

Analysis of Petal Longterm test data for the CMS-Experiment

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vorgelegt von
Diplom-Physiker Dirk Heydhausen
aus Kempen

Berichter: Universitätsprofessor Dr. rer. nat. Achim Stahl
Universitätsprofessor Dr. rer. nat. Lutz Feld

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Zusammenfassung

Der Start des Large Hadron Collider (*LHC*) am Europäischen Zentrum für Elementarteilchenphysik (*CERN*) in Genf ist für Ende 2008 geplant. Eines der Experimente am LHC ist der Vielzweckdetektor CMS (*Compact Muon Solenoid*). Ein Hauptbestandteil des CMS-Detektors ist das Spursystem. Dieses besteht aus dem Silizium-Pixeldetektor und dem Silizium-Streifendetektor. Der Pixeldetektor wird dabei vom Streifendetektor umschlossen. Momentan ist das Spursystem mit einer aktiven Fläche von 198 m^2 der größte Silizium-Detektor weltweit.

Der Streifendetektor wiederum besteht aus vier Subdetektoren. Einer davon sind die Trackerendkappen (*TEC*) mit einer aktiven Fläche von 82 m^2 . Neben dieser großen Fläche gibt die Position im Vorwärtsbereich den Endkappen eine Schlüsselrolle für Physikanalysen, da viele interessante Ereignisse in diesem Bereich erwartet werden (pp-Beschleuniger). Die Endkappen setzen sich wiederum aus 10.288 Sensoren mit insgesamt 3.988.765 Kanälen zusammen. Die Module wurden in zahlreichen Arbeitsschritten aufgebaut und mehrfach getestet, bis sie schließlich auf den finalen Substrukturen, den sogenannten Petals, integriert und einem intensiven Langzeittest unterzogen wurden, welcher diese für den Einbau in den Detektor qualifizierte.

Das Hauptaugenmerk dieser Arbeit liegt dabei auf dem Langzeittest. Die dabei verwendete Testprozedur wird beschrieben. Ferner wird eine Methode zur Fehlererkennung und -deklaration vorgestellt. Diese wurde mit Hilfe der Ergebnisse früherer Tests ("ARC-Test"), die an jedem Modul vor der Integration durchgeführt wurden, entwickelt. Ein Vergleich mit den Ergebnissen eines Tests nach dem Einbau der Petals in die TEC, wurde als Gegenprobe durchgeführt ("Sektor-Test"). Eine hohe Übereinstimmung zeigt die Konsistenz der gezeigten Ergebnisse. Mit Hilfe der Methode konnte eine Kanalfehlerrate von etwa 0.9‰ bestimmt werden. Weitere Defekte, wie 'tote' Komponenten, welche nach der Integration der Petals in die TEC gefunden wurden, erhöht die Zahl der nicht verwendbaren Kanäle auf 3.3‰.

Abstract

The Large Hadron Collider (*LHC*) at the European Organization for Nuclear Research (*CERN*) in Geneva will start end of 2008. One of the experiments at the LHC is the multipurpose detector CMS (*Compact Muon Solenoid*). A key part of the CMS detector is the tracking system, that is composed of a silicon pixel detector forming the innermost part, surrounded by silicon strip sensors. Currently, it is the largest silicon detector in the world with an active area of 198 m^2 .

The strip tracker itself consists of four subdetectors. One of these are the tracker end caps (*TEC*) with an active area of 82 m^2 . Besides this large aperture, their position in the forward region plays a key role for physics analysis due to the fact that many of the interesting events are expected to be boosted in the forward region (pp collider). This area splits up into 10,288 sensors with 3,988,765 channels in total. In several steps the modules constructed and tested before being mounted onto the final substructures (*petals*). An important longterm test has been performed which qualifies the petals to be installed into the detector.

The focus of the present work is in the longterm test. The test procedure is described. A method for identification and classification of defect channels is presented. This method has been developed based on the test results of a previous test ('ARC-test'), which has examined each module before the assembly onto the petals. A cross-check has been performed to compare the results with data from a subsequent test ('sector-test'), that is performed after the petals have been integrated into the TEC. A good agreement shows the consistency of the presented results. With the help of this method a channel defect rate of approximately 0.09% can be measured. Further defects like 'dead' components became visible after integration of the petals into the TEC and raised this number up to 0.33% defect and non-recoverable channels.

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Chapter 1

Introduction

Dass ich erkenne, was die Welt im Innersten zusammen hält [J.W.v.Goethe, 1808]

This phrase written by Johann Wolfgang von Goethe describes the human desire to understand the underlying mechanism of nature. Since centuries mankind is trying to investigate matter. Therefore they split it into smaller and smaller pieces. This leads to the topic of particle physics.

In the last century physicists developed the Standard Model of Particle Physics (*SM*) describing effects and particles which were measured. Nevertheless there is one particle predicted by the SM which could not be found until now, the Higgs boson. Furthermore there are questions the SM cannot answer. To solve these problems, to measure the Higgs boson and to find new physics, a new accelerator was built, the Large Hadron Collider¹ (LHC).

1.1 The Standard Model of Particle Physics

According to the SM the material in the universe is made up of fermions. The interactions between the fermions, the gravitational, electromagnetic, weak and strong interaction, are mediated by bosons, the Graviton G , photon γ , weak gauge bosons Z , W^+ , W^- and eight gluons g . All elementary fermions have spin $\frac{1}{2}$ while bosons have an integer spin. Both are given in units of $\hbar$.

In Table 1.1 an overview of the fundamental fermions is given. These can be divided into two categories, the quarks and the leptons. In addition these are grouped into three generations which differ only in mass. To get a more detailed overview of the SM see [1].

1.2 The Large Hadron Collider

The LHC which is under construction at CERN² in Geneva will take into operation end of 2008. Its accelerator ring has a circumference of about 27 km and was integrated into the old LEP³ tunnel (Fig. 1.1).

¹Large Hadron Collider

²Conseil Européen pour la Recherche Nucléaire, today: European Organization for Nuclear Research

³Large Electron Positron collider

	1	2	3	$Q[e]$	T_3	Y	colour
quarks	$\begin{pmatrix} u \\ d' \end{pmatrix}_L$	$\begin{pmatrix} c \\ s' \end{pmatrix}_L$	$\begin{pmatrix} t \\ b' \end{pmatrix}_L$	$2/3$	$1/2$	$1/3$	rgb
	u_R	c_R	t_R	$-1/3$	$-1/2$	$1/3$	rgb
	d_R	s_R	b_R	$2/3$	0	$4/3$	rgb
				$-1/3$	0	$-2/3$	rgb
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	$1/2$	-1	$-$
	e_R^-	μ_R^-	τ_R^-	-1	$-1/2$	-1	$-$
				-1	0	-2	$-$

Table 1.1: The three particle generations of quarks and leptons and their quantum numbers. Q is the electric charge given in elementary charge, T_3 is the third component of the weak isospin and Y the hypercharge.

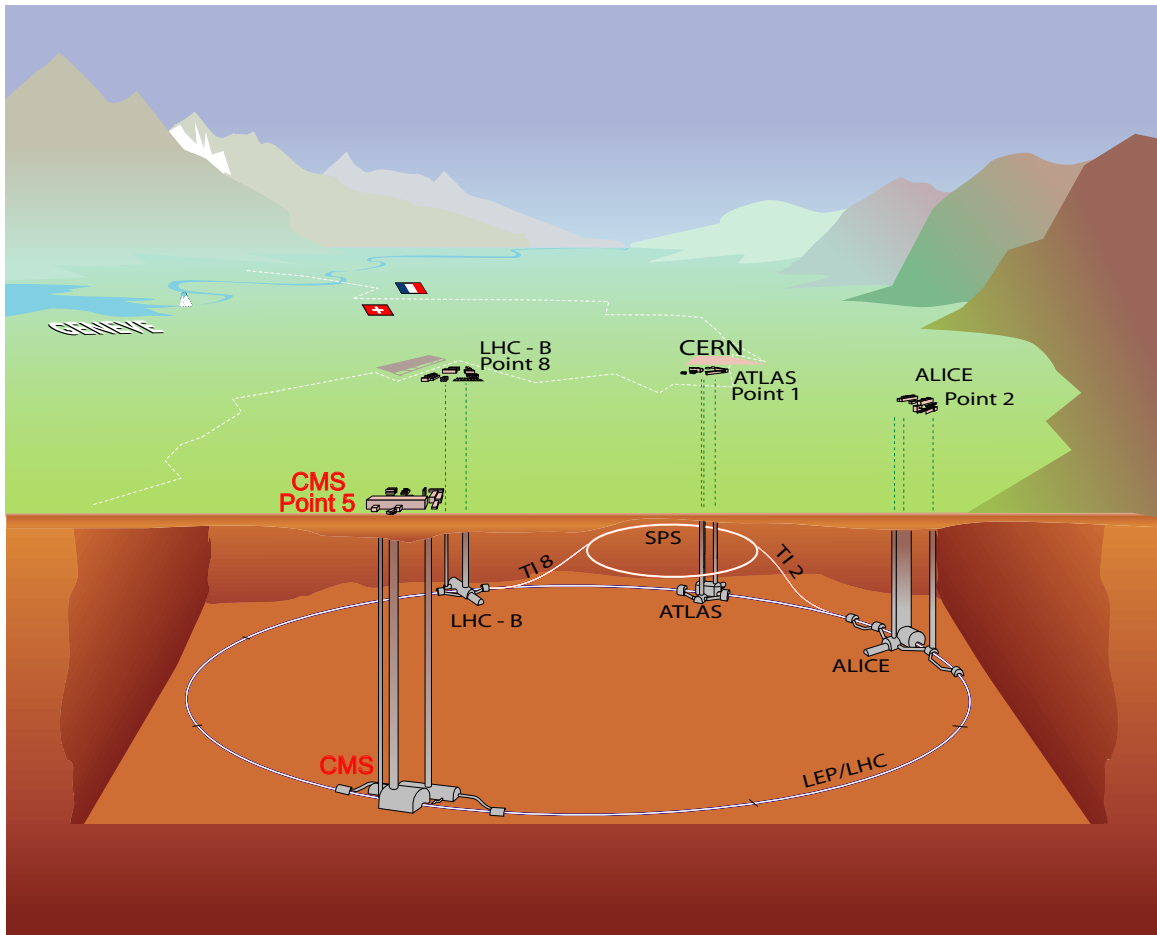


Figure 1.1: The LHC ring at CERN with its four experiments [2].

It will provide proton-proton collisions with a center-of-mass energy of $\sqrt{s} = 14 \text{ TeV}$ and at startup for the first year an instantaneous luminosity of $\mathcal{L} \approx 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$ and later a luminosity of $\mathcal{L} \approx 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$. The beams will circulate in two separate pipes. Dipole magnets with a field of 8.4 T force them onto their orbit. At four points the pipes intersect and the beams will collide every 25 ns which equates a bunch-crossing frequency of 40 MHz. At each of these four interaction points one of the following experiments is placed (s. Fig. 1.1):

ALICE	–	A L arge I on C ollider E xperiment	[3]
ATLAS	–	A T oroidal L HC A pparatu S	[4]
CMS	–	C ompact M uon S olenoid	[5]
LHC-b	–	L arge H adron C ollider b eauty Experiment	[6]

1.3 The CMS Experiment

CMS was designed as a typical multipurpose detector. It should be able to detect nearly all produced particles originating from the proton-proton collisions. It is equipped with a precise muon system, a good electro-magnetic calorimeter and a high resolution tracker to identify secondary vertices and to have a good momentum measurement. For the latter also a strong magnetic field is necessary. Therefore it has a superconducting solenoid with a uniform magnetic field of 4 T, a length of 12.5 m and a diameter of about 6 m. The magnetic flux is returned via an iron yoke of 1.8 m thickness. This yoke is instrumented with muon chambers. This gives the detector a compact design which is the reason for its name.

