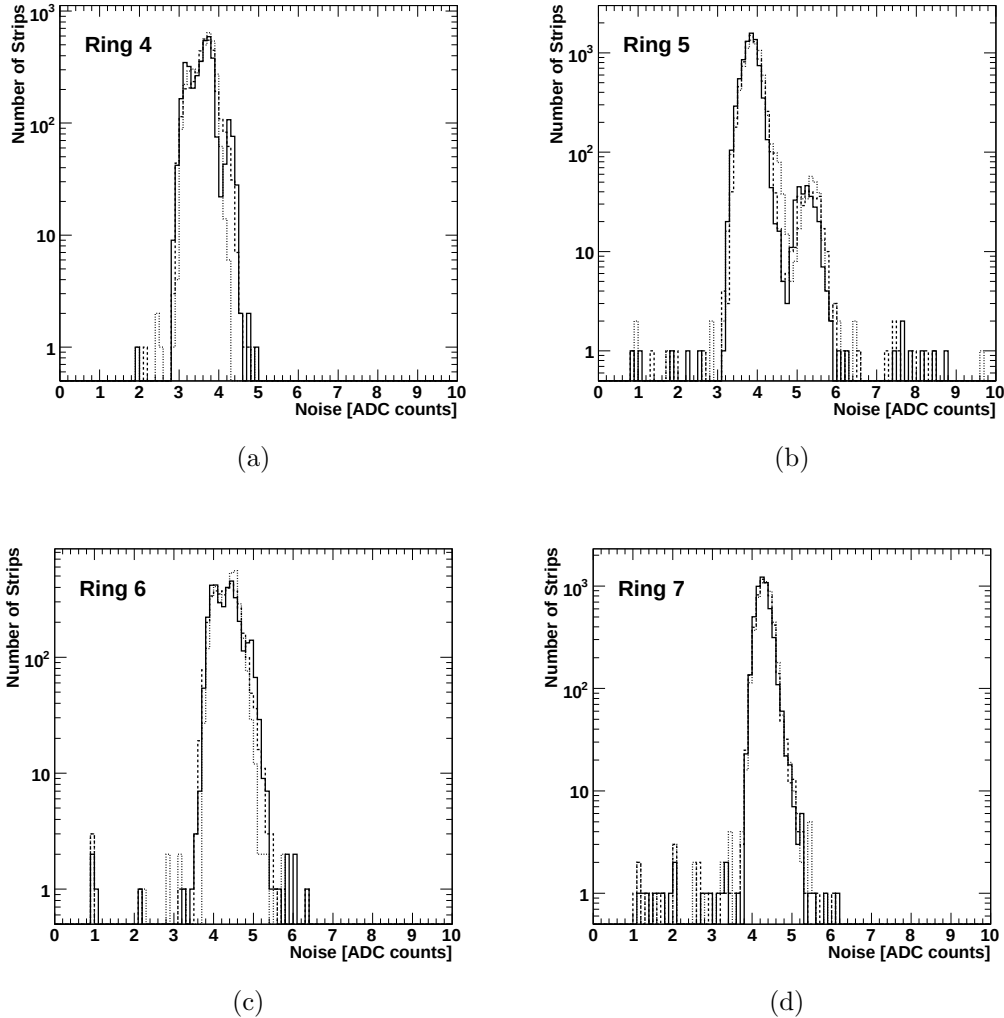


Figure 3.8: Tick mark height calibrated noise of (a) ring 4, (b) ring 5, (c) ring 6 and (d) ring 7 modules for three pedestal runs (solid: Run 20388, dashed: Run 20314, dotted: Run 20422) measured over a period of approximately one month and using $B = 0$ T for two runs and $B = 2$ T for the third one.

3.7.2.2 Noise Stability

To verify the stability of the noise behaviour with time and magnetic field the three different pedestal runs listed in table 3.2 are compared to each other. The run from August, 8th is used as reference so that the noise evolution can be calculated from one run taken 10 days later and another one taken 18 days later with respect to the reference run.

Again, this study is made separately for the different rings. Figure 3.8 shows the noise distributions obtained from the three runs. The variation with time is found to be very small.

To verify this behaviour on a single strip basis, the distribution of the noise difference for

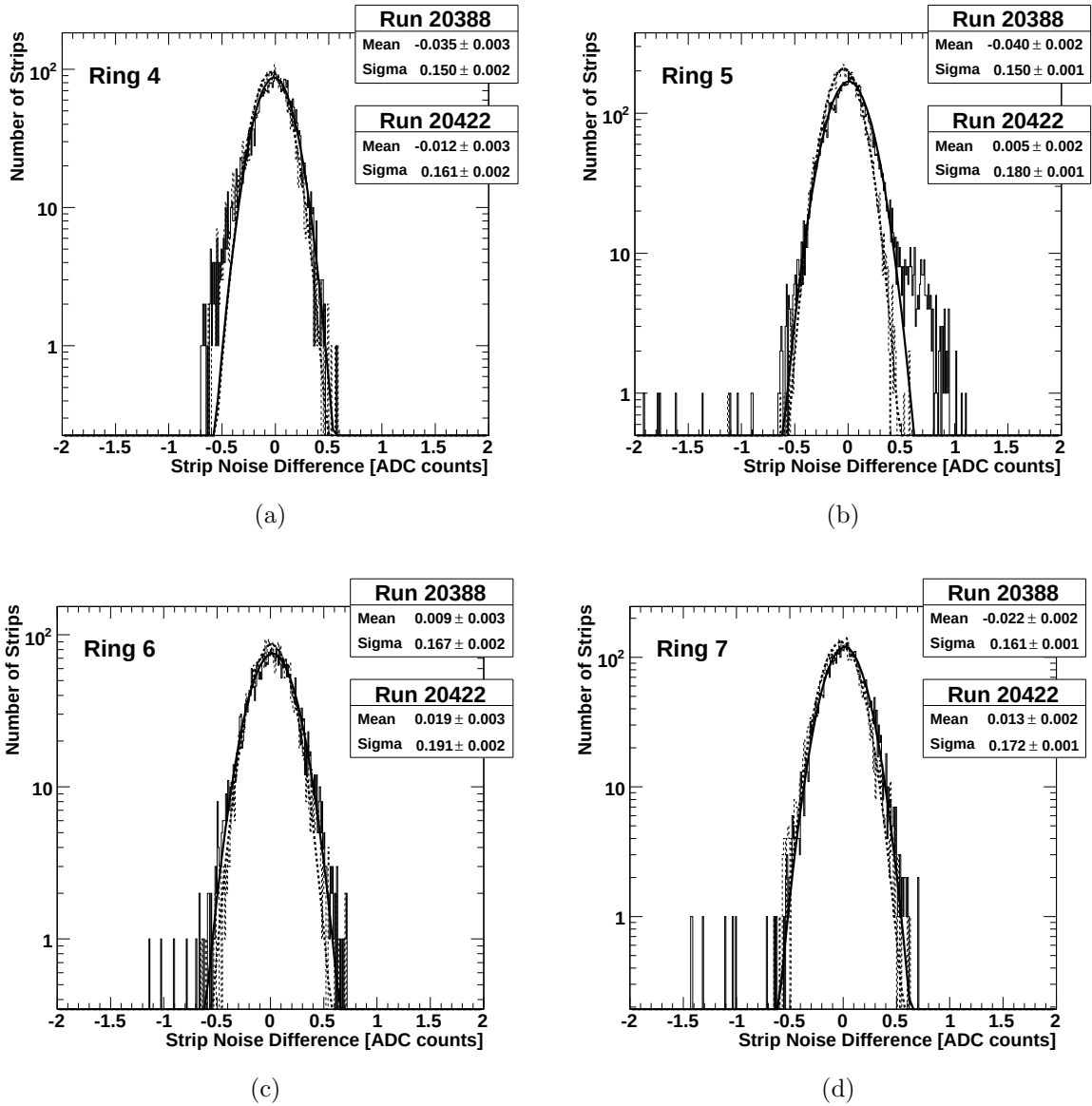


Figure 3.9: Single strip noise difference between two pedestal runs and a reference run after applying the tick mark height calibration for (a) ring 4, (b) ring 5, (c) ring 6 and (d) ring 7 modules. All distributions are centered around zero and show a small sigma corresponding to small noise variations.

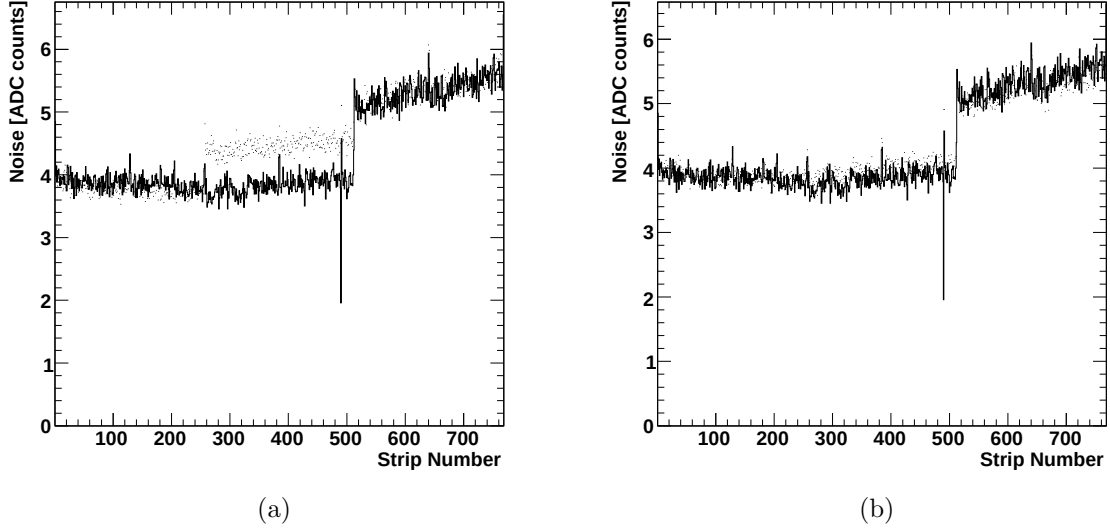


Figure 3.10: Tick mark height calibrated noise of module 5.3 on the front petal for the reference run (solid) and (a) the second pedestal run under investigation (dotted) and (b) the first pedestal run under investigation (dotted), respectively.

each individual strip is shown in figure 3.9 with respect to the reference run. Dashed lines correspond to the first and solid lines to the second run under investigation. All differences are in agreement with zero and all distributions are well described by a gaussian distribution with a sigma of only approximately 0.16 ADC counts. Run 20422 was measured using $B = 2$ T whereas the magnetic field was off during the other runs. No change in the noise behaviour is observed.

Only the comparison between the second run under investigation and the reference run for ring 5 modules shows a significant number of strips that have a higher difference in noise than the other channels. This behaviour is caused by a group of 256 strips of a single module as shown in figure 3.10(a). This silicon sensor on position 5.3 on the front petal has increased noise at the second laser during the last pedestal run analyzed here. This increase can be induced by a temporary change in the gain conditions for example due to a difference in the operation temperature. The deviation does not appear in the first pedestal run (see figure 3.10(b)).

Based on these results it can be concluded that the noise of the TEC modules was stable during the entire data taking period and independent of the magnetic field.

3.7.2.3 Comparison with Integration Data

Using the pedestal and timing runs performed in the LT setup it is possible to compare the tick mark height calibrated noise between the petal longterm test and the MTCC. Instead of using the noise in ADC counts it can be expressed as the number of electrons to which it corresponds, the so-called equivalent noise charge (ENC). Usually the conversion factor between ADC counts and electrons is calculated by comparing the most probable value of the signal distribution produced by Minimal Ionizing Particles (MIPs), such as cosmic ray muons, with the expected number of electrons. But since no cosmic trigger was available in

Ring number	Strip length [mm]	LT (production) warm	LT (production) cold	LT (MTCC) warm	LT (MTCC) cold	MTCC
1	87.2	946 ± 61	823 ± 54	—	—	—
2	88.1	971 ± 60	850 ± 53	—	—	—
3	110.6	1024 ± 60	891 ± 54	—	—	—
4	115.1	1027 ± 60	900 ± 51	999 ± 71	873 ± 54	1159 ± 94
5	147.2	1208 ± 71	1068 ± 66	1213 ± 84	1080 ± 94	1238 ± 66
6	183.9	1266 ± 76	1118 ± 67	1247 ± 72	1080 ± 60	1381 ± 101
7	205.7	1333 ± 69	1180 ± 66	1320 ± 55	1161 ± 48	1378 ± 64

Table 3.3: The mean ENC in electrons as measured in the petal longterm test (both for the production petals and the special MTCC petals) and the MTCC in peak mode. The uncertainty is the RMS of the resulting ENC distribution per ring.

the longterm setup and thus no MIP signals were measured the ENC cannot be determined with this procedure. It is calculated from the assumption that the measured tick height of an APV corresponds to 8 MIP signals and 1 MIP creates most likely 24000 electrons in $300 \mu\text{m}$ of silicon:

$$\text{Noise}[\text{electrons}] = \frac{\text{Noise}[\text{ADC counts}] \cdot 8 \cdot 24000e^-}{\text{TickHeight}[\text{ADC counts}]}$$

Figure 3.11 depicts the ENC for the different rings obtained with the longterm setup for both the production petals and the two MTCC petals. Petals tested at the CERN integration center are not taken into account since the test setup and thus the noise measured there was different compared to the other petal integration centers. The data shown are taken during the warm cycle, i.e. nearly at room temperature, with the APV chips operating in peak mode with inverter on. Comparing the production with the MTCC petals it can be seen that the noise behaviour is very similar. The same measurements are made in the cold

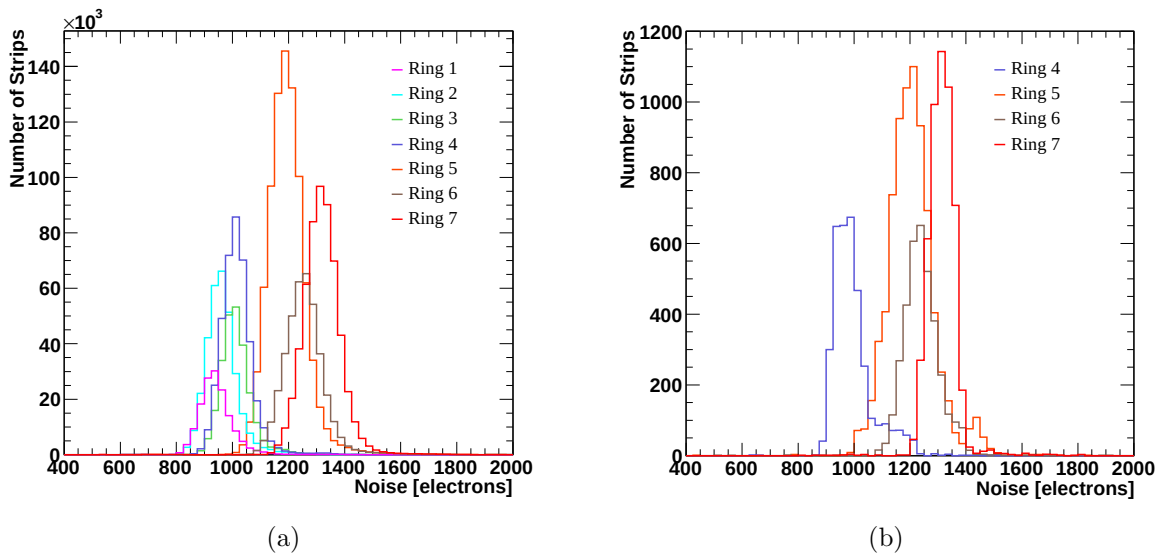


Figure 3.11: ENC per ring in peak mode for (a) the production petals and (b) the MTCC petals as measured in the warm cycle of the longterm test.

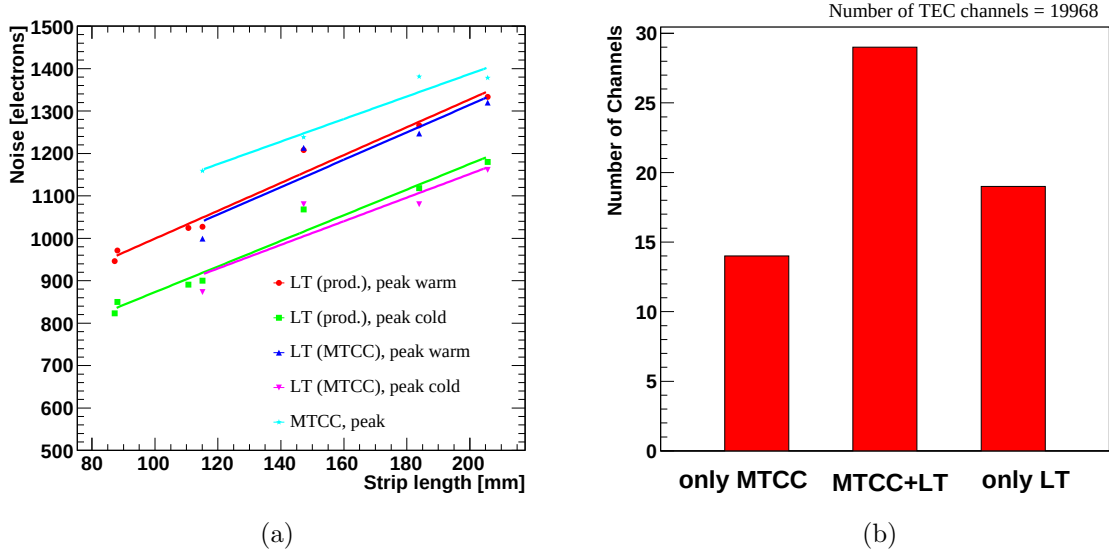


Figure 3.12: (a) The mean ENC versus the strip length for peak mode and the two test setups. For the longterm test it is distinguished between the two operating temperatures and between production and MTCC petals. (b) Comparison of the faulty channels that were flagged either in the MTCC or in the LT test or in both setups.

environment where the silicon temperature is below -10°C . Combining all the results a noise parametrization for the different tests with respect to the strip length is shown in figure 3.12(a). As expected, a linear dependence is observed for all measurements and the ENC is reduced in the cold environment by 11 % to 13 % with respect to the values obtained at room temperature. Despite the fact that the operating temperature of the silicon sensors is not known in the MTCC the mean noise is between 2% and 16% higher than the noise of the corresponding petals during the warm cycle of the longterm setup. The mean equivalent noise charges resulting from the different tests are summarized in table 3.3.

Because the behaviour of every readout channel in the petal longterm test is known it can be studied if strips that were flagged as bad in the LT test are also suspicious in the MTCC. Therefore the noise of each channel obtained in pedestal run 20314 is analyzed and compared to the LT grading. Figure 3.13 shows as an example the noise profile of two silicon modules measured in the MTCC (black line) together with the strips that were found to be bad in the longterm test (red markers). In figure 3.13(a) all channels showing a strange noise performance were also marked in the LT test whereas in figure 3.13(b) several strips that have strange noise values in the MTCC were not flagged in the petal test and vice versa, strips that were faulty in the LT test show a normal noise behaviour in the MTCC. To compare all conspicuous channels between the MTCC and the LT test the following procedure is applied:

- For each APV the median of the ENC strip noise is calculated.
- The difference between the strip noise and the corresponding median is computed. If the relative deviation from the median exceeds +15 % or is below -15 % the channel is flagged as faulty.
- The results are compared to the grading obtained with the petal longterm test.

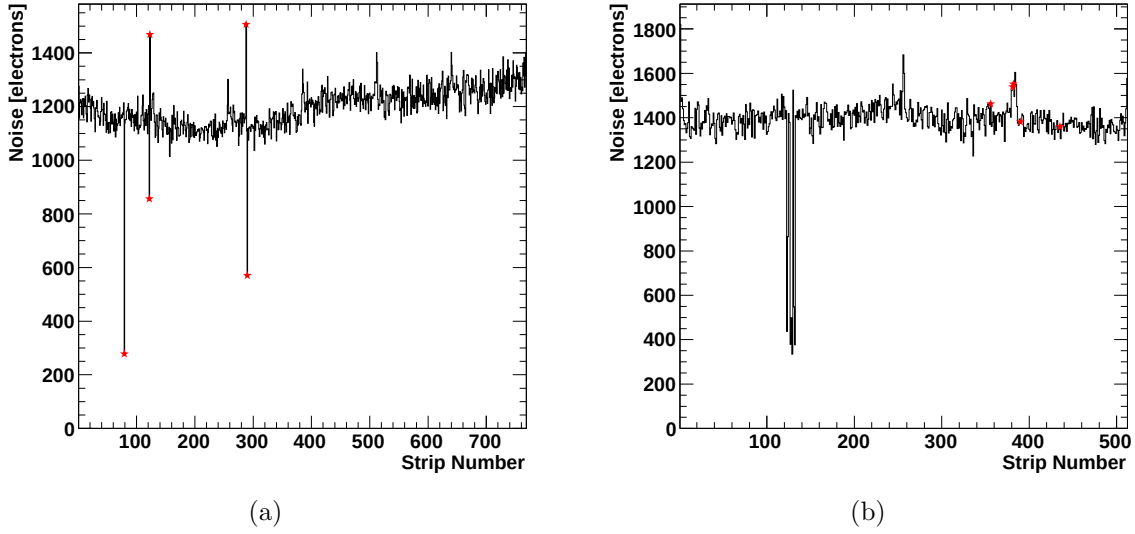


Figure 3.13: Noise profiles for two tracker end cap modules. The black line represents the noise measured in the MTCC while the red stars indicate strips that are flagged as faulty in the LT test. In figure (a) all channels that are conspicuous in the MTCC are also marked in the longterm test whereas in figure (b) several channels show a strange behaviour in only one of the two test setups.

- APV edge channels (strip number 1 and 128) are excluded from the analysis since they have a different noise behaviour with respect to the other channels.

The comparison of the channels flagged between the two setups is depicted in figure 3.12(b). Most of the faulty channels are conspicuous both in the MTCC and the LT test. Their abnormal behaviour is reproducible although the two setups are completely different. Some channels are only suspicious either in the MTCC or in the longterm test, as shown in figure 3.13(b). It has to be taken into account that for the MTCC only the noise profiles could be analyzed whereas in the LT test additional dedicated calibration runs were performed to find faulty channels. Furthermore, it is possible that during the installation of the petals in the MTCC setup some strips were damaged that were fully functional in the longterm test. Since the two MTCC petals are not used in the final tracker and the non-conforming channels represent only about 1.7% of all TEC readout channels operated in the MTCC these differences are not studied in detail.

3.7.3 Reconstruction Studies

3.7.3.1 Cluster Position

As described in section 3.4 the reconstruction process starts with the production of so-called digis, which are single strip signals after pedestal subtraction and zero suppression. Figure 3.14(a) shows the distribution of these digis with respect to the strip number summed up for all TEC modules for a subset of a cosmic run. Since in the setup used only ring 5 modules contain 768 channels while the other sensors have only 512 strips a step occurs at strip number 512. It can be observed that the APV edge channels, where the strip noise is

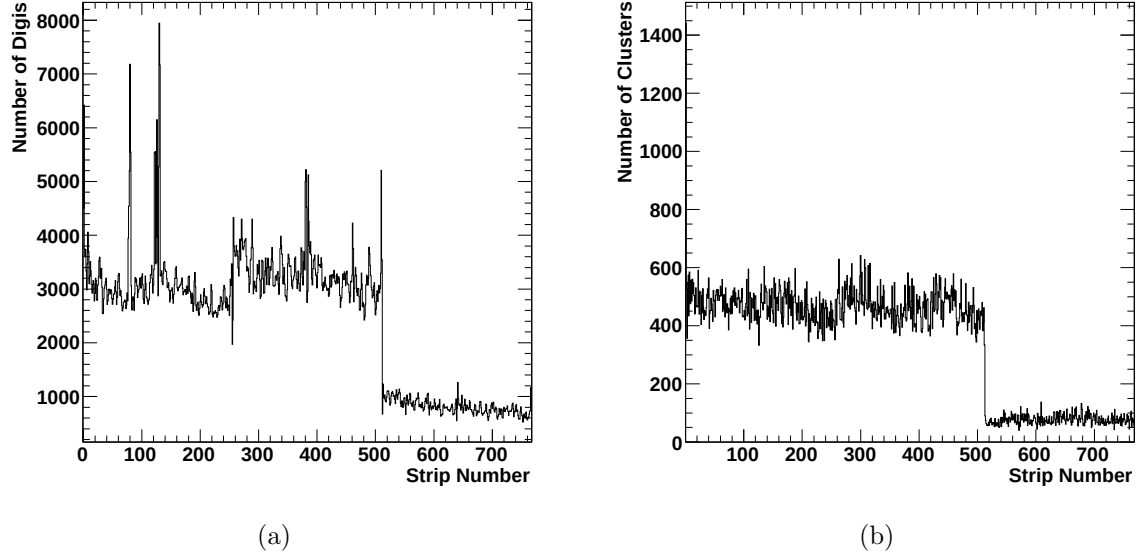


Figure 3.14: (a) Number of reconstructed digis per strip summed over all TEC modules. (b) Number of reconstructed clusters per strip summed over all TEC modules. Both distributions represent a subset of the cosmic runs measured at the MTCC. Since only 30 % of the modules (ring 5 modules) contain 768 strips a step occurs at strip number 512.

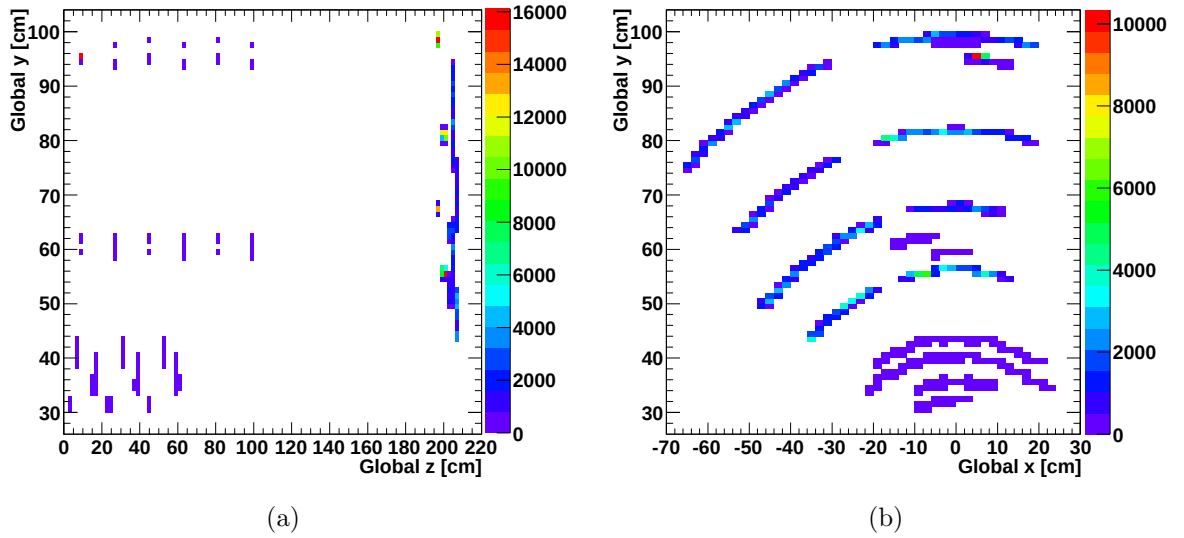


Figure 3.15: Position of reconstructed clusters in the global CMS coordinate system. The MTCC inner barrel part can be identified at $30 \text{ cm} < y < 45 \text{ cm}$, the outer barrel part at $y \approx 60 \text{ cm}$ and $y \approx 95 \text{ cm}$ and the end cap part at $z \approx 200 \text{ cm}$. (a) y - z -view and (b) y - x -view. For the definition of the coordinate system see section 3.7.1.

known to be higher, also collect more digis than the inner strips. In addition, there are some distinct peaks pointing to most likely faulty channels.

Neighbouring channels satisfying the three signal-to-noise thresholds applied to the clusterization algorithm are then combined to a higher level reconstruction object, the cluster. The center-of-gravity of the cluster charge distribution, referred to as the cluster position, is depicted in figure 3.14(b), again with respect to the module strip number and summed up for all TEC detectors. It is obvious that the clusterization process with its thresholds is able to eliminate signals coming from noise. Compared to the digi distribution the clusters are distributed more uniformly and most of the distinct peaks disappear. The number of clusters is much smaller than the number of digis. The distribution shown in figure 3.14(a) corresponds to 100,000 events while the measurement in figure 3.14(b) uses about 240,000 events.

The position of the clusters in the local module frame can be transformed to the global CMS coordinate system. The positions after such a transformation are shown in figure 3.15. Figure 3.15(a) depicts the global position of clusters reconstructed with the MTCC tracker setup in y - z -view whereas in figure 3.15(b) the x - y -view can be seen. Compared to figure 3.2 showing a schematic drawing of the tracker test layout the structures used can directly be identified: two shells of the inner barrel, two rods of the outer barrel and two petals of the endcap consisting of four rings each. The cluster position can be measured with high precision only in one dimension, that is perpendicular to the strips. The remaining two dimensions are only known within the module size and therefore the cluster position in the corresponding direction is set to the center of the silicon detector. For this reason the reconstructed clusters are not distributed over a whole petal for example, but are concentrated at a certain radius for every ring.

3.7.3.2 Cluster Charge

An important parameter of a reconstructed cluster is the charge collected by the corresponding strips. It can be used in combination with the cluster noise to distinguish between clusters originating from charged particles traversing the detector and clusters due to noise.

In figure 3.16 the cluster charge distribution is shown for ring 4 modules on the left side and ring 5 to ring 7 modules on the right side. Since these detectors have different thicknesses of about $320\,\mu\text{m}$ and $500\,\mu\text{m}$, respectively, the mean path length of particles crossing the active silicon material is larger for the thick sensors. Therefore the number of electron-hole-pairs produced and thus the charge is expected to be higher for ring 5, ring 6 and ring 7 detectors. This behaviour can be verified in the distributions: The cosmic muon hits peak at about 110 ADC counts in case of ring 4 modules and at 180 ADC counts for ring 5 to 7 sensors. The difference of about 60% corresponds to the ratio of the two sensor thicknesses.

In all measured distributions the signal peak is clearly separated from the tail of the noise at about 30 ADC counts. No difference is observed in the cosmic data between $B = 0\,\text{T}$, $3.8\,\text{T}$ and $4\,\text{T}$. However, the simulation, which was performed for $B = 0\,\text{T}$ and $4\,\text{T}$, shows deviations from the measurement. To compare the different data sets the integral of every distribution is scaled to unity. Since the cosmic measurements are dominated by the noise tail which is not of interest an additional signal-to-noise cut is applied to the reconstructed clusters that eliminates the first peak and simplifies the comparison between data and MC.

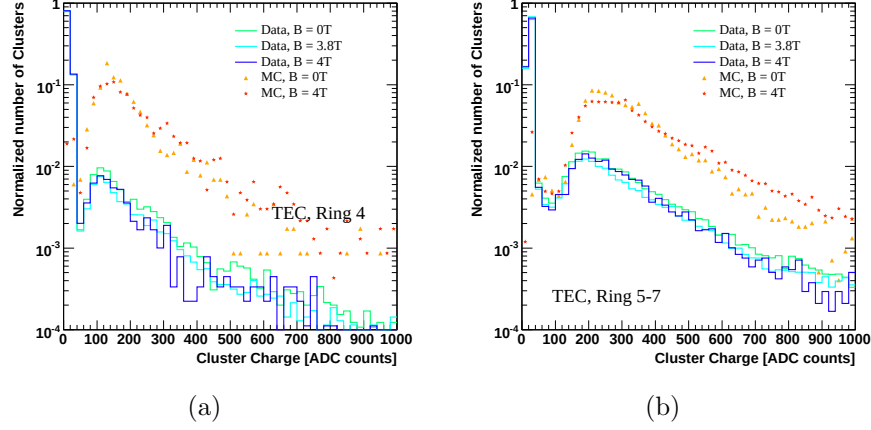


Figure 3.16: Cluster charge distributions for (a) ring 4 (thin) and (b) ring 5, 6 and 7 (thick) silicon modules in the TEC. As expected, the measured signal is larger in the thick sensors than in the thin ones. The data are shown for $B = 0$ T, 3.8 T and 4 T. The signal peak is well separated from the noise tail at about 30 ADC counts. The simulation is done for $B = 0$ T and 4 T. The integral of all distributions is normalized to unity.

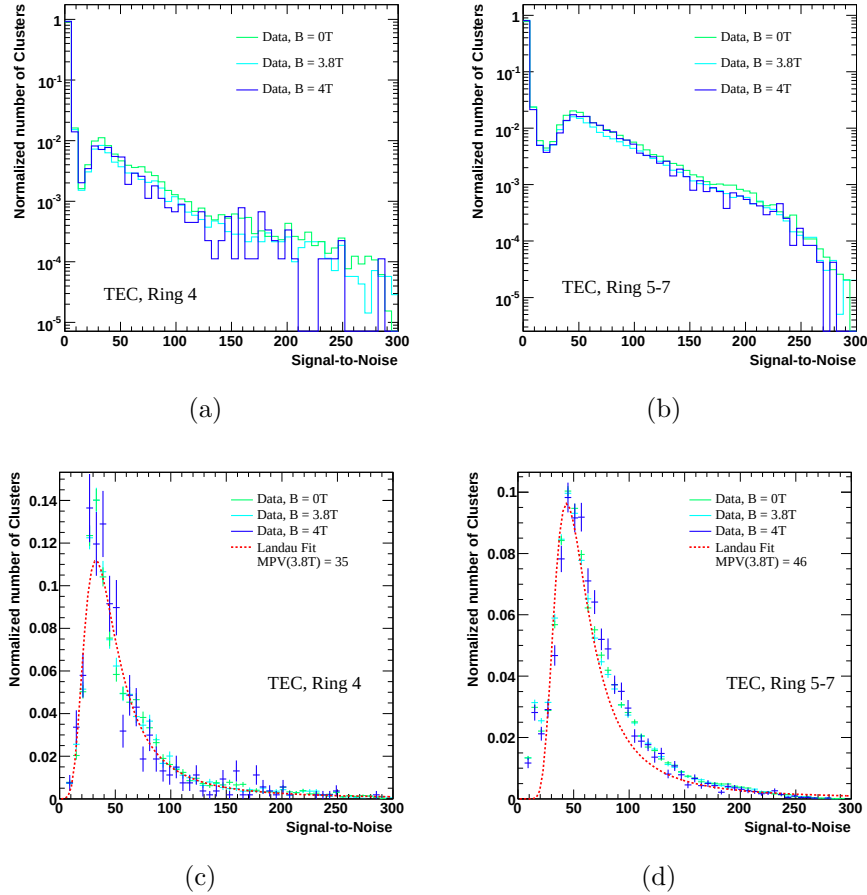


Figure 3.17: Signal-to-Noise ratio for ring 4 modules on the left side and ring 5, 6 and 7 modules on the right side. Figures (a) and (b) show the distributions without any cut whereas in figures (c) and (d) a cluster signal-to-noise cut of 10 is applied. In the signal region a landau function is fitted to the data that are shown for $B = 0$ T, 3.8 T and 4 T.

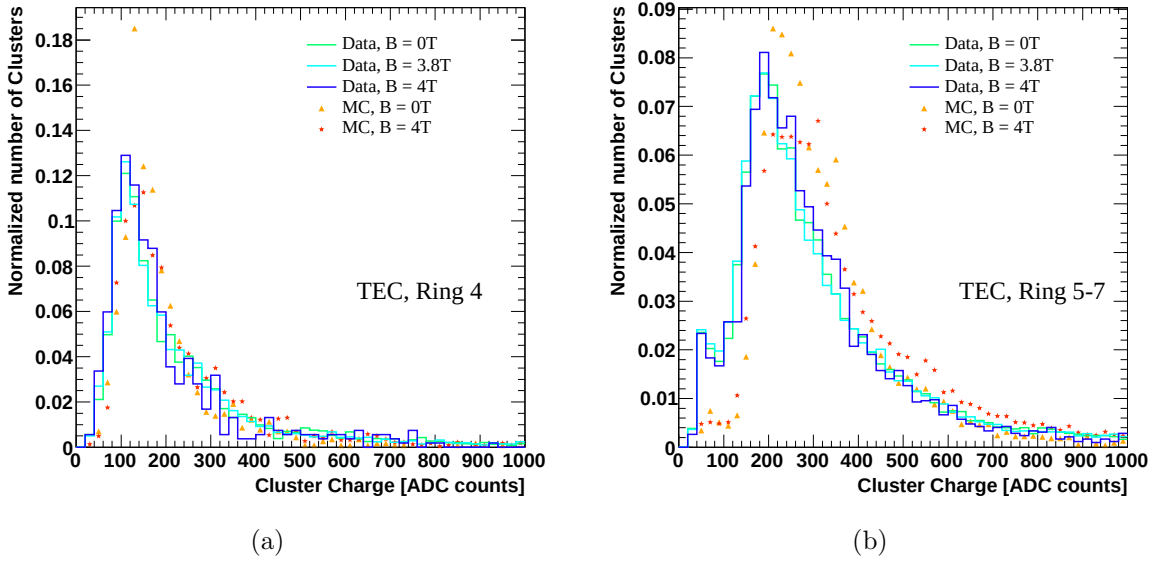


Figure 3.18: Cluster charge distributions for (a) ring 4 and (b) ring 5, 6 and 7 silicon modules in the TEC using a cluster signal-to-noise cut of 10. The simulation does not fit to the data since the angle of incidence of the incoming particle relative to the module surface is not taken into account.

Figures 3.17 (a) and (b) depict the cluster signal-to-noise ratio for ring 4 and ring 5-7 modules. Here, the cluster signal S and cluster noise N are calculated following the equations:

$$S_{\text{cluster}} = \sum_i s_i \quad \text{and} \quad N_{\text{cluster}} = \sqrt{\frac{\sum_i n_i^2}{\#\text{Strips}}} \quad (3.1)$$

where s_i is the signal and n_i the noise of channel i belonging to the cluster. Like in the cluster charge distribution, the signal peak is again well separated from the noise tail. Requiring a cluster signal-to-noise threshold of 10 leads to the distributions shown in figures 3.17 (c) and (d) where the noise peak disappears. Since the energy loss of a charged particle in a thin absorber is described by the Landau function (see section 2.1.1) the data are fitted using a Landau distribution. The resulting most probable value (MPV) for the signal-to-noise ratio is about 35 for ring 4 modules and 46 for ring 5-7 detectors⁴.

The cluster charge distributions obtained requiring a cluster signal-to-noise ratio of at least 10 are shown in figure 3.18. Although the Landau shape is clearly visible in the data the simulation does not fit to the measured curves. It has to be taken into account that the path length of the particle in the active silicon material does not only depend on the module thickness but also on the angle of incidence of the incoming particle. In case of perpendicular tracks the path length is minimal whereas it grows for increasing angles. This results in an increase of the measured cluster charge with increasing angle of incidence. Because of the geometry of the MTCC setup the particle trajectories of cosmic muons traversing the end cap part are highly diagonal incident so that this effect cannot be neglected. In addition, the trigger conditions used during the MTCC were not available in the simulation leading

⁴Since the noise varies for the different module geometries due to the different strip lengths the signal-to-noise ratio is supposed to be calculated for every ring separately. Because it is used here only to get an appropriate threshold to distinguish between noise and signal clusters the ratio is just differentiated by sensor thickness. A detailed analysis of the signal-to-noise ratio is presented in chapter 4.

to different angular distributions for data and MC. For this reason every cluster charge has to be corrected with respect to the corresponding angle of incidence by normalizing the measured charge to perpendicular incidence.