The coordinate system of CMS is defined as: x -axis pointing radially toward the center of the LHC, y -axis pointing vertically upward and the z -axis along the beam direction completing a right handed coordinate system. θ is the polar angle measured from the z -axis and ϕ the azimuth angle measured from the x -axis in the x - y plane. The pseudorapidity η is defined as: $\eta = -\ln(\tan(\theta/2))$. The plus side is the side with positive z -values and the minus side with negative z -values.

A sketch of the CMS detector gives 1.2. From the outside to the interaction point it is instrumented with:

- muon system integrated into the return yoke of the magnet
- superconducting magnet
- hadron calorimeter
- electro magnetic calorimeter
- silicon strip detector
- silicon pixel vertex detector

In total the detector has a length of 21.6 m, a diameter of 15 m and a weight of about 12,500 tons [5].

1.3.1 The Muon system

Muons are expected to provide clean signatures for many interesting physics processes, e.g. the Higgs decay $H \rightarrow ZZ^{(*)} \rightarrow \mu^+ \mu^- \mu^+ \mu^-$. For this reason the task of the muon system is a good muon identification, charge determination and in combination with the tracker a precise

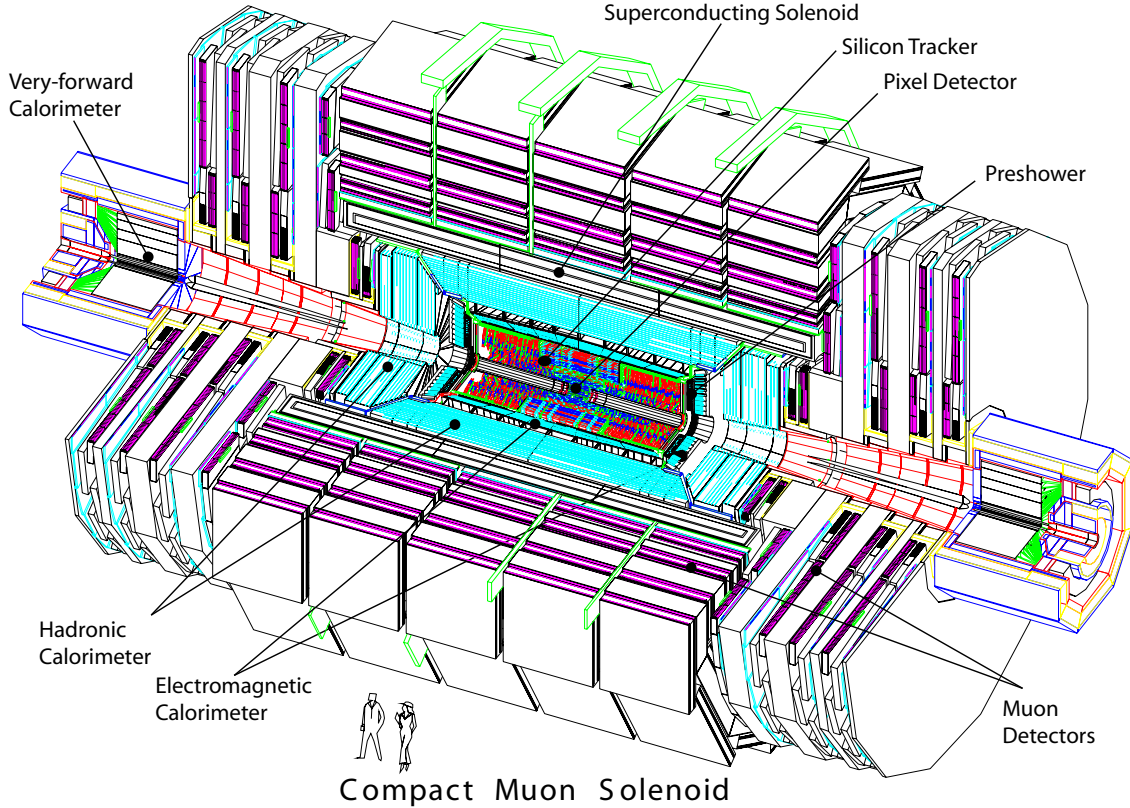


Figure 1.2: Overview of the CMS Detector [7].

muon momentum measurement. Also a fast trigger decision is needed. The muon chambers are the outermost part of the detector, because muons are the only charged particles which are able to traverse all detector parts without significant energy loss. In Fig. 1.3 the three different technologies used in the detector and their position are plotted. In the barrel region the muon detection is based on drift tubes (*DTs*). In the end caps cathode strip chambers (*CSCs*) are used, because they can be operated even in a strong magnetic field and at high particle rate. In addition both regions are equipped with resistive plate chambers (*RPCs*). Due to their fast response it will be possible to determine the bunch-crossing and to get a good trigger decision [9].

1.3.2 The Hadron Calorimeter

The hadron calorimeter (HCAL)[11] is the outermost component inside the solenoid. It is divided into two parts. The central calorimeter, including barrel and end cap region, reaches up to $|\eta| = 3.0$ and the forward calorimeter with $|\eta| \leq 5.0$. The HCAL measures the energy and direction of hadrons. Through its large hermetic coverage it is also possible to get a hint for neutrinos. This can be done by measuring the missing transverse energy. The HCAL also helps to identify electrons, photons and muons together with the tracker, electromagnetic calorimeter and muon system.

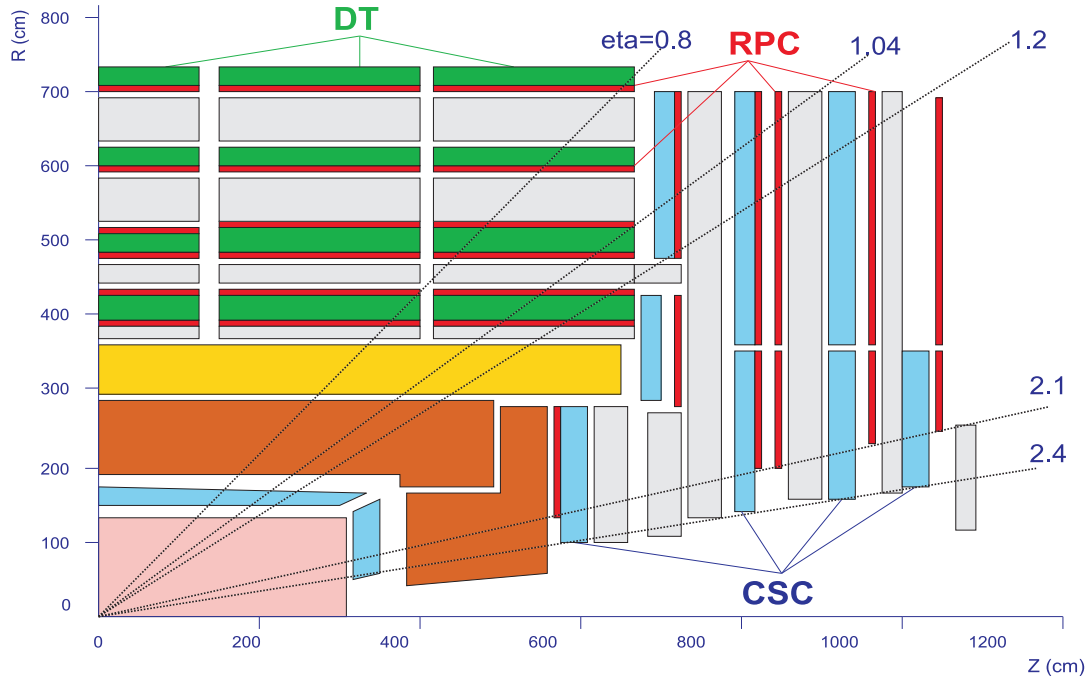


Figure 1.3: A quarter of the muon system. The different technologies are labeled and coloured [10].

Barrel and end cap calorimeter are sampling calorimeters with brass alloy absorber plates which are interleaved with scintillator sheets. The first and last absorber plate of the barrel region are made of stainless steel.

As the barrel HCAL inside the coil is not sufficiently thick to absorb all the energy of high energy showers additional scintillator layers are placed just outside the magnet. Together they reach eleven absorption lengths. The forward direction is situated within a harsh radiation field. Therefore instead of brass iron is used as absorber. This leads to narrower and shorter hadronic showers which fit the requirements in the forward region.

1.3.3 The Electromagnetic Calorimeter

The electromagnetic calorimeter (ECAL) [12] should give a precise measurement of the direction and energy of photons and electrons. An interesting process which could be detected by the ECAL is $H \rightarrow \gamma\gamma$. A clear signature is also given for a lot of other physical processes with leptons with a large transverse momentum (e.g. semi-leptonic t -quark decays[13]).

The ECAL consists of more than 80,000 lead-tungstate (PbWO_4) crystals. In the barrel region (EB⁴) they have a front face of about $22 \times 22 \text{ mm}^2$, which matches well the Molière radius, and a length of 23 cm. This allows a good separation of adjacent showers. In the endcap region (EE⁵) the front face is about $28.6 \times 28.6 \text{ mm}^2$ and the length 22 cm.

⁴ECAL Barrel

⁵ECAL Endcap

1.3.4 The Tracker

Within the ECAL the tracker is situated. It can be divided into two components: the silicon strip detector and the silicon pixel detector. Both are needed to determine tracks of charged particles and their vertices. Up to $|\eta| = 2.5$ there are at least 8 hits in the strip tracker to reconstruct a track (Fig. 1.4). The achieved accuracy can be seen in Fig. 1.5.

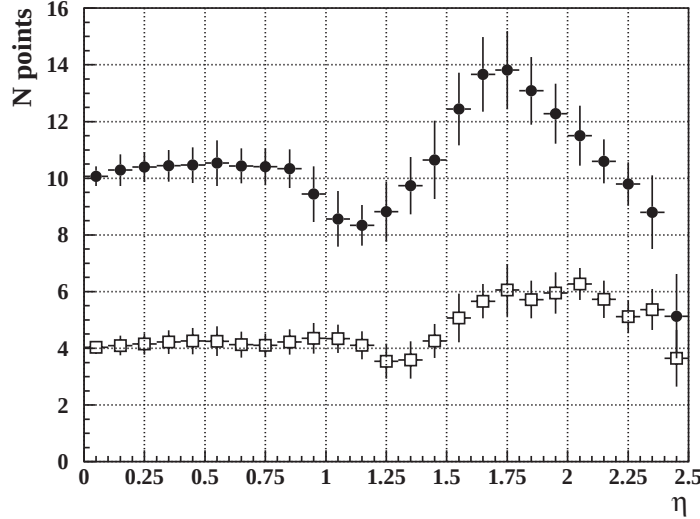


Figure 1.4: Number of measurement points in the strip tracker as a function of pseudo-rapidity η . Filled circles show the total number (back-to-back modules count as one) while open squares show the number of stereo layers (layers which deliver a three dimensional measurement) [14].

The Silicon Strip Tracker

The silicon strip detector can be split up again into four subdetectors (Fig. 1.6). The innermost part is the tracker inner barrel (TIB) which is enclosed by the tracker inner discs (TID). Both are inside of the outer barrel (TOB). To each side of TOB one tracker end cap (TEC) is mounted.

The tracker will be discussed in detail in the next chapter as parts of it are matter of this thesis.

The Vertex Detector

The Vertex Detector [15] is a silicon pixel detector and the innermost part of the CMS detector. It consist of three barrel layers (TPB) and two end caps (TPE) at each side. It must be able to identify secondary vertices from b-quark or τ -lepton decays. Therefore it is necessary to have a high hit resolution. In the barrel region the pixels have an area of $100 \times 150 \mu\text{m}^2$. They are delivering two dimensional points which allow a resolution of $15 \mu\text{m}$ in both coordinates. Fig. 1.7 is a sketch of the pixel detectors with three layers in the barrel region and two discs on each side. During the start up luminosity phase the innermost layer can be used at a distance of $r \approx 44 \text{ mm}$. After this phase it will be removed due to radiation damage. A second

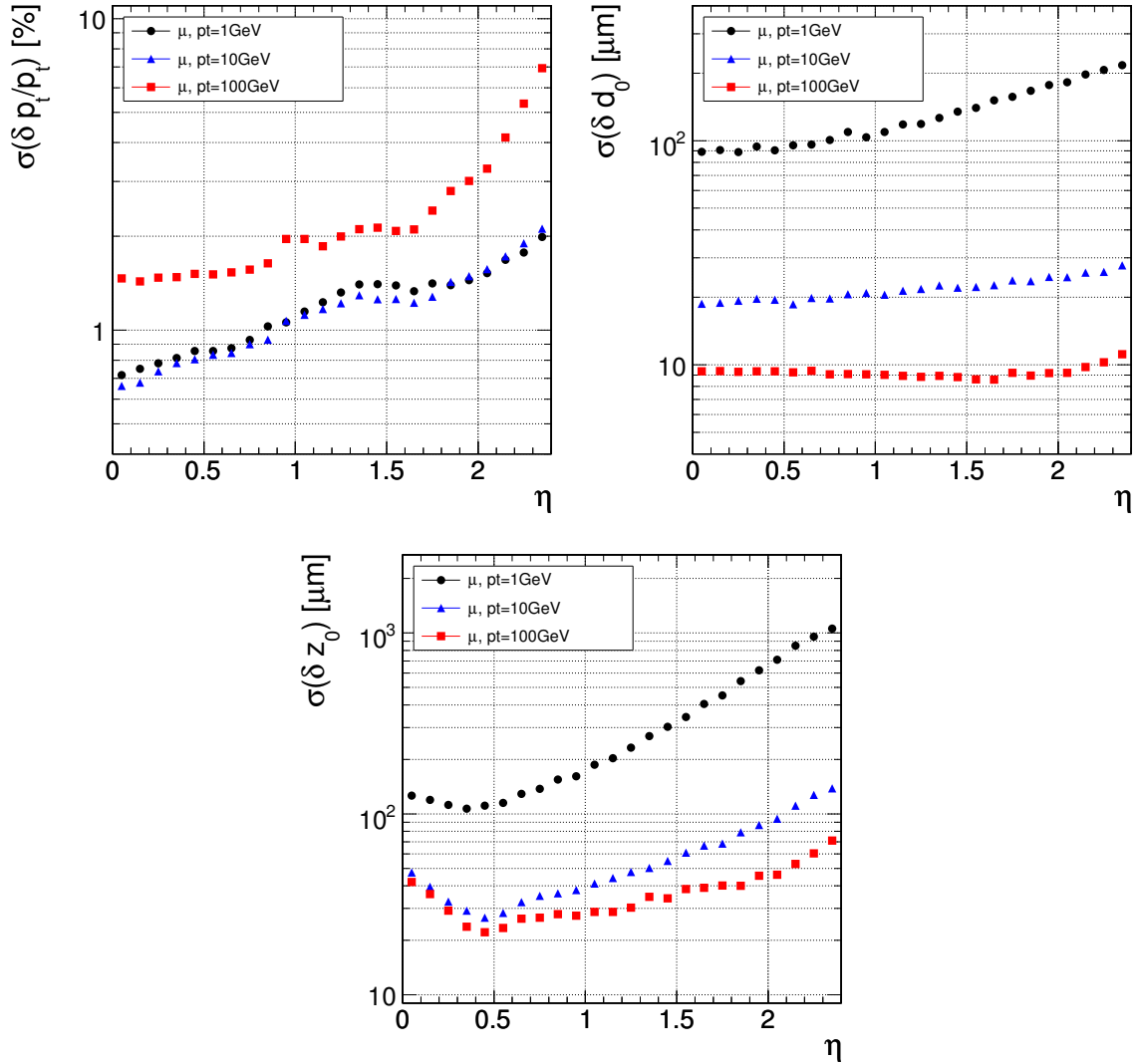


Figure 1.5: Resolution of several track parameters for single muons with transverse momenta of 1, 10 and 100 GeV: transverse momentum (left), transverse impact parameter (right), and longitudinal impact parameter (below) [14].

layer is mounted at a radius of 73 mm. In the phase of highest luminosity a third layer will be mounted at 102 mm. During the high luminosity phase it is expected that the innermost layer stays operational for at least two years and could be exchanged afterwards.

The end caps have a radius from 60 mm to 150 mm and are mounted at a distance of 34.5 cm and 46.5 cm to the vertex. Thus they cover a region up to $|\eta| = 2.4$.

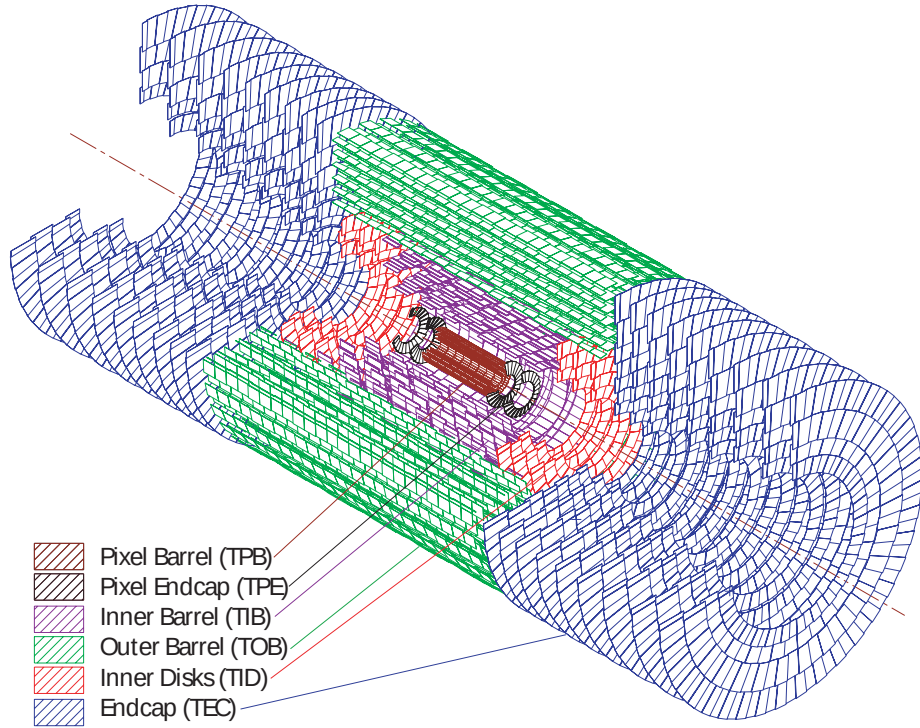


Figure 1.6: The CMS tracker: The different regions of the tracker are marked in different colours [8].

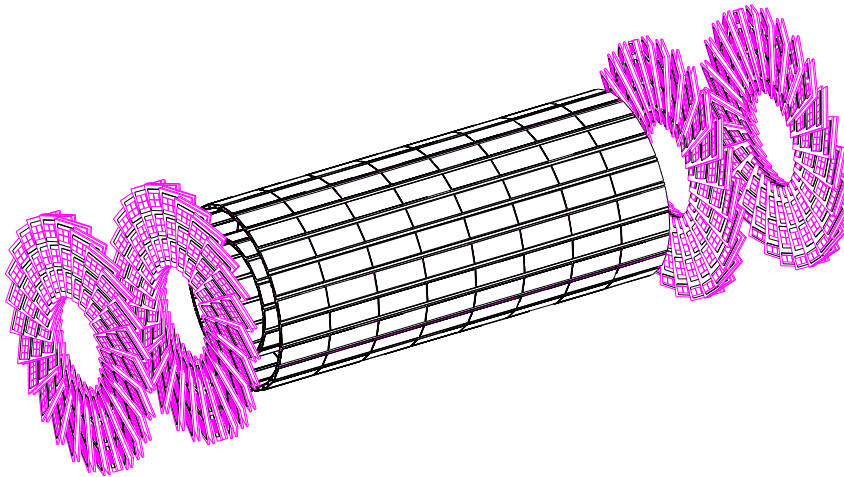


Figure 1.7: The pixel detector [15].

Chapter 2

The Silicon Strip Tracker

As described in the last chapter, the silicon strip tracker consists of four subdetectors (TIB, TID, TOB, and TEC). They are mounted into the tracker support tube (TST). The TST has a length of ≈ 5.5 m and a diameter of ≈ 2.2 m. On the inner side of the tube a thermal shield is mounted. The shield is necessary to guarantee the temperature difference of 30°C between tracker and ECAL. Fig. 2.1 shows a longitudinal cut through a quarter of the silicon strip tracker. It shows the position of sensitive areas and gives information about the module type. The strips of a module are orientated along the direction of z for TIB and TOB and in direction of r for TID and TEC. The strip pitch is in the range of $80\ \mu\text{m}$ to $205\ \mu\text{m}$. On some positions a second module with a stereo angle of $100\ \text{mrad}$ is mounted. This provides a measurement of the second coordinate (z in the barrel region and r on the disks). These modules are called stereo modules, the others are called normal modules. A normal module and stereo module in combination is a double sided module. Single sided modules are normal modules without a stereo module. They have 512 readout channels, double sided modules 768 channels each.

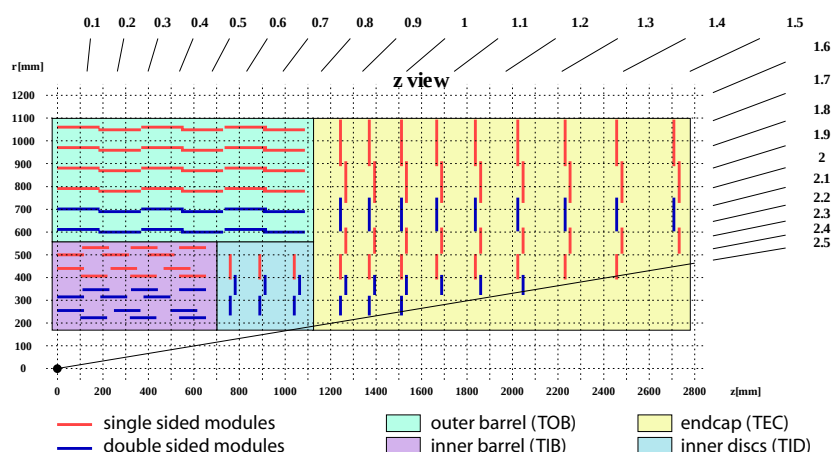


Figure 2.1: A quarter of the CMS tracker: The different subdetectors of the tracker are marked in different colors [16].

2.1 TIB

The TIB has four cylindrical layers, with each of them build of four half shells, (Fig. 2.2) two for the plus and two for the minus side, so in total 16 half shells. The half shells are located at radii of 255 mm, 399 mm, 418 mm and 498 mm. On the first two layers double sided modules are mounted. In total TIB has 2724 modules with 1,787,904 readout channels.