But, as described earlier, the TEC performance cannot be studied using tracks reconstructed in the tracker. Therefore it is not possible to correlate cluster quantities like the charge with track parameters like the angle. Instead, the information obtained with the trigger devices can be used to get a rough estimate of the trajectory properties.

3.7.3.3 Trigger Dependencies

A detailed description of the trigger setup used during the MTCC was given in section 3.2. The most important parts are the drift tube and the resistive plate chambers in the muon barrel region, that are arranged horizontally, and the cathode strip chambers in the muon end cap, that are arranged vertically. Since the TEC petals are also mounted in the vertical plane it is assumed that most of the cosmic muons traversing the petals with a relatively small angle of incidence also cross the CSCs and induce a trigger signal there. In contrast to that an event triggered by the DTs or RPCs should lead to a large angle of incidence if the corresponding muon also crossed one of the two petals.

Figure 3.19 shows the distribution of the triggers that caused the tracker to be read out. All triggers are meant to be inclusive meaning that in the event under investigation at least the studied trigger has responded. The analyzed subdetector (TIB, TOB or TEC) gets one entry per event and per involved trigger if at least one hit with a cluster signal-to-noise ratio above 10 is reconstructed in any of the corresponding silicon modules. The contributions of the three subdetectors are stacked.

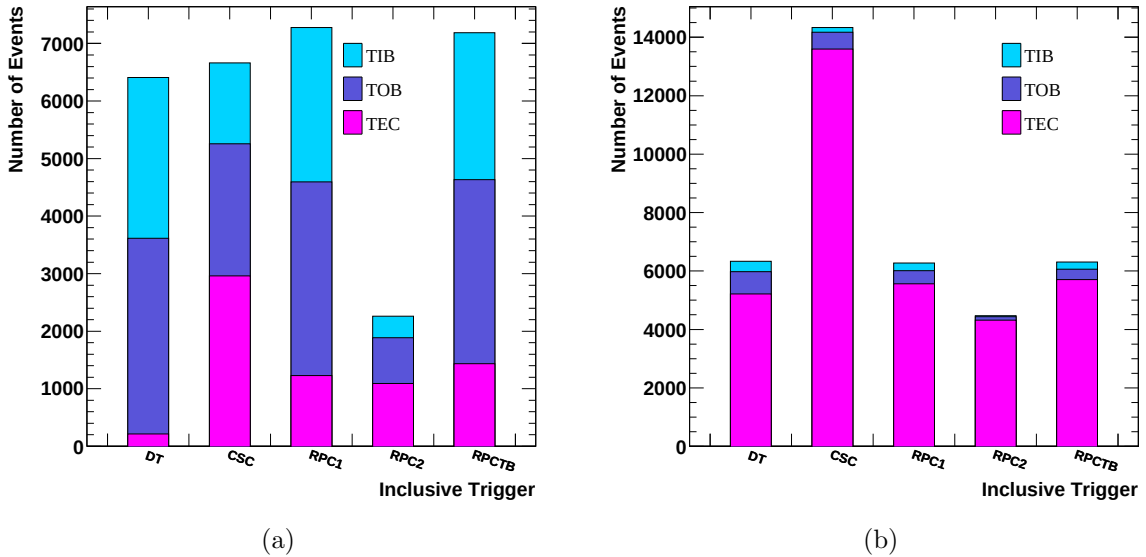


Figure 3.19: Inclusive trigger distributions for events where at least one hit with a cluster signal-to-noise ratio above 10 was reconstructed in the TIB, TOB or TEC, respectively. The histograms for the three subdetectors are stacked. (a) Distribution for a subset of the cosmic runs without any requirement on the hit pattern. (b) Distribution for the B = 0 T runs after preselection requiring at least one hit in the TEC.

In figure 3.19(a) the distribution is depicted for a subset of the cosmic runs without requiring any special tracker pattern in the events. It can be observed that most of the events with a hit in the inner or outer barrel are triggered by the DTs or RPCs which are mounted below the barrel part of the tracker while the majority of the hits in the TEC is triggered by the CSCs. In figure 3.19(b) the same kind of distribution is shown but this time only preselected events are analyzed using the requirement of at least one hit in the TEC (independent from its signal-to-noise ratio, see section 3.6). It is evident that most of the TEC hits are triggered by the CSCs. In addition, the number of events where at least one hit is reconstructed in the TIB or the TOB is greatly reduced for this data sample. This underlines the fact that the cosmic muons did not traverse the barrel and the end cap part of the tracker at the same time but either crossed the barrel or the end cap. Since for these events any hit in the TEC is required nearly no hits remain in the TIB and TOB.

Since this analysis has shown that TEC events are preferably associated with triggers from the CSCs the influence of the trigger condition on the reconstructed cluster charge can be studied. Figure 3.20 depicts the cluster charge distribution applying a cluster signal-to-noise cut of 10 for different triggers. Only TEC modules belonging to ring 5, 6 or 7 are taken into account. In figure 3.20(a) the charge distribution is shown separately for CSC inclusive and DT inclusive triggers whereas in figure 3.20(b) it is shown for CSC inclusive and RPCTB inclusive triggers, respectively. A clear signal peak is visible for hits triggered by the CSCs following a landau distribution while both for DT and RPCTB triggered events the distribution is nearly flat. The fact that the cluster charge is preferably higher in case of DT and RPCTB triggers is caused by the shallow incidence angle of tracks (with respect to the silicon detector surface) traversing the petals and the barrel muon system.

Since the requirement of a CSC trigger selects most of the good TEC events in agreement with the geometrical layout of the detectors to each other and additionally leads to reasonable distributions concerning the cluster charge, the track reconstruction based on the signals measured in the cathode strip chambers will now be used to get some information about the particle trajectories crossing the TEC part.

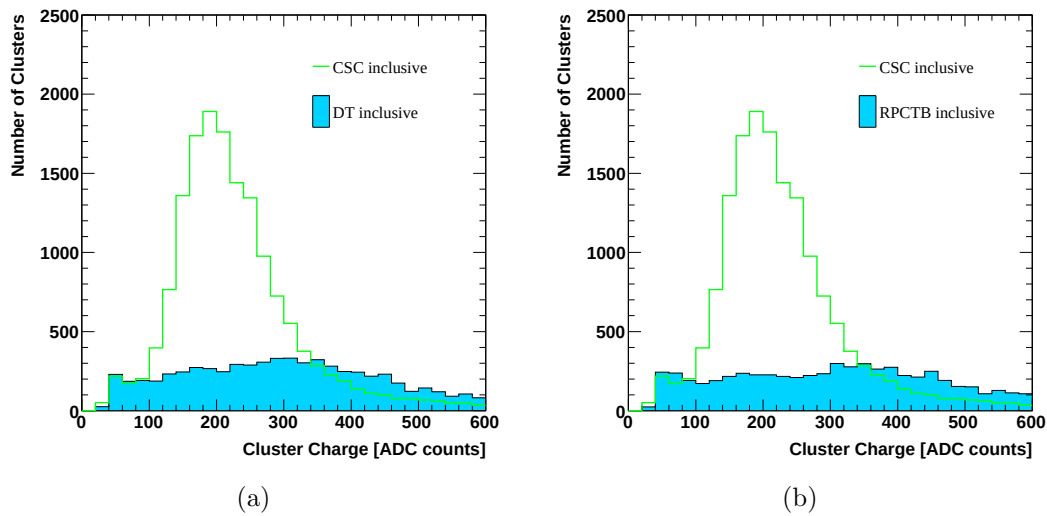


Figure 3.20: Comparison of the cluster charge distributions measured with TEC ring 5, 6 and 7 modules for different triggers. (a) CSC and DT inclusive trigger and (b) CSC and RPCTB inclusive trigger, both with a cut on $S/N > 10$.

3.7.3.4 Track Reconstruction using CSC Triggers

In addition to the tracker information the raw data files also contain the signals measured with the other detectors participating in the MTCC. Because of that it is possible to reconstruct tracks traversing the CSCs using the muon system itself and to associate them with the tracker response in the same event. The reconstruction chain is similar to the one used for the tracker: First, the raw data are unpacked in order to produce digis. These are used to create reconstructed hits in the different layers of the CSCs. Afterwards, the hits belonging to one chamber are combined to a track segment which represents a small part

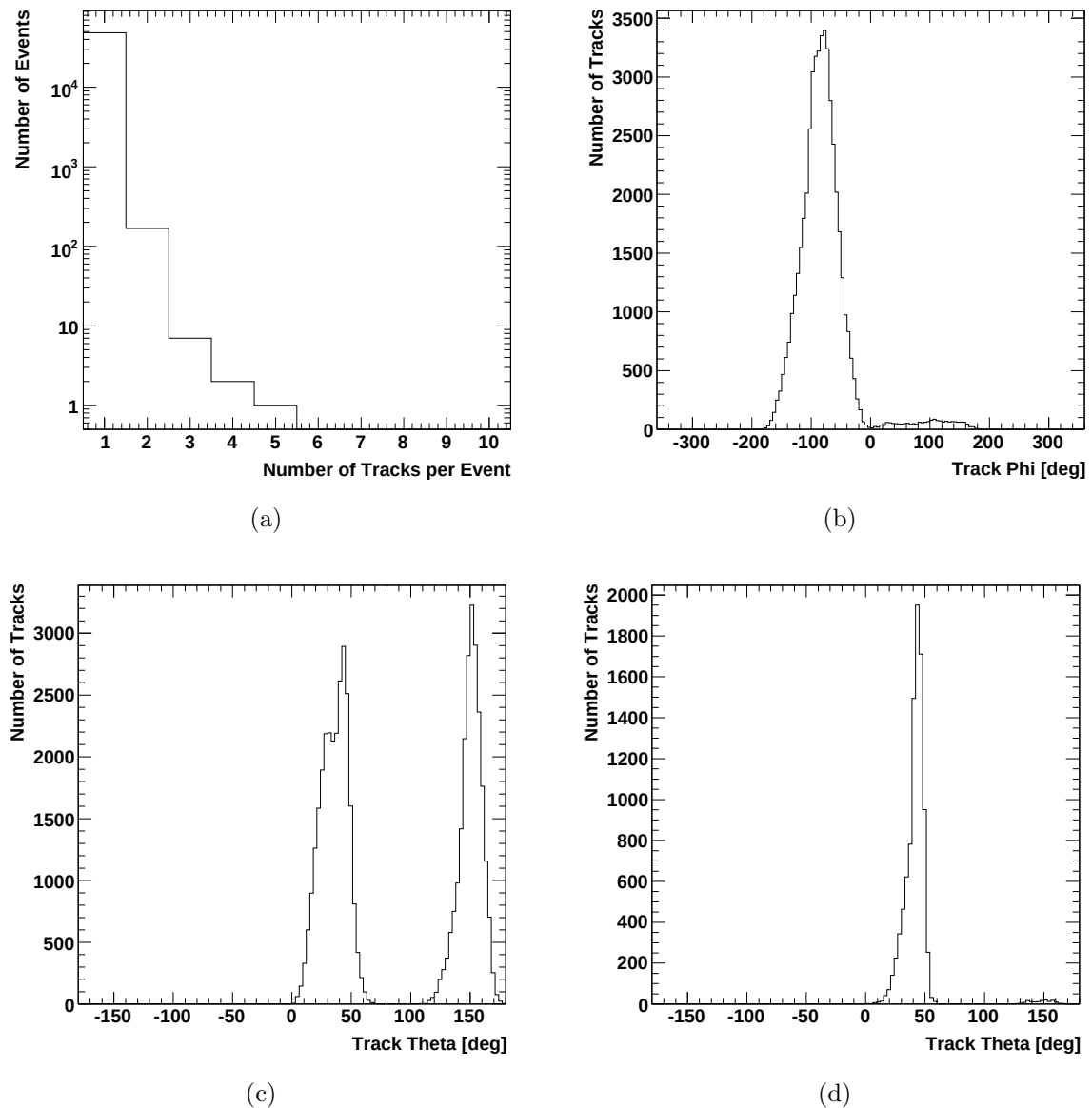


Figure 3.21: Cosmic track parameters obtained using the CSC reconstruction for $B = 0$ T. (a) Number of reconstructed tracks per event showing only events with at least one track. (b) Azimuthal angle ϕ indicating particles going from top to bottom ($-180^\circ < \phi < 0^\circ$). (c) Polar angle θ indicating sloping tracks ($0^\circ < \theta < 90^\circ$ or $90^\circ < \theta < 180^\circ$). (d) Polar angle θ requiring in the same event at least one hit in the TEC with $S/N > 10$.

of the particle trajectory. Finally, the segments are combined to the reconstructed track. A matching between reconstructed trajectories of the tracker and the muon system was not possible. A standalone muon reconstruction was performed for the CSCs adapted to cosmic muons.

In figure 3.21 some parameters of tracks obtained with the CSC reconstruction are shown for the $B = 0$ T sample. Figure 3.21(a) depicts the number of reconstructed tracks per event for those events where at least one track was found. In most of the cases one track is reconstructed. Only very few events contain several trajectories. Figures 3.21(b) and 3.21(c) show the angular distributions of the measured tracks with respect to the azimuthal angle ϕ and the polar angle θ , respectively. The azimuthal angle is defined from 180° to -180° . An angle of $\phi = -90^\circ$ describes particles coming from top down. Because cosmic ray muons are expected to traverse the CMS detector top-down the majority of tracks exhibits a ϕ angle in the interval from 0° to -180° with a mean value of approximately -90° . Only a small number of events is misreconstructed using the wrong flight direction. The θ distribution indicates that the particles are crossing the detector either from left to right corresponding to the peak at about 40° or from right to left according to the peak at about 150° . As expected, the cosmic muons are neither parallel to the beam axis ($\theta = 0^\circ$ or $\theta = 180^\circ$) nor is it possible to trigger particles with perpendicular incidence ($\theta = 90^\circ$) in the muon end caps.

Assuming that the center of the petals is located at $y = 0.75$ m, $z = 2.05$ m (see figure 3.15) and the center of the CSCs is at $y = -5$ m, $z = 8.30$ m cosmic muons crossing the petals and the CSCs at the same time should have a polar angle of about 43° . Figure 3.21(d) shows the θ distribution with the requirement that in addition to the CSC track at least one hit in the petals with a cluster signal-to-noise ratio exceeding 10 was reconstructed in the event. Since such a hit is a hint for a particle that traversed the petal the resulting distribution is in very good agreement with the expectation of a track polar angle around 43° . The disappearance of the peak at 150° underlines that there is a strong correlation between hits

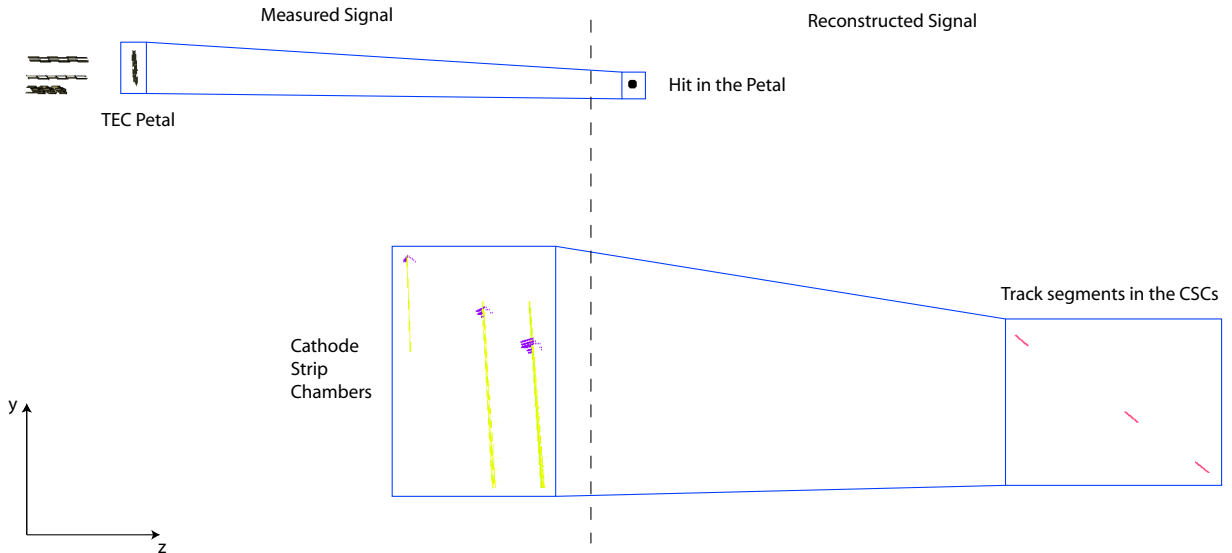


Figure 3.22: IGUANA event display of an event with a signal both in the TEC and the CSCs as seen in the y - z plane. On the left-handed side the measured signals in the CSCs are shown (the TEC signal is too small in this view) whereas on the right-handed side the reconstructed hit in the petal and the track segments in the CSCs are depicted.

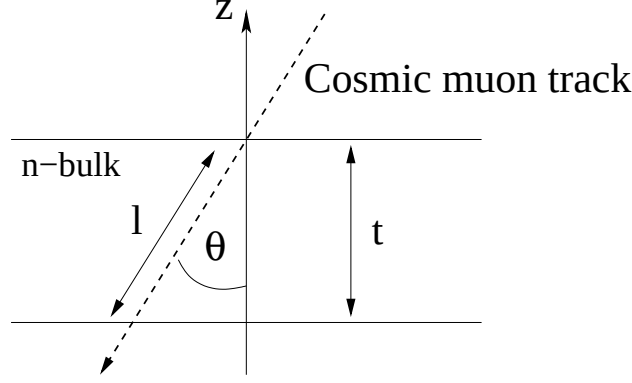


Figure 3.23: Schematic cross section of a silicon sensor showing the angle of incidence θ of a cosmic muon track and the resulting path length l inside the active material. The module thickness is given by t .

measured in the petals and tracks reconstructed in the CSCs pointing to the petals.

This property can be used to associate clusters measured in the petals with basic track parameters in first approximation, as demonstrated in figure 3.22 using the IGUANA event display. On the left side the tracker is shown together with the signals measured in the cathode strip chambers for one event. The cluster in the petal is too small in this view to be seen. On the right side the reconstructed hit in the TEC (enlarged for better visibility) and the reconstructed track segments in the CSCs are depicted. The measured trajectory is pointing to the tracker hit.

Selecting only events where exactly one CSC track and one petal hit with a cluster signal-to-noise ratio larger 10 was reconstructed, the cluster charge measured in the silicon detectors can be corrected for the angle of incidence of the incoming particle relative to the module surface using the track polar angle. To illustrate the relation between the θ angle and the effective path length of the particle traversing the silicon sensor, figure 3.23 shows a schematic cross section of a silicon module with thickness t . The angle of incidence of the cosmic muon track is labeled as θ . For perpendicular tracks ($\theta = 0^\circ$) the path length is given by t whereas for inclined trajectories it is larger. To compare the signals measured for different particle tracks, the cluster charge S_{meas} is normalized to perpendicular incidence (= path length t):

$$l = \frac{t}{|\cos \theta|} \quad \Rightarrow \quad S_{\text{norm}} = S_{\text{meas}} \cdot |\cos \theta| \quad (3.2)$$

Figure 3.24 shows the cluster charge distributions for ring 4 and ring 5-7 modules applying this correction. In case of data the normalization is done as described above using the CSC reconstruction whereas for the MC the angle information is taken from the simulation itself. Compared to figure 3.18 the corrected charge is decreased both for data and MC, as expected. The most probable values of about 90 ADC counts for thin and 140 ADC counts for thick sensors are comparable to test beam measurements with perpendicular particle incidence, where the cluster charge was in the range of 70 ADC counts $< S < 100$ ADC counts in case of thin and about 110 ADC counts $< S < 150$ ADC counts for thick modules [28]. But the agreement between data and MC has not improved.

The same behaviour can be observed for the signal-to-noise ratios depicted in figure 3.25. With a most probable value of about 23 for ring 4 and about 31 for ring 5-7 modules the S/N is significantly lower than the one obtained in figure 3.17. Since from the test beam

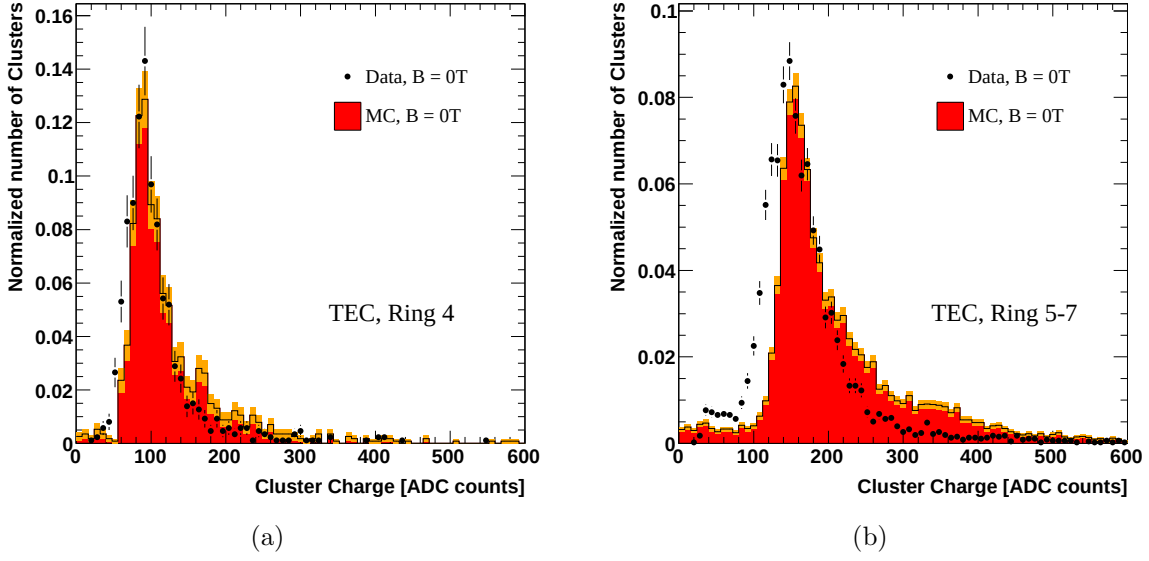


Figure 3.24: Cluster charge distributions for $B = 0$ T and TEC modules belonging to ring 4 on the left-handed side and ring 5-7 on the right-handed side. The charge is normalized to perpendicular incidence of the incoming particle with respect to the module surface. In case of the data the polar angle θ of the reconstructed tracks originating from the CSCs is used while for the MC the angle of the simulated particle can be retrieved. Only events with exactly one CSC track and one hit in the petals fulfilling $S/N > 10$ are considered.

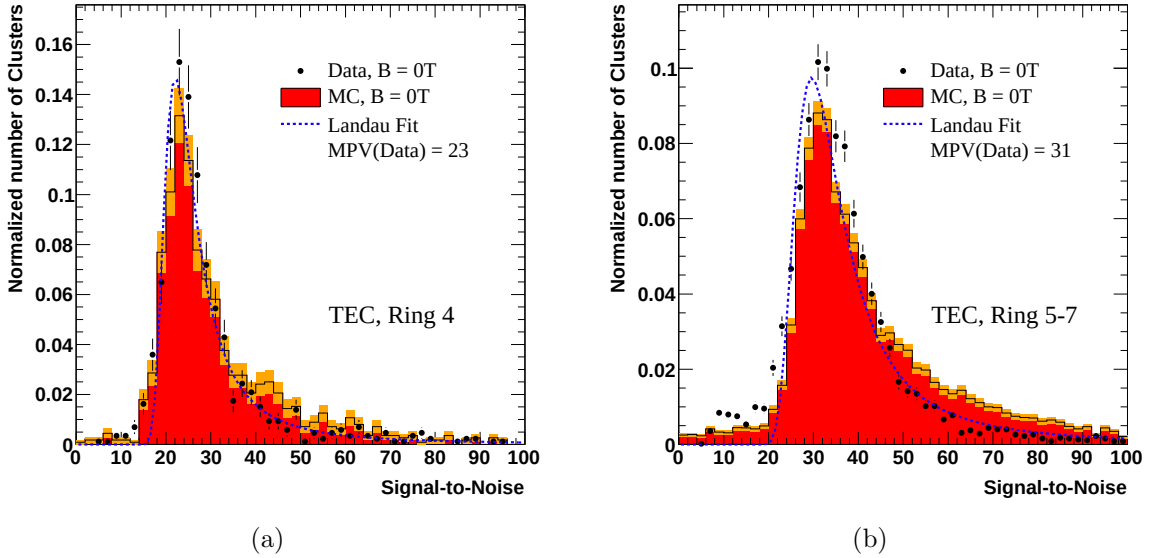


Figure 3.25: Signal-to-Noise ratio for (a) ring 4 and (b) ring 5-7 modules using $B = 0$ T. The signal is corrected with respect to the track incidence angle as described for the cluster charge distribution. The result of a landau fit to the data is shown.

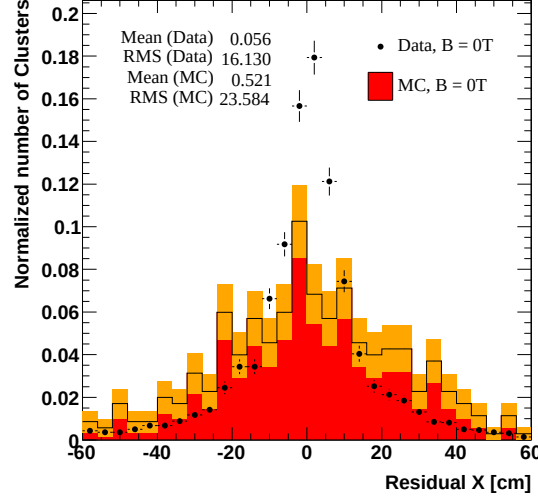


Figure 3.26: Residual in global x direction between the predicted hit in the petal derived from the CSC reconstruction and the measured hit in the silicon module. In the MTCC setup the global x direction is approximately the sensitive coordinate that can be measured in the TEC petals.

measurements [28], resulting in a value of 27-33 for thin and 35-42 for thick modules, the signal-to-noise ratio in peak mode is expected to be higher for perpendicular incidence than the values derived here using the angle normalization it can be assumed that the correct ratios are within the range of the normalized and the raw values presented in this section. A detailed S/N analysis using tracks and corresponding hits reconstructed in the tracker will be described in chapter 4.

Although in the MTCC the tracker and the muon system were not aligned to each other, it is possible to propagate the tracks reconstructed in the cathode strip chambers to the plane where the petals were mounted in order to predict the location of the impact point. By calculating the distance between the predicted space point and the one measured in the petals one can get a rough estimate of the precision in the setup. Figure 3.26 shows the residual in global x direction for the front petal (in case of the MTCC front petal this is approximately the sensitive coordinate of the silicon strip modules, see figure 3.15(b)) measured between the petal hit and the CSC track propagation for the $B = 0$ T runs and the corresponding MC.

The measured hit position is localized in the center of the strip along the strip direction. The tilt of the TEC strips with respect to the y axis is negligible here. It causes a deviation between predicted and measured hit of about 2.5 mm at the most. This is small compared to the uncertainty of the predicted position. The data and the simulation, with very limited statistics, are nearly centered around 0 cm. However, the width of the distribution is in both cases of the order of 10 cm. Considering the large lever arm of a few meters when extrapolating the reconstructed track from the CSCs back to the TEC, small uncertainties in the track reconstruction can cause such a distribution. In case of the MTCC setup an angular uncertainty of 1° would lead to a deviation between the predicted and the measured hit position of about $\Delta x \approx 11$ cm. Taking into account that the detectors were not aligned and that the track reconstruction was not in the final state, the measured residual is reasonable.

3.7.3.5 Cluster Multiplicity

The number of strips belonging to a reconstructed cluster depends on different parameters like the angle of incidence in the local x - z plane, the thickness of the silicon sensor and the pitch between neighbouring strips. To increase the spatial resolution to better than $\text{pitch}/\sqrt{12}$ a cluster should include more than one strip so that the center of gravity can be calculated. Figure 3.27(a) shows the cluster size distribution using the $B = 0$ T data for events triggered with the CSCs and the ones triggered with the DTs. Only clusters in the TEC modules with a signal-to-noise ratio above 10 are considered. Since the angular acceptance of the DT trigger with respect to the petals is different from the one using the CSCs leading to larger angles of incidence, the clusters are broader for DT triggered events with a mean size of about 4.2 strips compared to a mean width of 2.5 strips for CSC triggers. Because the angle of incidence in the local x - z plane is not known the dependence of the cluster size on this angle cannot be studied. An estimate of the cluster width for perpendicular incidence is not possible (for a detailed analysis see chapter 4).

In figure 3.27(b) the cluster width is depicted independently from the trigger (for the MC a trigger simulation was not available) both for data and MC at different magnetic fields. All distributions show a maximum at a cluster size of three strips, more distinct for the simulation than for the data. It is conspicuous that for the data distributions the amount of narrow clusters (one and two strips) is the highest for $B = 0$ T and drops with increasing magnetic field. At the maximum this ratio goes into reverse and the amount of broad clusters increases with increasing magnetic field. This may be an effect either of a larger angle of incidence when the magnet is turned on due to the bending of the charged particle tracks in the magnetic field or caused by the influence of the magnetic field on the drift of the produced charge carriers inside the silicon sensors.

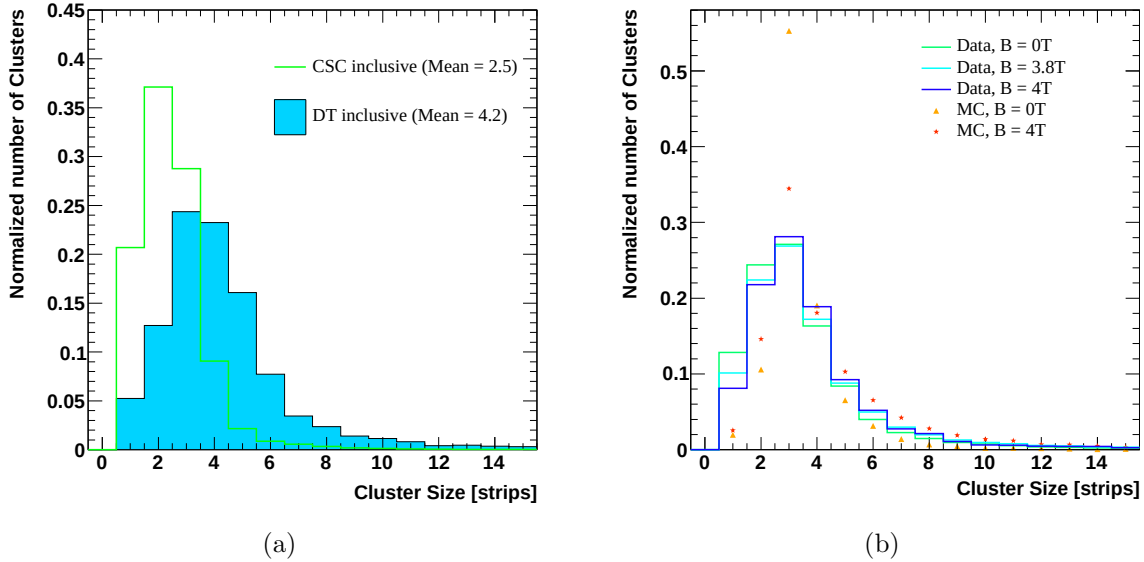


Figure 3.27: Cluster size distributions measured with the TEC modules considering only clusters with $S/N > 10$. (a) Cluster width at $B = 0$ T for events with CSC and DT inclusive trigger, respectively. Due to the larger angle of incidence of the incoming particle the cluster size is larger for DT triggered events. (b) Cluster width for data and MC at different magnetic fields independent from the trigger. For the data the amount of broad clusters increases with increasing magnetic field.

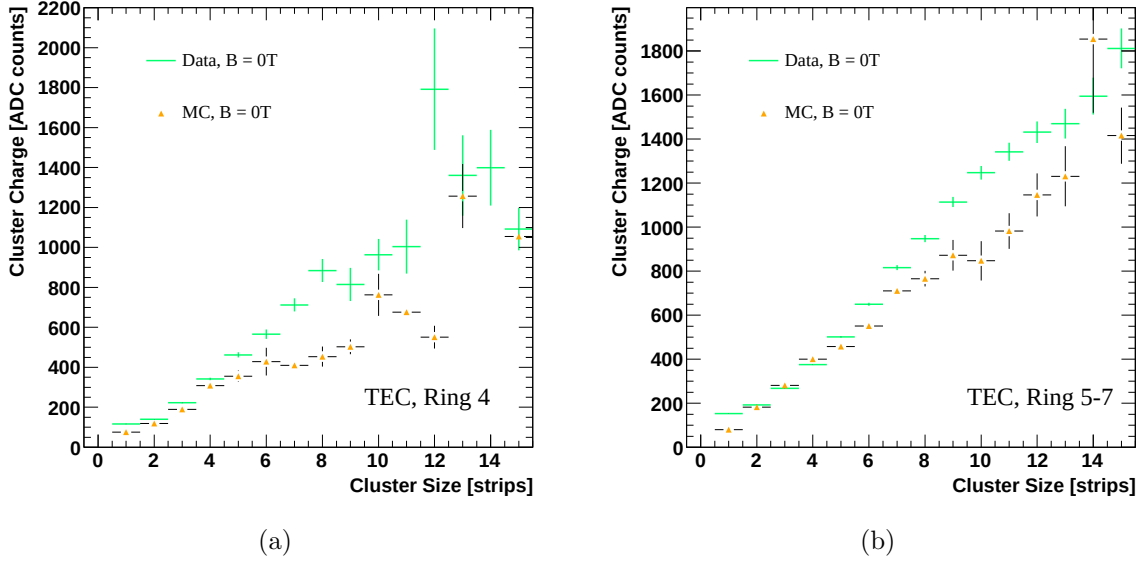


Figure 3.28: Mean cluster charge as a function of the cluster size measured for $B = 0$ T. The distribution is shown for thin sensors on the left side and for thick sensors on the right side. As expected, a linear behaviour is observed. The cluster charge for 1-strip clusters can be used as an estimate for the produced signal in case of perpendicular particle incidence.

Since the cluster charge depends as well on the track incidence angle and the module thickness, a correlation between the charge and the width of a cluster is expected. Figure 3.28 shows the mean cluster charge as a function of the measured cluster size applying a cut on $S/N > 10$ and taking into account only clusters with a width of 15 strips at the most (the statistics for broad clusters is very low especially in the MC). Both for ring 4 and ring 5-7 modules a linear behaviour is observable: The broader a cluster is the more charge is collected. In this sense the cluster size is an indicator for the angle of incidence and the charge measured for 1-strip clusters can be taken as an approximation for the cluster charge in case of perpendicular incidence. The measured values of about 100 ADC counts for thin and 150 ADC counts for thick sensors are in good agreement with the most probable values of the angle corrected cluster charge shown in figure 3.24.

Chapter 4

The Silicon Strip Tracker Slice Test

After the completion of the silicon strip tracker subdetectors all components were delivered to the so-called Tracker Integration Facility (TIF) at CERN. During the integration into the tracker support tube parts of the subdetectors were commissioned and tested both in calibration runs and using a trigger to detect cosmic ray muons passing the tracker. The integration was finished in March 2007 and afterwards the Tracker Slice Test including about 25 % of the $+z$ side of the entire tracker took place until July 2007. This test was done in the TIF and contained only the silicon strip tracker. Especially, no magnetic field was present. In this chapter the performance of the tracker during the test is described analyzing both commissioning runs and cosmic runs. Additional information concerning the slice test can be found in [29] and [30].

4.1 The Setup

In this thesis the entire setup including parts of all subdetectors will be analyzed. It covers approximately the first quadrant of the $+z$ side of the strip tracker and represents about 25 % of the silicon modules belonging to this tracker half. In total, the inner barrel contributed with 438, the inner disk with 204, the outer barrel with 720 and the end cap with 800 modules. The detailed distribution of the modules to the corresponding layers and rings is shown in table 4.1. A schematic view of the tracker support tube with the four subdetectors is depicted in figure 4.1. The different parts used in this test are highlighted in green.

The silicon modules participating in the slice test were chosen for every subdetector in such a way that they shared full control rings being complete segments in terms of electrical powering, grounding and control signal distribution. For example for the TEC, sectors two and three including all nine disks were used. The geometry of the whole setup was optimized such that cosmic ray muons could be measured in several layers and disks at the same time when traversing the tracker (see also figure 4.2).

All modules belonging to the test were powered with a bias voltage of 250 – 300 V. The tracker power supply system and the readout chain were operated in the same way as it will be done in the final experiment. Parts of the Tracker Safety System which is based on the information of one thousand hardwired sensors were fully functional. They provided an interlock in case of high temperature, power cuts etc..

To cool the tracker the active regions were connected to a cooling plant that provided C_6F_{14} . During the slice test different operation temperatures were used ranging from $+15^\circ\text{C}$

Subdetector	Layer/Ring	Type of Layer/Ring	Number of Modules	Number of Channels
TIB	layer 1	DS	114	87 552
	layer 2	DS	114	87 552
	layer 3	SS	90	46 080
	layer 4	SS	120	61 440
TID	ring 1	DS	72	55 296
	ring 2	DS	72	55 296
	ring 3	SS	60	30 720
TOB	layer 1	DS	180	138 240
	layer 2	DS	144	110 592
	layer 3	SS	90	46 080
	layer 4	SS	96	73 728
	layer 5	SS	90	46 080
	layer 6	SS	120	61 440
TEC	ring 1	DS	36	27 648
	ring 2	DS	72	55 296
	ring 3	SS	80	40 960
	ring 4	SS	126	64 512
	ring 5	DS	180	138 240
	ring 6	SS	126	64 512
	ring 7	SS	180	92 160

Table 4.1: Contribution of the different subdetectors to the Tracker Slice Test. Layers or rings containing double sided modules are indicated with DS while single sided parts are marked with SS (from [29]).

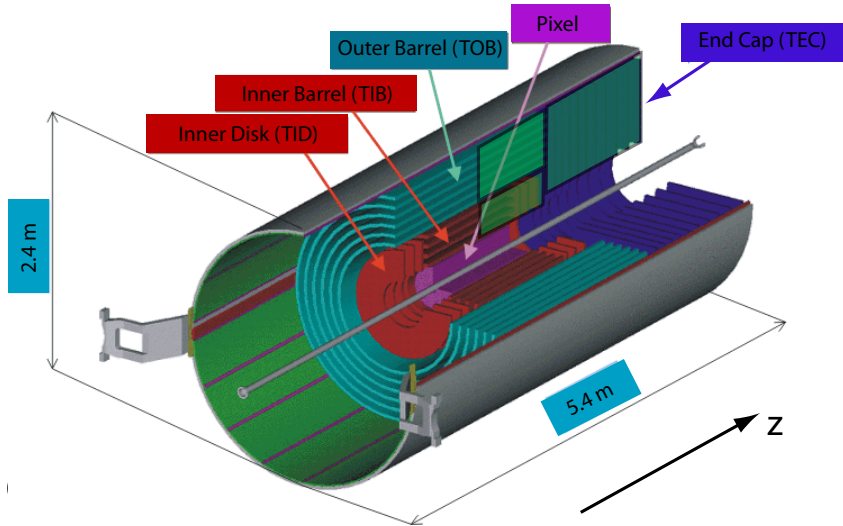


Figure 4.1: Schematic view of the tracker support tube with the four subdetectors TIB, TID, TOB and TEC (the pixel detector was not installed in the TIF). During the tracker slice test the highlighted parts in the first quadrant of the $+z$ side were powered and read out, representing approximately 25 % of the total number of silicon sensors in this tracker half.

to -10°C . For a subset of about 50 % of the full test setup the temperature was finally lowered to -15°C . In order to reduce the dew point inside the tracker an air dryer was used. For the low temperature operation a tent flushed with dry air was put around the support tube to avoid condensation on the in- and outgoing cooling pipes. The thermal screen of the tracker allowed to operate the inner volume in a cold environment while the temperature in the TIF was close to $+20^\circ\text{C}$.

4.2 The Trigger

To measure the signals of cosmic ray muons traversing the active silicon modules the tracker support tube was equipped on top and below with scintillators operated in coincidence. During the slice test different trigger configurations were used to cover different parts of the subdetectors so that tracks with different angles of inclination and various overlaps between the subdetectors could be reconstructed. The bottom scintillators were covered with a 5 cm lead shield to eliminate low momentum muons.

On top of the support tube six scintillators grouped in two arrays consisting of three scintillators each were positioned such that one array was placed above the barrel while the second one covered the end cap. The position of the bottom scintillator was changed with time. In configuration A which was the first one it was centered in z direction approximately around the interaction point. In configuration B it was moved to the $-z$ side of the tracker so that the measured tracks had larger angles of incidence. Finally, a second array of scintillators was added below the support tube leading to configuration C where one scintillator was

Scint.	Δx	Δz	Conf. A			Conf. B			Conf. C		
			x_c	y_c	z_c	x_c	y_c	z_c	x_c	y_c	z_c
T1	30	100	-20	155	50	-20	155	85	-20	155	85
T2	30	100	10	154	50	10	154	85	10	154	85
T3	40	80	45	160	50	50	160	75	50	160	75
T4	30	100	-20	155	160	-25	155	230	-25	155	230
T5	30	100	10	154	160	15	154	230	15	154	230
T6	40	80	45	160	160	50	160	230	50	160	230
MC T1	100	100	35	160	50	35	160	85	35	160	85
MC T2	100	100	35	160	160	35	160	230	35	160	230
B1	75	80	35	-155	-20	0	-155	-165	0	-155	40
B2	80	110	—	—	—	—	—	—	-20	-155	-200
MC B1	100	100	35	-160	40	0	-155	-165	35	-160	40
MC B2	100	100	—	—	—	—	—	—	0	-160	-200
Trigger Coincidence			(T1-T6) & B1			(T1-T6) & B1			(T1-T6) & (B1-B2)		

Table 4.2: Scintillator setup for the three configurations A, B and C. Top scintillators are indicated with T while bottom scintillators are named B. The dimensions of each scintillator are given by Δx and Δz in cm while the position of its center is given by x_c , y_c and z_c in cm (with respect to the global CMS coordinate system; measured by hand). The dimensions and positions used in the simulation are indicated with MC. The coincidences used in the different periods are shown in the last row.

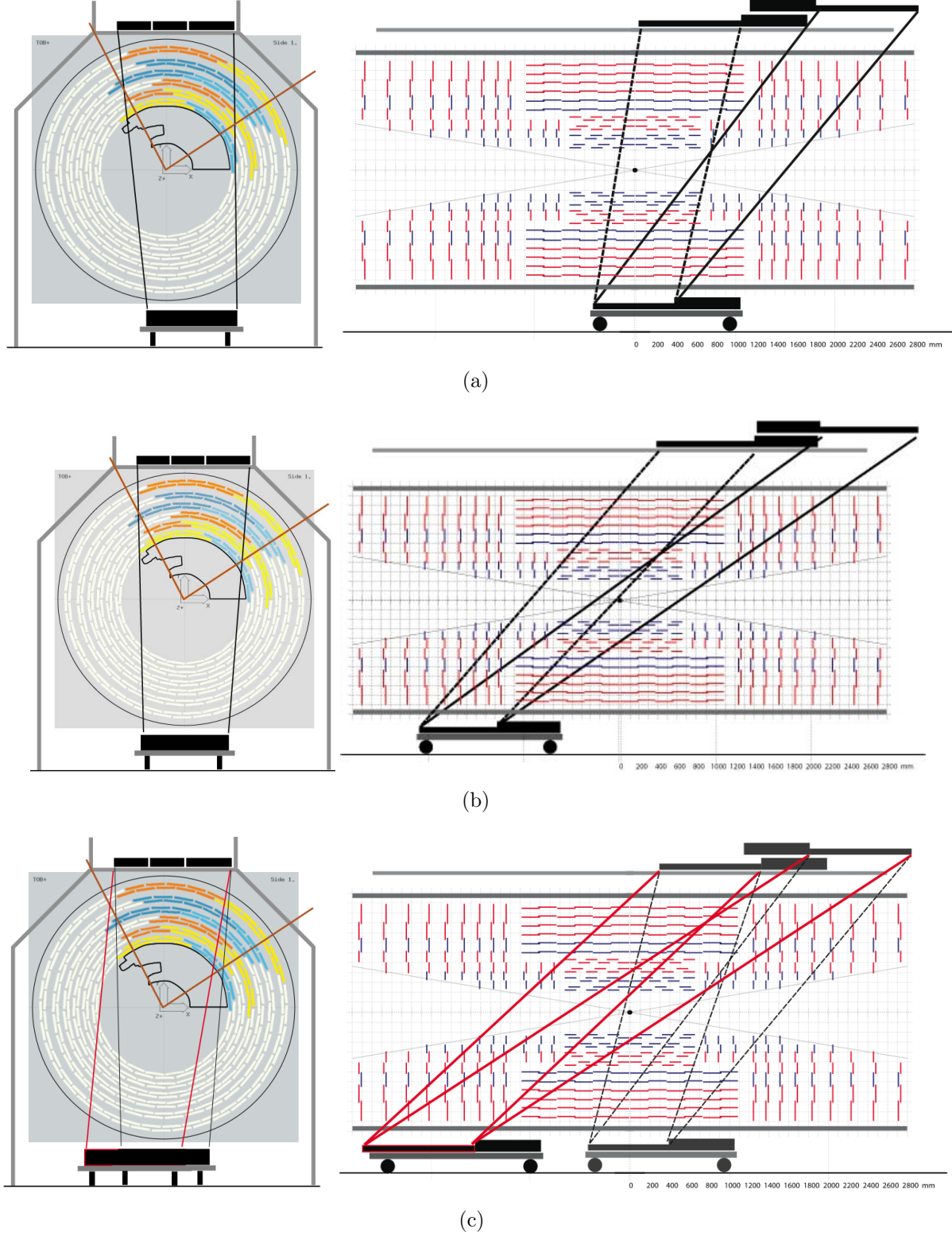


Figure 4.2: Schematic view of the three different trigger configurations. On the left the tracker support tube is shown in the $x - y$ plane. On the right it is seen in the $y - z$ plane. The top and bottom scintillators are connected by straight lines to indicate the coverage of the respective scintillator geometry with respect to the different subdetectors. On the left, the operated parts of the TIB, TOB and TEC are illustrated by lines. (a) The first scintillator configuration A, (b) the second scintillator configuration B and (c) the last scintillator configuration C. [29]

placed below the positive z half of the barrel region and the other one below the end cap on the $-z$ side.

In all configurations, a coincidence between any of the top and any of the bottom scintillators was used. Figure 4.2 gives a schematic overview of the three trigger setups. In the simulation of the tracker slice test (see section 4.5) these configurations were implemented. In table 4.2 the scintillator positions during the different periods are summarized.

4.3 Data Acquisition

Since the trigger rate was of the order 1 Hz the APV chips were operated in peak mode. The majority of the cosmic runs were performed in Virgin Raw mode while only a small number of runs was taken in Zero Suppressed mode. Before the cosmic runs were started, commissioning runs were done to obtain the pedestal and noise of each readout channel, to adjust the lasers of the analog opto hybrids etc.. Parameters like pedestal and noise were uploaded afterwards to the tracker online database to configure the FEDs and to the offline database to be available for offline reconstruction and analysis.

Because the data read out from the tracker were stored in a raw data format containing the raw FED buffers they had to be converted to the CMS Event Data Model (EDM) format before reconstruction and analysis could proceed. After saving the converted data on CASTOR at CERN they were published in the official CMS data bookkeeping system and transferred to remote sites using the official tool PHEDEX. The final data reconstruction took place at FNAL and the reconstruction output was also published in the data bookkeeping system so that it could be analyzed using the GRID tools.

The data taking at the slice test can be splitted in several periods according to the scintillator positions and the operating temperature. During the scintillator setups A and B the tracker was operated at about 15°C . The longest data taking period using scintillator configuration C comprised tests at cooling liquid temperatures ranging from 15°C to -15°C . It has to be taken into account that for -15°C only about 50 % of the tracker slice test was powered. An overview of the different periods including the number of good cosmic runs and corresponding events is given in table 4.3. In total, about 5 million trigger were recorded.

Trigger Setup	Temperature	# Good Runs	# Good Events
A	15°C	7	189 925
B	15°C	15	177 768
C	15°C	9	128 942
	10°C	21	534 759
	-0.5°C	32	886 801
	-10°C	30	902 863
	-15°C	27	655 301

Table 4.3: Data sets recorded during the entire tracker slice test. The periods can be distinguished by the trigger configuration and the operating temperature. The data taking at -15°C was performed with only about 50 % of the slice test powered.

4.4 Data Reconstruction

The reconstruction chain has already been described in section 3.4. During the tracker slice test the same procedure was used only differing in the thresholds for the clusterization algorithm. To identify a cluster seed the digis were scanned requiring a signal-to-noise ratio of $(S/N)_s > 3$. In the neighbourhood of a seed strip additional channels were added to the cluster if their signal exceeded the corresponding noise by a factor of at least two ($(S/N)_n > 2$). Finally, the whole cluster charge was expected to fulfill $(S/N)_c > 5$, where the cluster noise is defined as the quadratic sum of the single strip noise values normalized to the number of channels contributing to the cluster.

Since in the slice test several layers of silicon modules were used in the barrel and the end cap, particle trajectories could be reconstructed in all subdetectors. The tracking algorithms had to be adapted to cosmic muons where particles do not originate from a vertex located in the center of the experiment. In total, three different algorithms were available: The Combinatorial Track Finder (CTF), the Road Search (RS) and the Cosmic Track Finder (CosmicTF). Because of the absence of a magnetic field in the TIF setup the trajectories are extrapolated during the track reconstruction as straight lines to the next detector layer taking into account the energy loss and the multiple scattering due to the interaction with the material. In addition, the particle momentum is unknown so that a constant value of 1 GeV/c is used. Although the track fitting and smoothing is the same for the three algorithms, the seed creation and the pattern recognition are different for each of them. They are described in the following in more detail (see also [30]).

- **Combinatorial Track Finder:** In case of p-p collisions the track seed is created in the inner layers of the tracker assuming that the particle is originating from the beamspot. For the reconstruction of cosmic muons this procedure has to be changed taking into account the following conditions: 1. There is no vertex constraint, 2. Seeds should be also searched for in the outer layers because of the larger acceptance for cosmic muons and 3. No magnetic field is present in the TIF.

The seed creation is adapted such that a hit triplet containing different layers is required in the barrel while a hit pair is used in the end cap. The triplet has to be found either in layers 1, 2 and 3 of the inner barrel or in combinations of layers 2-6 of the outer barrel. In the end cap any hit pair belonging to adjacent disks is sufficient.

During the pattern recognition the track parameters obtained from the seed assuming a straight trajectory are extrapolated to the next layer. Within a window whose width depends on the precision of the track parameters a new hit that is compatible with the trajectory is searched for. A new track candidate is created for each hit fulfilling the requirements and the track parameters are updated accordingly. Only the five best candidates in terms of χ^2 and number of hits are retained and propagated to the next layer. If no compatible hit is found in a certain number of consecutive layers or a maximum number of layers is reached, the track propagation is stopped.

- **Road Search:** In the Road Search algorithm the tracker is divided in several rings where each ring contains all silicon modules located at a given $r - z$ position. Some of these rings are used as seed rings requiring a hit pair in two of the rings with a maximum $\Delta\phi$ distance to create a valid track seed. The inner seed rings contain the silicon modules belonging to layers 1 and 2 of TIB, layers 1 and 2 of TOB, rings 1 and

2 of TID and rings 1-3 of TEC. The outer seed rings are made of modules belonging to layers 5 and 6 of TOB and rings 6 and 7 of TEC. The different rings are grouped to pre-defined so-called roads representing possible particle trajectories in the $r - z$ plane.

The first estimate of the track resulting from the seed is then extrapolated as a straight line to the rings belonging to the road in the $r - z$ plane and all hits that are found within a certain window in each ring are added to a so-called cloud (which is a collection of reconstructed hits). In a second step the hits in the cloud are sorted in y and the track reconstruction starts on low-occupancy layers from inside out. Afterwards high-occupancy layers are also included and the hits are added to the trajectory in such a way that the final track contains not more than one hit per module. To reconstruct cosmic muons specific roads were created since these particles do not necessarily point to $z = 0$ as required in the standard Road Search algorithm.

- **Cosmic Track Finder:** The Cosmic Track Finder is a simple algorithm that is specially adapted to reconstruct cosmic particles. The track seeds are created using any combination of two hits that are measured in different layers of either the three innermost TIB layers or the three outermost TOB layers or the nine TEC disks with at most one intermediate disk separating the two hits. In addition, the seeds generated in the barrel have to fulfill the requirement that the corresponding modules have a distance in the global z direction below 30 cm and the corresponding hits in the global x direction less than two times the distance in the global y direction. These cuts are applied since cosmics are expected to be slightly inclined with respect to the vertical axis.

Because the seeds can be located at the top or at the bottom of the tracker slice all hits that are reconstructed in the event are sorted in decreasing or increasing order in y , respectively, with respect to the seed position. Afterwards, the track estimate is propagated to the different layers starting from the seed and a new hit is added to the trajectory if the χ^2 of the estimated position relativ to the measured one is less than 40. In this case the track parameters are updated and the propagation is continued. A track is only retained if at least four corresponding hits are found. If several tracks are reconstructed in the same event the best one is kept in terms of the number of crossed layers, the number of hits and the lowest χ^2 .

When the pattern recognition is finished and all hits that are compatible with a trajectory are collected, the track fitting is performed using a Kalman filter. The initial estimate of the track and the covariance matrix are propagated to the surface of the first hit, the predicted state and the hit position are combined and the updated state is extrapolated to the next surface. At the last track point the best estimate of the track parameters is available. To finally increase the accuracy the fit is repeated backward and the updated states are combined with the prediction of the forward fit. This procedure is known as smoothing.

4.5 Simulation of the Tracker Slice Test

Analog to the simulation of the MTCC setup (section 3.5) cosmic muon events detected in the tracker slice test were simulated using the Cosmic Muon Generator CMSCGEN [26]. Starting from the simulated vertex located on the surface of the entire CMS experiment the

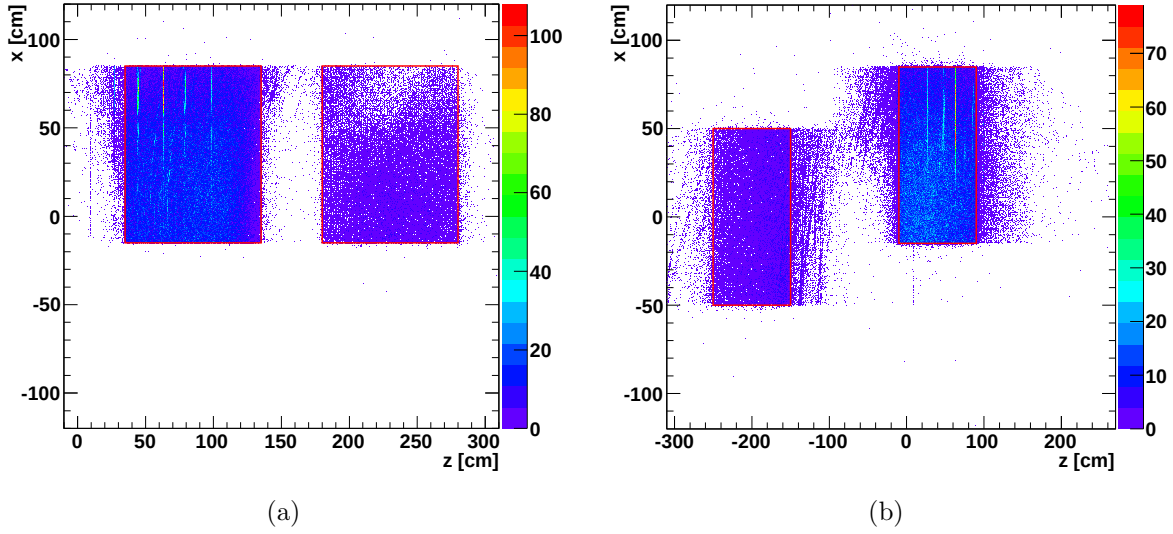


Figure 4.3: Reconstructed track positions in the $x-z$ view for (a) the top scintillator plane at $y = 160$ cm and (b) the bottom scintillator plane at $y = -160$ cm. The simulated data set for scintillator configuration C is used extrapolating the reconstructed trajectories to the intersection point with the scintillators. The red boxes represent the scintillator surfaces that were applied to the simulation. All coordinates refer to the global CMS coordinate system.

particle is propagated to the outer radius of the tracker. Since in the TIF setup nothing but the tracker was present the energy loss along this way is set to zero.

To consider the angular acceptance caused by the scintillation counters the arrays were simulated as 1 m^2 areas located on top and on bottom of the tracker support tube according to the configuration under investigation (see table 4.2). A filter was applied to the simulation such that only extrapolated muons crossing the scintillator areas and fulfilling the trigger logic were retained and processed further. In figure 4.3 the intersection points of the reconstructed tracks with the top scintillator plane at $y = 160$ cm and the bottom scintillator plane at $y = -160$ cm are shown for the configuration C setup. The dimensions of the scintillators used in the filter are displayed by the red boxes. It is clearly visible that the reconstructed tracks reflect the trigger configuration that was applied to the simulation process.

The valid particles were afterwards propagated through the tracker taking into account only the parts that were read out during real data taking. The muons were generated with an energy range of $200 \text{ MeV} < E < 10 \text{ TeV}$ and an angle of incidence within $0^\circ < \theta < 88^\circ$ with respect to the vertical axis. The lower energy bound had to be reduced to this value because in the surface hall of the TIF no low energy filter like earth, steel or other detector components was present resulting in a contribution of very soft muons [29].

In total, about 250,000 events in scintillator configuration A and about 1,000,000 events in configuration C were simulated.

4.6 Tracker Performance

Since in the tracker slice test both commissioning runs like pedestal and timing runs and cosmic runs were performed not only the noise behaviour and the resulting quality of the involved readout channels can be studied but also the signal and track reconstruction properties can be analyzed. The first part of this section deals with noise studies while the second part is devoted to the reconstruction of cosmic muon events.

4.6.1 Noise Studies

In the following analysis the single strip noise stored in the condition database for a given interval of validity is used. This noise is based on pedestal runs performed in regular intervals during the slice test in peak mode and consisting of a few thousand random triggers each. It is the same noise that is used during the cosmic muon reconstruction for example in the clusterization algorithm. The tick mark height for each laser of the analog opto hybrids is derived from different time synchronisation scan runs at the corresponding operation temperature.

4.6.1.1 Bad Strip Identification

The identification of bad channels in the tracker is important to know which strips should be masked and excluded from the data reconstruction because they are not providing reliable signal measurements. In addition, it is important to monitor the number of faulty channels with time in order to see if the tracker performance is stable and to ensure that all detector components are working well. To identify readout channels in the tracker slice test that have a conspicuous behaviour in noise, the pedestal runs are analyzed systematically in the following way:

- The noise of each single strip is corrected with respect to the optical gain by normalizing the measured tick height of the corresponding laser to 640 ADC counts.
- An iterative procedure is applied to each APV in order to get the mean noise and the RMS of the noise per APV independent from faulty channels:
 - The median noise of all channels belonging to the APV is calculated and channels exceeding the median value by ± 200 electrons, APV edge channels (strip numbers 1, 2, 127 and 128), and the five lowest and five highest noise values are excluded from the further processing (truncated mean).
 - The mean and the RMS of the APV noise is determined and strips exceeding the mean noise by $\pm 5 \cdot \text{RMS}$ are excluded.
 - Mean and RMS are updated and the last step is repeated once so that a stable mean and RMS independent from outliers is achieved for each APV.
- The noise of all channels belonging to the APV is analyzed using the resulting mean and RMS and a channel is flagged as bad if its noise exceeds the mean by $\pm \text{Cut} \cdot \text{RMS}$ where Cut is a threshold that is optimized for different groups of strips.

Strip range per APV	Subdetector	Lower Threshold	Upper Threshold
3 - 126	All	$-5 \cdot \text{RMS}$	$+5 \cdot \text{RMS}$
2 and 127	All	$-4 \cdot \text{RMS}$	$+6 \cdot \text{RMS}$
1 and 128	TID, TOB, TEC	$-2 \cdot \text{RMS}$	$+10 \cdot \text{RMS}$
1 and 128	TIB	$-2 \cdot \text{RMS}$	$+12 \cdot \text{RMS}$
Module edge strips	TEC rings 5, 6 and 7	$+2 \cdot \text{RMS}$	$+16 \cdot \text{RMS}$

Table 4.4: Noise thresholds for the different subdetectors used to identify dead and noisy strips, respectively. The thresholds are meant with respect to the APV mean noise taking into account the APV RMS.

Strips with a noise value above the threshold are called *noisy* channels and the ones with a value below the threshold are referred to as *dead* channels. The cut values that are used to distinguish between noisy, dead and normal channels are shown in table 4.4. The thresholds are increased for APV edge channels since these strips have in general higher noise values with respect to the APV inner strips.

For each of the five temperature settings of the tracker slice test one pedestal run was analyzed to see if these thresholds are reliable with respect to the data. Figure 4.4 shows for the four subdetectors TIB, TOB, TID and TEC the deviation of the single strip noise from the mean noise of the corresponding APV measured in units of RMS of the noise distribution of the APV. In these plots only the inner strips of the readout chips (strip number 3 to 126) are taken into account. It is clearly visible that all distributions are centered around zero and that the normal behaviour is within a range of $\pm 5 \cdot \text{RMS}$ for all subdetectors and all temperatures (the green band represents the strips that fulfill the required threshold). Only in case of TOB modules an excess of noisy channels is observed. This behaviour is known as *wing noise* since the noise increases at the outer channels of the readout chips mostly for modules mounted closest to the rod's CCUM board and the power supply cables. This indicates that the TOB rods are susceptible to external noise pickup (see also [29]).

In figure 4.5 the same distributions are depicted for APV edge strips (strip number 1 and 128) and module edge strips for ring 5-7 modules of the TEC. As expected, the noise is higher compared to the APV mean noise leading to a shift of the distributions to values above zero. Because of that the thresholds to identify conspicuous strips were raised for these classes of channels according to their normal behaviour. Since for the module edges of the thick TEC sensors there is also a variation with respect to the operating temperature the thresholds were slightly loosened in this case to fit to all temperatures.

In addition to the single strip analysis also parameters of the whole readout chips and the lasers are tested for their compatibility with expected values. This is done in the following way:

- The APV mean noise is compared to the APV mean noise distribution of all modules belonging to the same strip length. If the mean noise exceeds absolute thresholds the APV is flagged as faulty (high noise or low noise).
- The APV RMS of the noise is compared to the APV RMS distribution of all modules belonging to the same strip length. If the RMS of the noise exceeds absolute thresholds the APV is flagged as faulty (high RMS or low RMS).

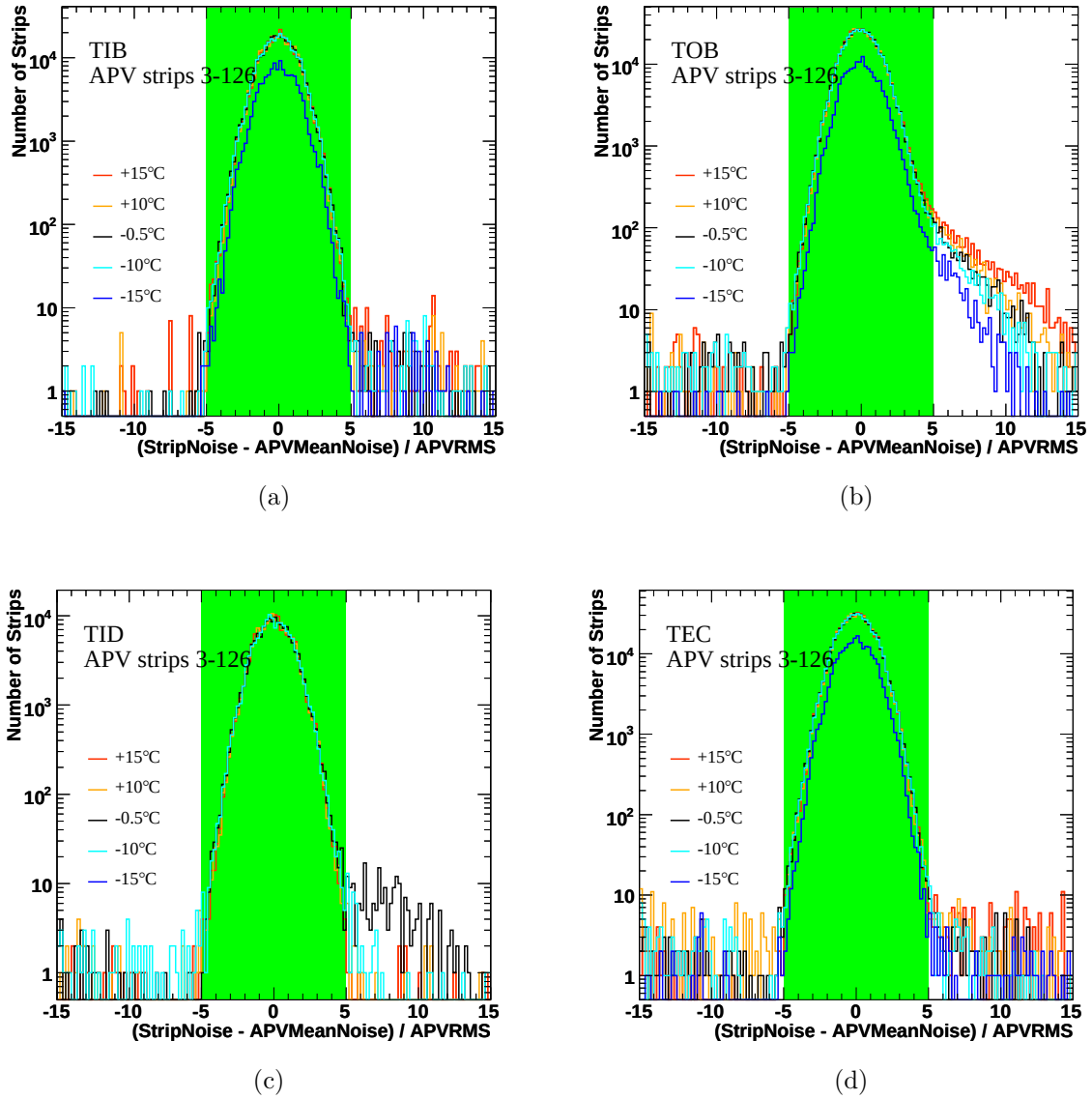


Figure 4.4: Deviation of the single strip noise from the corresponding APV mean noise measured in units of RMS. The distributions are shown for the five different temperatures used during the slice test and the four subdetectors (a) TIB, (b) TOB, (c) TID and (d) TEC. The green bands indicate the strips that are within the required threshold of $\pm 5 \cdot \text{RMS}$. Only APV inner strips (strip number 3 to 126) are shown. Channels below $-5 \cdot \text{RMS}$ are called *dead* and the ones above $+5 \cdot \text{RMS}$ are called *noisy* strips. In case of the TOB modules the effect of the so-called *wing noise* is clearly visible.

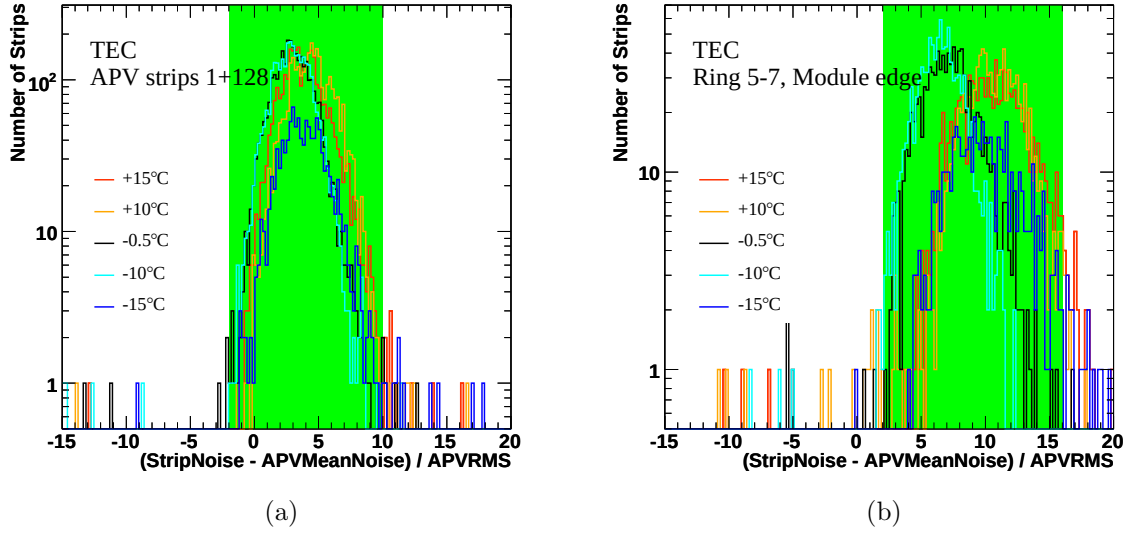


Figure 4.5: Deviation of the single strip noise from the corresponding APV mean noise measured in units of RMS. The distributions are shown for the five different temperatures used during the slice test and the APV edge strips 1 and 128 of TEC modules (a) and the module edge strips of TEC ring 5-7 modules (b), respectively. Since the edge channels have in general a higher noise, the thresholds to identify dead and noisy strips are also raised.

- The tick mark height of each laser has to be above an absolute value. If it is below, the laser is flagged as faulty (low tick mark).
- The maximum of the tick mark (tick top = baseline + height) has to be below an absolute value. Otherwise the laser is flagged as faulty (saturated tick mark).

The thresholds applied to the different module geometries are summarized in table 4.5. They are set such that the main distributions are within the accepted range and that only outliers are rejected. The mean noise per APV is analyzed separately for each module geometry since the noise depends linearly on the strip length so that the thresholds have to be increased for increasing strip length. The RMS of the noise distribution per APV is very narrow and a RMS of approximately zero indicates that the APV is not working well while a high RMS points out large variations in the noise. To identify dead or low signal fibers a lower threshold on the tick mark height can be used. On the other hand, the tick height is not allowed to go into saturation which can be monitored by an upper threshold on the tick mark and the tick top¹. The tick mark information are extracted from time synchronisation scan runs performed individually for each operating temperature.

Figure 4.6 shows the mean noise per APV for TEC ring 3 modules and the RMS of the noise distribution per APV for TEC ring 6 modules, respectively, with respect to the different temperatures. The accepted regions are underlined in green. Only very few outliers depending on the operating temperature are visible which means that the noise and the variation of the noise per APV belonging to the same module geometry is very stable.

¹The information about the baseline of the tick mark, necessary to calculate the tick top, is in this analysis only available for TEC modules. Therefore in case of TIB, TID and TOB modules a reduced upper limit also on the tick mark height is applied to check for saturation.

Parameter	Subdetector	Lower Threshold [ADC counts]	Upper Threshold [ADC counts]
APV mean noise	TEC ring 1	2	4
	TEC ring 2	2	4
	TEC ring 3	2.5	4.2
	TEC ring 4	2.5	5
	TEC ring 5	2.5	5.5
	TEC ring 6	2.5	6
	TEC ring 7	3.3	6
	TID ring 1	2	4
	TID ring 2	2	4
	TID ring 3	2.5	4.2
	TIB	2	4.5
	TOB	3	6
APV RMS	TEC & TID	0.01	0.2
	TIB	0.01	0.15
	TOB	0.01	0.3
Laser tick height	TIB, TID, TOB	400	900
	TEC	400	—
Laser tick top	TEC	—	1000

Table 4.5: Thresholds applied to the mean noise and the RMS of the noise distribution per APV and to the tick mark to identify bad APVs and lasers, respectively. The APV mean noise is analyzed with respect to the expected behaviour for the given strip length.

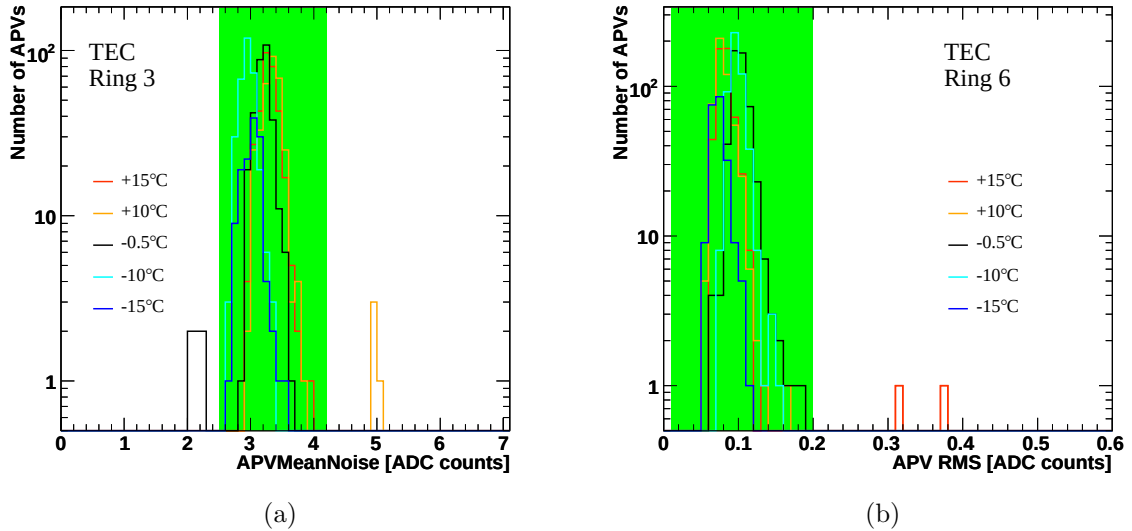


Figure 4.6: (a) Mean noise per APV for TEC ring 3 modules and (b) RMS of the noise distribution per APV for TEC ring 6 modules. The required ranges are underlined in green. For all temperatures only very few APVs show a deviation from the main distribution.

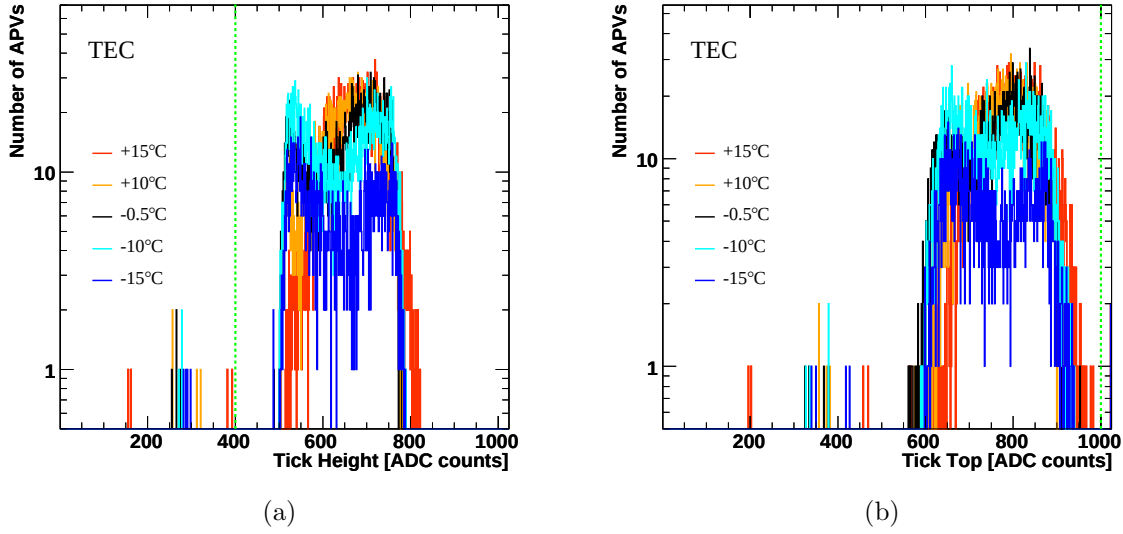


Figure 4.7: (a) The tick height and (b) the tick top for all TEC APVs. The green line indicates in (a) the lower threshold and in (b) the upper threshold to identify low tick marks and saturated tick marks, respectively.

In figure 4.7 the tick height and the tick top for all TEC APVs are shown. In case of low temperatures the distributions show two peaks with a minimum in between since the laser gain is tuned such that the tick height is around 640 ADC counts. For high temperatures this requirement is reached using the same gain setting for nearly all lasers so that the tick height distribution is gaussian like. But for low temperatures this setting is at the edge between two possible gains resulting in approximately half of the lasers having a lower gain setting than the other half. This causes the two peak structure according to the end region of the lower distribution and the initial region of the upper distribution, respectively. The green lines indicate the thresholds that are used to distinguish between an abnormal behaviour and the expected one.

To study the time stability of the defects and the influence of the operating temperature the whole analysis has been performed for several pedestal runs spanning a period of approximately three months. Figure 4.8 shows the result for one pedestal run at +15°C taking into account only the TEC modules. To compare the noise of all ring geometries directly to each other the common-mode subtracted and tick height corrected noise is normalized to the ring 1 noise by normalizing the APV mean noise of all APVs to the same APV mean noise of a well working ring 1 module. On the left-handed side all possible faults mentioned before are depicted. In total four lasers (three with a low and one with a saturated tick mark) and three APVs (two with low noise and one with high RMS) are conspicuous in this run. Taking all detected faults into account about 0.6 % of all used TEC channels got an error flag. On the right-handed side the same distribution is shown only for good, noisy and dead channels neglecting faulty flagged APVs and lasers. Analyzing these channels about 0.1 % of the strips are noisy or dead which is in very good agreement with the results obtained in the ARC test and the petal longterm test.

Table 4.6 summarizes the faulty components (APVs and lasers) of the TEC that are spotted by analyzing the noise and the tick mark behaviour as described above and that are

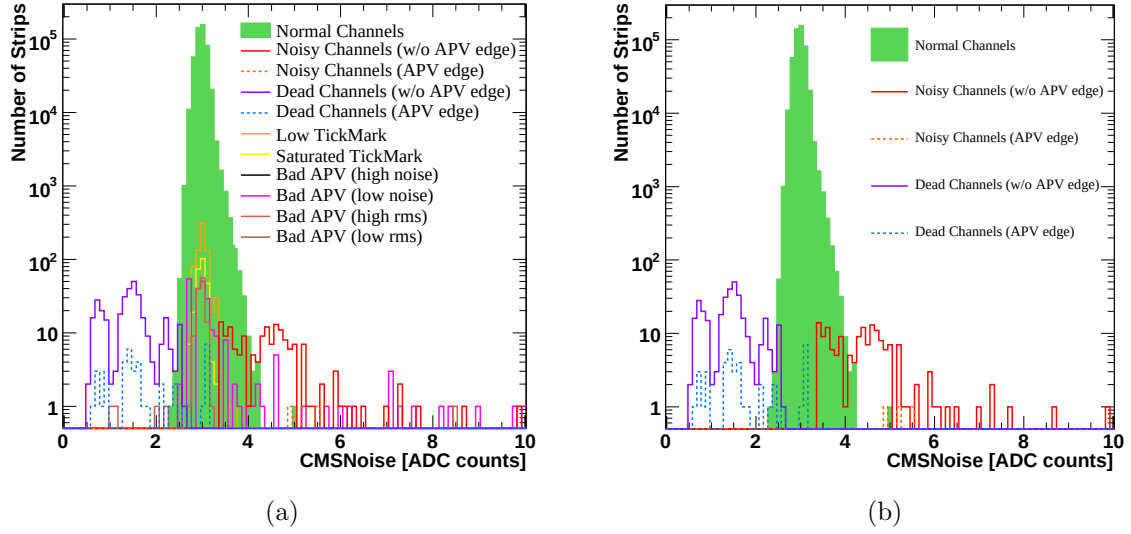


Figure 4.8: Common-mode subtracted and tick height corrected noise of the TEC channels measured in a pedestal run at $+15^\circ\text{C}$. The noise of all strips is normalized to the ring 1 noise by normalizing the corresponding APV mean noise to the APV mean noise of one ring 1 APV. Good channels are depicted in green while faulty flagged channels are shown in an appropriate colour. In (a) all possible faults are taken into account whereas in (b) only the strip specific ones are displayed.

invalid in several pedestal runs. They are confirmed also by another independent analysis [31] and were partially already known before the tracker slice test. It has to be taken into account that the defects were not necessarily present for all temperature settings but occurred only in the warm or in the cold environment. In addition to the defects listed here it is possible that single APVs or lasers showed a conspicuous behaviour in single runs that could not be reproduced systematically.