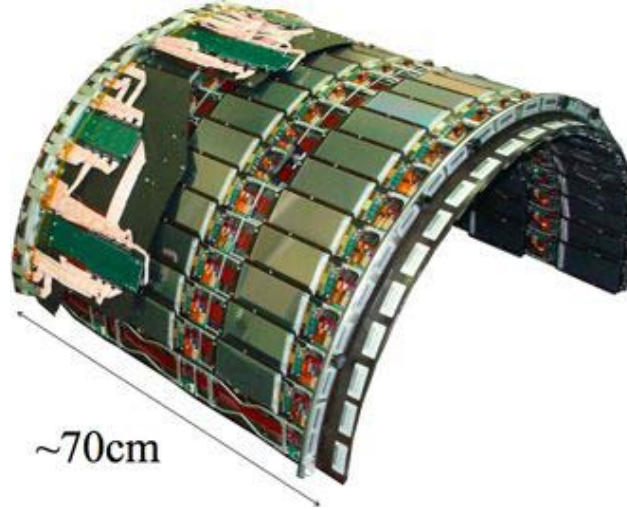


Figure 2.2: A half shell of the third layer of TIB [34].

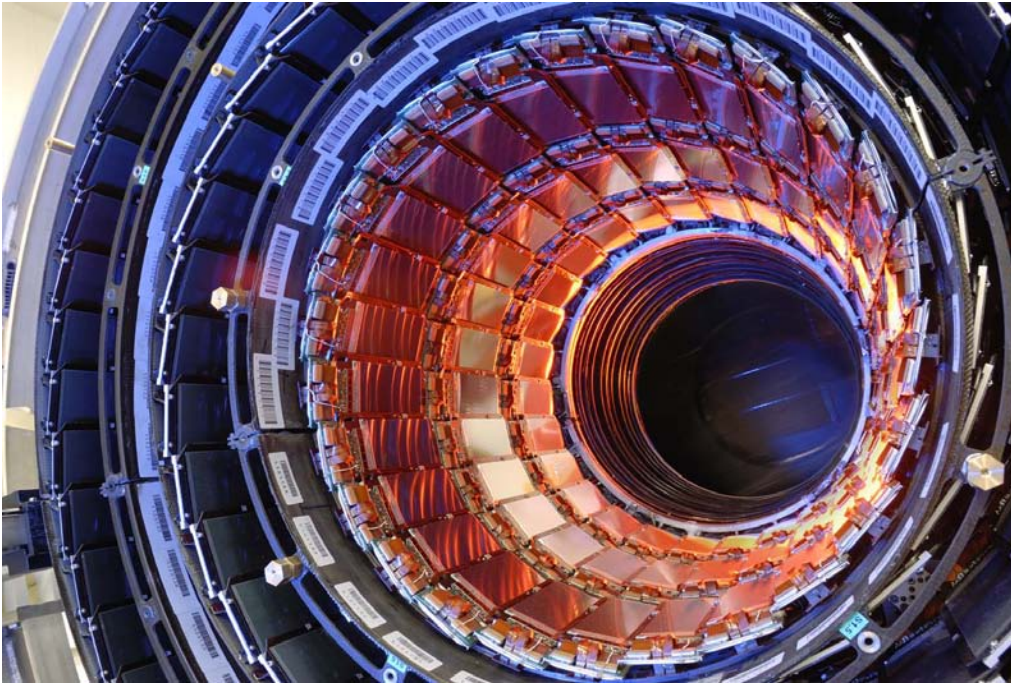


Figure 2.3: View of TIB/TID. Visible are the silicon modules of the first TIB layer, as well as the inner radius of the TID disks at the back [14].

2.2 TID

To each end of TIB one TID is attached. Three discs (Fig. 2.4) with an inner radius of approximately 23 cm and outer radius of approximately 51 cm are mounted at a distance between 80 cm and 90 cm from the interaction point. On rings one and two double sided modules are mounted. In total 816 modules with 565,248 readout channels are assembled. Fig. 2.3 shows a photograph of TIB and TID.

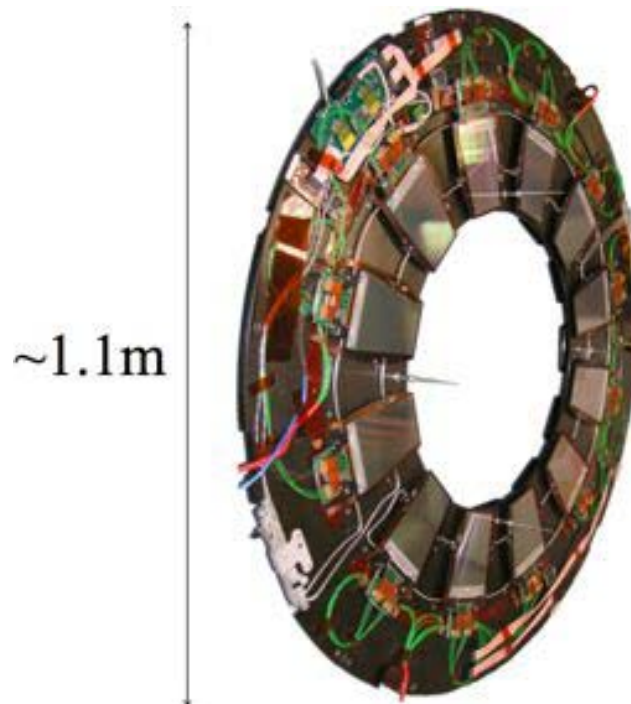


Figure 2.4: The innermost ring of a TID disc [34].

2.3 TOB

TIB and TID are located inside of TOB. TOB consists of six cylindrical layers at radii between 600 and 1,080 mm. Each layer is composed of substructures called rods (Fig. 2.5). Rods are the 'equivalent' to the halfshells of TIB. The first two layers are layers with double sided modules so each rod has, depending on the layer, six or twelve modules. TOB has in total 5,208 modules with 3,096,576 readout channels. Fig. 2.6 shows a picture of TOB.

2.4 TEC

Next to each end of TOB one TEC is placed. Each TEC has nine discs and each disc has up to seven rings of modules (discs 1 to 3: 7 rings, discs 4 to 6: 6 rings, discs 7 and 8: 5 rings and disc 9: 4 rings; counting from the interaction point). The TECs have a substructure called petals. On every disc 16 petals are mounted, 8 facing the interaction point (front petals)

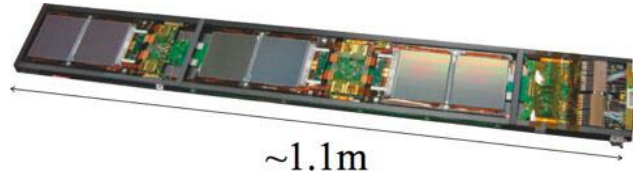


Figure 2.5: A rod of the TOB [34].

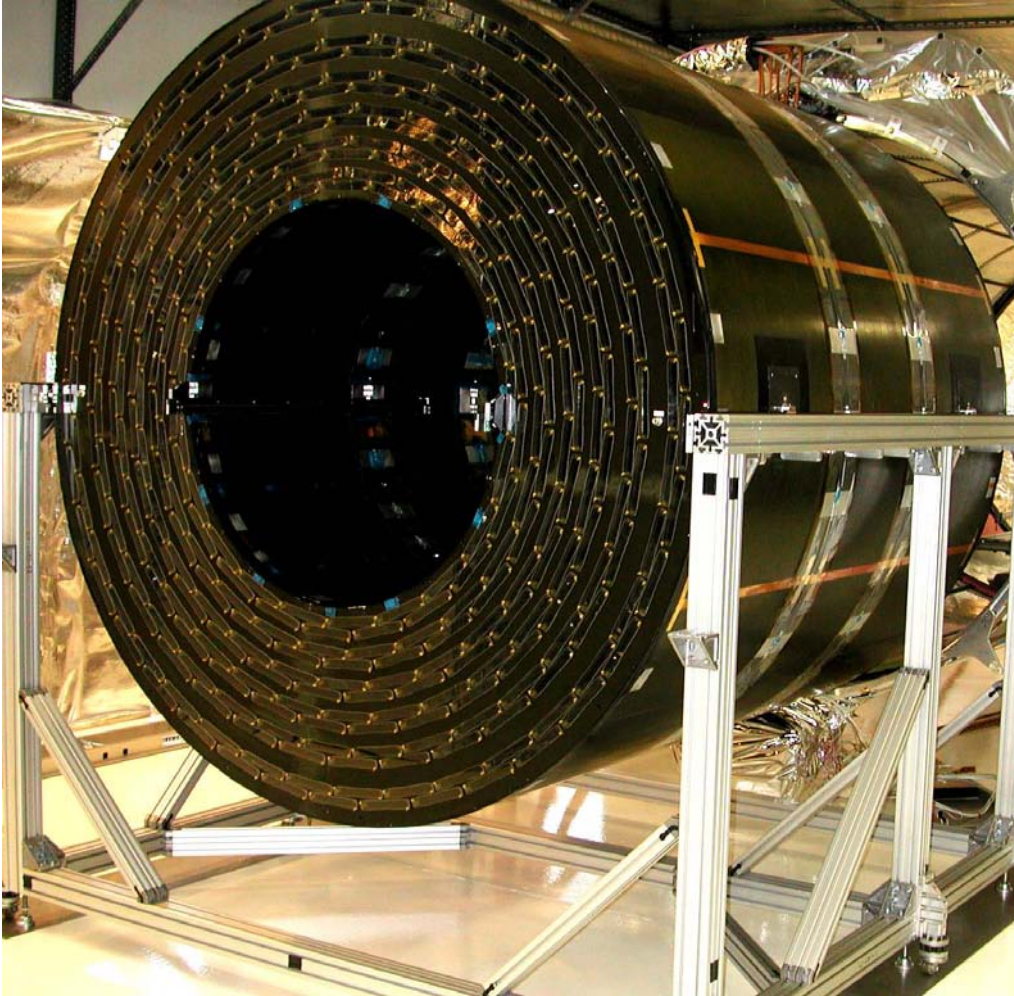


Figure 2.6: Picture of TOB support structure [14].

and 8 on the far side (back petals). The front and back petals are slightly overlapping to ensure a complete coverage with silicon. On the rings one, two and five double sided modules are mounted. Both TECs together contain 10,288 sensors on 6,400 modules with 3,866,624 readout channels. More details on the tracker can be found in [14].

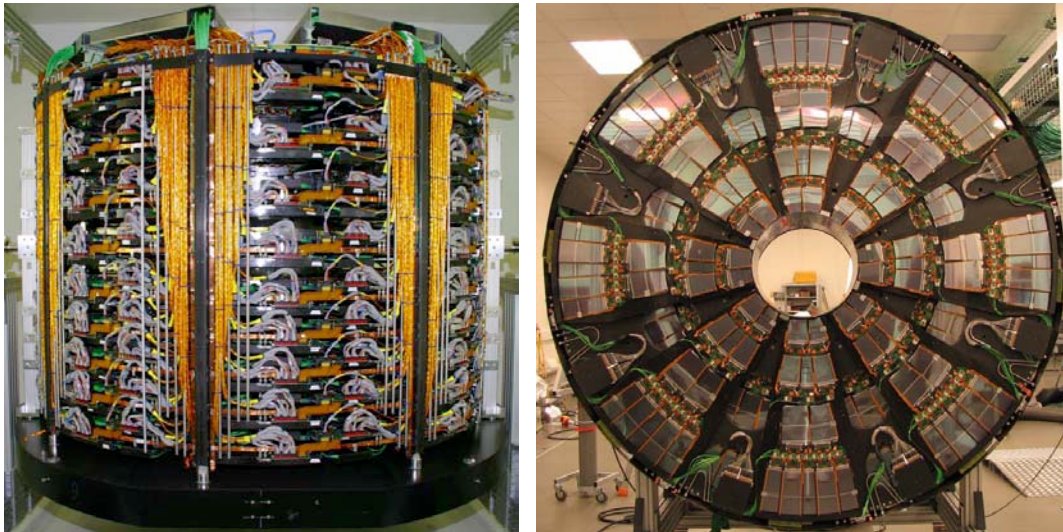


Figure 2.7: Side and front view of a TEC [14].