As an example, figure 4.9(a) shows the tick top profile of the TEC module denoted in row seven of table 4.6 for a timing run performed at -15°C . It is obvious that the tick top of the second laser (strip number 257-512) is in saturation of the 10-bit ADC of the corresponding FED. Therefore it is not possible to measure the full signal height of a physics event using

Sector	Disc	Petal	Ring	Module	Defect	Temp.
2	2	back	7	5	Laser 0 shows low tick, low noise and low pedestal	cold
2	6	back	2	1	Laser 2 shows large variations in noise	warm
2	7	front	5	4	The PLL chip is not working	all
3	1	back	5	3	Laser 0 shows a low tick	all
3	3	back	4	3	APV 1 shows low noise	cold
3	4	back	2	1	Laser 0 shows low tick, low noise and high pedestal	all
3	4	back	7	2	Laser 2 shows saturated tick	cold
3	5	back	7	3	APVs 2 and 3 show low noise with large variations	all

Table 4.6: Defective APVs, lasers or module control chips of the TEC slice that showed a conspicuous behaviour in noise and tick mark during several runs. The temperature environment where the error occurred is given in the last column. The up to three lasers belonging to one analog opto hybrid are numbered with 0, 1 and 2.

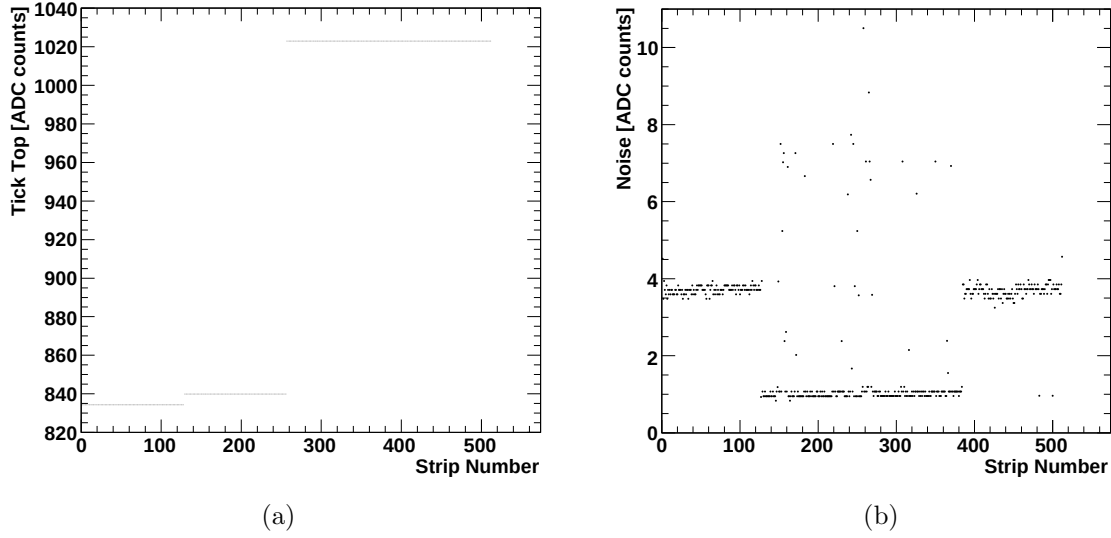


Figure 4.9: (a) Tick top profile of the TEC module described in row seven of table 4.6 as measured in a timing run at -15°C . The second laser is in saturation of the 10-bit ADC of the FED. (b) Tick height corrected noise profile of the TEC module denoted in row eight of table 4.6 as measured in a pedestal run at -15°C . APV two and three have a very low mean noise with several noisy channels.

this laser. Another example of two bad working APVs according to row eight is depicted in figure 4.9(b). The tick height corrected noise profile is shown where APV two and three display a very low mean noise with several channels being very noisy.

The results of the bad strip and faulty components identification performed for 18 pedestal runs and 9 timing runs under the various temperature conditions are shown in figure 4.10 (a) to (d) as a function of the run number where the first run analyzed here was done end of March and the last one end of June 2007 so that the x axis range corresponds to a time period of three months. The number of faulty channels is given relative to the total number of strips read out in the subdetector under investigation. It has to be taken into account that for -15°C only a reduced part of the slice test was used for the TIB, TOB and TEC while the TID did not participate at that temperature.

All subdetectors show a bad strip number of about 1 % including bad APVs and lasers. In some runs special components are more conspicuous than in other runs, for example the APV mean noise in the TEC at 10°C . There are several APVs with a mean noise much lower than the expected value. A detailed investigation showed that the affected APVs are all belonging to the ring 5 and ring 7 modules of the same petal. It turned out that the power group 3 of this petal had a very low current during these runs and since ring 5 and 7 share this power group all corresponding modules were affected. After exchanging the power supply unit the problem disappeared.

In figures 4.10 (e) to (f) and 4.11 the same distributions are shown excluding bad APVs and lasers so that the behaviour of single dead and noisy strips can be studied in more detail. The number of dead strips is stable while the noisy channels show some variations with time and temperature. Nevertheless, the fraction of dead (noisy) strips is very low during the whole data taking, namely about 0.05 % (0.04 %) for the TIB, 0.04 % (0.4 %) for the TOB, 0.04 % (0.1 %) for the TID and 0.08 % (0.02 %) for the TEC. In addition, the

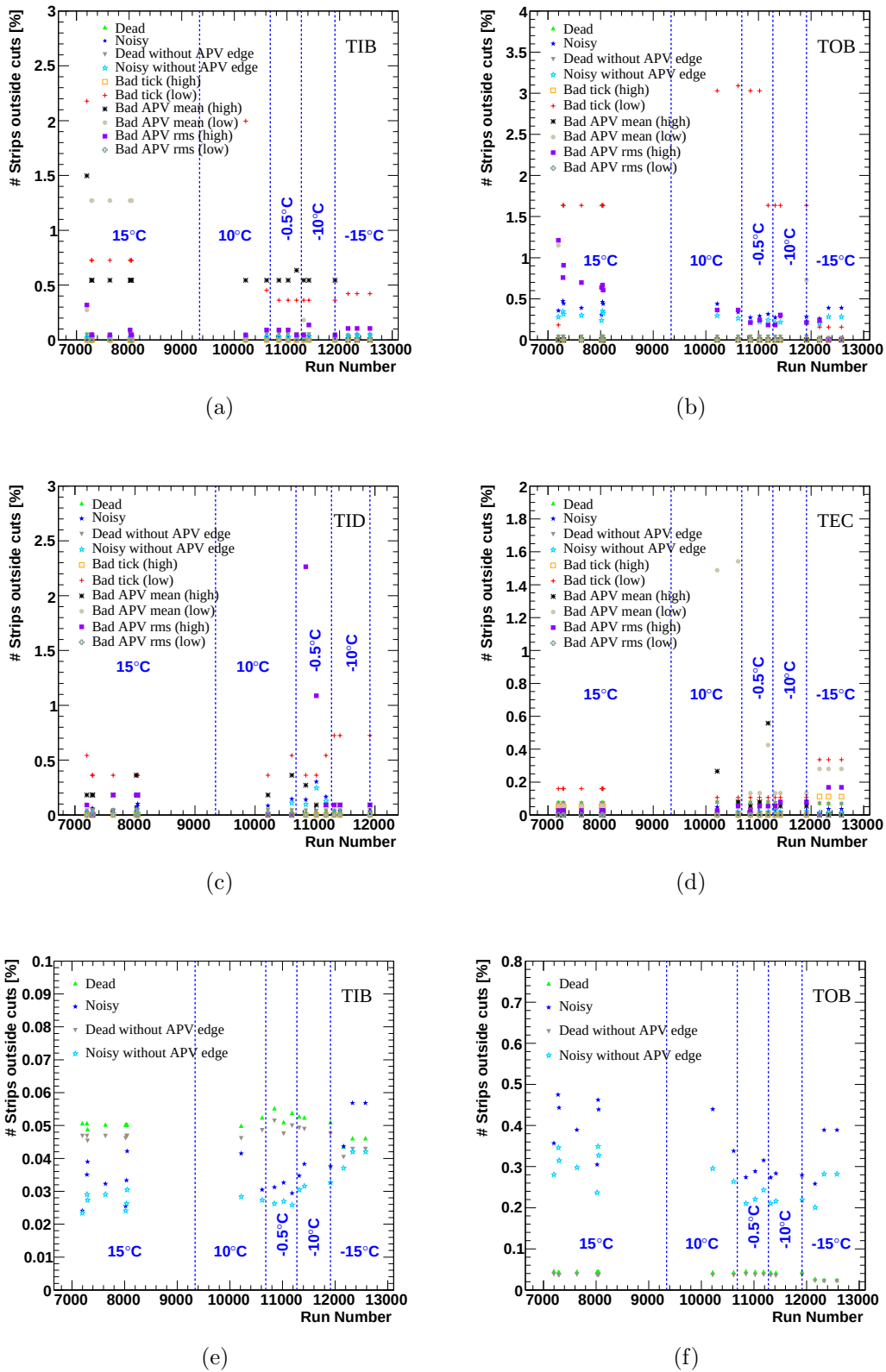


Figure 4.10: Fraction of faulty flagged channels with respect to the total number of strips read out during the tracker slice test. The range of run numbers corresponds to three months of data taking. The periods of different operating temperatures are indicated by the blue lines. In (a) to (d) all defects in the four subdetectors are taken into account while in (e) to (f) bad APVs and lasers are excluded for the TIB and the TOB.

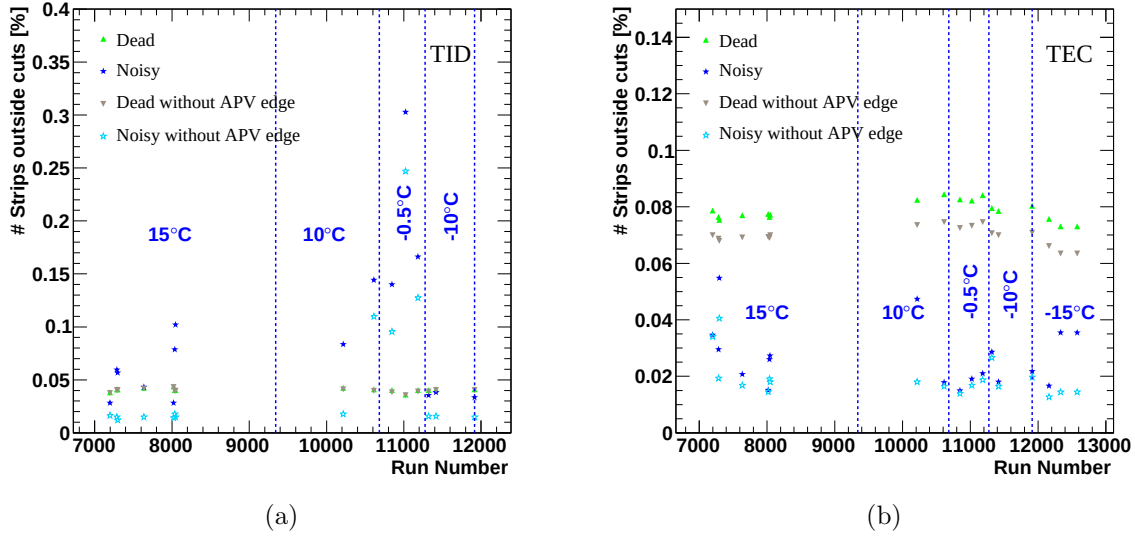


Figure 4.11: The same distributions as shown in figure 4.10 (e) and (f) but for the TID and the TEC.

special treatment of the APV edge channels mainly affects the noisy channel identification since these strips are more noisy than the others. The large number of noisy channels in the TOB compared to the other subdetectors is caused by the *wing noise* that was already mentioned earlier.

Since for the TEC the behaviour of each readout channel during the integration of the silicon modules in the tracker substructures is available in the analysis from the tracker construction database, the faulty flagged channels from the slice test can be compared to the ones that are flagged as bad in the ARC test. For this comparison one pedestal run of the slice test performed at 15°C is used. Whole APVs and lasers that showed a conspicuous behaviour are not taken into account.

Figure 4.12(a) shows the agreement between the slice test (ST) and the ARC test. Most of the faulty channels are identified as bad in both tests but nevertheless there are a lot of strips that were conspicuous only in the slice test or the ARC test. Because the noise of the readout channels is always influenced by the test setup itself and in addition noisy channels can in general be used for event reconstruction, channels that are flagged as noisy in the slice test or the ARC test are neglected in figure 4.12(b) to disentangle the effects of noise pickup from real module defects. It is obvious that the agreement between the two test is only slightly reduced while the number of channels that are flagged in only one of the two tests is largely decreased. This gives evidence that the real defects already known from the ARC test can also be identified in the slice test data by the analysis described here although the ARC test was a much more sophisticated test whereas for the slice test only the noise is analyzed.

The remaining strips that are only marked in the ARC test are mostly unknown errors, shorts or likely shorts and likely open bonds, which means that they could not be classified clearly in the ARC test so that they are most probably inconspicuous in the slice test by only studying the noise profiles. On the other hand channels that are only conspicuous in the slice test can be new defects that appeared during the tracker integration or the abnormal

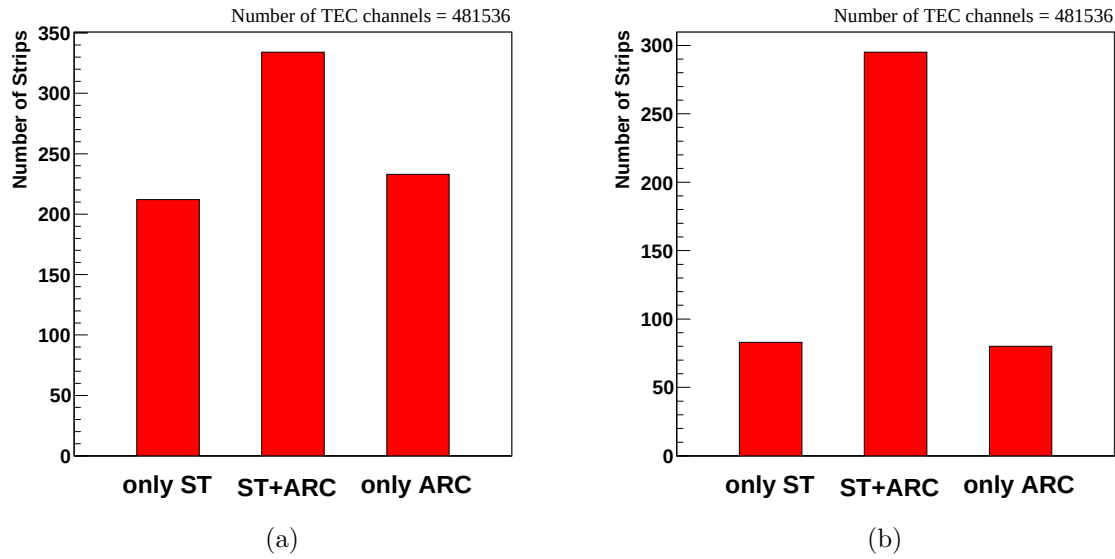


Figure 4.12: Comparison of faulty flagged channels between the slice test (ST) and the ARC test. For the slice test the results of one pedestal run performed at 15°C are used. In (a) bad APVs and lasers are not taken into account while in (b) additionally channels that are flagged as noisy in the slice test or the ARC test are neglected.

behaviour is temporary and affects only the pedestal run that is used for this comparison meaning that there is no real defect.

Summarized the results obtained with the single module test before mounting the sensors on the petals, the petal longterm test and the tracker slice test show a very good agreement concerning the identification of faulty channels leading to a bad strip number in the order of only 1 ‰. In addition, these results have shown that the very good quality has not decreased during the tracker integration due to additional defects.

4.6.1.2 Noise Stability and Strip Length Dependence

To monitor the stability of the single strip noise during the 18 pedestal runs mentioned in the last section the noise distributions of the layers and rings of the different subdetectors are calculated separately excluding bad APVs and lasers to get a trend that is independent from faulty components. Figure 4.13 shows the mean common mode subtracted and tick height corrected noise of the TIB and TOB layers and the TID and TEC rings with respect to the run number. The errors correspond to the RMS of the respective noise distribution.

Apart from the dependence on the temperature the noise is very stable (better than $\pm 0.5\%$). The commissioning procedure of the tracker was extended during the 10°C running and for all runs performed later on by the optimization of a special APV parameter (called VPSP) in order to equalize the average level of the pedestal values for all APVs. This led to a change in the mean noise of the readout channels. In addition, according to the operating temperature some other APV parameters were tuned in order to reach the best performance for the given temperature. Because of that the observed change in the noise behaviour with respect to the temperature periods is a combination of the temperature effect and the adjusted APV parameters. Nevertheless, as expected a decrease of the strip noise

with decreasing temperature is visible which should increase the signal-to-noise ratio (see section 4.6.2).

In the TID and TEC distributions a dependence of the mean noise on the module geometry, i.e. the ring number is observable. Since the noise of the modules is determined by the input capacitance to the APV which is dominated by the capacitance of the readout channels one would expect a linear dependence of the noise on the strip length connected to the APV. Because of that the noise increases with increasing ring number (which means increasing strip length) in the TEC for all operating temperatures. In case of TID modules it has to be considered that ring 2 sensors have the smallest strip length followed by ring 3 and ring 1, which is in agreement with the measured noise behaviour.

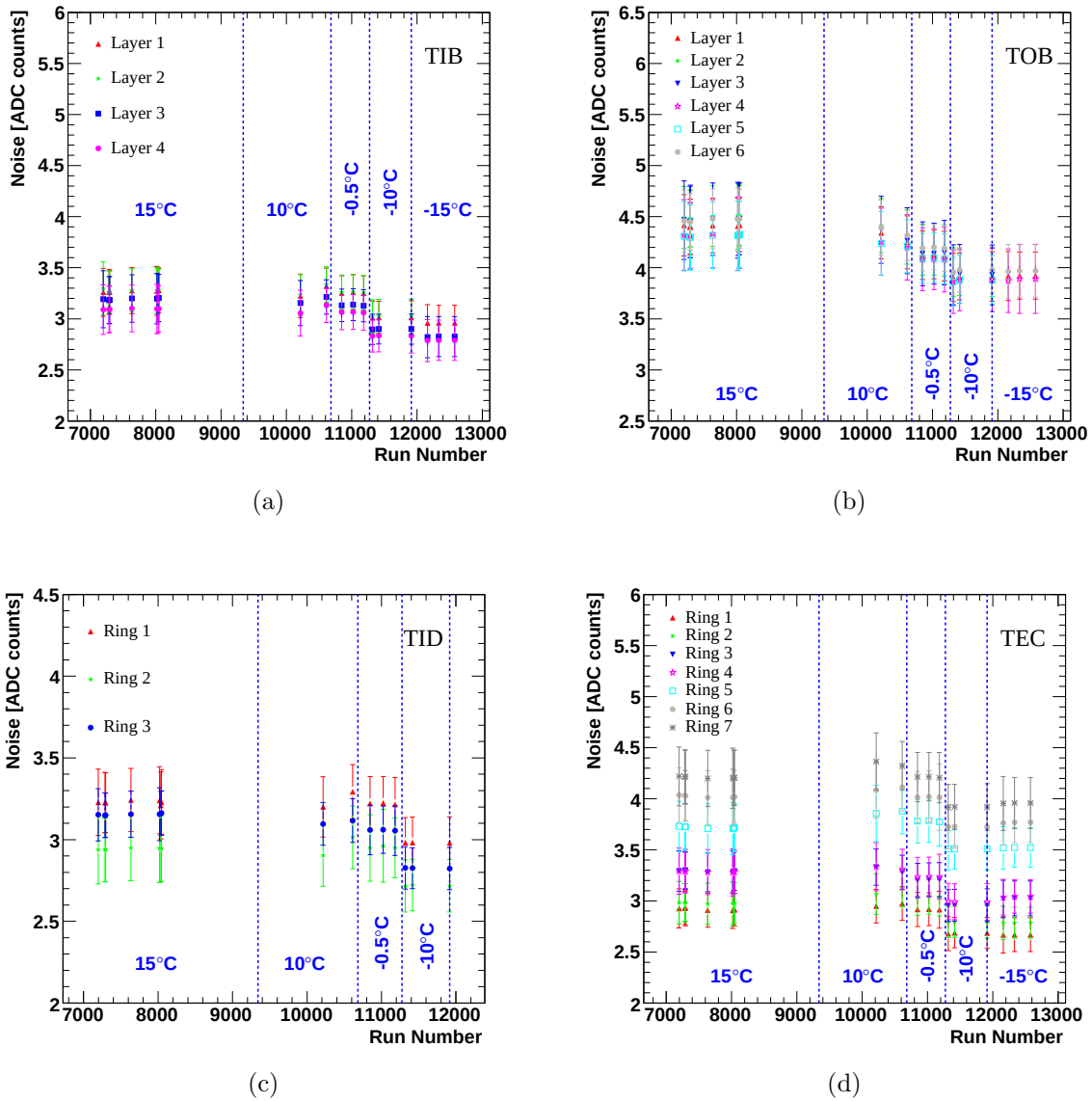


Figure 4.13: Mean common mode subtracted and tick height corrected noise per layer for (a) the TIB and (b) the TOB and per ring for (c) the TID and (d) the TEC with respect to the run number. The error bars correspond to the RMS of the respective noise distribution. The different temperature periods are indicated by the blue lines.

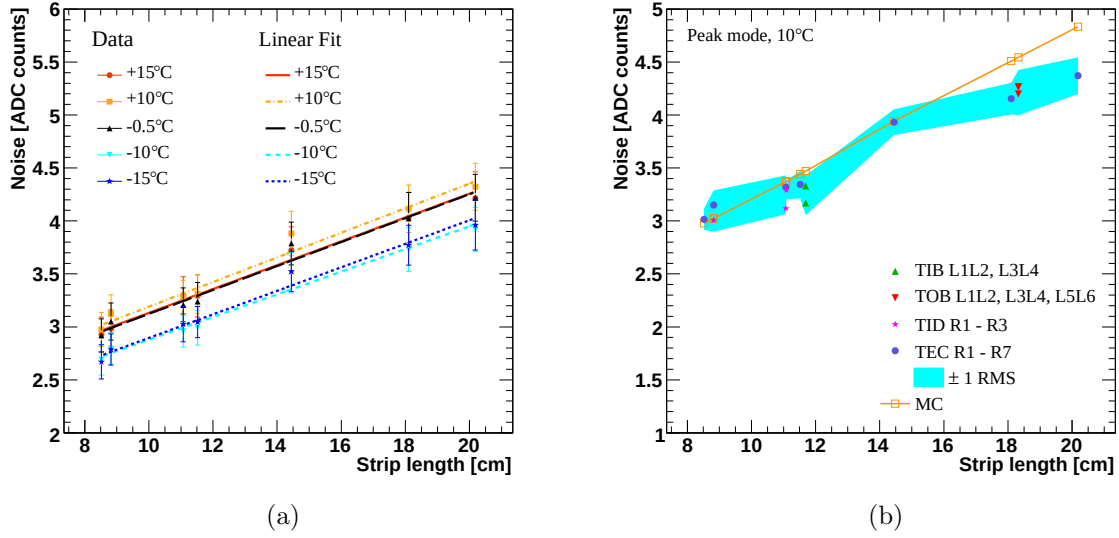


Figure 4.14: Mean common mode subtracted and tick height corrected noise as a function of the active strip length measured in peak mode. (a) The linear dependence of the seven TEC rings is shown for the five temperatures of the slice test. The error bars represent the RMS of the resulting noise distributions. (b) Mean noise of the different layers of the TIB and the TOB and the different rings of the TID and the TEC measured at 10°C. The blue band corresponds to the ± 1 RMS region of the respective distributions. In addition, the noise parametrization used in the simulation is shown in orange.

To study the correlation between noise and strip length in more detail, figure 4.14(a) shows the mean common mode subtracted and tick height corrected noise per TEC ring as a function of the active strip length. For the calculation of the mean and the RMS values (represented by the error bars) bad APVs, bad lasers and faulty flagged channels were excluded. The results of one pedestal run per temperature setting are depicted together with linear fits on the data. For each temperature the correlation fits well with the linear expectation with nearly the same slopes but different absolute values due to the change in the temperature and the APV settings. Again, the noise is in general reduced for decreasing temperature. At -10°C and operating the APVs in peak mode the fit leads to the following noise parametrization as a function of the strip length l :

$$\text{Noise}_{\text{ADC}}[l] = (0.11 \pm 0.02) \frac{\text{ADC}}{\text{cm}} \cdot l + (1.81 \pm 0.21) \text{ADC} \quad (4.1)$$

$$\text{or } \text{Noise}_{\text{ENC}}[l] = (34.4 \pm 6.3) \frac{e^-}{\text{cm}} \cdot l + (565.6 \pm 65.6) e^- \quad (4.2)$$

Here, the Equivalent Noise Charge is calculated under the assumption that a tick height of 640 ADC counts, to which the actual tick height was calibrated for each laser, corresponds to 200,000 electrons. The resulting parametrization is in good agreement with measurements performed during the TEC integration and during TEC cold tests [32], where the ENC was calculated at -10°C and in peak mode to $\text{ENC} = 605.9 e^- + 3.2 e^-/\text{mm}$. The difference in the intercept can occur due to different operating conditions in the two test setups whereas the slope agrees well between the two measurements. In addition, the fitted slopes of the different temperature settings used in the slice test agree within their errors to each other

so that the change in the noise behaviour due to the changing operating conditions in terms of temperature and APV settings is equal to all ring geometries.

In figure 4.14(b) the common mode subtracted and tick height corrected noise is shown for different layers and rings of all strip tracker subdetectors versus the corresponding strip length. The markers identify the mean values while the blue band represents the ± 1 RMS uncertainty derived from the respective noise distributions. It is observable that also for sensors of the same length differences in the noise value can occur. These variations can be caused for example by different temperatures in the different parts of the tracker or by different APV settings that were used for the different subdetectors.

In addition to the measurements the noise simulation used for the MC events is shown in the plot. It is also based on a parametrization of the noise as a function of the strip length derived from the so-called Cosmic Rack (CRACK) setup corresponding to

$$\text{Noise}_{\text{ENC}}[l] = (38.8 \pm 2.1) \frac{e^-}{\text{cm}} \cdot l + (414 \pm 29) e^- \quad (4.3)$$

Comparing this parametrization with the one measured in the slice test it is obvious that both the intercept is significantly smaller and the slope of the linear dependence is higher in the simulation than in the data which means that the strip noise used in the MC events is too large compared to the noise values measured at the tracker slice test especially for long sensors. This circumstance is also visible in figure 4.14(b) and has to be taken into account when results obtained in the test are compared to simulated events.

Since the noise behaviour depends on several effects like temperature and APV settings as already discussed, the final choice of the noise parametrization used in the simulation has to be done with the final setup when the noise behaviour of the tracker is measured inside CMS.

4.6.2 Reconstruction Studies

Most of the studies concerning the data reconstruction from digis up to tracks are based on cosmic runs performed with the scintillator configuration C, since the majority of events

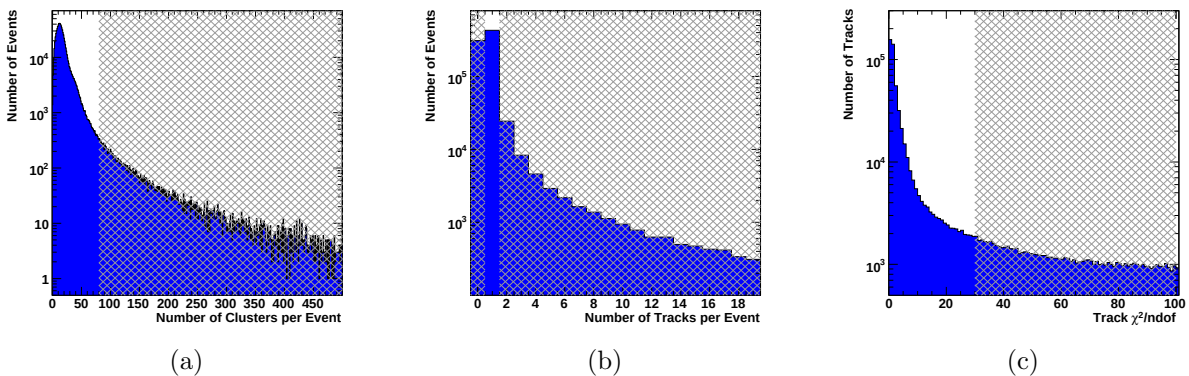


Figure 4.15: Quality criteria used for track based studies in order to analyze only events with one good reconstructed muon. The grey area indicates the excluded region. The data correspond to the cosmic runs recorded at -10°C . (a) Number of clusters per event. (b) Number of tracks per event. (c) Normalized χ^2 of the reconstructed tracks.

was recorded using this setup. The angular acceptance for cosmic particles was the largest and the operating temperature was varied only in this setting. The results presented in this section are obtained with the Combinatorial Track Finder. Analyses using the other two track reconstruction algorithms were also done and some comparisons of the different procedures are described later in this section. Some quality criteria have been applied to each event in case of track based studies in order to analyze only events with a good reconstructed muon (see figure 4.15). To pass the selection the total number of reconstructed clusters in the tracker slice has to be less than 80, the number of reconstructed tracks has to be one and the normalized χ^2 of the track has to be less than 30.

4.6.2.1 Reconstructed Trajectories and the Scintillator Setup

To get an impression of the tracks and the corresponding hits that were reconstructed using the slice test setup figure 4.16(a) shows the global position of the clusters and figure 4.16(b) the global location of the trajectories reconstructed for a cosmic run at -10°C (for the definition of the CMS coordinate system see section 3.7.1). In figure (a) the four subdetectors are highlighted by different colours. The read out layers in the barrel and disks in the end cap region are clearly visible. In figure (b) the reconstructed innermost and outermost points of the tracks are connected by straight lines, due to the absence of a magnetic field, to visualize the particle trajectories. In the barrel region the tracks are only slightly inclined while in the end cap part the trajectories show larger angles of incidence with respect to the vertical axis.

The correlation between the reconstructed tracks and the scintillator setup in configuration C is depicted in figure 4.17. On the left side the track position in the bottom scintillator plane at $y = -150\text{ cm}$ and on the right side its position in the top scintillator plane at

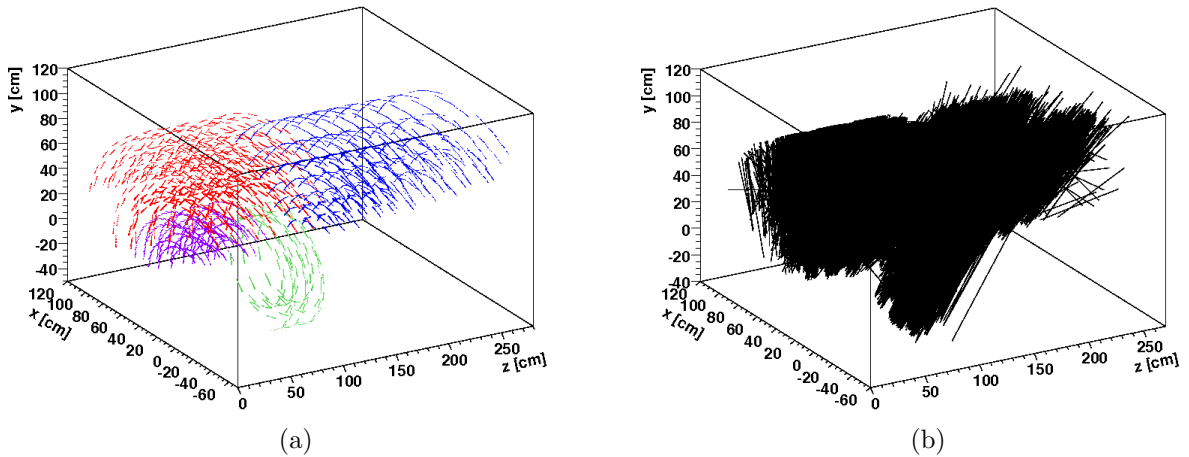


Figure 4.16: (a) Global position of reconstructed clusters for one cosmic run. Hits measured in the TIB are highlighted in purple, the ones in the TOB in red, in the TID in green and in the TEC in blue. The resulting structure reflects the strip tracker parts that were read out during the slice test. (b) Global position of reconstructed tracks for one cosmic run. The trajectories are visualized connecting the innermost and the outermost track point with a straight line. As expected, tracks passing through the end cap are more inclined with respect to the y axis than the ones in the barrel region.

$y = 150$ cm is shown. These intersection points are calculated by extrapolating the reconstructed trajectories to the respective planes using a straight line. The shapes of all nine scintillation counters can be clearly distinguished. The physical locations of the scintillators on top and on bottom of the tracker support tube, that are measured by hand (see table 4.2), are indicated by the red boxes. The agreement between the expected and the reconstructed

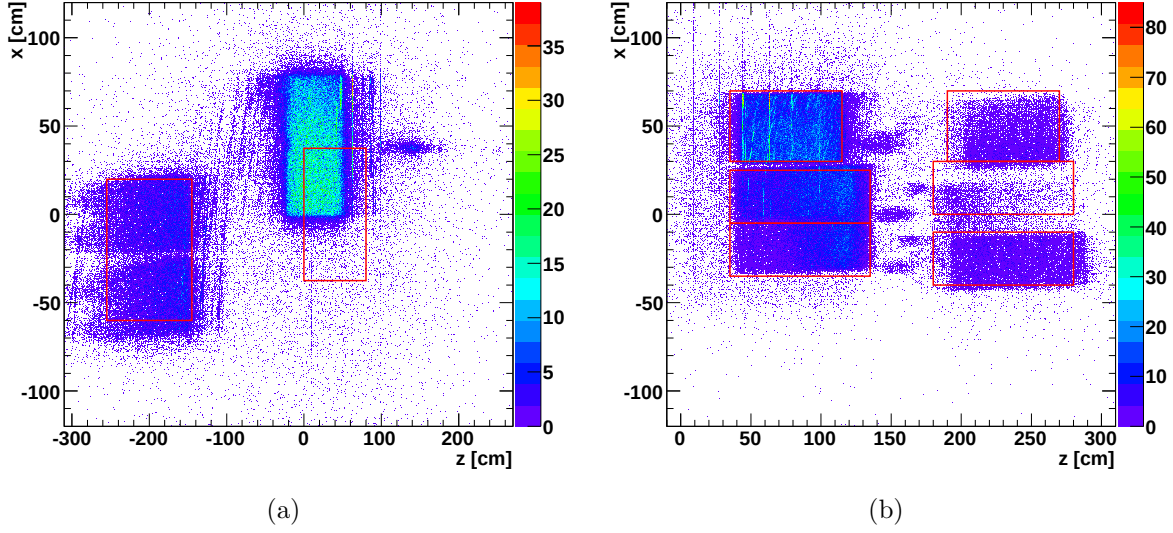


Figure 4.17: Intersection points in the global $x - z$ plane of the reconstructed tracks with the scintillator surfaces for (a) the bottom scintillators at $y = -150$ cm and (b) the top scintillators at $y = 150$ cm. The red boxes indicate the scintillator positions measured by hand.

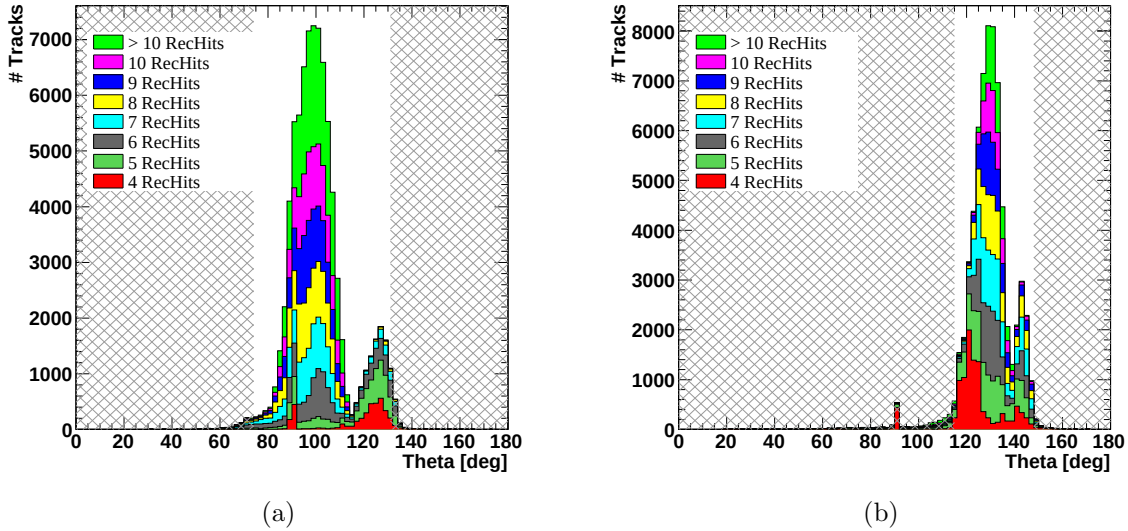


Figure 4.18: Distribution of the polar angle θ of the reconstructed tracks using (a) scintillator configuration A and (b) scintillator configuration B. The grey areas indicate the regions that are geometrically excluded by calculating the angular acceptance of the trigger setup based on the scintillator position measurements.

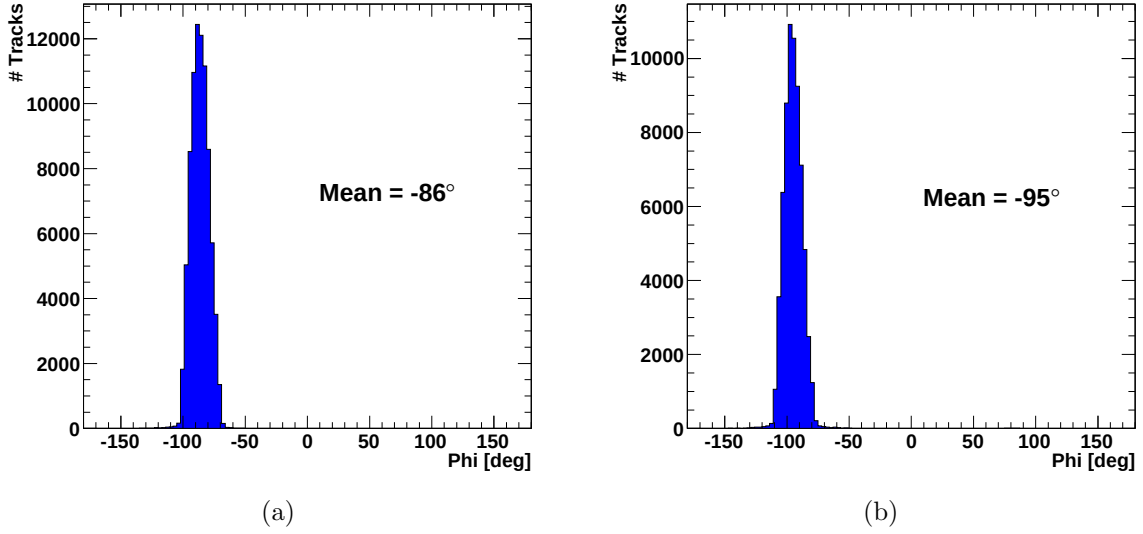


Figure 4.19: Distribution of the azimuthal angle ϕ of the reconstructed tracks using (a) scintillator configuration A and (b) scintillator configuration B. The shift in the mean value is due to a shift of the bottom scintillator in x direction.

track position is very good, except for the bottom scintillator located at $z \approx 0$ cm. Since the dimensions of the reconstructed scintillator position reflect very well the actual dimensions it is most probable that the location of this scintillator was measured wrong for example by using the position of the lower right edge instead of the center as for the other scintillators.

The polar angle θ of the reconstructed tracks with respect to the beam axis is depicted in figure 4.18, on the left-handed side for scintillator configuration A and on the right-handed side for configuration B. In figure (a) two peaks can be identified, the one around 100° corresponding to tracks traversing the barrel and the other one around 130° corresponding to particles measured in the end cap. Most of the tracks are reconstructed in the barrel region since in the TIB and the TOB the modules are mounted horizontally which is much more efficient for detecting cosmic particles than the modules mounted vertically on the end cap disks. In addition, it is obvious that in the barrel more hits contribute to a reconstructed track than in the end cap which means that the cosmic muons going from top to bottom through the tracker cross more layers in the barrel part with slightly inclined tracks than in the end cap where the angle of incidence is increased.

Considering the measured scintillator positions it is possible to calculate the angular acceptance of the slice test setup. The grey areas in figure 4.18 show the excluded regions from this geometrical point of view. As seen the reconstructed tracks are in very good agreement with the expected θ region. Furthermore, the change in the scintillator setup from configuration A to B is clearly visible in the θ distribution where both the barrel and the end cap tracks show larger angles of inclination in case of the second setup.

In figure 4.19 the azimuthal angle ϕ of the reconstructed tracks is shown, again for configuration A on the left-handed side and configuration B on the right-handed side. Since ϕ is measured with respect to the x axis, an angle of $\phi = -90^\circ$ corresponds to trajectories traversing the tracker perpendicular from top to bottom in the $x-y$ plane. Therefore cosmic muons are expected to peak around -90° as seen in the distributions. It has to be taken

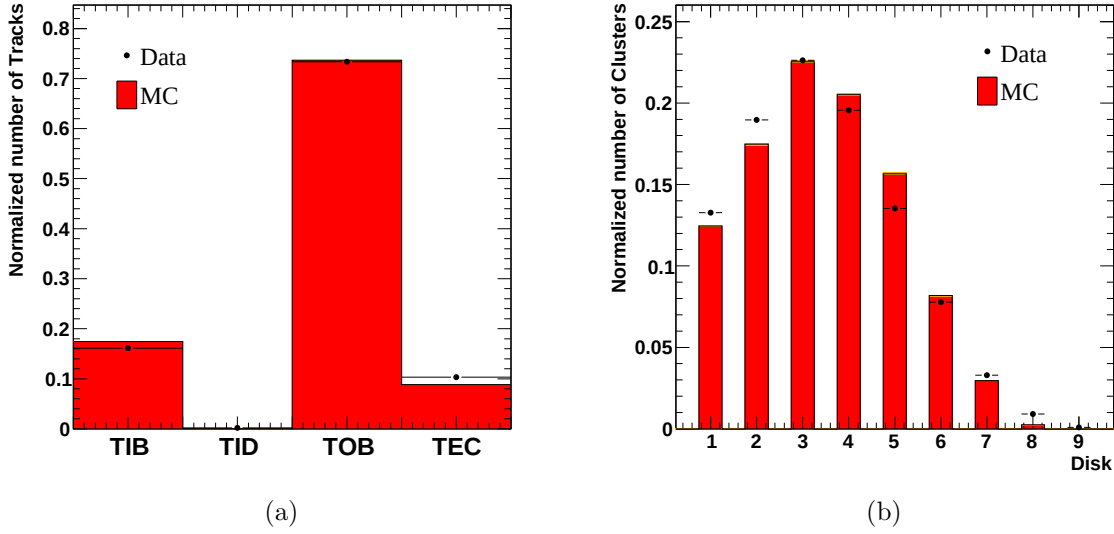


Figure 4.20: (a) Fraction of the reconstructed tracks in the different subdetectors. Both data and MC are shown for scintillator configuration C. (b) Fraction of the measured hits belonging to a reconstructed track as a function of the TEC disk number. The analyzed events are the same as in (a).

into account that the top and bottom scintillators are not exactly arranged on top of each other with respect to the x direction (see figure 4.2 and table 4.2). In configuration A the bottom scintillator is slightly shifted to the right and in configuration B to the left relative to the center of the top array. Calculating the mean direction of motion according to these setups the particle trajectories should peak around $\phi \approx -87^\circ$ in case of configuration A and around $\phi \approx -93^\circ$ for configuration B. This shift can be verified directly by the reconstructed ϕ distributions shown in figure 4.19.

To visualize the contribution of the four subdetectors to the measured tracks, figure 4.20(a) depicts the relative number of reconstructed trajectories in the TIB, TID, TOB and TEC, respectively. Since the tracking algorithm requires at least four hits belonging to a track in order to reconstruct it, in this figure a trajectory is counted for the respective subdetector if at least four of the tracking hits are measured in this tracker part so that the trajectory would have been reconstructed using this subdetector standalone. In this sense no tracks were reconstructed in the TID alone because it consists only of three disks. Nevertheless, the TID contributed to the reconstruction in cooperation with the other subdetectors. It is obvious that most of the tracks were reconstructed in the TOB ($\approx 73\%$) due to the larger number of layers and modules with respect to the TIB ($\approx 17\%$) and due to the better orientation to measure cosmics with respect to the TEC ($\approx 9\%$). This behaviour is confirmed by the simulation where nearly the same fraction of tracks is reconstructed in the different subdetectors.

From the TEC point of view it is not possible to use in the slice test the performance of all nine disks for particle identification. As shown in figure 4.20(b) the number of clusters belonging to a reconstructed track is very different for the nine disks since the scintillator setup does not cover the whole TEC. Both in data and simulation disk three contributes the most to reconstructed trajectories while the distribution is decreasing for all other disks.

Especially disk eight and nine cannot deliver tracking hits because they are not positioned within the angular acceptance of the trigger which is confirmed by the measurements. The small differences between data and MC can be caused by the slightly different scintillator simulation with respect to the real setup.

The results presented in this section give confidence that the reconstructed tracks in the slice test are reasonable and that both the tracker itself and the cosmic particle reconstruction works as expected.

4.6.2.2 Corrections on the Cluster Width and Cluster Charge

As already shown in chapter 3 the angle of incidence of the incoming particle has a large impact on the measured cluster size and cluster charge, especially for cosmic muon detection where highly inclined trajectories can occur. Since for the cluster size the flight direction in the plane perpendicular to the strips is relevant whereas for the cluster charge the effective path length of the particle in the silicon sensor has to be considered, different angles have to be taken into account for the two effects.

Figure 4.21(a) depicts a schematic view of a silicon sensor showing in blue the plane perpendicular to the module surface and the readout channels. The projection of the particle trajectory in this local $x - z$ plane defines the angle of incidence with respect to the z axis, called in the following xz -angle or ϕ_{local} . If this angle is 0° (perpendicular incidence) then the cluster size is minimal. It grows towards $\pm 90^\circ$. Assuming that the sensor thickness is given by t and the strip pitch by p , the mean cluster width w can be calculated in a simple

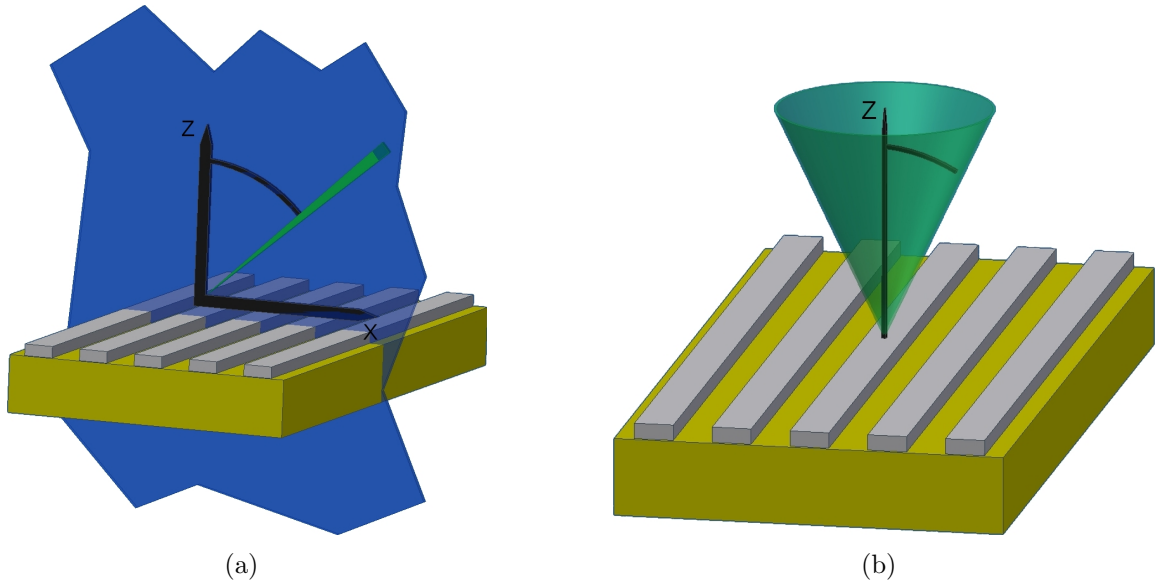


Figure 4.21: (a) Definition of the angle of incidence in the local $x - z$ plane of the module frame. The angle of the particle track (in green) with respect to the z axis is relevant for the measured cluster width. (b) Definition of the polar angle θ_{local} in the local module frame. The angle of the track cone (in green) with respect to the z axis is relevant for the measured cluster charge.

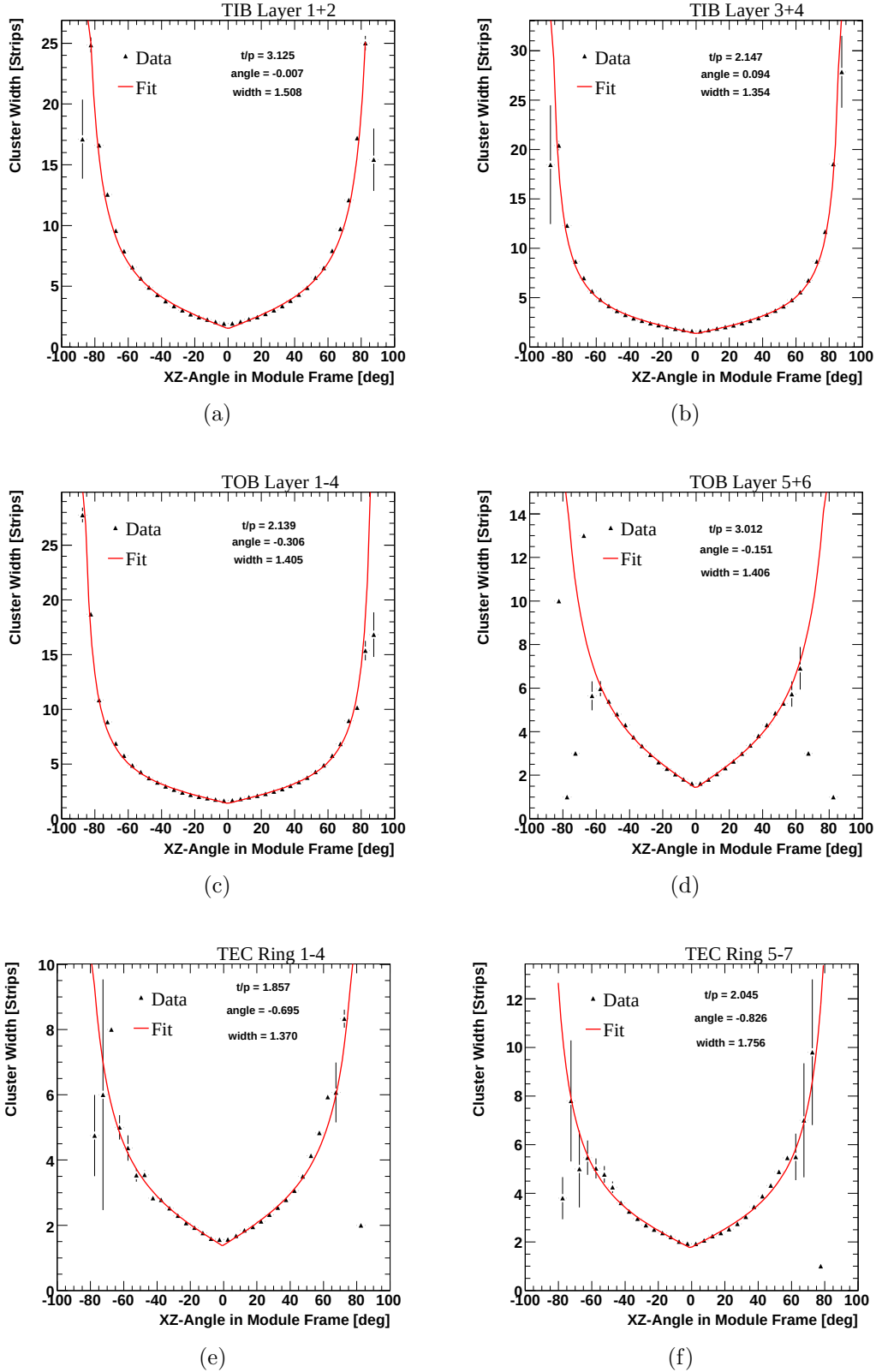


Figure 4.22: The measured cluster width of clusters belonging to a reconstructed track as a function of the local xz -angle. The red line shows the result of a fit according to the expected $\tan \phi$ dependence. The fitted parameters t/p , ϕ_{lorentz} (in degrees) and w_0 (in strips) are given in the plots. The distributions are for (a) TIB layer 1&2, (b) TIB layer 3&4, (c) TOB layer 1-4, (d) TOB layer 5&6, (e) TEC ring 1-4 and (f) TEC ring 5-7.

model as follows:

$$w[\mu\text{m}] = t[\mu\text{m}] \cdot |\tan(\phi_{\text{local}})| \quad \text{and} \quad w[\text{strips}] = w[\mu\text{m}]/p[\mu\text{m}] \quad (4.4)$$

$$w[\text{strips}] = \frac{t}{p} \cdot |\tan(\phi_{\text{local}}) - \tan(\phi_{\text{lorentz}})| + w_0 \quad (4.5)$$

ϕ_{lorentz} is the Lorentz angle caused by the deviation of the charge carriers influenced by the Lorentz force in a magnetic field leading to a shift in the measured signal position and thus to a minimum cluster width not at 0° but at ϕ_{lorentz} . Since in the slice test no magnetic field was present the Lorentz angle is zero. The minimum cluster width is given by w_0 . Figure 4.22 shows the measured cluster width for on-track clusters as a function of the xz -angle derived by extrapolating the reconstructed trajectory to the respective module surface and calculating the angle of incidence in the local $x-z$ plane. In case of the inner and outer barrel the distributions are shown for layers having the same t/p ratio. Since the TEC sensors have a variable pitch due to their trapezoidal geometry, the corresponding distributions are only distinguished by the module thickness.

The data are fitted by the function described above where the ratio t/p , the Lorentz angle ϕ_{lorentz} and the minimal cluster width w_0 are used as free parameters. The resulting curve is shown in red and the three parameters are given in the plots. The data are well described by the expected behaviour in the central region with the angle taken from the track reconstruction itself. Only for larger angles, where a reliable measurement is hard, some deviations are observable. The fitted t/p ratio is in the proper range for all layers (see table A.1 and A.2) considering that the active sensor thickness is not exactly known. The calculated Lorentz angle is around 0° and the mean cluster width at the minimum is about 1.4 strips. It has to be taken into account that the cluster width is also influenced by the charge carrier diffusion and the capacitive coupling between nearby channels (see section 4.6.2.5).

Since the Lorentz angle is a very important parameter for the event reconstruction, measurements like the ones presented here but using the design magnetic field are also necessary in the final experiment in order to correct the measured cluster position with respect to the Lorentz shift to obtain the real track intersection point.

The cluster charge depends on the angle of incidence of the incoming particle, too. Since the number of charge carriers produced is proportional to the path length of the particle inside the active sensor material, the local polar angle θ_{local} of the trajectory has to be taken into account. This angle measured with respect to the module's perpendicular is visualized in figure 4.21(b) and figure 3.23. Considering that the effective path length l is proportional to $1/|\cos(\theta_{\text{local}})|$ the measured cluster charge C can be parametrized as follows:

$$C = C_0/|\cos(\theta_{\text{local}})| \quad (4.6)$$

where C_0 is the average cluster charge for perpendicular incidence (i.e. $\theta_{\text{local}} = 0^\circ$) for the respective module thickness t .

Figure 4.23 depicts the measured cluster charge as a function of the reconstructed local polar angle for the TIB, TOB and TEC distinguishing different sensor thicknesses. The data are fitted according to equation 4.6 with the minimal cluster charge C_0 as free parameter. The result of the fit is shown in red and the derived value of C_0 is given in the plots. For the barrel modules the observed behaviour is well described by the theoretical expectation except for very inclined trajectories around $\theta_{\text{local}} \approx 90^\circ$. In case of the TEC modules the

angular acceptance is limited due to their vertical orientation and the scintillator setup so that neither perpendicular tracks nor highly inclined tracks can be measured. Apart from outliers at the edges of the measurement region the data is in agreement with the expected $1/|\cos(\theta_{\text{local}})|$ dependence.

Comparing the fit results for the minimum cluster charge of the thin modules (thin TEC sensors) with 102 ADC counts and of the thick modules (thick TEC sensors) with 165 ADC counts, the ratio of these values $C_{0,\text{thick}}/C_{0,\text{thin}} \approx 1.62$ reflects very well the ratio of the two effective sensor thicknesses $t_{\text{thick}}/t_{\text{thin}} = 470/290 \approx 1.62$.

Because the impact of the track incidence angle on the measured cluster charge is not

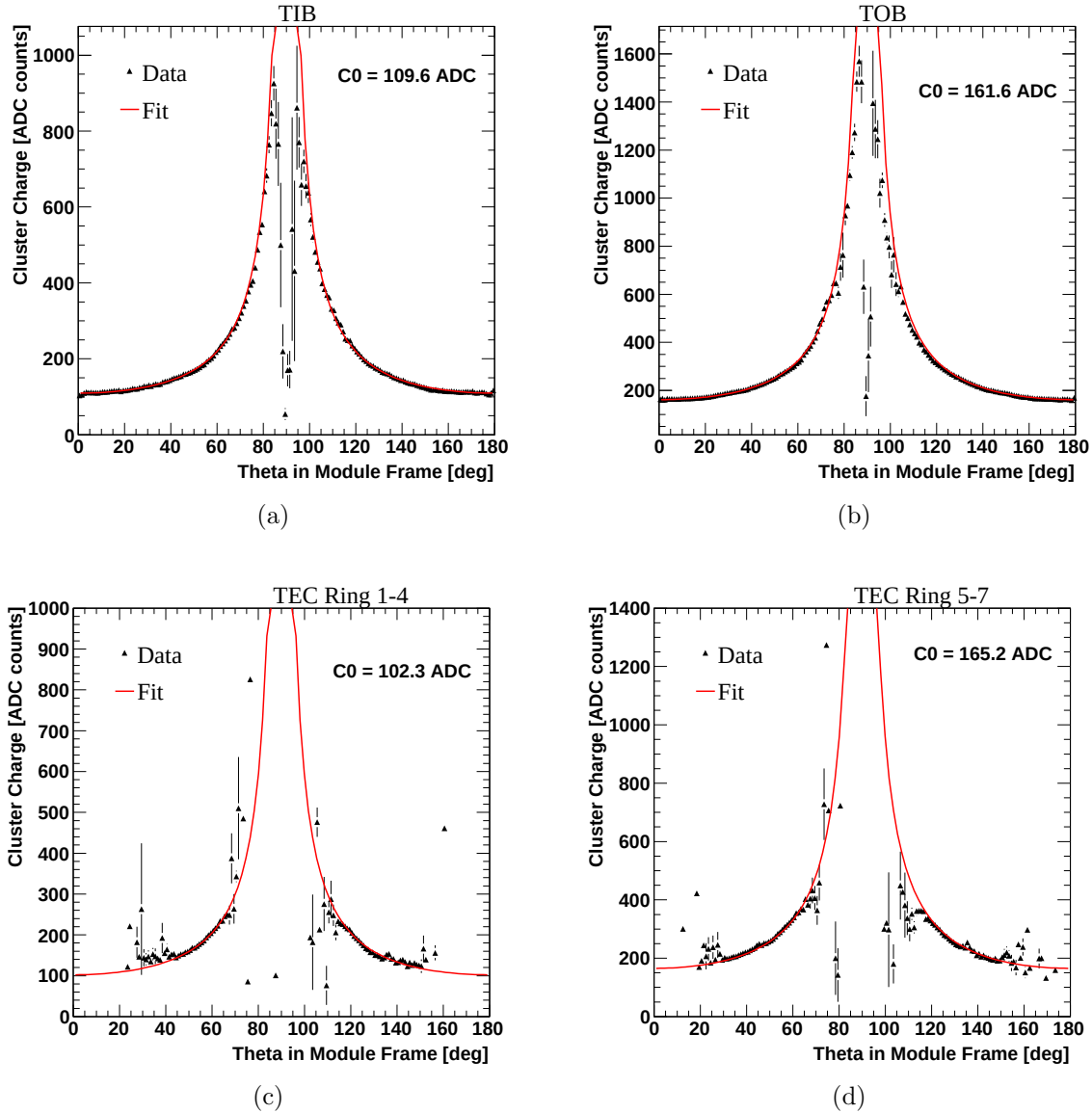


Figure 4.23: The measured cluster charge of clusters belonging to a reconstructed track as a function of the local polar angle θ_{local} . The red line shows the result of a fit according to the expected $1/|\cos(\theta)|$ dependence. The range $[80^\circ, 100^\circ]$ is excluded from the fit. The fitted parameter C_0 is given in the plots. The distributions are for (a) TIB, (b) TOB, (c) TEC ring 1-4 and (d) TEC ring 5-7.

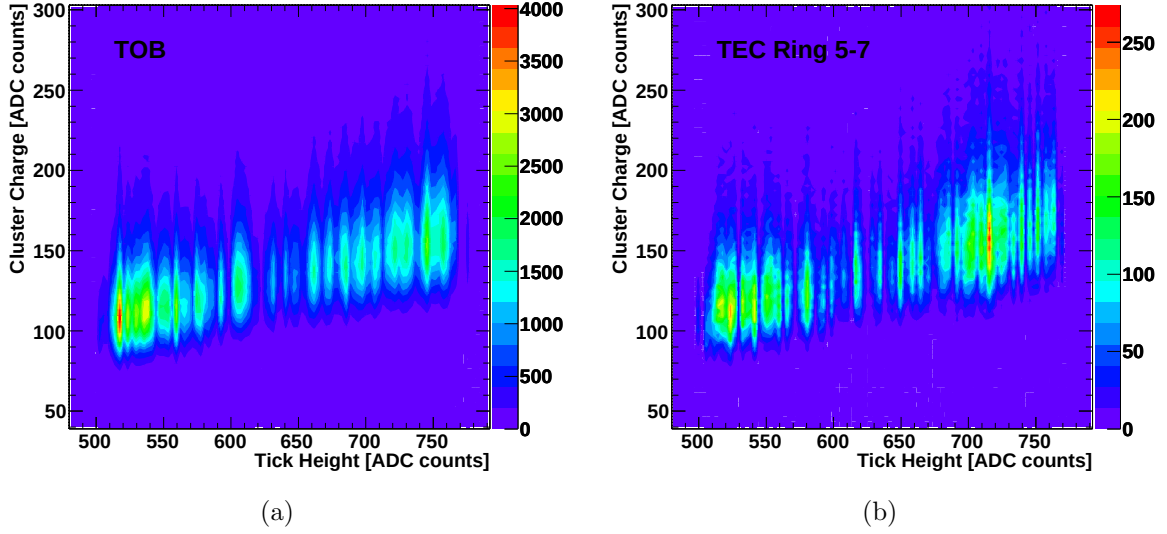


Figure 4.24: The angle corrected cluster charge as a function of the tick mark height. An increase of the charge with increasing tick height is clearly visible. On the left-handed side the distribution is shown for TOB clusters and on the right-handed side for TEC ring 5-7 clusters.

negligible as seen above, the charge has to be corrected for this effect in order to compare clusters belonging to different tracks and to study cluster charge distributions and signal-to-noise ratios. This is done by calculating for each cluster contributing to a reconstructed track the local polar angle based on the measured trajectory and normalizing its charge according to equation 3.2.

Another effect that has to be taken into account is the different tick mark height of the different lasers. This aspect has already been discussed in the noise analysis where the single strip noise is corrected for the tick height since a larger tick mark leads to larger noise values. The same procedure has to be done for the cluster charge. Because the measured charge depends on the tick height of the corresponding laser, the charge has to be normalized to a common tick height, i.e. 640 ADC counts in this analysis. In figure 4.24 the correlation between the cluster charge and the tick height is shown as an example for TOB and TEC clusters. The increase of the charge with increasing tick height is clearly visible. To disentangle this effect from different cluster charges due to different particle energies each cluster charge C is normalized according to the following equation:

$$C_{\text{norm}} = \frac{C_{\text{meas}} \cdot 640}{\text{TickHeight}} \quad (4.7)$$

where the tick height for each laser is obtained from timing runs performed at the respective operating temperature.

4.6.2.3 Cluster Behaviour at the APV Edges

As already seen in several noise profiles, the single strip noise is higher for the APV edge channels (strip numbers 1, 2, 127 and 128) than for the inner channels. Because of that the behaviour of the reconstructed clusters measured at the APV edges is studied and compared

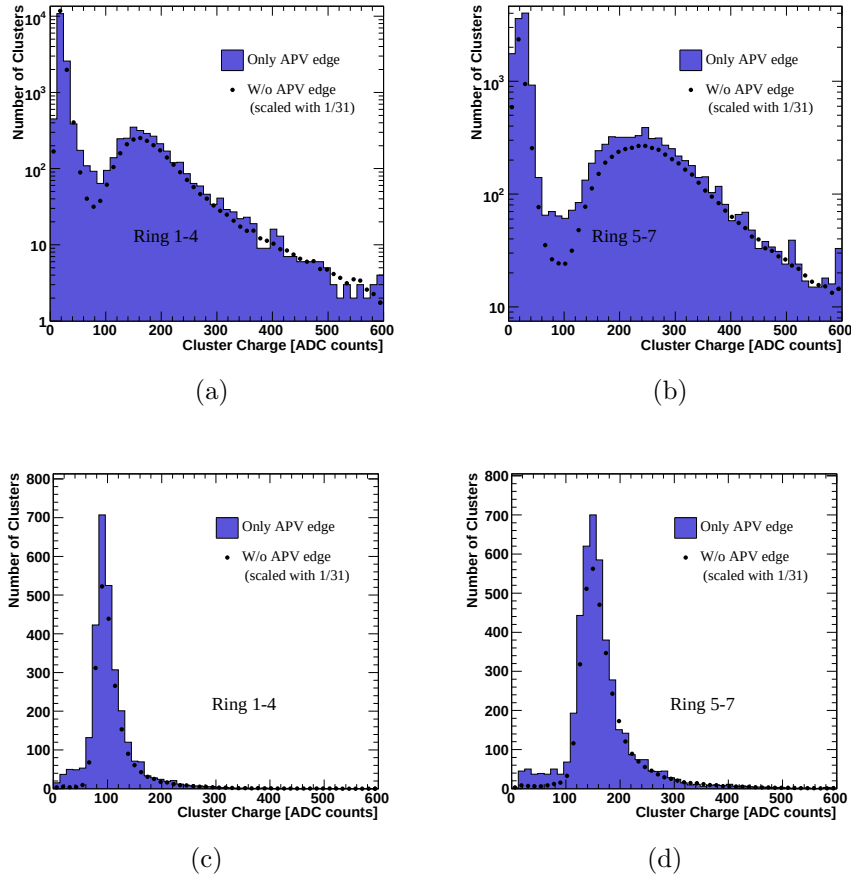


Figure 4.25: Cluster charge distributions for hits reconstructed at the APV edge strips (in blue) and without APV edge channels (black markers). To compensate the smaller statistics in case of the edge strips, the black distribution is scaled with 1/31. (a) and (b) show the cluster charge of all clusters measured in the thin and the thick TEC sensors, respectively. (c) and (d) show the cluster charge only for on-track clusters including the angle and the tick height correction, again for thin and thick TEC sensors.

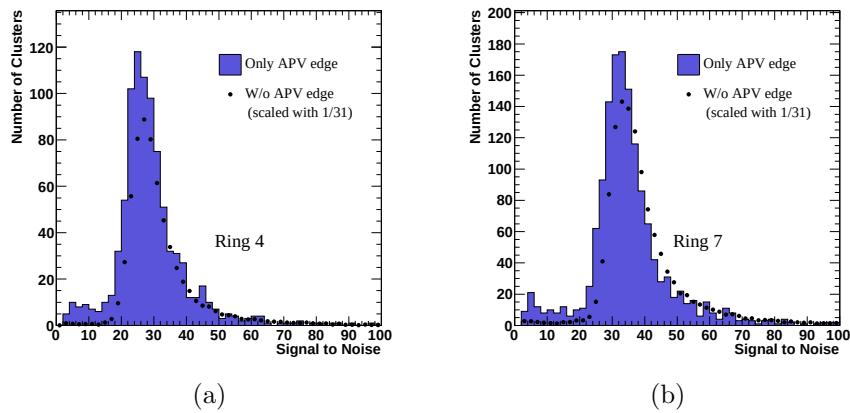


Figure 4.26: Signal-to-Noise distributions for APV edge clusters (in blue) and without APV edge strips (black markers), as an example for (a) TEC ring 4 and (b) TEC ring 7 modules. Only on-track clusters with the angle corrected cluster charge are taken into account.

to the one of clusters located in the inner region. The center of gravity of the cluster is used as a position estimation. It is treated as an APV edge cluster if it is located within the first two or the last two channels of the respective readout chip. The remaining hits are counted as APV inner clusters.

In figure 4.25 (a) and (b) the cluster charge measured in the thin and thick TEC sensors is shown without applying any cuts or corrections to the reconstructed charge. The markers indicate APV inner clusters while the blue histogram represents the charge distribution for APV edge clusters. Since the APV edge strips comprehend 4/128 and the APV inner strips 124/128 of one readout chip, the distribution for inner clusters is scaled with 1/31 to compensate the lower statistics at the edges. It is visible that both for the APV inner and the edge distribution fake clusters with a very low charge are dominating. Nevertheless, in both cases the signal region is clearly observable around 150 ADC counts for thin and 230 ADC counts for thick sensors. Especially the ratio between fake and signal clusters is in the same order for edge and inner strips and the number of reconstructed clusters in the APV edge channels is comparable to the estimation derived from the inner cluster distribution.

Figure 4.25 (c) and (d) depicts the same distributions but only for clusters belonging to a reconstructed track and correcting the charge for the angle of incidence and the tick mark height. The low charge peak disappears both for APV edge and inner clusters and the signal region is in good agreement between the two groups of hits. In figure 4.26 the cluster signal-to-noise ratio is shown as an example for TEC ring 4 and ring 7 modules, again for clusters belonging to a track and correcting the charge for the track incidence angle. The tick mark height has not to be taken into account in case of signal-to-noise distributions since both the signal and the noise depend on the tick height so that this effect cancels for the ratio of these parameters. It is obvious that the performance of the edge hits is decreased by about 6 % concerning the S/N behaviour with respect to the APV inner clusters due to the higher noise. With the high signal-to-noise ratio of the silicon sensors this is no limitation for particle detection.

These results show that the APV edge channels have nearly the same performance as the inner strips so that they do not have to be treated separately for the event reconstruction, although they have in general a higher noise than the APV average.

4.6.2.4 Cluster Charge and Signal-to-Noise Behaviour in the Tracker Subdetectors

Taking into account the corrections of the cluster charge with respect to the track incidence angle and the tick mark height of the corresponding laser, the cluster charge distributions can be analyzed using all clusters belonging to a reconstructed track. Figures 4.27 (a) to (e) show the corrected charge distributions for the four subdetectors and the different module thicknesses. The points correspond to the data measured in scintillator configuration C at -10°C while the red histograms represent the results of the simulation.

As expected, the data fit very well to a landau distribution convoluted with a gaussian function, shown as solid lines. The most probable values of the data distributions can slightly differ between subdetectors of the same module thickness since the APV parameters were set differentially for each subdetector. Therefore, a direct comparison is not possible. Only in case of thick and thin TEC modules the same APV parameters were used. Thus, the ratio of the most probable values $134 \text{ ADC counts} / 83 \text{ ADC counts} \approx 1.61$ is compatible with the ratio of the effective module thicknesses $470 \mu\text{m} / 290 \mu\text{m} \approx 1.62$ because the cluster

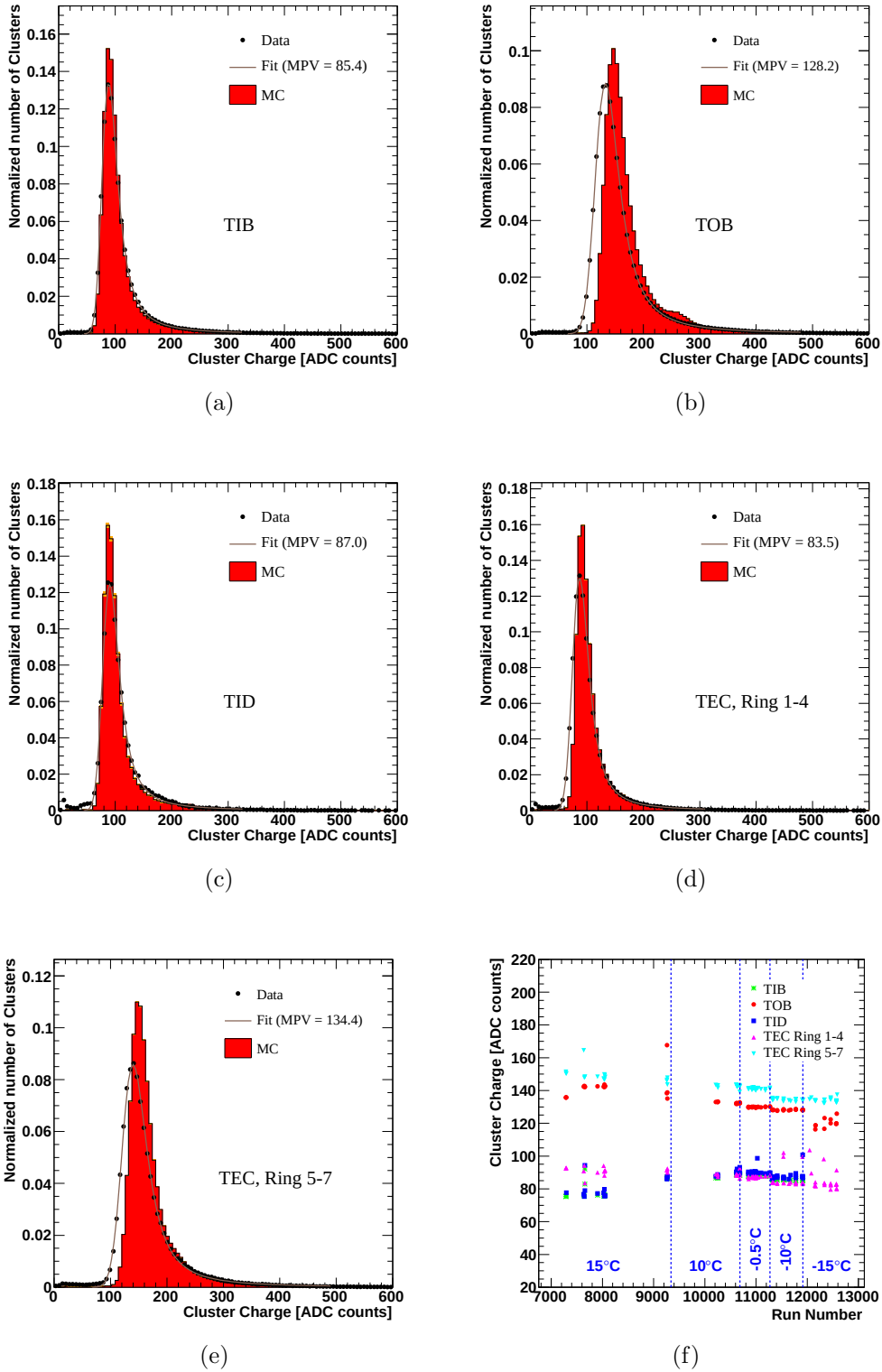


Figure 4.27: (a) to (e): Cluster charge distributions measured in scintillator configuration C at -10°C for TIB, TOB, TID, TEC ring 1-4 and TEC ring 5-7. The charge is corrected for the track angle and the tick mark height in case of cosmic data (dots) and only corrected for the track angle in case of simulated events (red histograms). The data are fitted with a landau distribution convoluted with a gaussian function and the resulting MPV is given in the plots. (f): MPV of the fitted cluster charge distributions (track angle and tick height corrected) for the different subdetectors as a function of the run number. The temperature periods are indicated by blue lines.

charge distributions are normalized to perpendicular incidence where the produced charge is proportional to the module thickness. This agreement cannot be observed in case of the TIB and TOB values due to the different APV settings.

Comparing the measured data with the simulation results it is obvious that the MC predicts larger charges, especially for the thick sensors. This indicates that the signal simulation has to be tuned once collision data are available. It has to be taken into account that the simulation is zero suppressed while the cosmic runs are performed in virgin raw mode. This causes a saturation effect at 255 ADC counts (corresponding to the limited dynamical range of 8 bit in zero suppression instead of 10 bit in virgin raw) which leads to an excess in the MC signal distribution around 255 ADC counts, particularly visible in the TOB histogram.

Figure 4.27(f) shows the most probable value of a fitted landau convoluted with a gaussian function for the cluster charge distributions obtained during the different cosmic runs. The values for the various subdetectors and module thicknesses are depicted separately. In the first run period shown here a wrong latency value was used resulting in a change of the measured cluster charge before and after run number 8400, which affects mostly the barrel and the inner disk modules. Apart from that a slight decrease of the cluster charge with decreasing temperature and partially adjusted APV parameters can be observed. Within one temperature configuration the most probable charge is quite stable. Some outliers visible in the trend plot are due to a failing fit procedure. There is a clear difference between thick and thin sensors.