2.4.1 Petal

One petal has modules belonging to up to seven rings, depending on the disc the petal is mounted to. In total there are eight different types of petals. The modules are mounted on both sides of a petal to guarantee a complete coverage with silicon (Fig. 2.8). The precision with which the modules are positioned on the petal is in the order of $20\,\mu\text{m}$ [14].

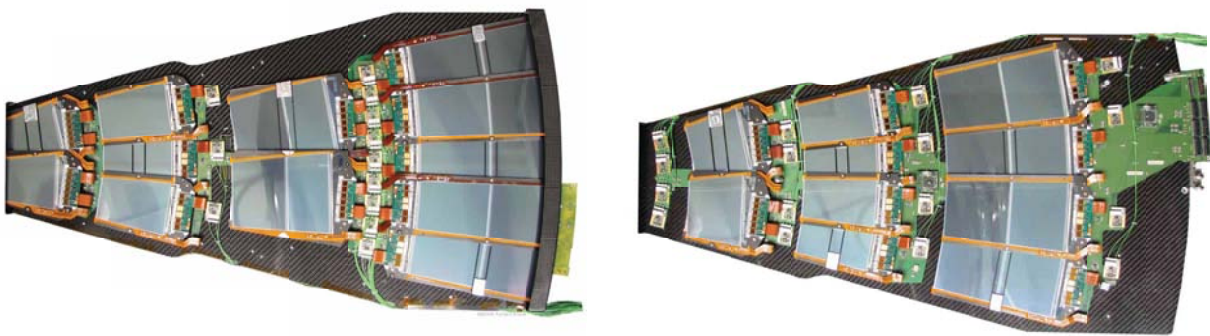


Figure 2.8: Photograph of front and back side of a TEC front petal with seven rings [14].

The body of the petal is made of 10 mm NOMEX¹ in a honeycomb structure within 0.4 mm Carbon Fiber Composite (CFC) skins (Fig. 2.9). A cooling pipe is integrated within the body (Fig. 2.10). The whole system is optimized for a good heat flow with low material budget. On the petal body the interconnect board (ICB [19]) is mounted. It sends communication signals via the CCUs² and also voltages (ground, Low Voltage with 1.25 V and 2.5 V and

¹Flame resistant meta-aramid material developed by DuPontTM <http://www.dupont.com/>

²Communication and Control Unit [17]

High Voltage with up to 500 V) to the different modules. Readout signals of the modules are transported to the analogue opto hybrids (AOH [18]), also mounted onto the ICB, and from there via optical fibers to the read out system (Fig. 2.11). The read out link is optical to minimize cross talk. More information can be found in chapter 4 and also in [14, 22].



Figure 2.9: Structure of a part of petal body could be seen (NOMEX within CFC). The honey comb structure was partially destroyed during removal of the CFC skin.

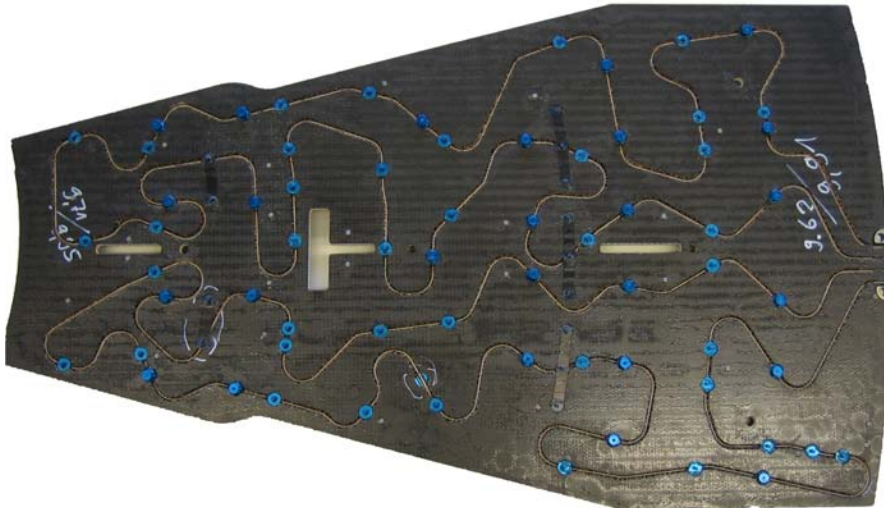


Figure 2.10: Photograph of petal body with cooling pipe. The cooling pipe can be seen, since the outermost carbon skin is not yet glued.

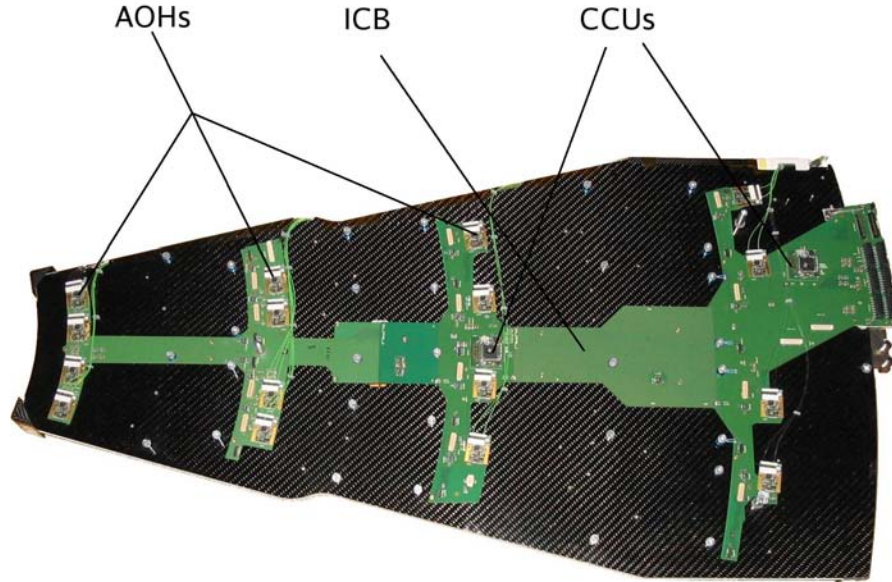


Figure 2.11: Petal after assembly of ICB, CCU and AOH. Only three out of 16 AOHs are marked.

2.4.2 Silicon strip module

The silicon strip module consist out of four main parts: the silicon strip sensor, the support frame, the readout electronics on the so-called front-end hybrid and a flat Kapton circuit which delivers the bias voltage to the sensor backplanes and insulate the sensor from the frame (Fig. 2.12).

The silicon strip sensor

The major component of a module is the silicon sensor [20]. The function principle of such a sensor can be described with help of a semiconductor diode (Fig. 2.13(a)). The diode is driven with reverse biased conditions. Only a very small current the so called I_{leak} flows into this direction. The width of the depleted region is increased. If a charged particle transverses this region it creates electron-hole pairs along its track. A MIP³ loses about 260 eV per μm while 3.6 eV are needed to create an electron-hole pair. Thus gives about 70 electrons per μm . The charges of the respective sign move in the direction given by the electric field. This induces charge pulses in both electrodes of the diode which can be used to identify the crossing of a particle. It is to mention, that the diode has to be thick enough, so that the pulses are high enough to be detected. The principle of the particle detection can be improved if segmented electrodes are used. Those work like many different diodes and provides a more detailed information about the position of the transversing particle (Fig. 2.13(b) and (c)). The sensitive region of a diode is equal to the depleted region. Therefore it is of interest to

³Minimum Ionizing Particle

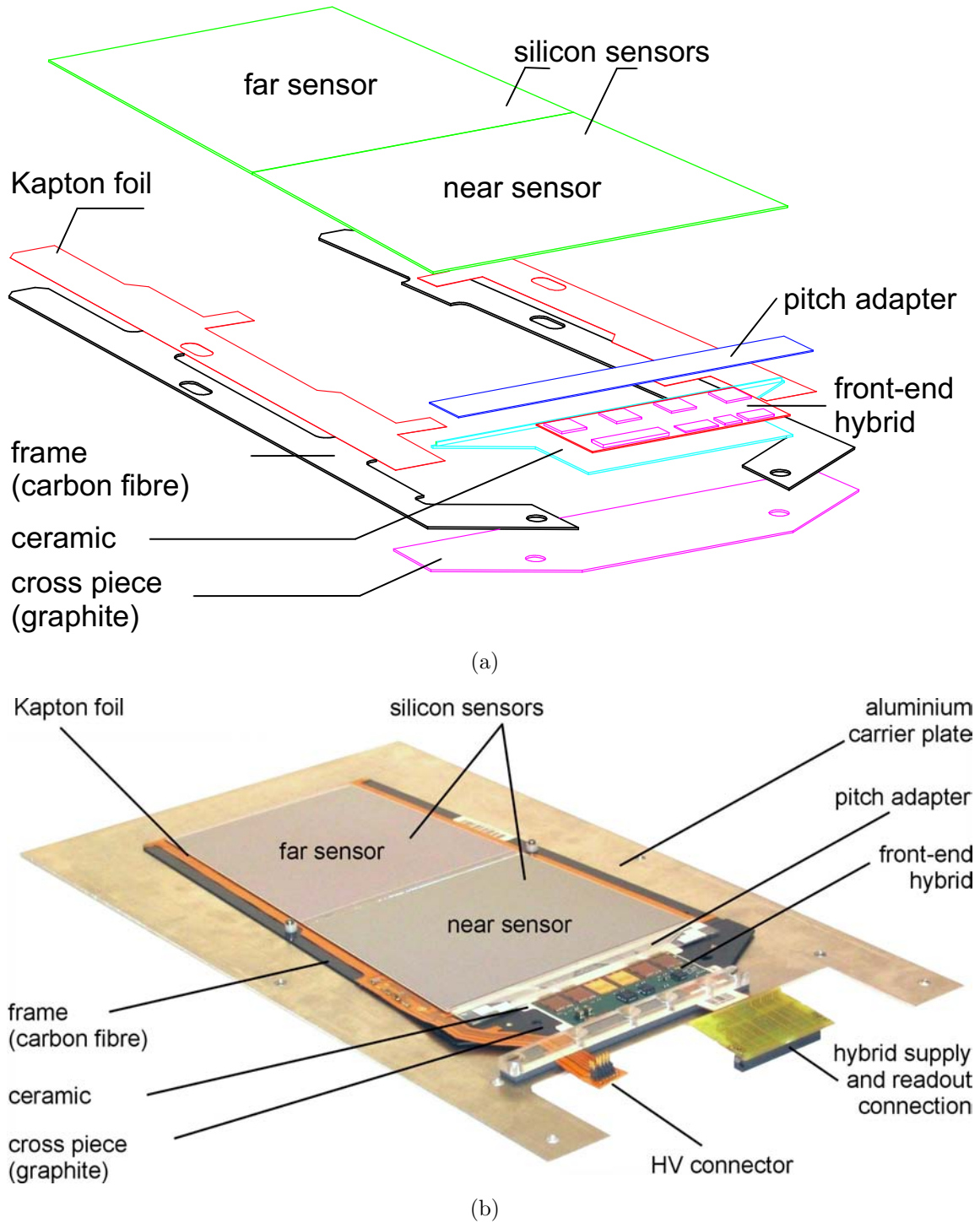


Figure 2.12: (a) Exploded view of a ring 6 TEC module. (b) Photograph of a ring 6 TEC module, mounted on a carrier plate [14].