In contrast to the cluster charge the ratio of the cluster signal over cluster noise should be independent of gain corrections since both the signal and the noise are influenced by the electronics gain in the same way. Thus, this ratio is better suited to compare different modules or operating temperatures or cosmic runs to each other and to measure the detectors stability. According to the previous sections, the cluster signal and noise are defined following

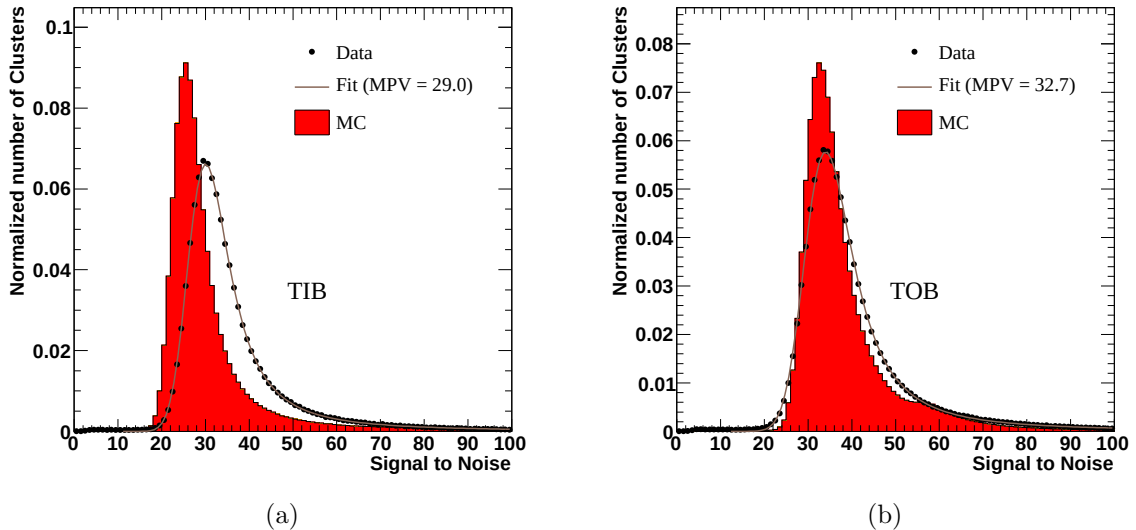


Figure 4.28: Signal-to-Noise distributions measured in scintillator configuration C at -10°C for TIB and TOB. The charge is corrected for the track angle both for cosmic data (dots) and for simulated events (red histograms). The data are fitted with a landau distribution convoluted with a gaussian function and the resulting MPV is given in the plots.

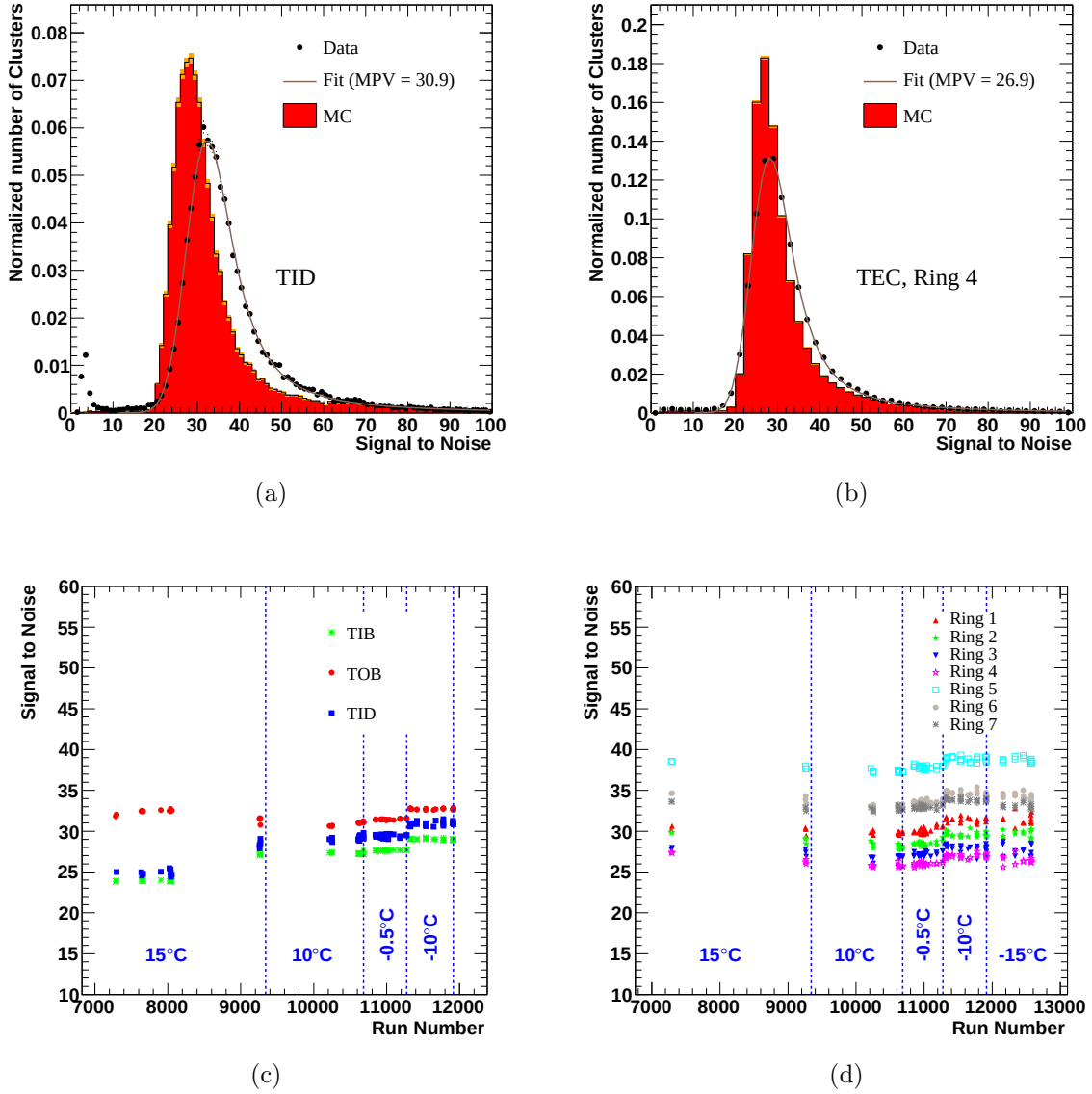


Figure 4.29: (a) and (b): Signal-to-Noise distributions measured in scintillator configuration C at -10°C for TID and TEC ring 4. The charge is corrected for the track angle both for cosmic data (dots) and for simulated events (red histograms). The data are fitted with a landau distribution convoluted with a gaussian function and the resulting MPV is given in the plots. (c) and (d): Trend plots of the MPV of the fitted S/N distributions for the TIB, TOB, TID and the seven TEC geometries. The temperature periods are indicated by blue lines.

equation 3.1.

Figures 4.28 and 4.29 (a) and (b) show the signal-to-noise ratio of on-track clusters measured in the different subdetectors both in cosmic data and simulation. The signal is again normalized to perpendicular incidence using the reconstructed track angle. The data are fitted using a landau distribution convoluted with a gaussian function. The resulting most probable value is in all cases of the order $S/N \approx 30$ demonstrating the very good performance of the silicon sensors. Compared to the data the S/N ratio is underestimated in the simulation. This is caused by the noise used in the MC. As already shown in figure

4.14(b) the noise parametrization applied to the simulation leads to higher noise values with respect to the measured ones resulting in a reduced S/N .

In figures 4.29 (c) and (d) the MPV of the fitted signal-to-noise distributions of the different subdetectors are shown as a function of the run number. In case of the TEC the seven ring geometries are depicted separately. As already mentioned for the cluster charge a wrong latency value was used during the first run period leading to a step also in the S/N trend, visible for the barrel and the inner disk modules. Furthermore, during the 10°C running the VPSP optimization was introduced in the commissioning procedure affecting the noise performance (see section 4.6.1.2). For the remaining run periods the S/N ratio is very stable within one temperature environment and shows a slight increase with decreasing operating temperature. For the TEC the dependence both on the module thickness and the strip length is clearly visible. The thin sensors (ring 1-4) have a smaller signal-to-noise than the thick ones (ring 5-7). In addition, in each of these two groups the S/N value decreases with increasing ring number corresponding to increasing strip length. This causes the S/N ratio to be minimal for ring 4 modules and maximal for ring 5 modules.

At -10°C the TIB detectors have a signal-to-noise ratio of about 29, the TOB ones of about 33, the TID ones of about 31 and the TEC ones between 27 and 39.

4.6.2.5 Capacitive Coupling

When charge carriers are produced inside a silicon sensor induced by the crossing of a charged particle, they can be shared between neighbouring strips due to the extension of the charge cloud by diffusion, the drift in the electrical field and the deviation caused by the lorentz force in the magnetic field, and the track angle of incidence. In addition, a strip is coupling a fraction of its charge capacitively to its neighbours. The value of this capacitive coupling can be extracted from the data using the so-called η function. This function determines the ratio of the charge measured by neighbouring strips. Two definitions, the asymmetric η and the symmetric η , can be used to calculate the capacitive coupling:

$$\eta_{\text{asymm}} = \frac{Q_{\text{left}}}{Q_{\text{left}} + Q_{\text{right}}} \quad \text{or} \quad \eta_{\text{symm}} = \frac{Q_{\text{left}} + Q_{\text{right}}}{2 \cdot Q_{\text{seed}}} \quad (4.8)$$

In case of the asymmetric function the two strips of a cluster with the highest amplitudes are taken into account and the charge of the one with the smaller strip number is denoted as Q_{left} and the signal of the channel with the higher strip number as Q_{right} (see figure 4.30 left). For the symmetric approach the charge of the seed strip of the cluster is used as Q_{seed} while the signals on the left and right neighbour are indicated by Q_{left} and Q_{right} . An example is shown in figure 4.30 right. If a cluster consists of less strips than needed for the respective η definition, the left and right neighbouring digis (i.e. the charge of a strip that does not fulfill the cluster thresholds) are considered. Only datasets obtained in Virgin Raw mode can be used since these data contain the charge information for all digis.

To measure the capacitive coupling the different sources of charge sharing have to be disentangled. The diffusion is expected to be very small with respect to the strip pitch so that it can be neglected. The deviation due to a magnetic field is not present in the tracker slice test since no magnetic field was used. To reduce the influence of charge sharing due to inclined tracks with respect to the module surface a cut on the local xz -angle (see figure 4.21(a)) is applied. The cluster eta is analyzed only if the respective reconstructed angle

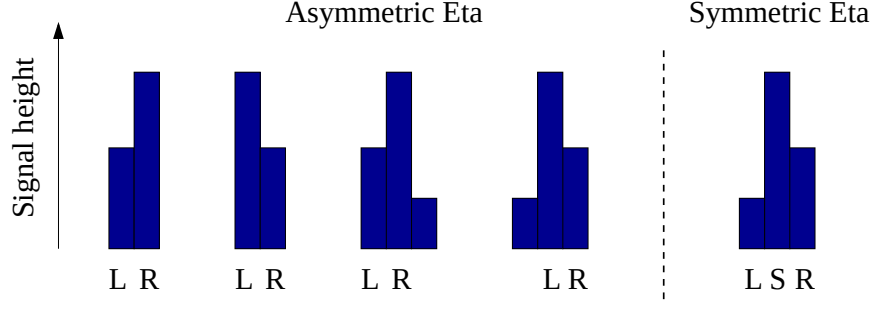
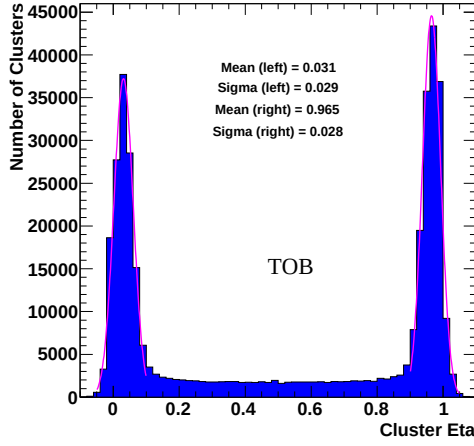
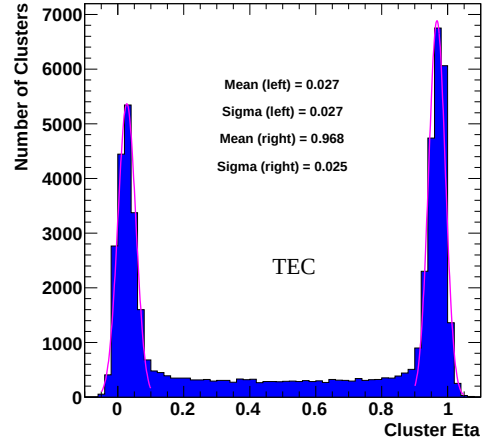


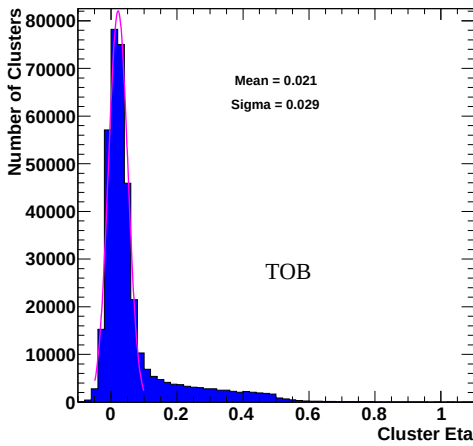
Figure 4.30: Schematic view of the relevant charges used for the η calculation. The sketch shows as an example clusters consisting of two or three strips. The height of the bars represents the measured signal. L is the strip corresponding to Q_{left} , R is the one associated with Q_{right} and S indicates Q_{seed} .



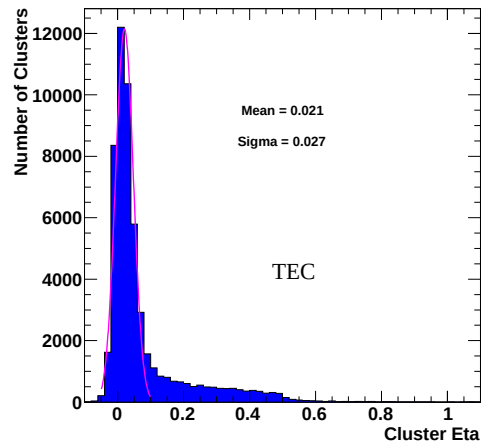
(a)



(b)



(c)



(d)

Figure 4.31: Cluster η distributions obtained requiring perpendicular tracks with $\phi_{\text{local}} < 0.1$ and cluster sizes less than five strips. Only Virgin Raw data are taken into account³. On top the asymmetric η and on bottom the symmetric η is shown, both for the TOB and the TEC. The results of gaussian fits to the peaks are given in the plots.

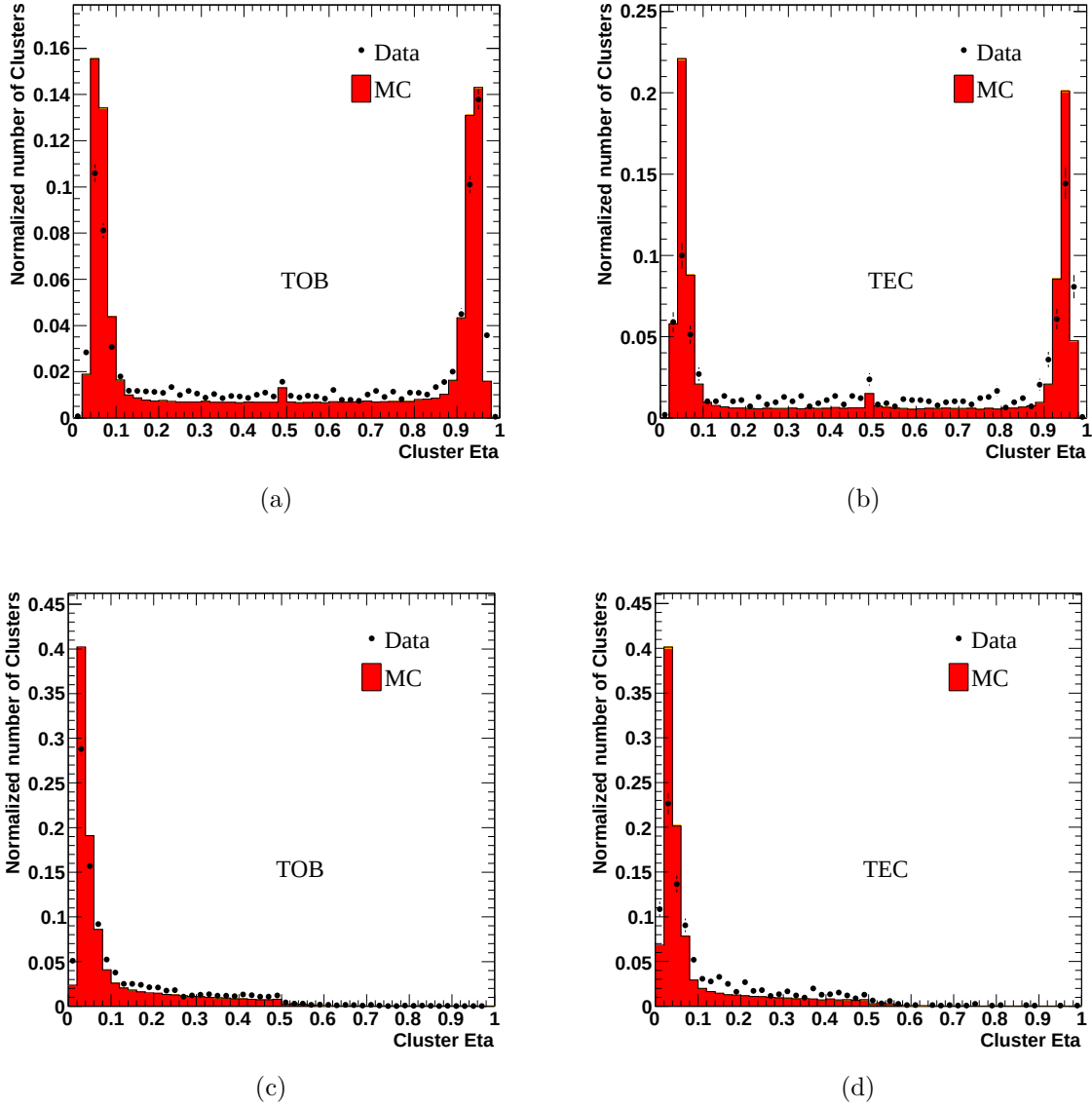


Figure 4.32: Comparison of the cluster η distribution obtained with the Zero Suppressed MC (in red) and Zero Suppressed cosmic runs (dots). On top the asymmetric η and on bottom the symmetric η function is shown, both for the TOB and the TEC. Only clusters with $\phi_{\text{local}} < 0.1$ and cluster size < 5 are used.

fulfills $\phi_{\text{local}} < 0.1$ rad. In addition, the cluster width is required to be smaller than five strips.

The resulting asymmetric and symmetric η distributions for the TOB and the TEC are shown in figure 4.31. The corresponding distributions for the TIB and the TID are depicted in appendix F. In case of the asymmetric function two peaks are expected, one located around 0 corresponding to hits measured on the right strip and the other one around 1 for hits measured on the left strip. The intermediate region between the two peaks is dominated by charge sharing. For the symmetric η distribution one peak around 0 is expected indicating

³Since in Virgin Raw mode all signals are retained after pedestal subtraction, meaning positive and negative ones, the η value can be below 0 or above 1. This is not the case in Zero Suppressed mode.

that most of the charge is collected by the seed strip of the cluster, again with charge sharing towards higher η values. The capacitive coupling can be determined from the mean of a gaussian fit to the peaks. The results obtained with the various distributions indicate a value of about 2 % in case of the symmetric and about 3 % in case of the asymmetric definition. In addition to the capacitive coupling of the measured signal to the neighbouring strips, the noise of the respective channels has to be taken into account. Therefore, the width of each peak is determined by the noise magnitude and can be approximated by $\sigma_{\text{peak}} \approx N/S$ [33] where S is the cluster signal and N the cluster noise. Thus, the inverse of the sigma of about 0.029 leads to a signal-to-noise ratio of about 34 for the TOB and the sigma of about 0.026 results in a S/N ratio of about 38 for the TEC which is in good agreement with the measured signal-to-noise ratios presented in the previous section.

The η distributions calculated using Virgin Raw data cannot be compared to the results of the simulated events. Since the digitizer in the simulation performs Zero Suppression, the digis are only retained if their signal is above the required threshold of two times the strip noise. This leads to a bias in the capacitive coupling towards larger values because in Virgin Raw mode all digis after pedestal subtraction, both positive and negative ones, are kept. Therefore, to compare data with MC, cosmic runs performed in Zero Suppression have to be used. Figure 4.32 shows the η distributions obtained in Zero Suppression for the TOB and the TEC in data and MC. Here, the capacitive coupling which is a parameter in the simulation was set to 3 %. The distributions show a good agreement between data and MC using this value. A capacitive coupling of 7 % derived from the MTCC measurements turned out to be too large comparing the simulation and the slice test data. However, the capacitive coupling depends for example also on the trigger timing [29] so that the final tuning can only be performed with the final setup.

4.6.2.6 Tracking Performance using different Algorithms

As described in section 4.4 three track reconstruction algorithms were available for the cosmic muon reconstruction in the tracker slice test: The Cosmic Track Finder (CosmicTF), the Combinatorial Track Finder (CTF) and the Road Search algorithm (RS). In figure 4.33 some track related distributions are shown comparing the results of the three algorithms to each other. For this study one cosmic run performed at -10°C in scintillator configuration C and containing about 100000 events is used. The run was analyzed separately for the different track reconstructions leading to slightly different numbers of analyzed events due to the failure of a few analysis jobs. Because of that all distributions are scaled to unity in order to compare relative instead of absolute numbers to each other.

Figure 4.33(a) depicts the number of reconstructed tracks per event. In 40 – 45 % of the recorded triggers no particle trajectory could be found in neither algorithm. This shows that the track reconstruction efficiency is comparable among the three approaches. It has to be taken into account that the CosmicTF retains one track per event at most while the CTF and the RS are able to reconstruct several trajectories in the same event. Therefore the number of single track events is highest for the CosmicTF.

In figure 4.33(b) the number of reconstructed hits belonging to a reconstructed track is shown. At least four hits are required in all algorithms to build a trajectory. The most probable value of the number of hits is 6 for both the CTF and the RS whereas it is 8 for the Cosmic Track Finder. This difference is caused by the fact that the CosmicTF treats both the $r\phi$ and the stereo hits separately while the CTF and the RS combine the clusters of

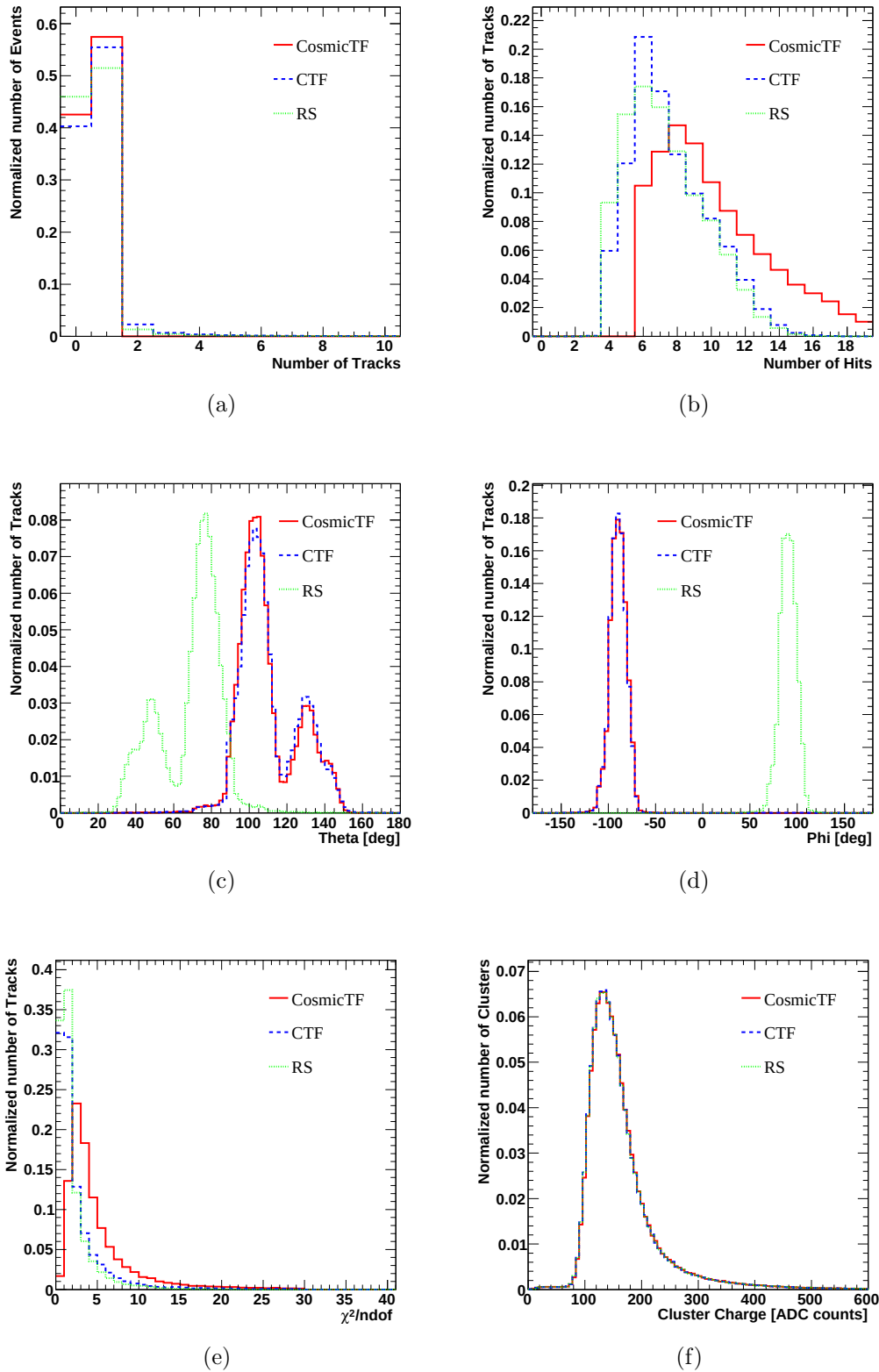


Figure 4.33: Comparison of the three tracking algorithms available for the cosmic muon reconstruction: The Cosmic Track Finder (in red), the Combinatorial Track Finder (in blue) and the Road Search algorithm (in green). (a) Number of reconstructed tracks per event, (b) Number of hits belonging to a track, (c) Polar angle θ and (d) azimuthal angle ϕ of the reconstructed tracks, (e) Normalized χ^2 per track and (f) Angle and tick height corrected cluster charge of on-track clusters in the TOB.

a double-sided module to a so-called matched hit that is associated with the reconstructed track.

Figures 4.33(c) and 4.33(d) show the angular distributions of the trajectories with respect to the polar angle θ and the azimuthal angle ϕ . The distributions for the CosmicTF and the CTF are in very good agreement and reflect the expectation of cosmic muons originating from the top of the detector and travelling outside in ($\phi \approx -90^\circ$), reconstructed either in the barrel ($\theta \approx 100^\circ$) or in the endcap region ($\theta \approx 130^\circ$). In contrast to that the Road Search distributions are flipped horizontal since the direction of the reconstructed tracks is not adapted to cosmic muons but points inside out. This causes the ϕ angle to peak around $+90^\circ$ and the θ angle around 80° and 50° , respectively. Changing the direction of flight for the RS all three algorithms result in similar angular distributions that are in agreement with the geometrical acceptance of the scintillator setup used.

The track normalized χ^2 given in figure 4.33(e) is a bit higher for the CosmicTF with a most probable value of about 3 compared to 1-2 for the CTF and the RS. Nevertheless, the angle and tick height corrected cluster charge of clusters belonging to a reconstructed track (figure 4.33(f) shows the distribution for TOB hits as an example) is in very good agreement for the three algorithms and indicates that neither algorithm is tended to pick up noise hits due to the clear signal peak around 130 ADC counts and the absence of a noise contribution at low cluster charges.

Since the results of the three tracking algorithms are very similar only the distributions according to the Combinatorial Track Finder are shown in this chapter.

4.6.2.7 Measurements of the Track Residuals

To get a first estimate of the alignment of the silicon strip tracker the track-hit residuals are calculated. Therefore the track position on the surface of each module is extrapolated and the point of impact is compared to the measured cluster position on the module. Since the silicon strip detectors provide a precise position measurement only in the direction perpendicular to the strips, only the distance between the measured and the predicted hit along x ($\Delta x = x_{\text{meas}} - x_{\text{pred}}$) in the local module frame (see section 3.7.1) is determined.

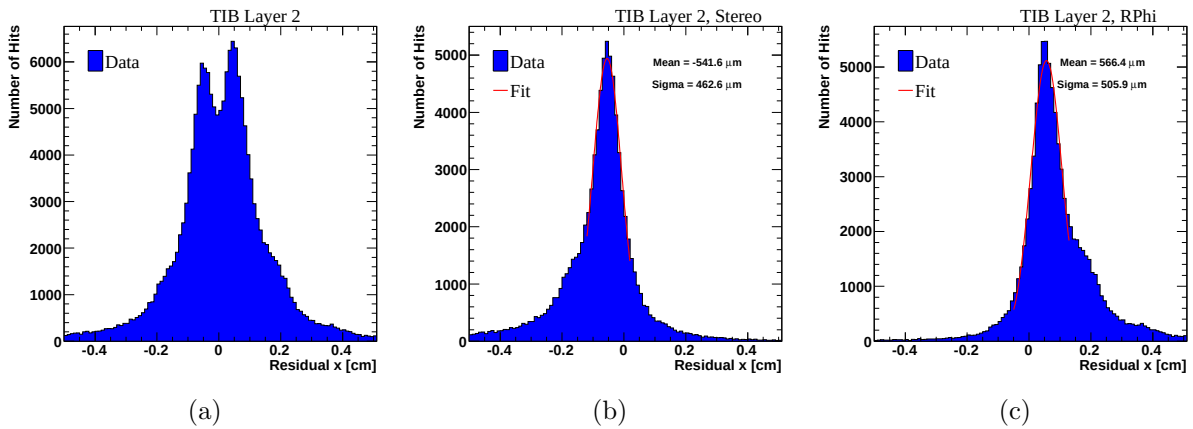


Figure 4.34: Track residuals measured in the local x direction for TIB layer 2 modules without alignment corrections. (a) All modules, (b) only stereo modules and (c) only $r\phi$ modules are taken into account.

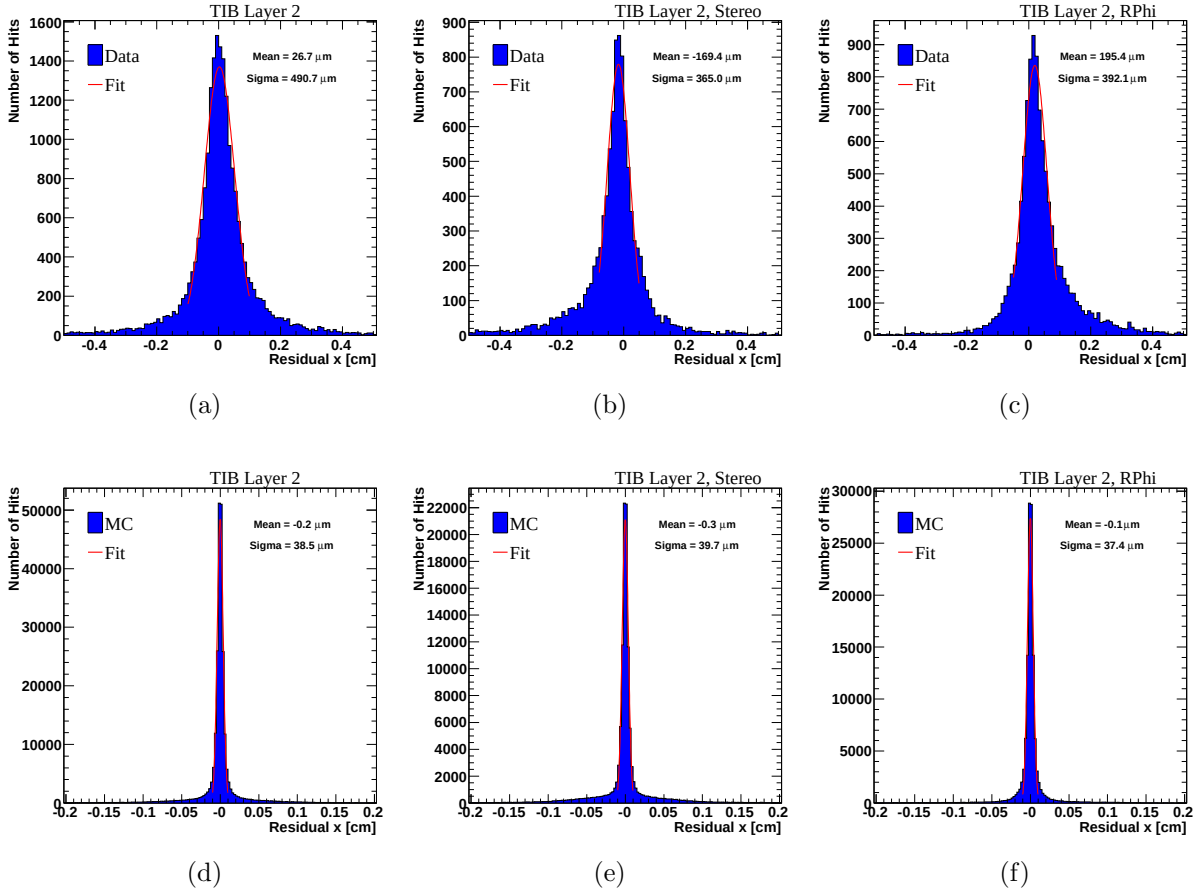


Figure 4.35: Track residuals measured in the local x direction for TIB layer 2 modules. (a) All modules, (b) only stereo modules and (c) only $r\phi$ modules are taken into account using alignment corrections. (d) All modules, (e) only stereo modules and (f) only $r\phi$ modules are taken into account using MC events.

Figure 4.34(a) shows the residual distribution obtained with the TIB layer 2 modules. A clear two peak structure centered around $\Delta x = 0$ cm is visible indicating a displacement of this layer. The two peaks that are shifted symmetrically to negative and positive Δx values originate from the double-sided modules mounted on this TIB layer. Since the mono and the stereo modules are mounted back to back, the local coordinate system is rotated and the sign of Δx is inverted although the shift points in the same direction. Figures 4.34 (b) and (c) depict the distribution separately for stereo and $r\phi$ detectors. The two peak structure disappears and the remaining distribution is shifted towards negative and positive Δx values, respectively. A gaussian fit to the central distribution results in a mean of about $550 \mu\text{m}$ indicating a common shift of the modules belonging to this TIB layer with respect to the ideal geometry.

Figures 4.35 (a) - (c) depict the same distributions for one cosmic run performed under the same conditions but using alignment corrections during the data reconstruction. The information about the relative position of the modules within the detector components and of the larger-level structures within the tracker are available from optical survey measurements [34]. In addition, parts of the barrel region are aligned with cosmic tracks using the runs recorded in scintillator configuration A [34]. These results are applied to the reconstruction

to correct the ideal geometry and improve the tracking procedure.

As shown in figure 4.35(a) the two peak structure disappears after applying the alignment corrections. Nevertheless, analyzing the residuals on mono and stereo detectors separately (figures 4.35 (b) and (c)) indicates that a displacement is still remaining since the alignment based mostly on the survey information has to be improved using a fully track based alignment. Figures 4.35 (d) to (f) depict the residuals obtained with the TIF simulation. It is obvious that the ideal geometry results in narrow distributions centered around $\Delta x = 0 \mu\text{m}$ with a sigma of about $38 \mu\text{m}$ which is in the order of the spatial resolution for single hits given by $\text{strip pitch}/\sqrt{12}$.

The residuals measured in the TOB layer 1 modules without alignment corrections are shown in figure 4.36 (a) to (c). Compared to the TIB results the distributions reflect a more precise positioning. The shift in the local x direction is about $1 \mu\text{m}$ in case of stereo and about $38 \mu\text{m}$ in case of mono detectors with a sigma of $321 \mu\text{m}$ and $255 \mu\text{m}$, respectively. The same distributions applying the alignment corrections are depicted in figures 4.36 (d) to (f). The mean residual is still of the order $10 \mu\text{m}$ while the sigma has improved to about $210 \mu\text{m}$. The simulation results again in distributions located at $0 \mu\text{m}$ with a sigma of about $70 \mu\text{m}$ which is comparable to $183 \mu\text{m}/\sqrt{12}$ (see figure 4.37).

To illustrate the residuals measured in the TEC modules the so-called measurement frame

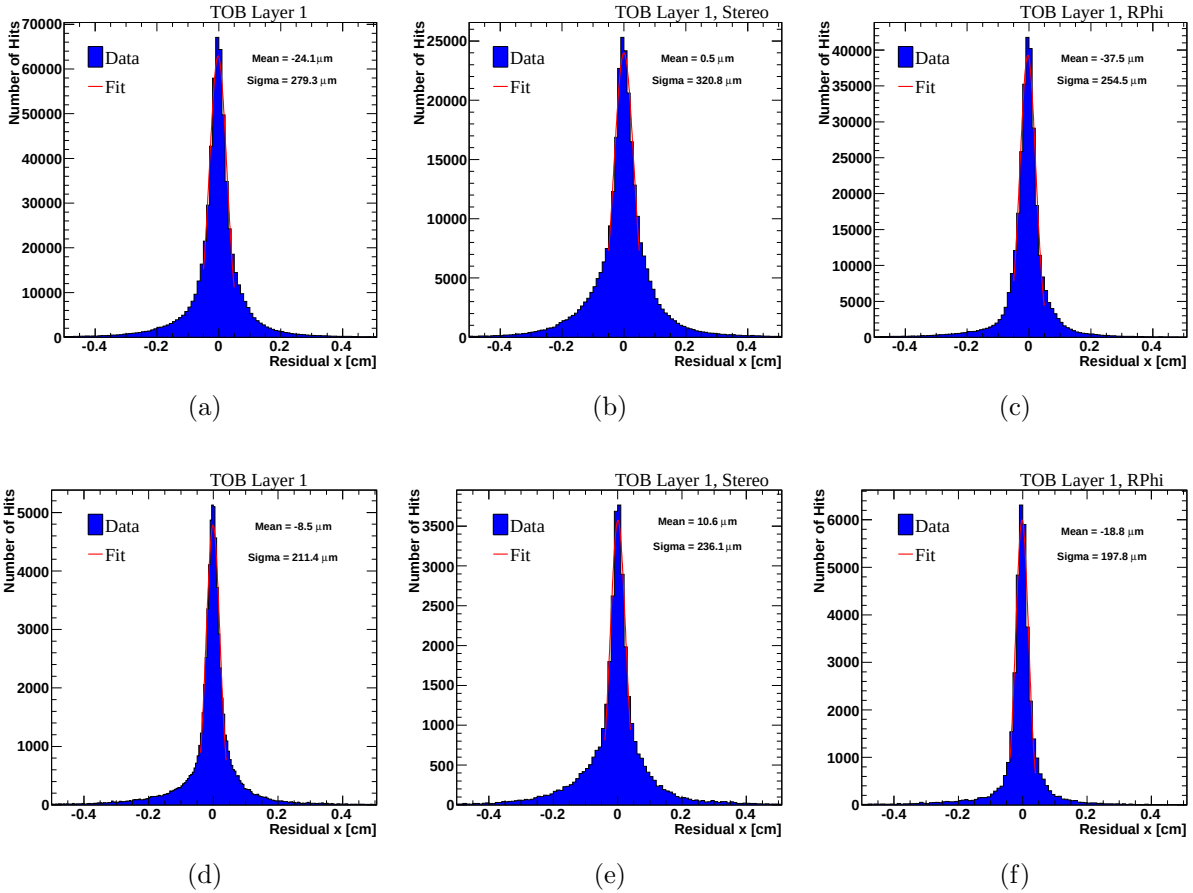


Figure 4.36: Track residuals measured in the local x direction for TOB layer 1 modules without (top) and with (bottom) alignment corrections. (a) and (d) All modules, (b) and (e) only stereo modules and (c) and (f) only $r\phi$ modules are taken into account.