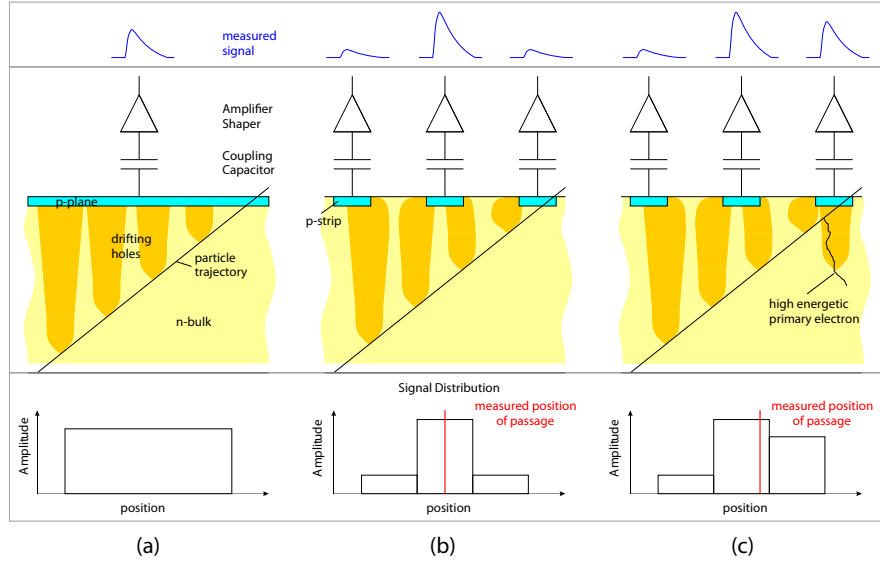


Figure 2.13: Principle of the particle detection using a reversely biased diode. [23] (a) Charges created by an ionizing particle drift to their respective electrode and induce a signal, that indicates the passage of a particle. (b) Charges drifting to neighboring electrodes induce signals and the signal height is a measure for the amount of charge drifting to the respective electrode. By weighting the signals the spatial resolution can be improved to values below the size/width of the segments. (c) High energetic primary electrons can create charges and thus signals in regions far away from the particle's track. Thereby the spatial resolution gets deteriorated. High energetic primary electrons are responsible for the long tail of the Landau Distribution.

deplete the whole diode. In addition the noise of an amplifier is proportional to the input capacitance [24]. This is mainly determined by the capacitance of the p-n diode which is smallest if the diode is fully depleted. An other source for noise is the leakage current [25]. More information can be found in [26] and [27].

Each module has one or two silicon sensors (two sensors for modules in TOB and modules on ring 5 to 7 of TEC) of roughly $10\text{ cm} \times 10\text{ cm}$ and a thickness of $320\text{ }\mu\text{m}$ for 'thin' and $500\text{ }\mu\text{m}$ for 'thick' sensors. The sensor consists of n-doped bulk material with p⁺-type strip implants on the front side (Fig. 2.14). Single-sided modules have 512 strips and double-sided 768 strips each. The p⁺-strips are AC-coupled to aluminum strips. A separation of both is given by multiple layers of SiO₂ and Si₃N₄ providing the dielectric for the capacitors made of each pair of p⁺- and aluminum strip. The width of the aluminum strips is about 15% larger compared to the width of the p⁺-implants, to avoid high fields at the edges of the p⁺-implants. The width of the implanted strips depends on the strip pitch: a constant width/pitch ($\frac{w}{p}$) of 0.25 is used for all sensor geometries. The total capacitance of a strip per unit length C_{tot} depends on the interstrip capacitance and the backplane capacitance. In a range of $300\text{ }\mu\text{m}$ to $500\text{ }\mu\text{m}$ silicon thickness, C_{tot} can be parameterized as

$$C_{tot} = (0.8 + 1.7 \frac{w}{p}) \text{pF/cm} \quad (2.1)$$

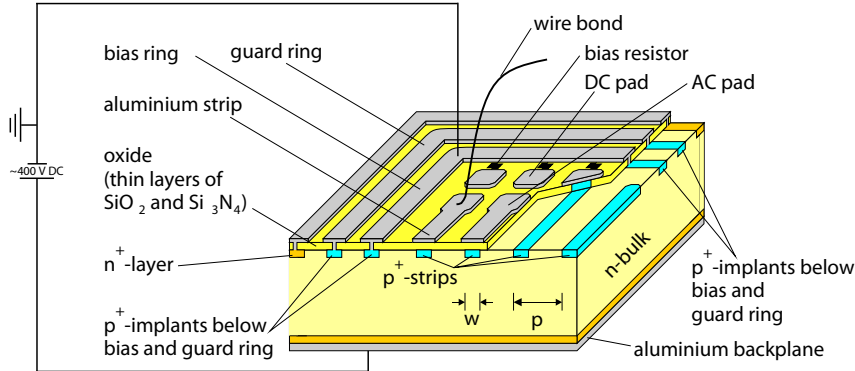


Figure 2.14: Schematic design of one corner of a silicon strip sensor.

It is worth mentioning that C_{tot} in this range is independent from the silicon thickness as the contribution of the interstrip capacitance cancels the contribution of the backplane capacitance [25]. The capacitance for modules on the rings 5 to 7 of TEC and for modules of TOB is largest as the strip length for these modules is up to 20 cm. Hence the noise for those modules is largest. To obtain a good signal-to-noise ratio also in this region, the signal has to be increased. This is done by using 'thick' sensors as the signal height is proportional to the sensor thickness. The capacitance and therefore also the noise is not influenced by this change (see Eq. 2.1). The back side of the sensor consists of a uniformly metalized n^+ -layer. This layer is connected to positive voltage of up to 500 V. The n^+ -layer provides the necessary ohmic contact between the bulk and the aluminum layer. The sensitive area is surrounded by a p^+ -bias ring and several p^+ -guard rings. The bias ring is at ground potential. The guard rings are at floating potential in order to gradually reduce the electric field between the bias ring and the n^+ -layer at the sensor edges. At the end of each strip are two bond pads to connect the strips to the readout electronic or in the case of two sensors the far sensor (the sensor which has more distance to the readout chips) is connected via wire bonds to the near sensor. Each strip has a test pad which is directly connected to the p^+ implant. During LHC operation each sensor suffers from radiation damage. The radiation induces impurity in the lattice which results in additional energy levels between the valence and conduction band. Therefore the I_{leak} increases after several years of operation. The time evolution of such impurities and their impact are described by two effects. The first effect is called *annealing* and takes place within some hours up to some weeks and reduces the leakage current and the depletion voltage. The second effect is called *reverse annealing* and takes place on a time scale of month. In contrast to annealing it has a negative effect to the leakage current and the depletion voltage. Fortunately this second effect could be suppressed if the sensor is kept at low temperatures. Therefore the CMS silicon tracker will be operated at temperatures below 0°C , the 'design value' for the sensors is -10°C .

The support frame

The sensors of the TECs are glued to a U-shaped support frame made of graphite or a combination of graphite and carbon fiber (Fig. 2.12). This support frame provides the necessary

stability to the sensors. Further it carries the readout electronics. Graphite and carbon fiber provide the requirements of high stiffness, low mass, and efficient heat removal from the sensors as radiation hardness as well. In addition they have approximately the same thermal coefficient of thermal expansion as silicon, so that the difference could be absorbed by the glue.

The readout electronics

The readout electronics on the front-end hybrid consists of four or six Analogue Pipeline Voltages (APVs [35]) with 128 readout channels each, one multiplexer chip (APVMUX [36]), one chip for the trigger decoding, Tracker Phase Locked Loop (TPLL [37]) and one chip for the surveillance of environment parameters, Detector Control Unit (DCU [38]). It monitors values like hybrid and sensor temperature, supply voltage and currents at the hybrid as also I_{leak} . The sensors are connected via wire bonds to the pitch adapter which adjusts the pitch of the sensors to the pitch of the readout unit APV ($44\ \mu\text{m}$). The APV is the main read out component on the front-end hybrid. For operation it needs, two voltages of 1.25 V and 2.5 V as well as a 40 MHz clock, the bunch crossing frequency of the LHC. The charge signals of the strips get amplified by low noise amplifiers (Fig. 2.15). The amplifier is followed by a signal

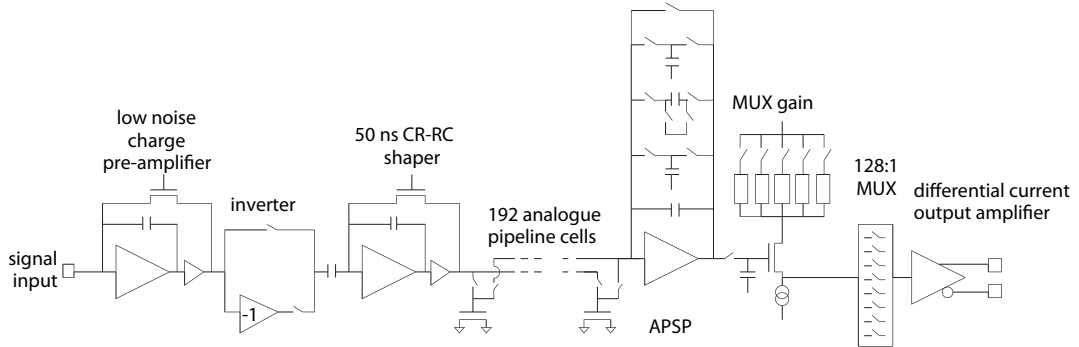


Figure 2.15: Block diagram of one channel of an APV25 readout chip [35].

inverter unit which can be switched on or off. A CR-RC shaper produces a pulse with the output voltage:

$$U(t) = \frac{AQ_c t}{\tau} \cdot \exp \frac{-t}{\tau} \quad (2.2)$$

with a peaking time of $\tau = RC = 50\ \text{ns}$. Q_c is the collected charge and A an amplification factor determined by the preamplifier. The shaped voltage pulses are then continuously sampled every 25 ns and stored in an analogue pipeline with 192 cells per readout channel. The pipeline stores the signals for more than $4\ \mu\text{s}$. In case of no trigger signal the cell becomes overwritten within $4.8\ \mu\text{s}$. The following Analogue Pulse Shape Processor (APSP) allows to run the APV in three different operation modes and returns data with different peaking times. Depending on the operation mode one or three pipeline cells are reserved for read out. The modes are *peak mode*, *deconvolution mode* and *three sample mode*. In peak mode the stored signal is transmitted to the next processing step. Two consecutive hits could not be disentangled, since the shaping time of 50 ns is twice as large as the time between two hits and so entails an overlap of the two shaped signals.

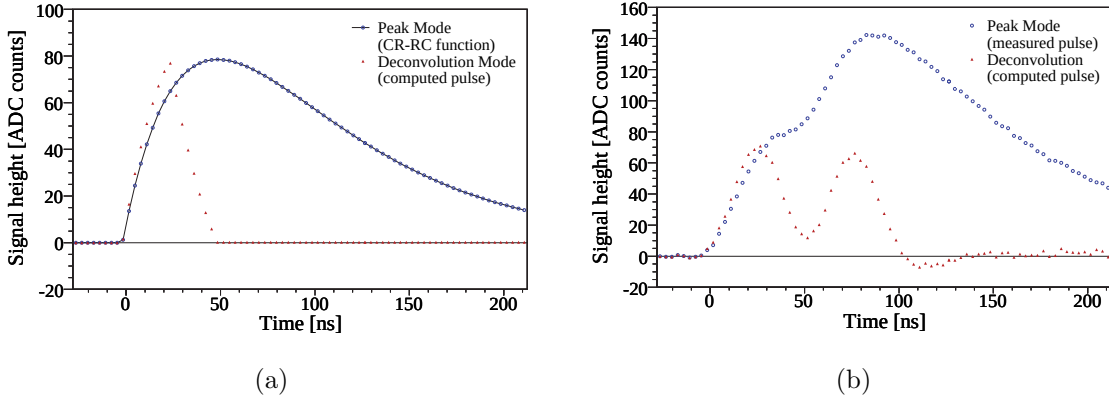


Figure 2.16: Result of the deconvolution mode if one or two peaks are convoluted. (a) Ideal CR-RC function sampled in 3.125 ns intervals is used as input for the deconvolution algorithm [30]. (b) Two peak-mode pulses separated by two clock cycles [30].

In deconvolution mode (dec mode) this problem can be reduced by a weighted summation of three subsequent samples of the shaped pulse. The weights used by the APV can be calculated to: $(w_1:w_2:w_3 = 1.457:-1.759:0.534)$ including a scaling factor so that the pulse height in deconvolution mode is approximately the same as in peak mode [28]. In Fig. 2.16 the result of such a deconvolution can be seen. Unfortunately the deconvolution logic introduces additional noise to the signal, so that this mode is foreseen to be used at high event rates only (LHC high luminosity phase). It is expected to reach an signal-to-noise ratio (S/N) of 27-33 for 'thin' sensors and 35-42 for 'thick' sensors in peak mode and in deconvolution mode a ratio of 19-22 for 'thin' and 20-24 for 'thick' sensors [14].

The third operation mode (*three sample mode*) returns also a summation of the same three pipeline cells but without a weighting. For this thesis the APV was used in four different modes: 'peak mode inverter on' (peakinon), 'peak mode inverter off' (peakinoff), 'deconvolution mode inverter on' (decinon) and 'deconvolution mode inverter off' (decinoff). After the APSP the data can be read out through an analogue multiplexer, that combines all 128 readout channels to one single channel.

A typical data frame released by the APV can be found in Fig. 2.17. It is composed of a digital header with 12 bit length. The analogue data follows with a length of 128 bit corresponding to the 128 strips. The data frame is terminated by a tick mark, a digital 1. If no data is present every 35 clock cycles a tick is sent to keep synchronization with the DAQ system.

In order to test the connected strips and the corresponding APV channel the APV can release a certain amount of charge to the strips. The feedback gives information about the characteristics of the corresponding channel.

The APVMUX chip is the next step in the readout chain of the hybrid. It is a multiplexer chip which, in order to minimize the number of readout channels, combines the output of two APVs to one single channel. This results in two readout channels per module for single sided modules and three for one side of a double sided module. In total a petal can have up to 68 readout channels, here front petal for disc 1-3.

The TPLL chip allows to shift the signal of the clock in steps of 1.04 ns up to 25 ns. With help of this chip it is possible to synchronize the APVs of different modules to the same phase of the LHC clock.

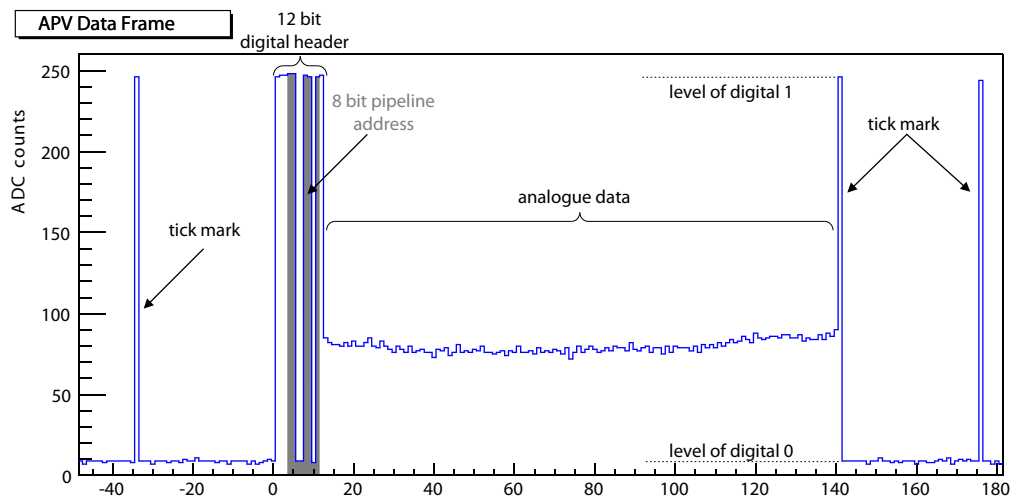


Figure 2.17: Typical APV data frame. [23]

A Kapton circuit attached to the backplane of the sensor is used to connect the sensors to HV. The return line goes via bonds to the pitch adapter. More detailed information about the modules can be found in [14, 23, 30].

2.4.3 AOH

The AOH (Fig. 2.18) transforms analogue electrical signals coming from the APVMUX into analogue optical signals. These signals are sent, in case of the longterm test⁴, via optical fibers to a patch panel where the fibers are connected to six optical multi ribbon cable (Fig. 2.19). Each ribbon has twelve fibers. Due to the length of the fibers and the wish to always have a complete module on one ribbon there are constraints to the mapping of AOH to ribbon. The mapping used in the longterm test setup can be found in appendix A.1.

Each AOH is responsible for one module and contains one laser transmitter per data stream coming from the APVMUX. This means that an AOH that is responsible for a single sided module has two lasers and three lasers for one side of an double sided module. The lasers are commercially available multi-quantum-well InGaAsP edge-emitting devices and were chosen due to their high linearity. Each laser diode is steered by a laser driver which receives the data stream from the APVMUX and provides a bias current to the laser diode. The laser diodes can be driven in four gain modes. With help of those gain modes and a bias offset the optimal working point of the laser diode can be determined. During the longterm test always gain two was chosen. More details on the AOHs can be found in [14].

The whole assembly of ICB, CCU and AOH and also modules was performed in cooperation of several institutes across Europe. After the assembly of all components a long intensive test was necessary to check the state of each component, the long term test (Chapter 4). Furthermore this test is the first test on the complete substructure of the TEC, including communication, readout and cooling. The test routine contains the co-operation of all component as well as several stress tests to reach knowledge if a petal could withstand several LHC shut down cycles.

⁴Test of a whole petal directly after the assembly of all modules. Described in Chap. 4

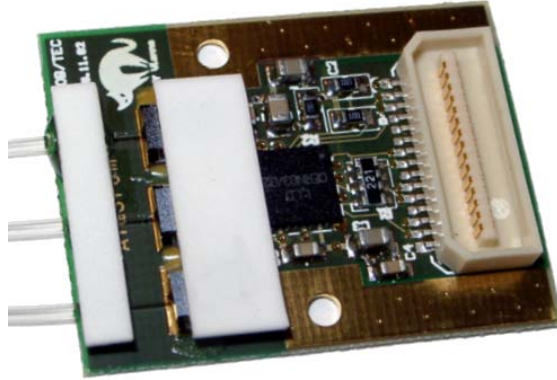


Figure 2.18: Photograph of an AOH.

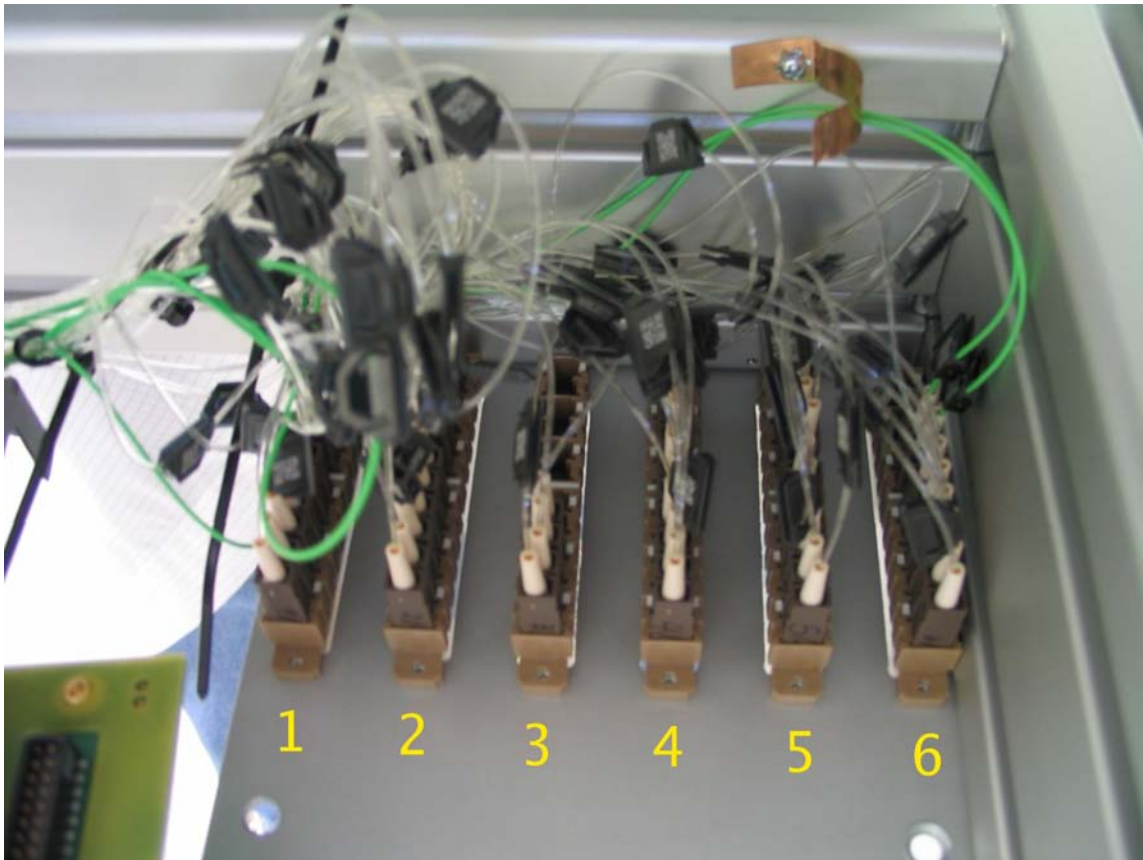


Figure 2.19: Photograph of a fiber mapping used during the long term test. A lot of fibers coming from the AOHs can be seen. These are connected to six ribbons which have twelve input slots each. The ribbon number used in appendix [A.1](#) is shown in yellow.

Chapter 3

Single module test

The single module test setup ARC¹ is a specialized setup to test modules and to determine their faults with high reliability. This implies not only to find general problems with a module, but also to find and identify defects of single strips. In the following two test procedures of the ARC setup and some defect types of the module will be introduced. Those will also be used later during the LT test. Detailed information about the ARC setup and the tests can be found in [23, 33].