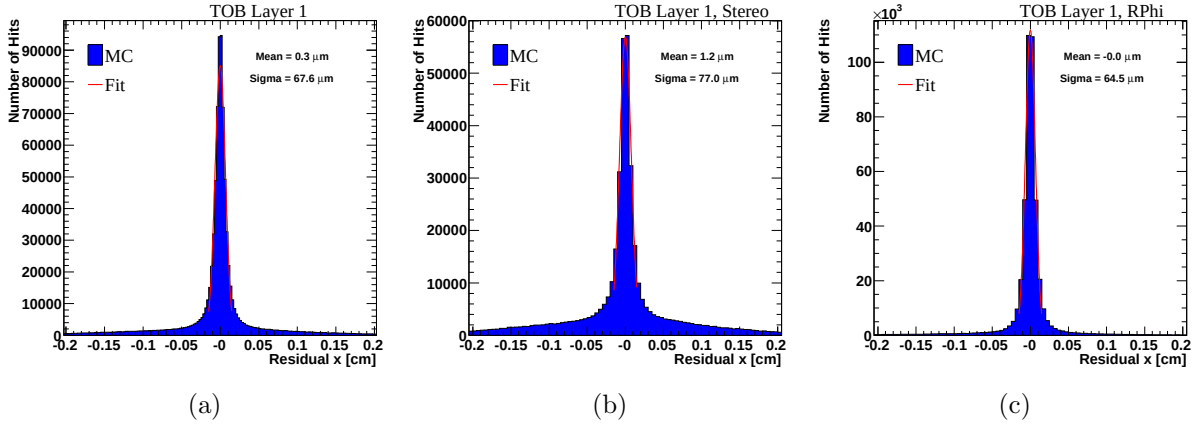


Figure 4.37: Track residuals measured in the local x direction for TOB layer 1 modules. (a) All modules, (b) only stereo modules and (c) only $r\phi$ modules are taken into account using MC events.

of the strip detectors is used since the pitch of these wedge-shaped sensors is not constant along the modules so that the distance between the measured and the predicted hit depends on the position of the particle crossing which is unknown in the direction parallel to the readout channels. Therefore, the residuals are given in units of strips which is independent from the particle transition in the local y direction but does not provide an absolute length for the residuals.

The results for the front tower of the TEC sector 2 are shown in figure 4.38 without using the alignment corrections in (a), applying the alignment constants in (b) and using the simulation in (c). All distributions are in very good agreement with $\Delta x = 0$ strips showing a mean of less than 1 strip corresponding to the order $10 \mu\text{m}$. Assuming a pitch of $140 \mu\text{m}$ on average, the width of the data distributions corresponds to about $380 \mu\text{m}$ and the one measured in the simulation to about $70 \mu\text{m}$. It has to be taken into account that also for TEC petals some rings are equipped with double sided modules and rotated detectors from the hybrid point of view causing a change in the local module frame. These different

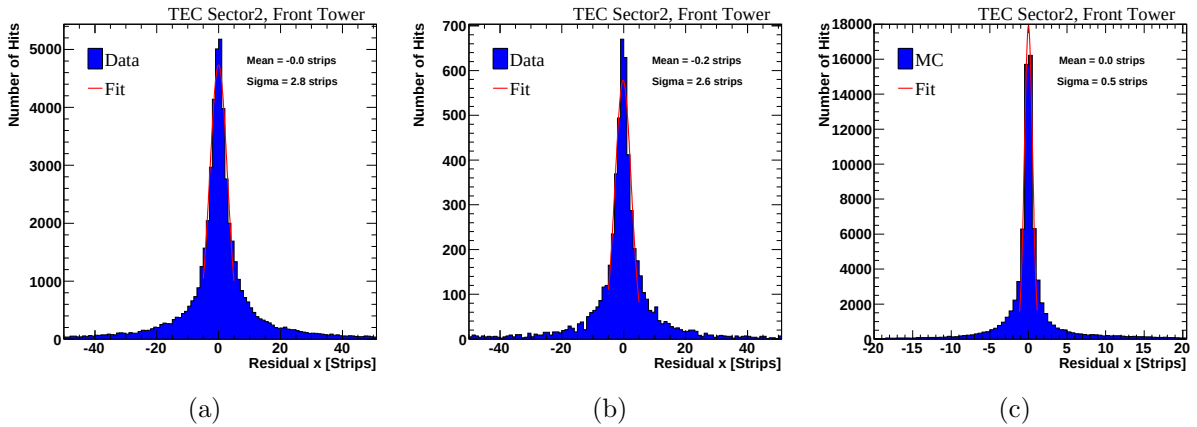


Figure 4.38: Track residuals measured in the local x direction for TEC sector 2 front tower modules. (a) Data without alignment corrections, (b) data with alignment corrections and (c) MC events.

coordinate systems have not been studied separately resulting possibly in a widening of the residual distributions.

An overview of the measured residuals in all TIB layers, TOB layers and TEC towers participating in the slice test, both without alignment corrections and applying the alignment constants and using the simulated events is given in appendix E. All results presented here are preliminary and represent a first approximation of the tracker alignment since the final alignment corrections have to be obtained using the laser alignment system and beam collision events. In addition, the trajectories of cosmic muons with a most probable energy below 1 GeV are dominated by multiple scattering causing broader residual distributions with respect to the spatial resolution of the silicon detectors.

Chapter 5

Conclusions

This thesis deals with the performance of the silicon strip tracker for the CMS experiment during different construction phases from the single module test to the final assembly of all subdetector components in the tracker support tube. Special emphasis is laid on the functionality of the tracker end caps since the substructures of the TEC called petals were partially integrated and tested in Aachen and in addition, one end cap (TEC+) was completely assembled at the I. Physikalisches Institut B in Aachen.

In total, 6544 silicon strip modules with approximately 4,000,000 readout channels were mounted on petals used for the two tracker end caps (including spare petals). Before their integration on the petals they had to pass a single module test called ARC test to check their functionality and grade their quality. A failure rate of less than 2 % defective channels per module was required but the ARC test identified on average only about 0.2 % bad strips on a 4 APV module and 0.1 % on a 6 APV module. A total fraction of 1.4 ‰ faulty strips reflects the very good quality of the silicon sensors. The largest fraction of these channels was marked as noisy. They can still be used for the data reconstruction with a probably lower signal-to-noise ratio. The leakage current measured at a depletion voltage of 450 V is well below the required 10 $\mu\text{A}/\text{sensor}$ projecting a proper functionality of the silicon modules with an acceptable leakage current also after several years of irradiation.

The high quality of the silicon modules was confirmed in the following petal longterm test after mounting the detectors on the petal bodies. The assembly and the test procedure were performed in six Petal Integration Centers, one in the III. Physikalisches Institut B in Aachen. Out of 294 production petals usable for the tracker end cap integration (288 petals are needed, the rest is spare) 286 petals received the best quality grade A. The remaining 8 petals had to be graded manually since the test data were corrupted. Due to the lack of time a retest was not possible. The fraction of faulty channels was about 1.2 ‰ in total, in very good agreement with the ARC results showing that nearly no additional damages occurred during the petal integration and that the entire petal structure is of very high quality as well. Most of the channels that were known to be faulty from the ARC test were identified in the petal test. The strips being conspicuous in only one of the two test setups were mainly related to high noise.

Approximately 1 % of the final strip tracker consisting of two shells for the TIB, four rods for the TOB and two petals for the TEC were operated together with parts of all CMS subdetectors in the Magnet Test and Cosmic Challenge. Analyzing the noise behaviour of the TEC modules in dedicated commissioning runs conspicuous channels could be identified and compared to the corresponding petal longterm test results. Most of the known faulty flagged

strips were confirmed. Only about 1.7‰ of the operated TEC readout channels showed a different behaviour in the two test setups. The single strip noise was very stable during the whole data taking period and no systematic variations with the magnetic field were observed. Cosmic rays detected in the muon chambers were used to trigger the readout of all participating CMS subsystems. Signals related to cosmic muon events could be analyzed and clearly separated from noise signals. For the thin TEC sensors a signal-to-noise ratio of about 23 and for the thick ones a ratio of about 31 was achieved.

Finally, 25% of the $+z$ side of the silicon strip tracker were commissioned after the entire assembly of all subdetectors into the tracker support tube was finished. A setup of scintillation counters allowed to measure approximately 5 million cosmic muon events under various trigger positions and operating temperatures. Excluding single bad APVs or lasers the TIB, TID and TEC showed about 1‰ readout channels that were conspicuous in the noise behaviour. Only in the TOB the fraction of noisy channels is larger (about 5‰) because of the so-called wing noise which affects mostly modules mounted closest to the rod's CCUM board and the power supply cables. As expected, the single strip noise was reduced with decreasing operating temperature and adjusted APV parameters. The linear dependence of the noise on the input capacitance to the APV corresponding to the strip length could be proven. From tracks reconstructed in all tracker subdetectors the impact of the track incidence angle on the detector performance such as the measured cluster charges and cluster multiplicities could be studied. The track reconstruction itself was verified and found to be in excellent agreement with the constraints given by the geometrical setup of the scintillation counters. The signal-to-noise ratio of the measured hits was determined to be in the order of 30 and the capacitive coupling between adjacent strips was calculated in the slice test to be about 3%.

Appendix A

Module Dimensions and Tracker Subdetectors

A.1 Module Characteristics

To instrument the full CMS strip tracker with silicon modules 15 different geometries are needed. They differ in shape (rectangular in the barrel and wedge-shaped in the end-caps), length, number of readout channels (512 or 768) and strip pitch. In addition, modules mounted on the inner layers and rings, respectively, consist of only one sensor whereas the outer silicon detectors contain two sensors that are wire-bonded to each other. This increases the strip capacitance which scales with its length and, because the ratio strip width w to strip pitch p is $\frac{w}{p} = 0.25$ for all sensor types, the electronics noise N is a linear function of the strip length as well.

Layer	Nr. Strips/Det	Pitch [μm]	Active strip length [mm]	Thickness [μm]	Nr. Sensors/Det
TIB1	768+768	80	116.9	320	1
TIB2	768+768	80	116.9	320	1
TIB3	512	120	116.9	320	1
TIB4	512	120	116.9	320	1
TOB1	512+512	183	183.2	500	2
TOB2	512+512	183	183.2	500	2
TOB3	512	183	183.2	500	2
TOB4	512	183	183.2	500	2
TOB5	768	122	183.2	500	2
TOB6	768	122	183.2	500	2

Table A.1: Module characteristics for inner and outer barrel detectors.

To obtain a high signal to noise ratio $\frac{S}{N}$ anyhow, the sensor thickness of these modules is increased leading to a higher charge production and thus to a better signal performance such that the $\frac{S}{N}$ ratio is still good. Tables A.1 and A.2 summarize some module characteristics for the different layers and rings, respectively.

Layers or rings equipped with double modules consisting of a normal and a stereo module are indicated with two values for the number of strips per detector. Since the barrel modules

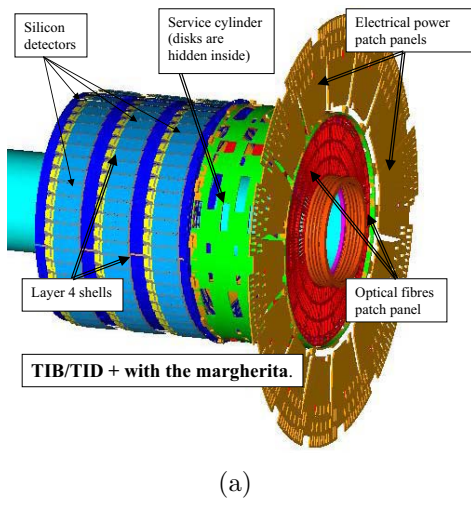
Ring	Nr. Strips/Det	Pitch [μm]	Active strip length [mm]	Thickness [μm]	Nr. Sensors/Det
TID1	768+768	80.5-119	110.9	320	1
TID2	768+768	113-143	88.2	320	1
TID3	512	123-158	110.7	320	1
TEC1	768+768	81-112	85.2	320	1
TEC2	768+768	113-143	88.2	320	1
TEC3	512	123-158	110.7	320	1
TEC4	512	113-139	115.2	320	1
TEC5	768+768	126-156	144.4	500	2
TEC6	512	163-205	181	500	2
TEC7	512	140-172	201.8	500	2

Table A.2: Module characteristics for inner disk and end-cap detectors.

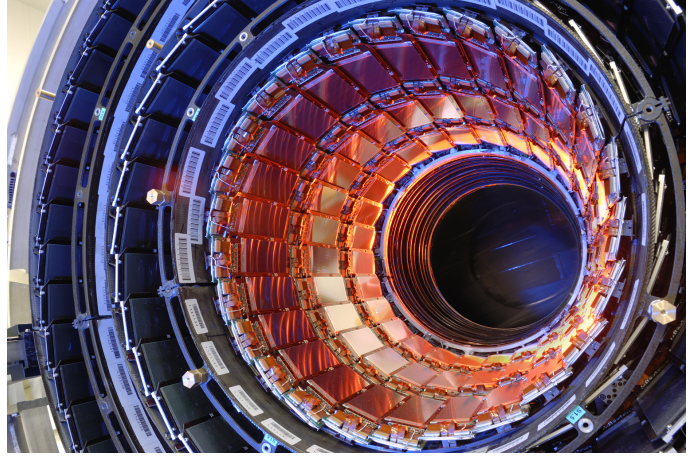
are rectangular-shaped they have a well-defined constant pitch within one detector. This is not the case for the wedge-shaped end-cap modules where the pitch decreases from the broad to the narrow end of the detector. Because of that a pitch range is given for these modules.

A.2 Tracker Subdetectors

To illustrate the layout of the silicon strip tracker in the following some photographs and schematic drawings of the subdetectors TIB, TID, TOB and TEC are shown as well as the substructures (shells, rods, petals) on which the modules are mounted.



(a)



(b)

Figure A.1: Layout of a part of the inner barrel and inner disk. (a) Schematic drawing of the TIB/TID+ subassembly. (b) View of the $+z$ half of the TIB/TID. Visible are the silicon modules of the first TIB layer, surrounded by layers two to four, as well as the inner radius of the TID disks in the back. [11]

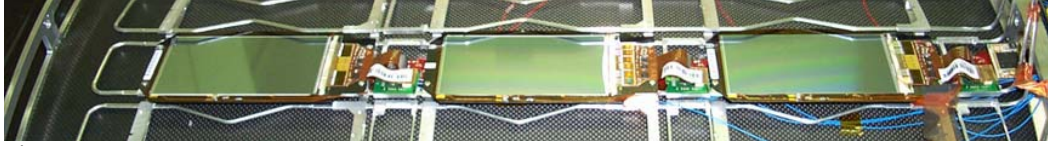
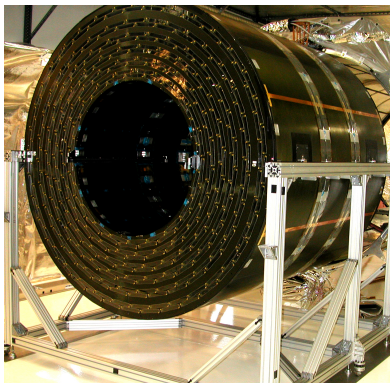
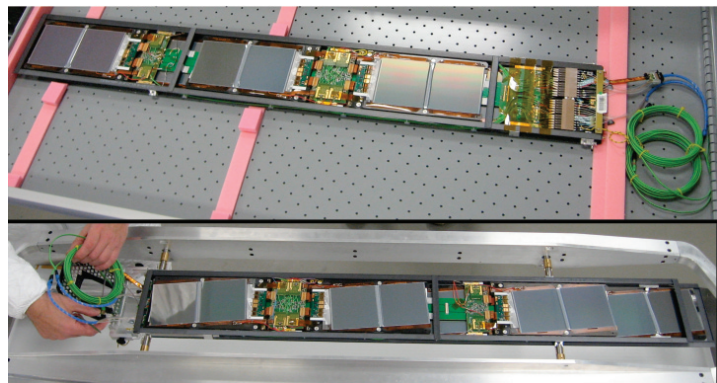


Figure A.2: Three TIB modules mounted on a layer 3 shell. Also visible are the three analog opto hybrids and fibers. [11]

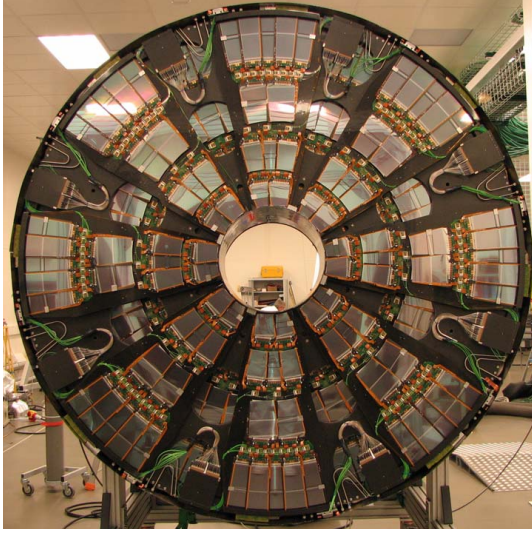


(a)

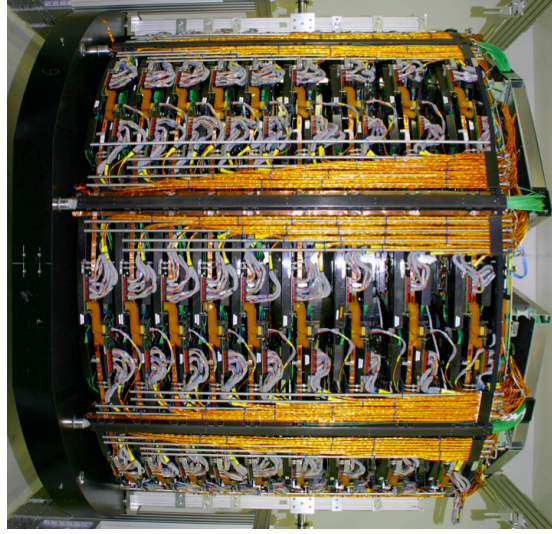


(b)

Figure A.3: Layout of the outer barrel. (a) Picture of the TOB wheel. (b) Photo of an assembled double-sided rod. [11]

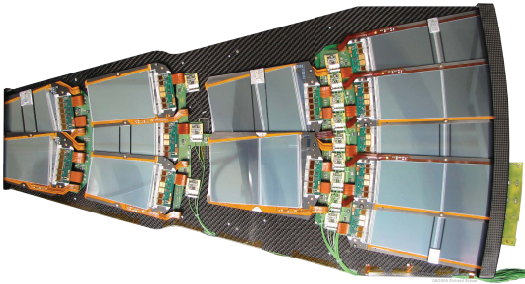


(a)

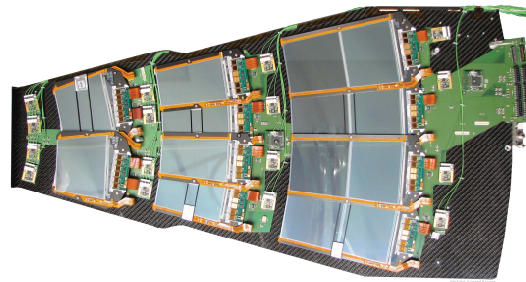


(b)

Figure A.4: Layout of the end-cap. (a) Photograph of a TEC as seen from the interaction point. The diameter of the TECs is 2.3 m. (b) Side view of a TEC. [11]



(a)



(b)

Figure A.5: Photograph of front and back side of a fully integrated TEC petal. [11]

Appendix B

Channel Flags in the ARC and Longterm Tests

If a readout channel shows a suspicious behaviour during the ARC or the petal longterm test it is classified with respect to the defect that occurred. The following table B.1 summarizes the different flags that a faulty channel can get:

Flag	Description
2	Open between pitch adapter and sensor
4	likely Open between pitch adapter and sensor
8	Open between two sensors
16	likely Open between two sensors
32	likely Open (conflicting location results) or possible mid-sensor Open
64	Noisy
128	Short or likely Short
256	likely Pinhole or Saturated channel
512	Pinhole or likely Pinhole
1024	unidentified problem (pinhole/high noise) or faulty due to unknown reason
2048	Saturated channel
4096	defect Inverter

Table B.1: Possible channel flags for defect readout strips.

It is also possible that a channel is tagged with a sum of these flags in case that several defects are present at the same time.

Appendix C

Module Structuring Scheme in the TEC

The following table gives an overview of the layout of a Tracker End Cap consisting of nine disks where disk 1 is the innermost and disk 9 the outermost. Each disk is equipped with front and back petals of different types depending on the petal body. A petal has up to seven rings with a different number of modules per ring. In addition, the assignment of the three power groups to the corresponding rings, the number of APVs belonging to a module of a certain ring and the total number of modules per petal type is shown.

				Front Petals				Back Petals				
Type				1	2			3	4			
Disk				1-3	4-6	7-8	9	1-3	4-6	7-8	9	
Ring	1^6 APVs	Power Group	1	4	–	–	–	2	–	–	–	Number of Modules
	2^6 APVs		1	4	4	–	–	2	2	–	–	
	3^4 APVs		2	3	3	3	–	2	2	2	–	
	4^4 APVs		2	4	4	4	4	3	3	3	3	
	5^6 APVs		3	4	4	4	4	6	6	6	6	
	6^4 APVs		2	4	4	4	4	3	3	3	3	
	7^4 APVs		3	5	5	5	5	5	5	5	5	
per Petal				28	24	20	17	23	21	19	17	

Table C.1: Overview of the module structuring scheme in the TEC.

Appendix D

Additional Quality Plots concerning the LT-Test

In the following, additional quality distributions obtained with the four APV modes (peak and deconvolution mode, inverter on/off) and the three test cycles (First, Cold and Last) in the petal longterm test are shown. The distributions depict the behaviour of all readout channels belonging to the TEC production petals. Normal channels are indicated in green while strips outside the required ranges are marked in red. The fraction of cut channels is given in each plot.

First Temperature Cycle

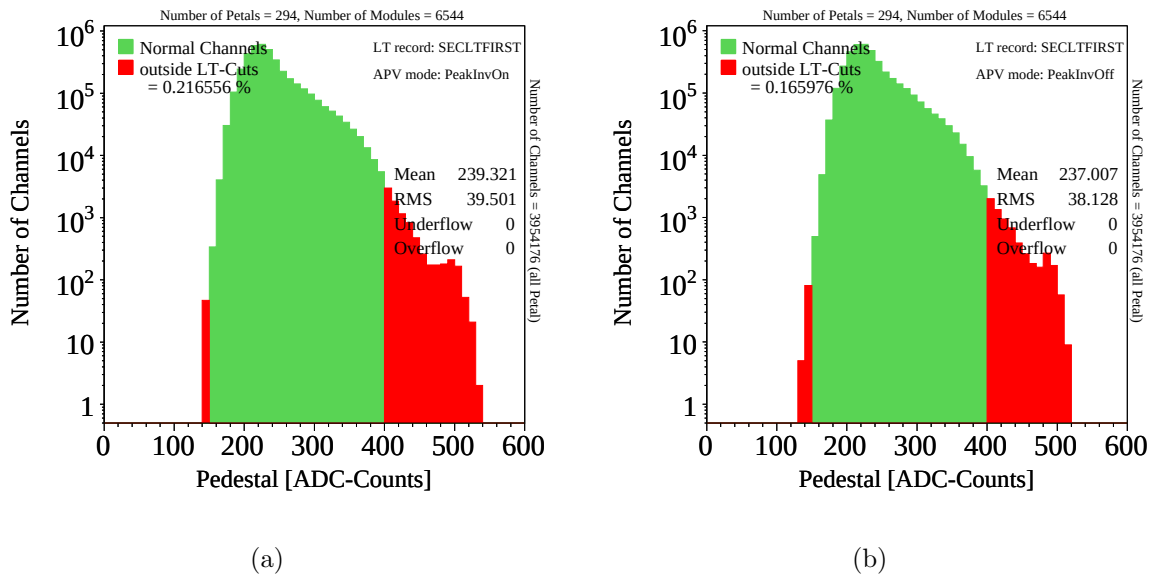


Figure D.1: Pedestal distributions measured in the first test cycle at room temperature.

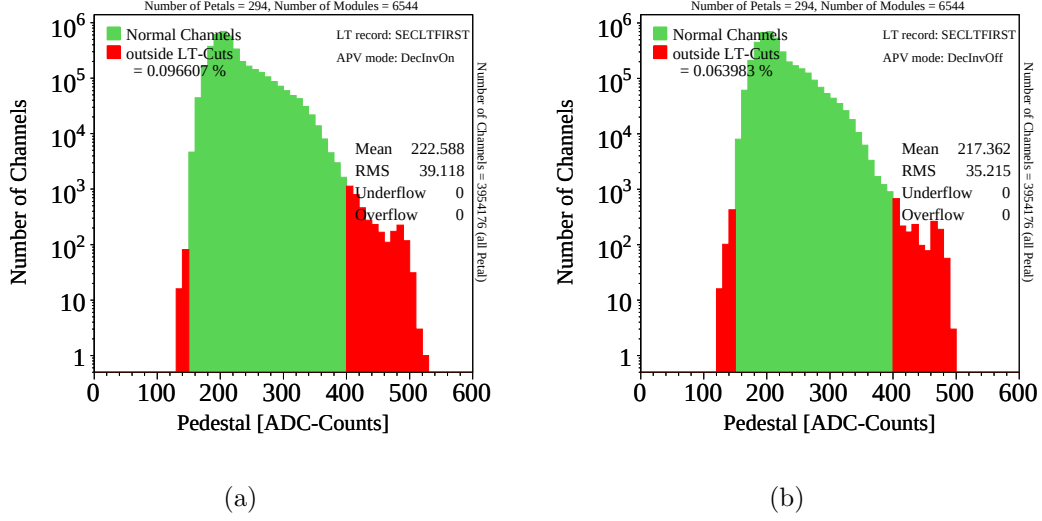


Figure D.2: Pedestal distributions measured in the first test cycle at room temperature.

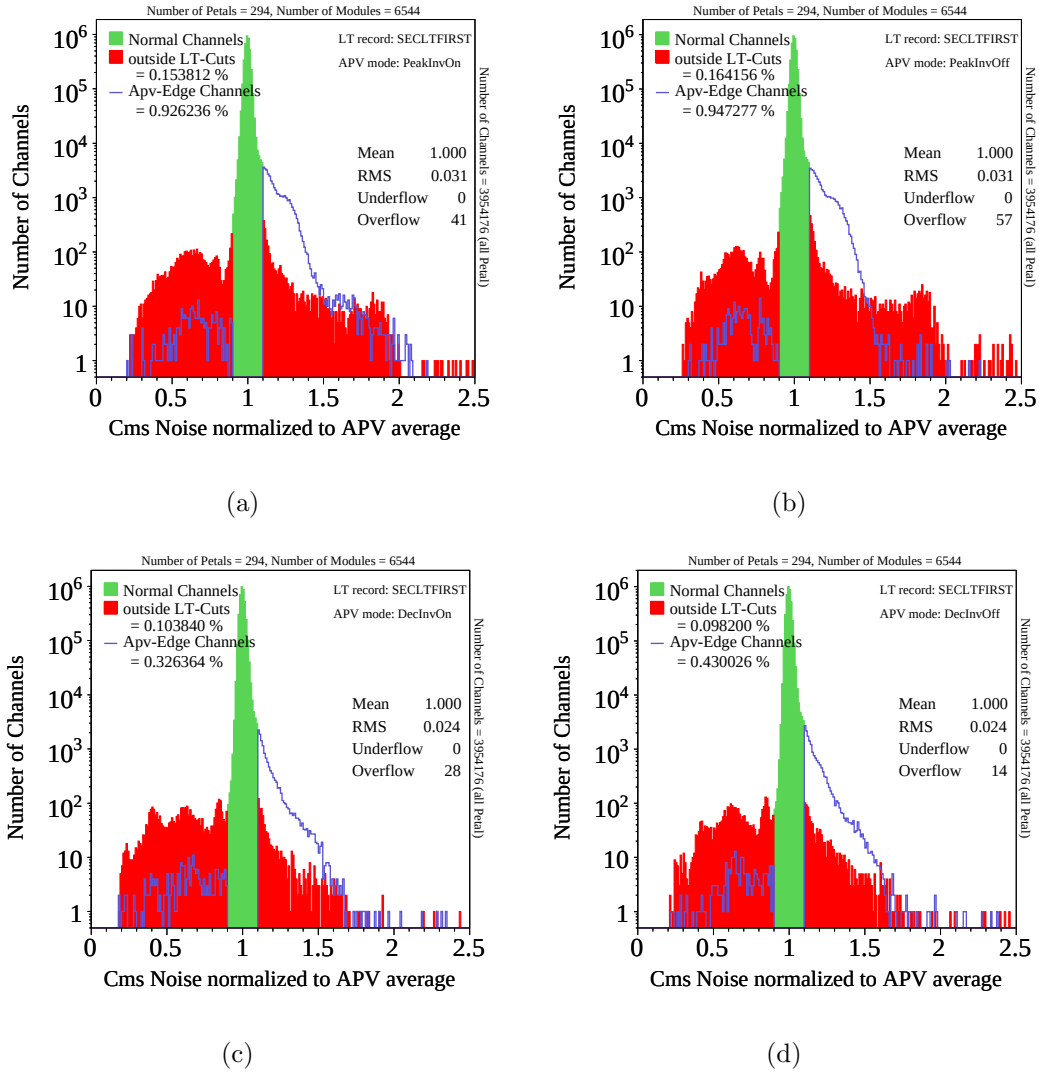


Figure D.3: Noise distributions measured in the first test cycle at room temperature.

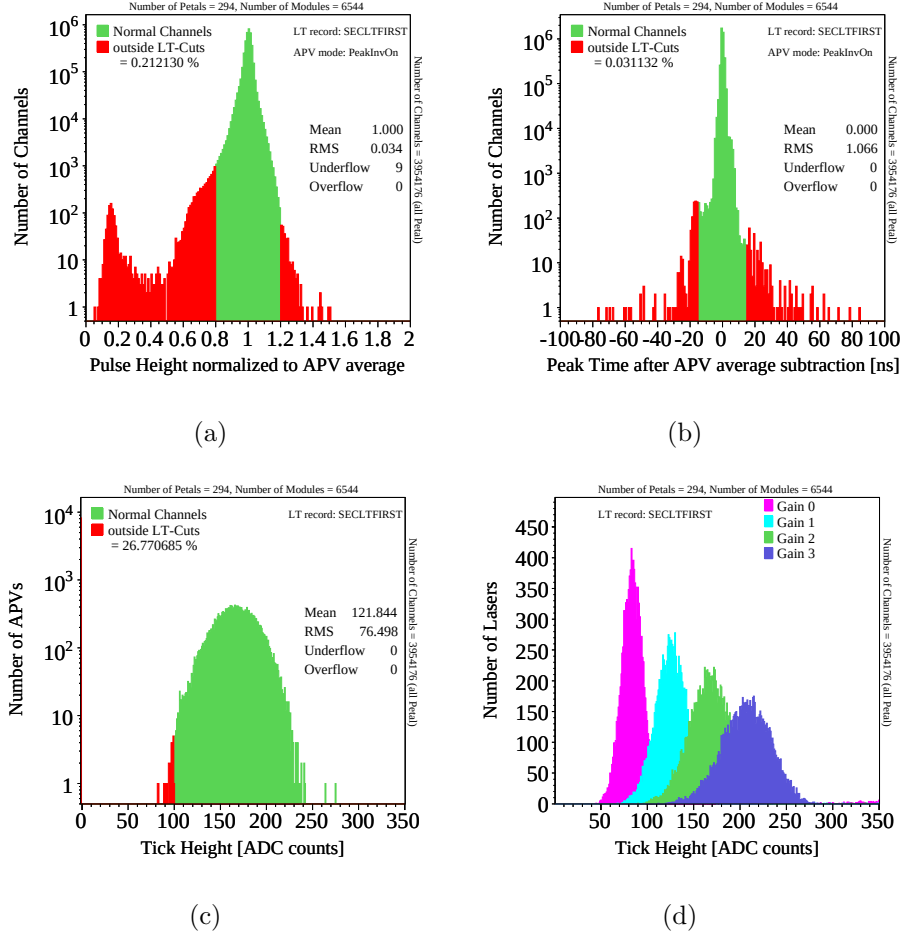


Figure D.4: Normalized pulse height (a) and average subtracted peak time (b) of the injected calibration pulse and tick mark distributions (c) and (d) measured in the first test cycle at room temperature.

Cold Temperature Cycle

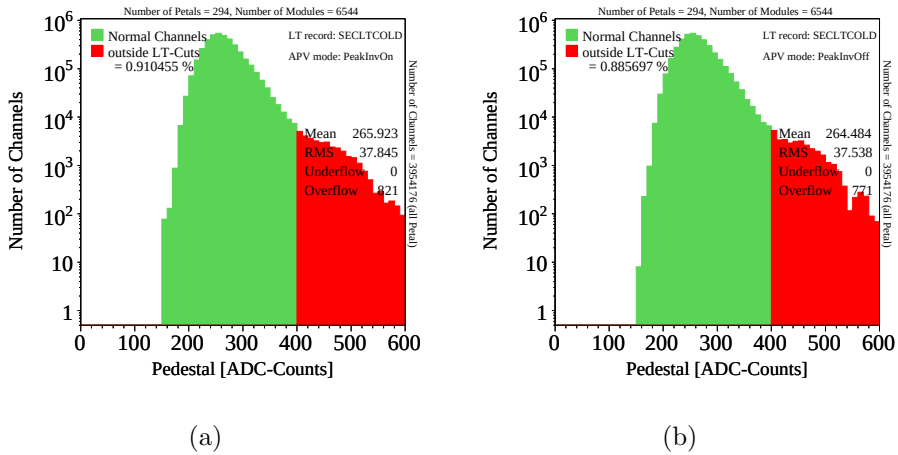


Figure D.5: Pedestal distributions measured in the cold test cycle.

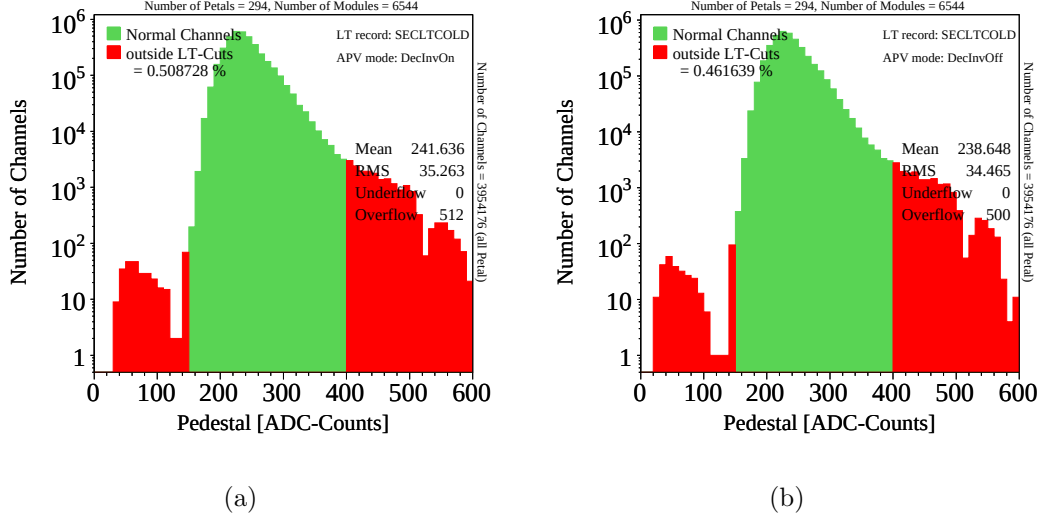


Figure D.6: Pedestal distributions measured in the cold test cycle.

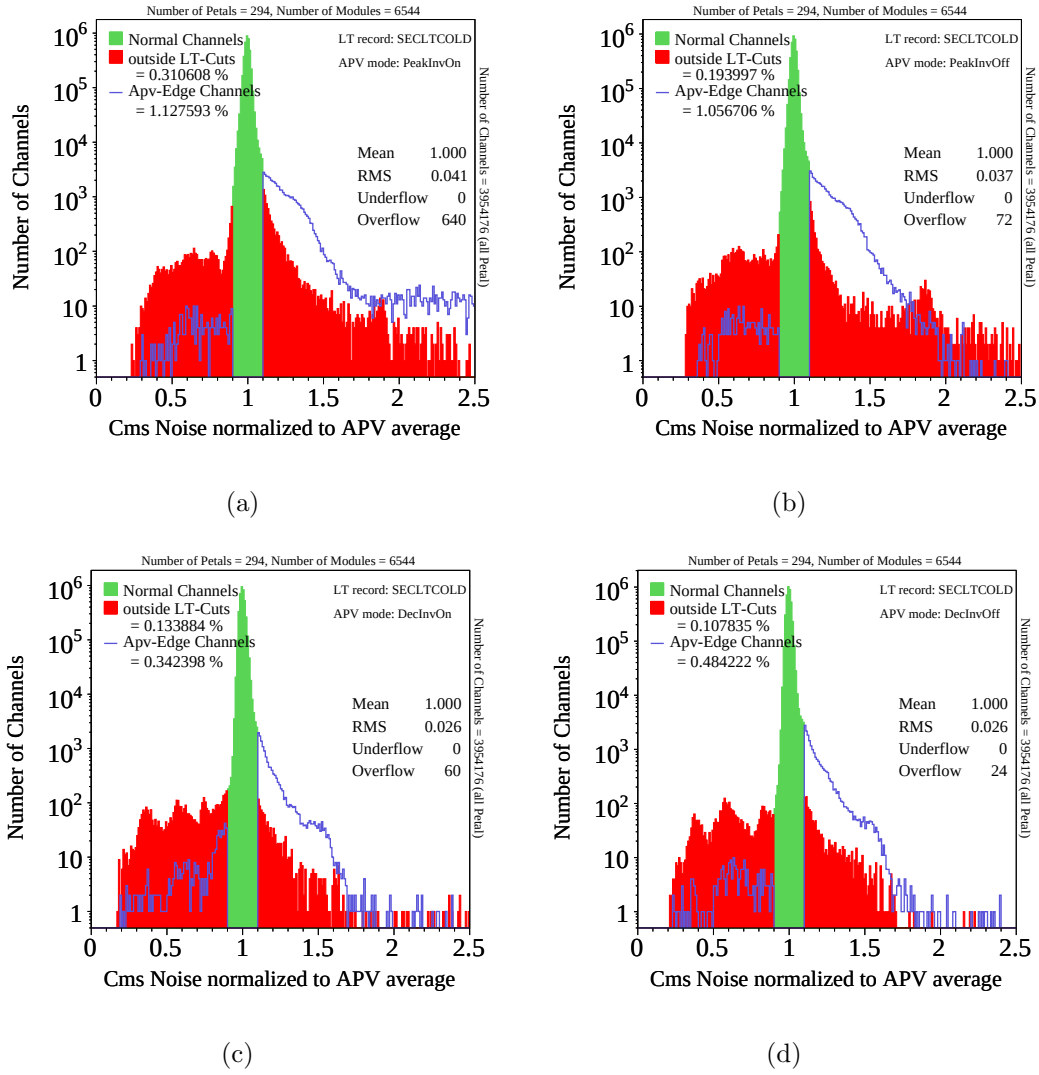


Figure D.7: Noise distributions measured in the cold test cycle.

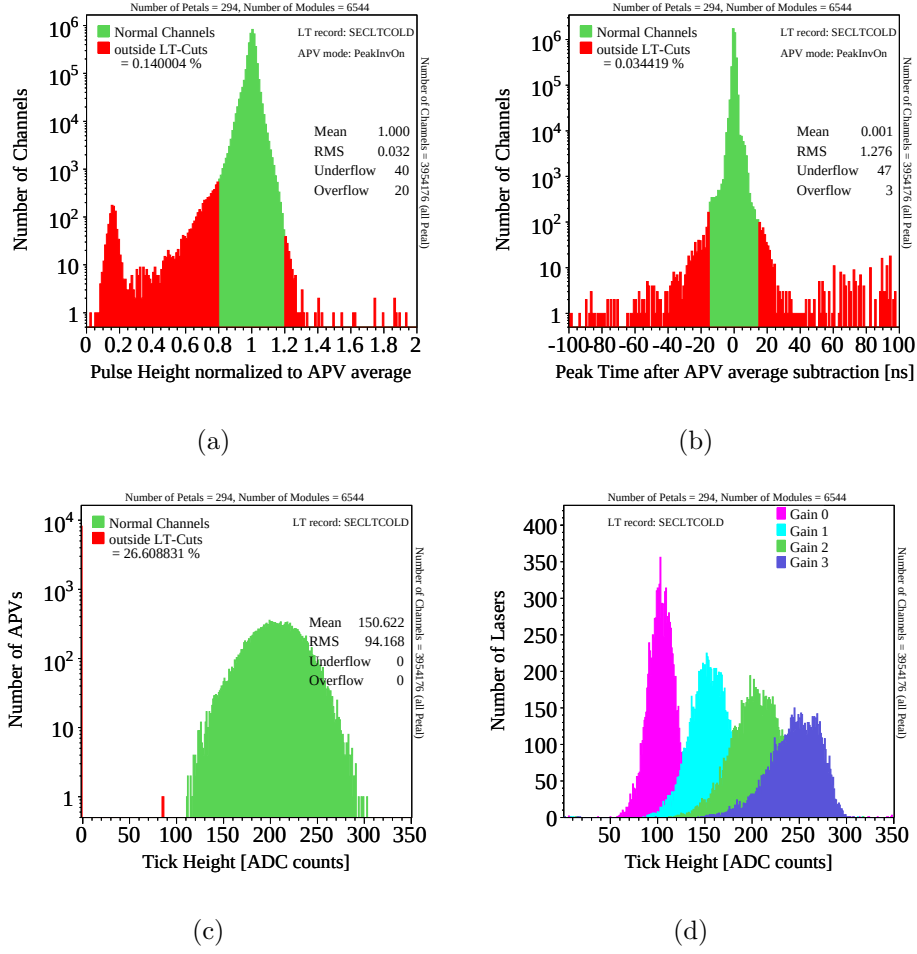


Figure D.8: Normalized pulse height (a) and average subtracted peak time (b) of the injected calibration pulse and tick mark distributions (c) and (d) measured in the cold test cycle.

Last Temperature Cycle

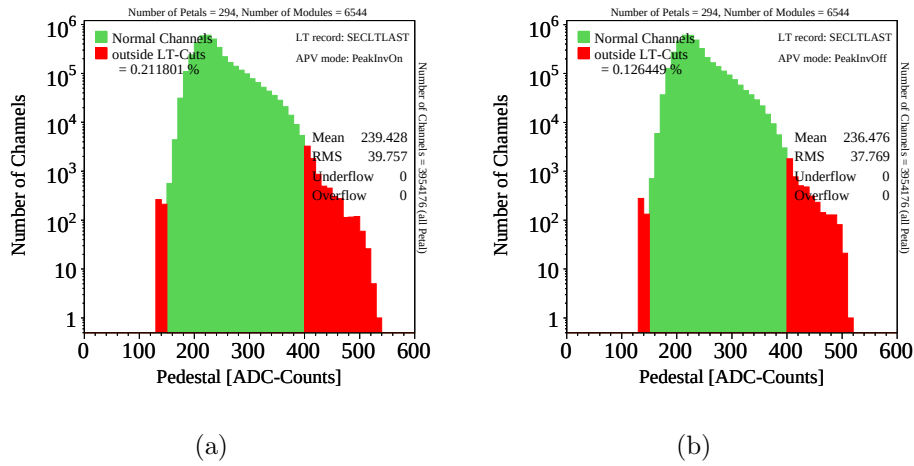


Figure D.9: Pedestal distributions measured in the last test cycle at room temperature.

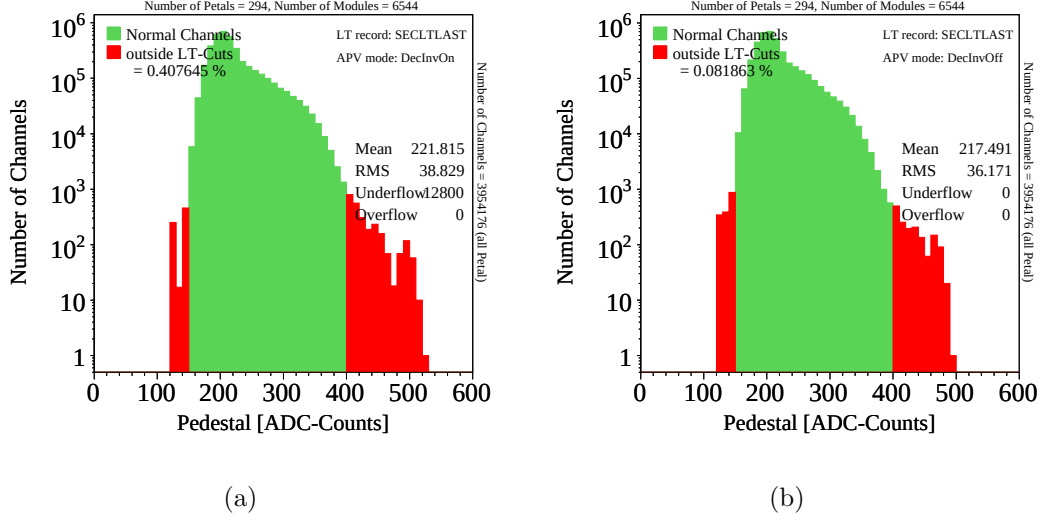


Figure D.10: Pedestal distributions measured in the last test cycle at room temperature.

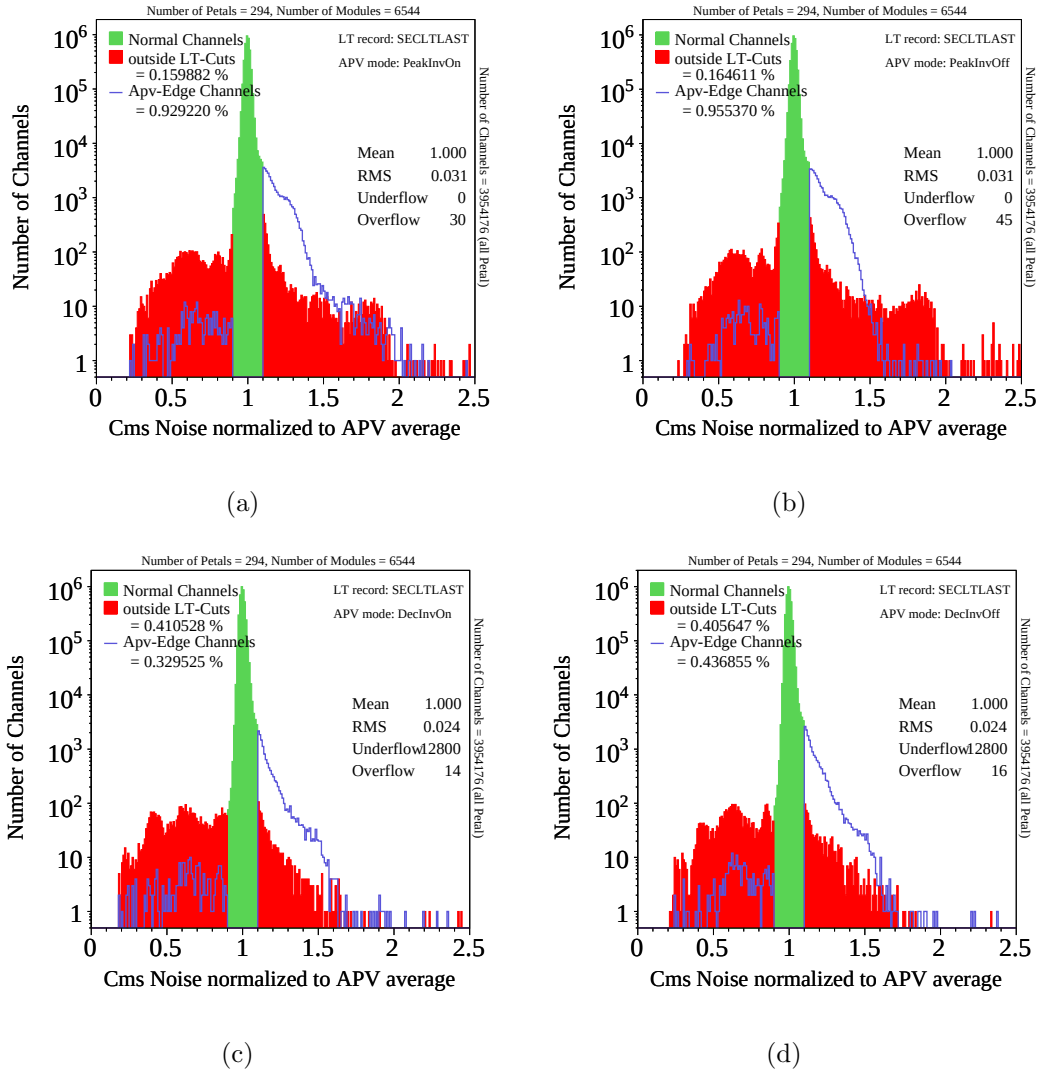


Figure D.11: Noise distributions measured in the last test cycle at room temperature.

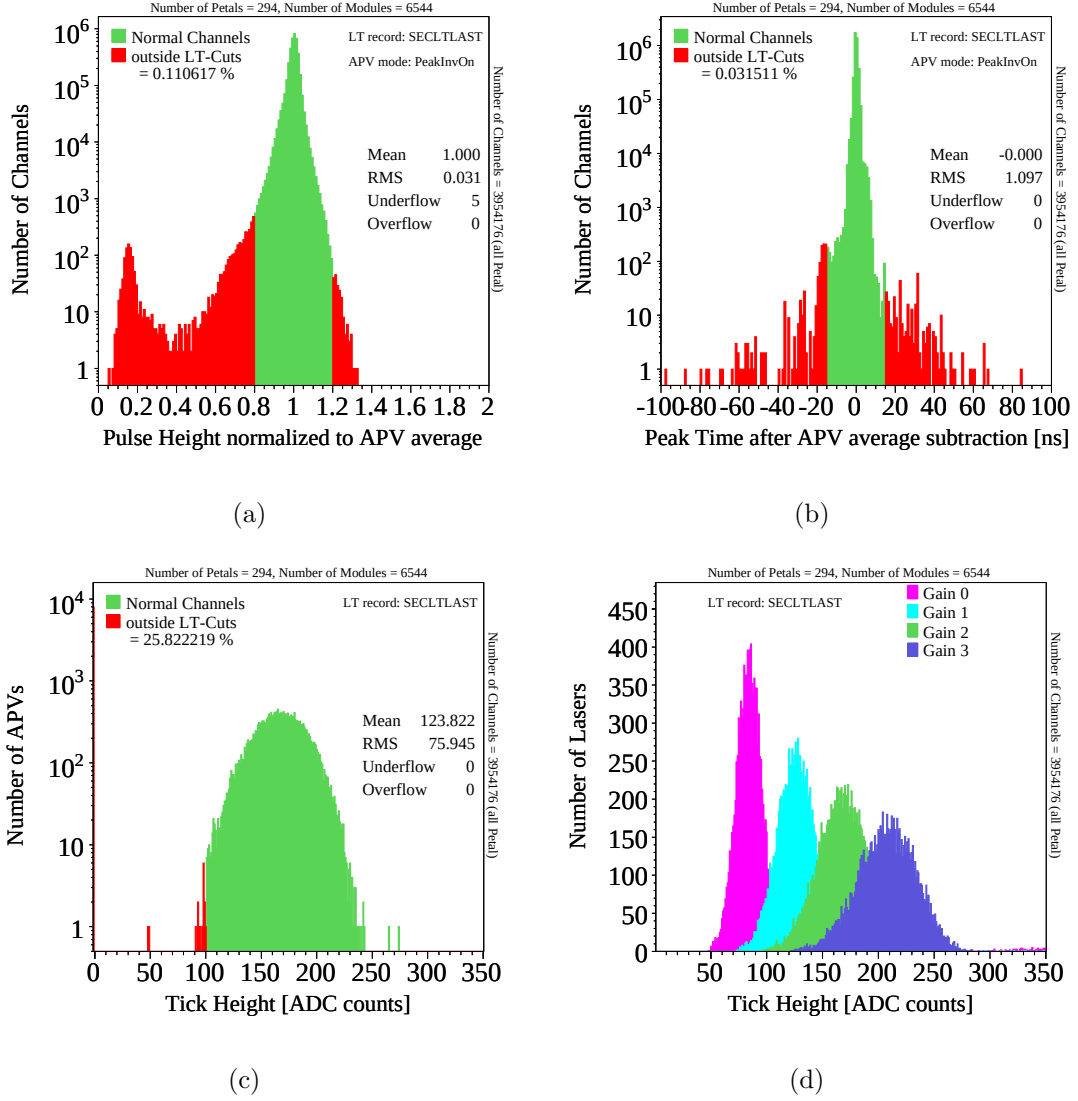


Figure D.12: Normalized pulse height (a) and average subtracted peak time (b) of the injected calibration pulse and tick mark distributions (c) and (d) measured in the last test cycle at room temperature.

Appendix E

Residuals measured in the TIB, TOB and TEC

In the following, the track residuals representing the distance between the measured hit position and the predicted one (derived from the reconstructed tracks) are shown for each TIB layer, each TOB layer and each TEC tower participating in the tracker slice test separately. The residuals are calculated for the sensitive coordinate (perpendicular to the strips) which is the x direction in the local module frame. The distributions are determined without using alignment corrections (for all cosmic runs performed in scintillator configuration C at -10°C), applying the alignment constants derived from optical survey and cosmic track measurements (for one cosmic run performed in scintillator configuration C at -10°C) and for simulated events using the configuration C setup. The given mean and RMS values are obtained from the histograms themselves.

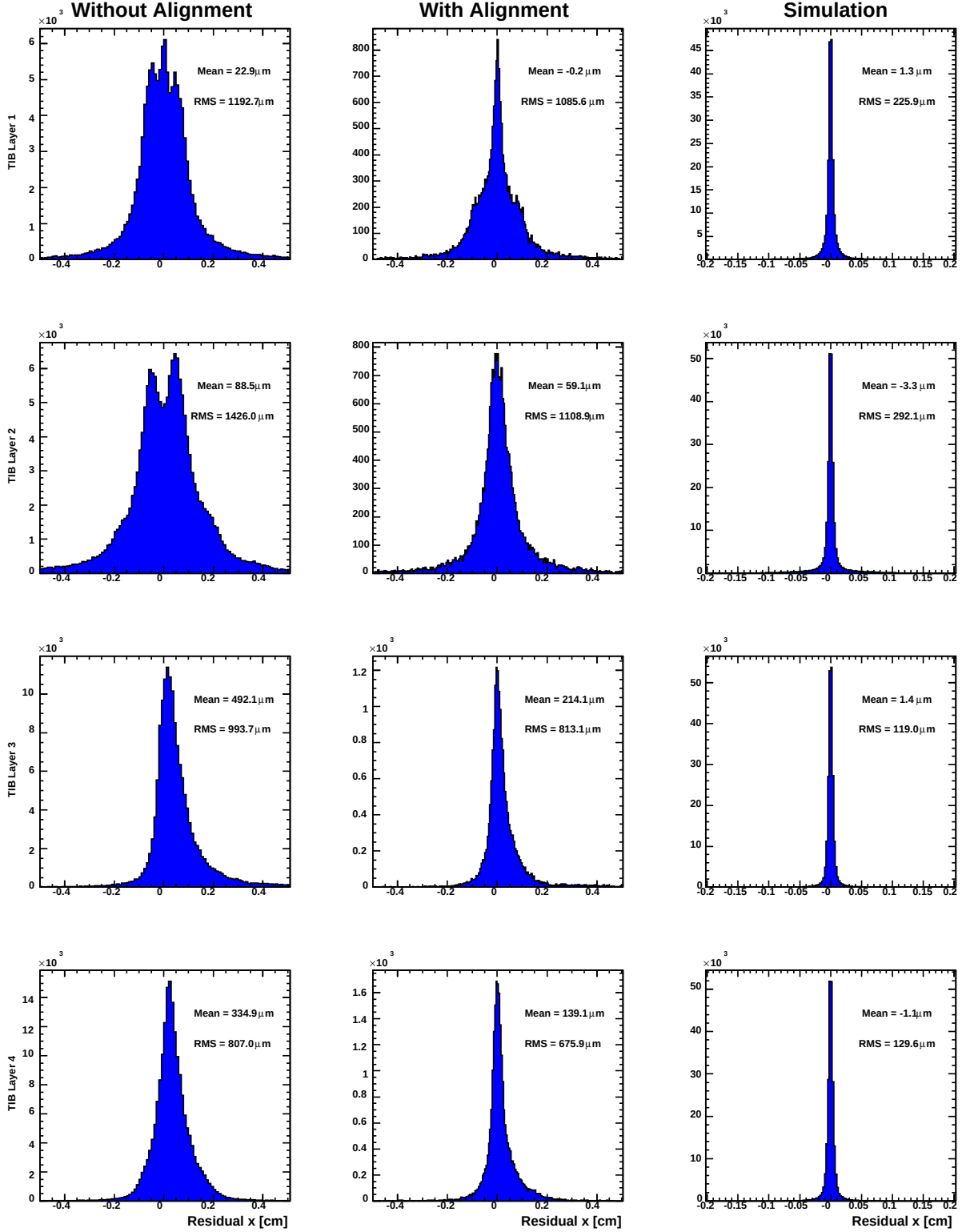


Figure E.1: Track residuals measured in the local x direction for the different TIB layers (from top to bottom: layer 1 to layer 4). From left to right: Data without alignment corrections, data applying the alignment constants and simulated events.

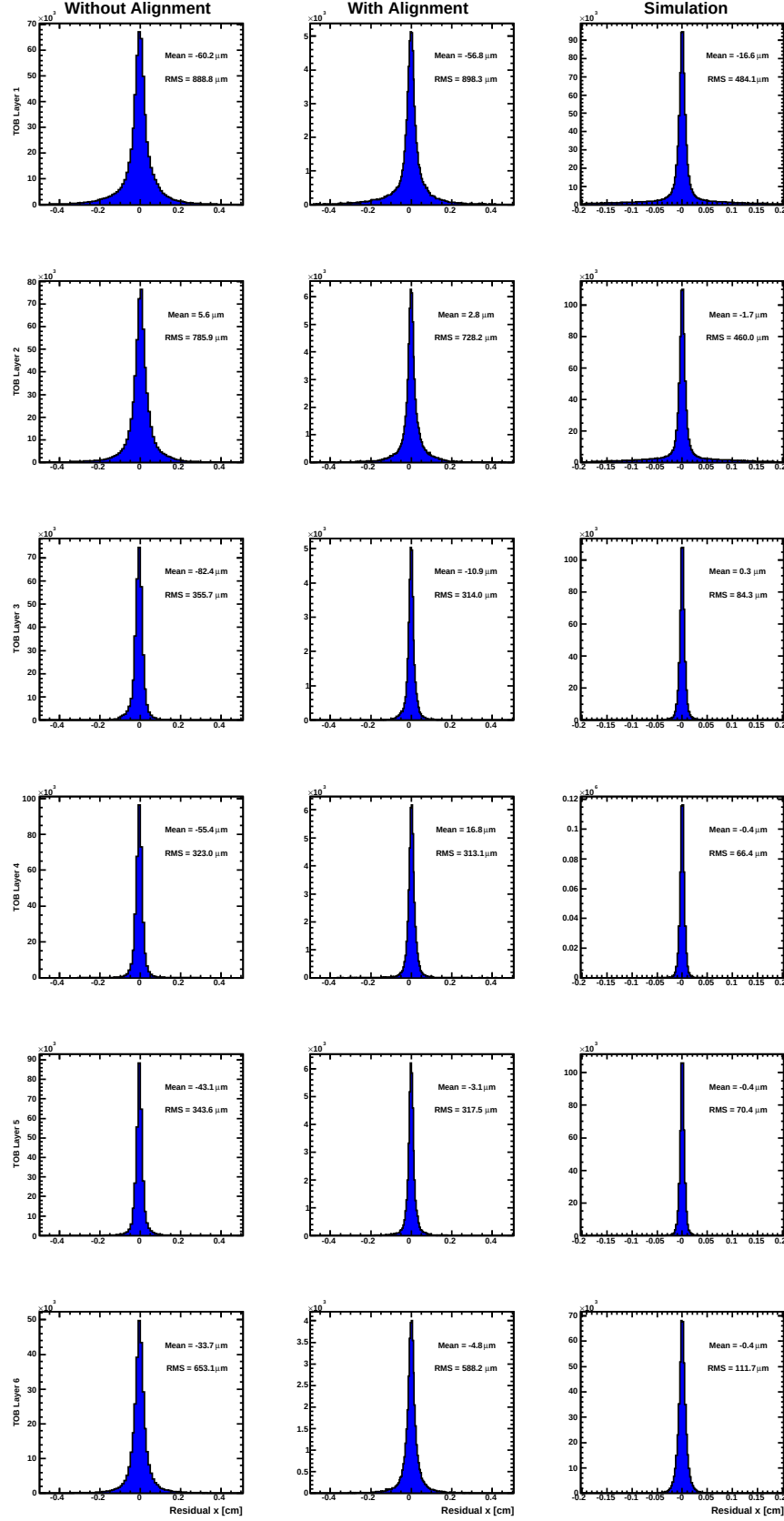


Figure E.2: Track residuals measured in the local x direction for the different TOB layers (from top to bottom: layer 1 to layer 6). From left to right: Data without alignment corrections, data applying the alignment constants and simulated events.

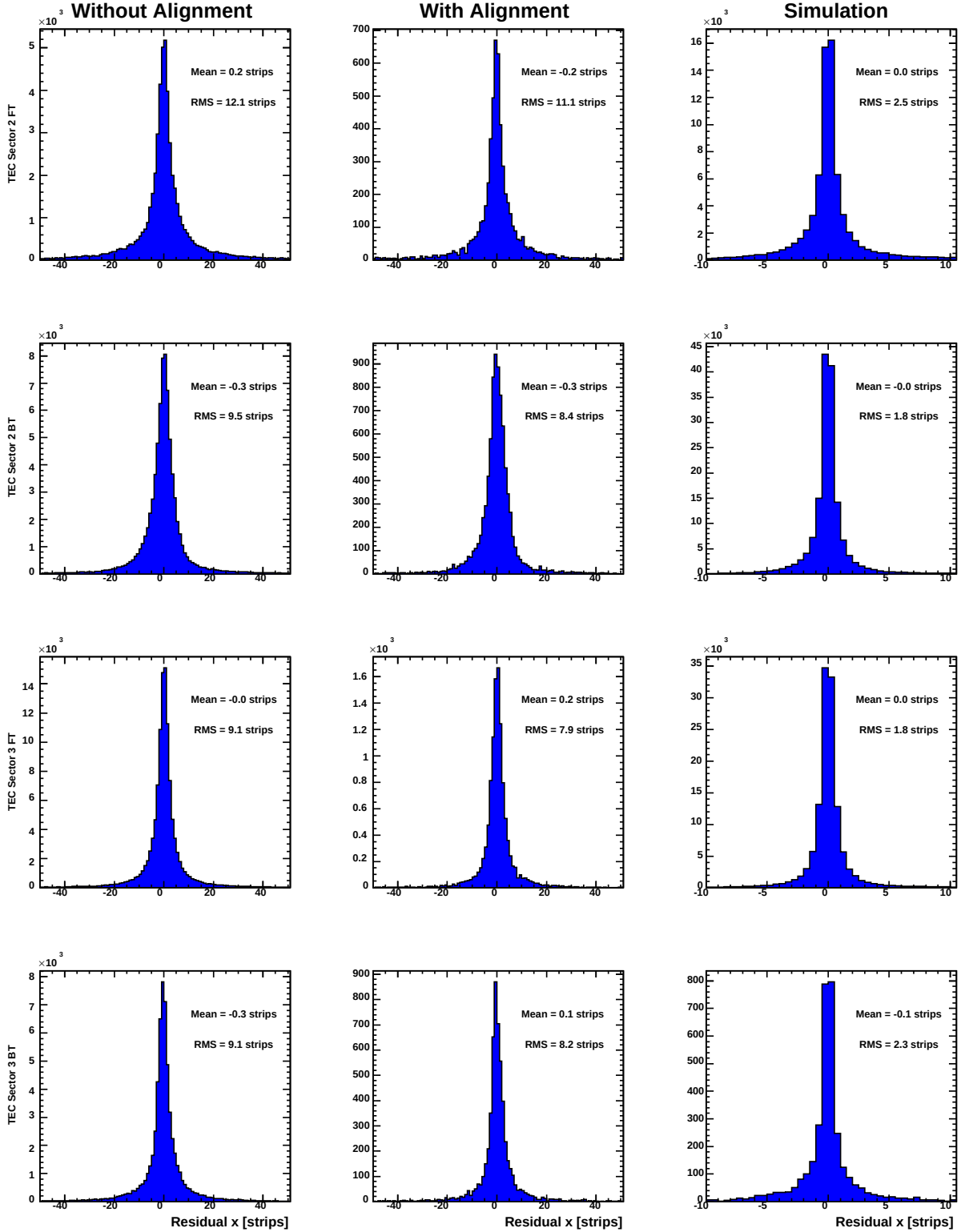


Figure E.3: Track residuals measured in the local x direction for the different TEC towers (from top to bottom: sector 2 front tower, back tower, sector 3 front tower, back tower). From left to right: Data without alignment corrections, data applying the alignment constants and simulated events.

Appendix F

Cluster η Distributions for the TIB and the TID

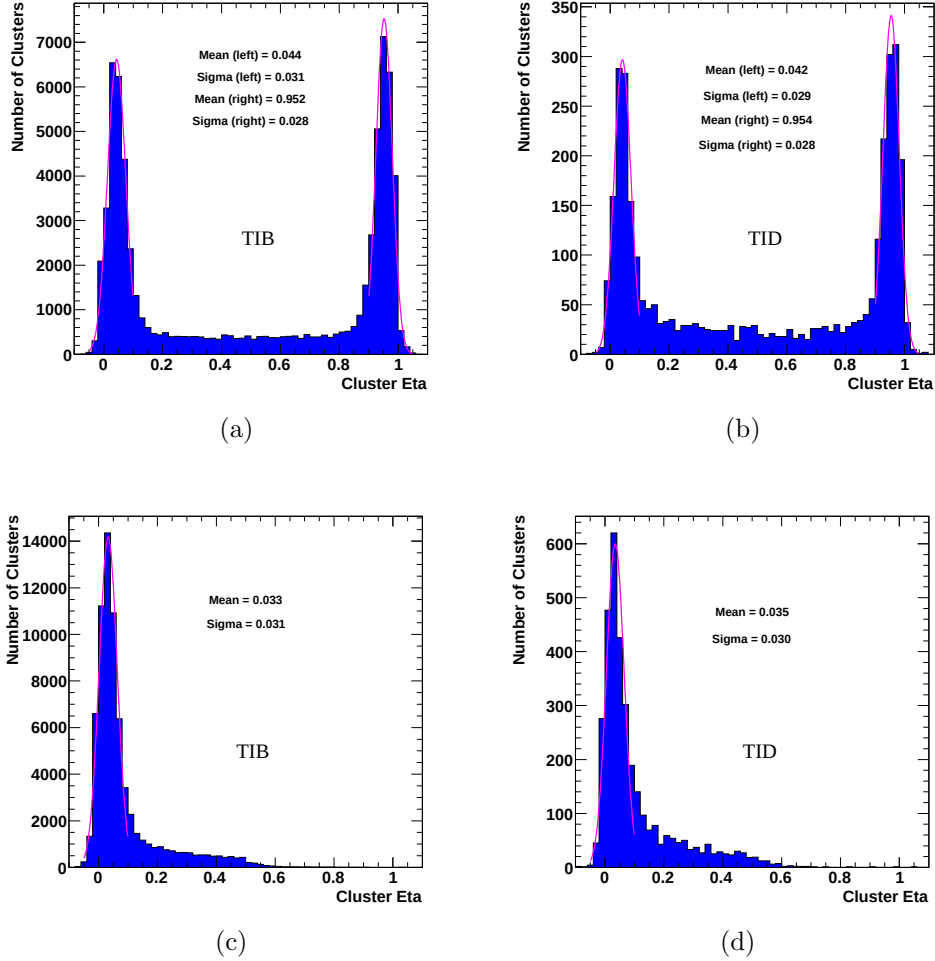
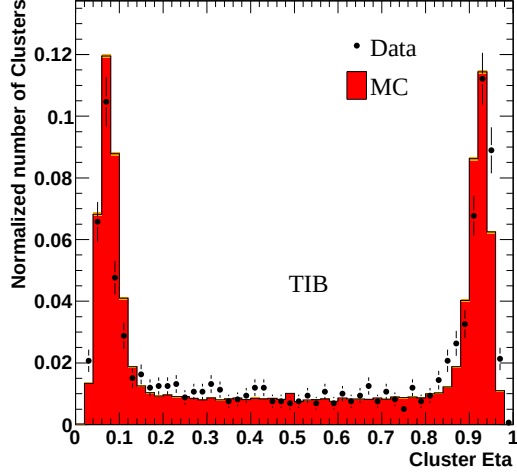
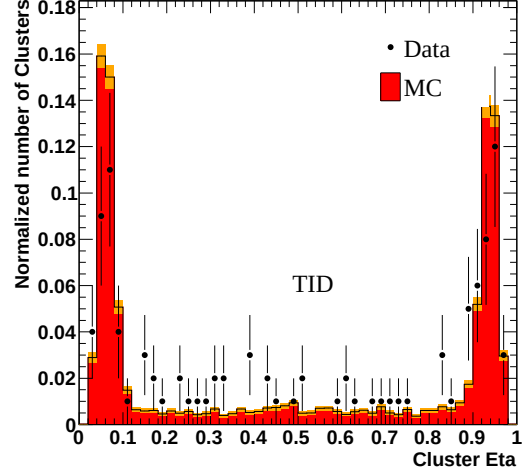


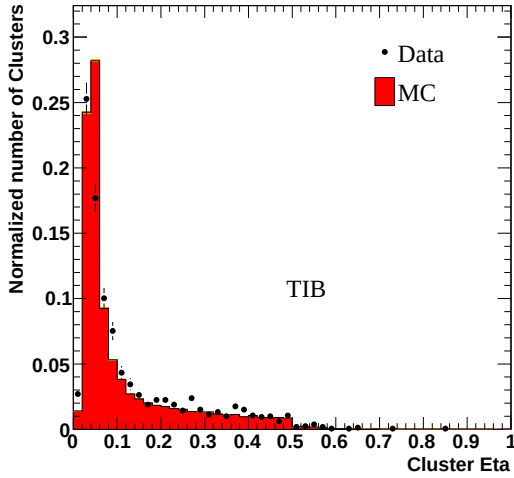
Figure F.1: Cluster η distributions obtained requiring perpendicular tracks with $\phi_{\text{local}} < 0.1$ and cluster sizes less than five strips. Only Virgin Raw data are taken into account. On top the asymmetric η and on bottom the symmetric η is shown, both for the TIB and the TID. The results of gaussian fits to the peaks are given in the plots.



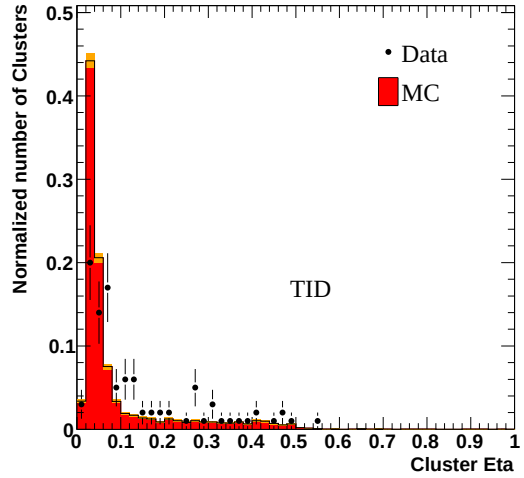
(a)



(b)



(c)



(d)

Figure F.2: Comparison of the cluster η distribution obtained with the Zero Suppressed MC (in red) and Zero Suppressed cosmic runs (dots). On top the asymmetric η and on bottom the symmetric η function is shown, both for the TIB and the TID. Only clusters with $\phi_{\text{local}} < 0.1$ and cluster size < 5 are used.

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Bibliography

- [1] LEP Higgs Working Group. Search for the Standard Model Higgs Boson at LEP. *Phys. Lett.*, B 565, 61, 2003.
- [2] ALICE Collaboration. Technical Proposal for A Large Ion Collider Experiment at the CERN LHC. Technical report, 1995.
- [3] LHCb Collaboration. Technical Proposal, A Large Hadron Collider Beauty Experiment for Precision Measurements of CP Violation and Rare Decays. Technical report, 1998.
- [4] ATLAS Collaboration. Technical Proposal for a General-Purpose pp Experiment at the Large Hadron Collider at CERN. Technical report, 1994.
- [5] CMS Collaboration. Technical Proposal, The Compact Muon Solenoid. Technical report, 1994.
- [6] CMS Collaboration. 3d drawing of cms, with realistic colouring. <http://cmsinfo.cern.ch/outreach/CMSdocuments/DetectorDrawings/DetectorDrawings.html>.
- [7] CMS. The Muon Project, Technical Design Report. Technical report, 1997.
- [8] CMS. The Magnet Project, Technical Design Report. Technical report, 1997.
- [9] CMS, The Hadron Calorimeter Project, Technical Design Report. Technical Report CERN/LHCC 97-31, CMS TDR 2, CERN, 1997.
- [10] CMS, The Electromagnetic Calorimeter, Technical Design Report. Technical Report CERN/LHCC 97-33, CMS TDR 4, CERN, 1997.
- [11] W. Adam et al. The CMS Tracker. CMS Note in preparation, CERN.
- [12] D. Abbaneo. The Tracker Layout. <http://abbaneo.home.cern.ch/abbaneo/cms/layout/whole.html>.
- [13] CMS, The TriDAS Project, Technical Design Report, Volume 1: The Trigger Systems. Technical Report CERN/LHCC 2000-38, CMS TDR 6.1, CERN, 2000.
- [14] CMS, The TriDAS Project, Technical Design Report, Volume 2: Data Acquisition and High-Level Trigger. Technical Report CERN/LHCC 02-26, CMS TDR 6, CERN, 2002.
- [15] T. Franke. *Development and Evaluation of a Test System for the Quality Assurance during the Mass Production of Silicon Microstrip Detector Modules for the CMS Experiment*. PhD thesis, III. Physikalisches Institut B, RWTH Aachen, 2005.

- [16] T. Bergauer et al. Petal Integration for the CMS Tracker End Caps. CMS Note in preparation, CERN.
- [17] G. Lutz. *Semiconductor Radiation Detectors*. Springer-Verlag Berlin Heidelberg, 1999.
- [18] S. Eidelmann et. al. Passage of Particles through Matter. In *Phys. Lett. B 592, 1 (2004), Chapter 27*. Particle Data Group, 2004. <http://pdg.lbl.gov/2004/reviews/passagerpp.pdf>.
- [19] M. Axer et al. Test of CMS tracker silicon detector modules with the ARC readout system. *Nucl. Instrum. Meth.*, A518:321–323, 2004.
- [20] The ROOT System Home Page. <http://root.cern.ch>.
- [21] W. Beaumont et al. Defect analysis of the CMS silicon strip detectors. CMS Internal Note 2004/043, CERN, 2004.
- [22] Lawrence Jones. APV25-S1 User Guide. *RAL Microelectronics Design Group*, Version 2.2, 2001.
- [23] A. Linn. *Construction of the CMS Tracker End Caps and an Impact Study on Defects*. PhD thesis, III. Physikalisches Institut B, RWTH Aachen, in preparation.
- [24] D. Abbaneo et al. Tracker Operation and Performance at the Magnet Test and Cosmic Challenge. CMS Note 2007/029, CERN, 2007.
- [25] The LCG TDR Editorial Board. LHC Computing Grid, Technical Design Report. Technical report, 2005.
- [26] P. Biallass et al. Simulation of Cosmic Muons and Comparison with Data from the Cosmic Challenge using Drift Tube Chambers. CMS Note 2007/024, CERN, 2007.
- [27] D. Heck et al. CORSIKA: A Monte Carlo code to simulate Extensive Air Showers. Report fzka 6019, Forschungszentrum Karlsruhe, 1998.
- [28] R. Brauer et al. Design and Test Beam Performance of Substructures of the CMS Tracker End Caps. CMS Note 2005/025, CERN, 2005.
- [29] P. Azzi et al. Silicon Strip Tracker Detector Performance with Cosmic Ray Data at the Tracker Integration Facility. CMS Note in preparation, CERN.
- [30] W. Adam et al. Track Reconstruction with Cosmic Ray Data at the Tracker Integration Facility. CMS Note in preparation, CERN.
- [31] E. Butz. Performance of the Tracker End Caps in the Slice Test. Presentation at the FSP-CMS Meeting, Zeuthen, September 2007.
- [32] R. Brauer. *Integration of the End Cap TEC+ of the CMS Silicon Strip Tracker*. PhD thesis, I. Physikalisches Institut B, RWTH Aachen, 2008.
- [33] R. Turchetta. Spatial resolution of silicon microstrip detectors. *Nucl. Instrum. Meth.*, A335:44–58, 1993.
- [34] G. Flucke et al. CMS Tracker Alignment at Integration Facility. CMS Note in preparation, CERN.

- [35] CMS, The Tracker System Project, Technical Design Report. Technical Report CERN/LHCC 98-6, CMS TDR 5, CERN, 1998.
- [36] R. Honecker G. Otter. *Atome-Moleküle-Kerne, Band I Atomphysik*. B.G. Teubner Stuttgart, 1998.
- [37] D. Heydhausen. *Analysis of Petal Longterm Test Data for the CMS-Experiment*. PhD thesis, III. Physikalisches Institut B, RWTH Aachen, in preparation.
- [38] C. Bloch. *Studies for the Commissioning of the CERN CMS Silicon Strip Tracker*. PhD thesis, Atominstitut der Österreichischen Universitäten (E141), Technische Universität Wien, 2007.
- [39] M. Axer. *Development of a Test System for the Quality Assurance of Silicon Microstrip Detectors for the Inner Tracking System of the CMS Experiment*. PhD thesis, III. Physikalisches Institut B, RWTH Aachen, 2003.
- [40] A. Venturi. Sector test: (not only) TIB/TID status. http://venturia.home.cern.ch/venturia/temporary/scheme_frame.htm.

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