3.1 Pedestal test

During the pedestal test (sometimes also called noise test) raw data $DR_{ch,n}$ is measured strip wise. The index ch is the channel under investigation and n the event. Repetitive measurements allow to extract the mean value P_{ch} (the pedestal Eq. 3.1) and the RMS RMS_{ch} (the noise Eq. 3.3) of the raw data of every strip (Fig. 3.1). The total amount of measurements is $N = 5000$ in both test setups, ARC and LT test. Furthermore it is possible to extract the common mode CM_n which is a common shift of the signal height of all strips of one APV in event n . Each APV is divided into 4 subgroups of 32 channels and the $CM_{n,group}$ is calculated per group (Eq. 3.2). Reasons for this shift could be variations in the power supply voltage which affects all strips and pick up noise. To extract the RMS of every strip the common mode is subtracted. In the following the equations to calculate P_{ch} , $CM_{n,group}$ and RMS_{ch} are listed:

$$P_{ch} = \frac{1}{N} \cdot \sum_{n=1}^N DR_{ch,n} \quad (3.1)$$

$$CM_{n,group} = \frac{1}{32} \cdot \sum_{ch \in group} DR_{ch,n} - P_{ch} \quad (3.2)$$

$$RMS_{ch} = \sqrt{\frac{\sum_{n=1}^N (DR_{ch,n} - CM_{n,group} - P_{ch})^2}{N}} \quad (3.3)$$

The RMS depends on the strip length and the quality of the readout system. Due to the fact that the readout system and strip length is the same for all strips of a module, the

¹APV Readout Control

noise varies only slightly from strip to strip, especially in the range of one APV. In case of a possible defect the capacitance of the strip changes and so the measured noise changes. So the information about the noise helps to understand the quality of the detector. An exception is the behavior of edge strips of the APV. Here the noise is always higher. The reasons therefore are not completely understood but the effect can be reduced by a improved grounding scheme ([14, 23]). The measured signal $S_{ch,n}$ of channel ch in event n is defined as: $S_{ch,n} = DR_{ch,n} - P_{ch}$.

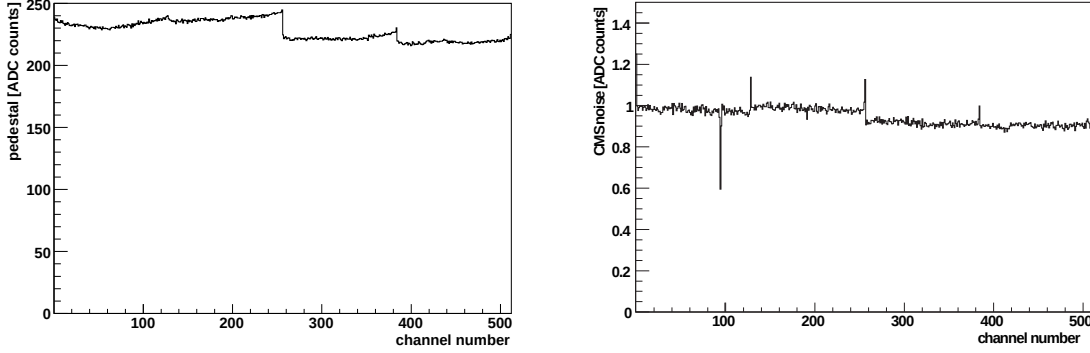


Figure 3.1: Pedestal and common mode subtracted (CMS) noise of a ring 3 module. Obviously the noise of the APV-edge channels (1, 128, 256, 384) is higher. The noise of channel 94 indicates a strip defect.

The values described above are all derived by offline calculations. Instead of this method an event by event calculation is preferred as there is no need to keep all raw data and the information is available instantaneously. Unfortunately some of those on-line calculations are only approximations to the values mentioned above. The Pedestal $P_{ch,m}$ for channel ch in event m is calculated with following equation:

$$P_{ch,m} = \frac{P_{ch,(m-1)} \cdot (m-1) + RD_{ch,m}}{m} \quad (3.4)$$

For $m = N$ this equation is identical to Eq. 3.1. For the noise calculation a stable pedestal with only low statistical fluctuations is needed. Therefore the noise computation starts after the first l events with $l = 1000$ for the ARC test and later $l = 200$ for the LT test. The raw noise $RN_{ch,m}^2$ for channel ch in event m is given with following term:

$$RN_{ch,m}^2 = \frac{RN_{ch,(m-1)}^2 \cdot (m-l-1) + (RD_{ch,m} - P_{ch,m})^2}{m-l} \quad (3.5)$$

and the common mode CM_m in event m is calculated by:

$$CM_m = \frac{1}{128} \sum_{ch=1}^{128} (RD_{ch,m} - P_{ch,m}) \quad (3.6)$$

The common mode corrected noise $CMN_{ch,m}$ for channel ch in event m is finally calculated by:

$$CMN_{ch,m}^2 = \frac{CMN_{ch,(m-1)}^2 \cdot (m - l - 1) + (RD_{ch,m} - CM_m - P_{ch,m})^2}{m - l} \quad (3.7)$$

The situation gets even more complicated as the calculation of the common mode is again for groups of 32 channels. In addition noisy and dead channels have to be excluded from the computation. Therefore an iterative algorithm is necessary. The exact algorithms and their performance can be found in [21].

3.2 Calibration Profile test

During the **Calibration Profile** (CalProf) test the APV emits a charge (adjustable between 0 fC and 25.5 fC) to each single strip. The APV does this simultaneously for every eighth strip, called calibration group. Each calibration group differs slightly in the amount of charge sent to the strips. In a second step the APV gets a trigger to read out the sensor. The time between emitting the charge and readout can be controlled with help of LATENCY and CSEL² in 80 steps of 3.125 ns [23]. Thus the time evolution of the APV response could be measured which is a method to get information about the connected capacitance. Subtracting common mode CM and pedestal P from the measured height RD gives the signal height $S = RM - P - CM$. To minimize statistical fluctuations onto this height each measurement is repeated 400 times. Further a new pedestal is taken after every LATENCY change. The exact implementation can be found in [33]. The implementation for the LT test is a bit different. As an approximation for pedestal and common mode the median med of the neighbouring and next to neighbouring channels are taken $S = RM - med$ [32].

A standard pulse which is read back can be found in Fig. 3.2. It is to mention, that the pedestal is subtracted. A behavior like a CR-RC-circuit is expected (see Eq. 2.2). This form of this peak could be generalized with the following equation:

$$ADCcounts = A \cdot \frac{(t - t_p + \sigma)}{\sigma} \cdot \exp \frac{1 - (t - t_p + \sigma)}{\sigma} \quad (3.8)$$

where h_p gives the height of the peak, t_p the position and σ the width which is equal to the shaping time $\tau = RC = 50$ ns. t is equal to the time on the 'x-axis' and $ADCcounts$ to the height on the 'y-axis'. Using this equation for a fit, the position t_p (peak time) and the maximum h_p (peak height) can be determined. The distribution of the peak heights and peak times for a single module can be found in Fig. 3.3. Problems with a strip can be observed if the peak height or peak time differs from reference value. The amount of the deviation depends on the type of defect of the strip. So a classification of strip defects is possible.

3.3 Defect types

There are different types and sources of defects. Some affect the whole module, some a group of 128 channels and others only individual strips. In the following single strip defects will be discussed. These can be divided into different defect classes. The general signature is given in the following. At the end of this chapter a short overview of the ARC test procedure and

²LATENCY and CSEL are APV registers for fine tuning. LATENCY delays the write signal with respect to the trigger in steps of 25 ns. CSEL can adjust the time of calibration injection in eight steps of 3.125 ns

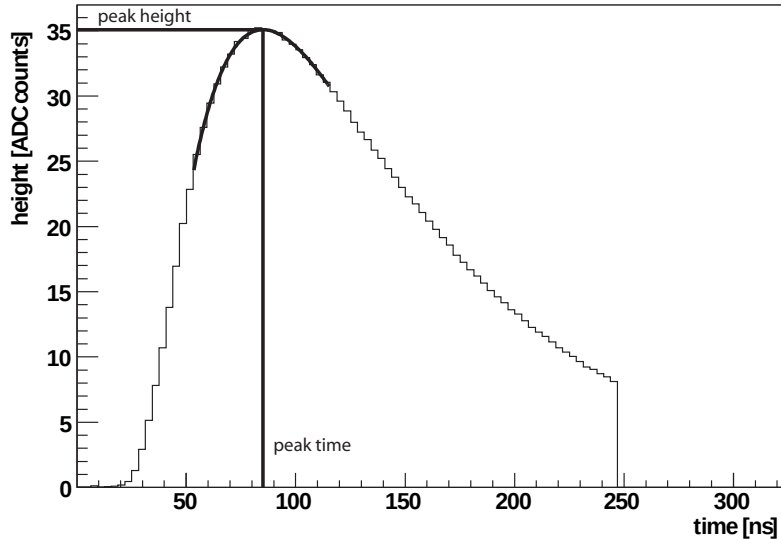


Figure 3.2: Typical profile of one channel. Here measured on a ring 3 TEC module. For the fit the Eq. 3.8 was used. The Fitting range is 10 bins around the maximum.

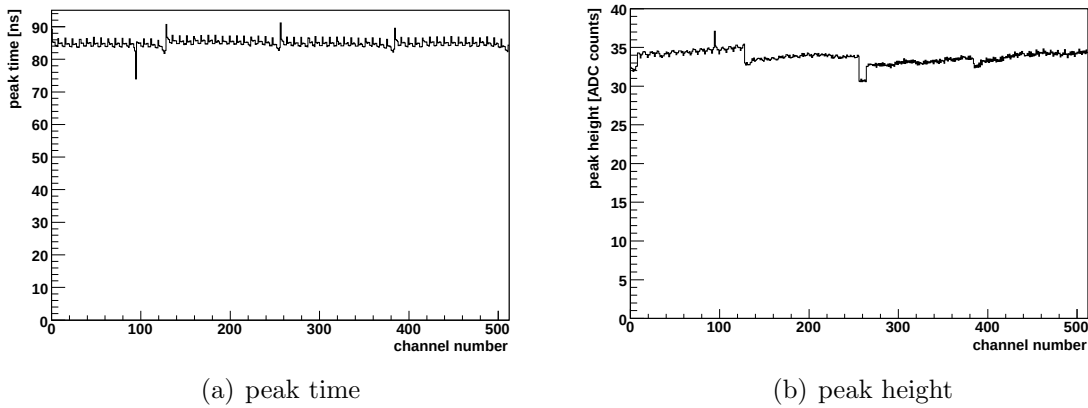


Figure 3.3: Distribution of peak time and peak height of the same ring 3 module. A periodic pattern of the length of eight can be seen due to the calibration groups. Channel 94 again stands out in these plots indicating a single strip defect (compare Fig.: 3.1).

the implementation of those defect classes will be given. The cuts were found with the help of a statistical analysis of all data [23].

3.3.1 Open

The first main class are the 'opens'. An 'open' is a strip which is not or only partly connected to the readout system. Depending on the location and source an open can be either a 'pitch adapter-sensor open', a 'sensor-sensor open' or a 'mid sensor open'.

Pitch adapter-sensor open ('PA-S open')

The location of this defect is somewhere between the sensor and the APV. So the whole strip is disconnected from the readout system. In most cases the reason is a bond which is destroyed by mishandling or disconnected due to other problems of the channel (Fig. 3.4(a) and Fig. 3.4(b)). The missing bond is normally between pitch adapter and sensor. Therefore it is called 'PA-S open'. The consequences are lower noise, earlier peak time and a larger peak height. The lower noise can be explained by the fact, that the noise of the amplifier is proportional to the connected capacitance which is in the order of 10-25 pF (see Eq. 2.1). The capacitance is lowest for a disconnected strip. The shaping time is also proportional to the connected capacitance and hence reduced. Consequently the peak height gets larger and the peak time decreases (see Eq. 3.8 and Fig. 3.5). This is also true for the other open types. They just differ in the amount of deviation. So channel 94 of the ring 3 module shows the signature of an open, confirmed by optical inspection with a microscope.

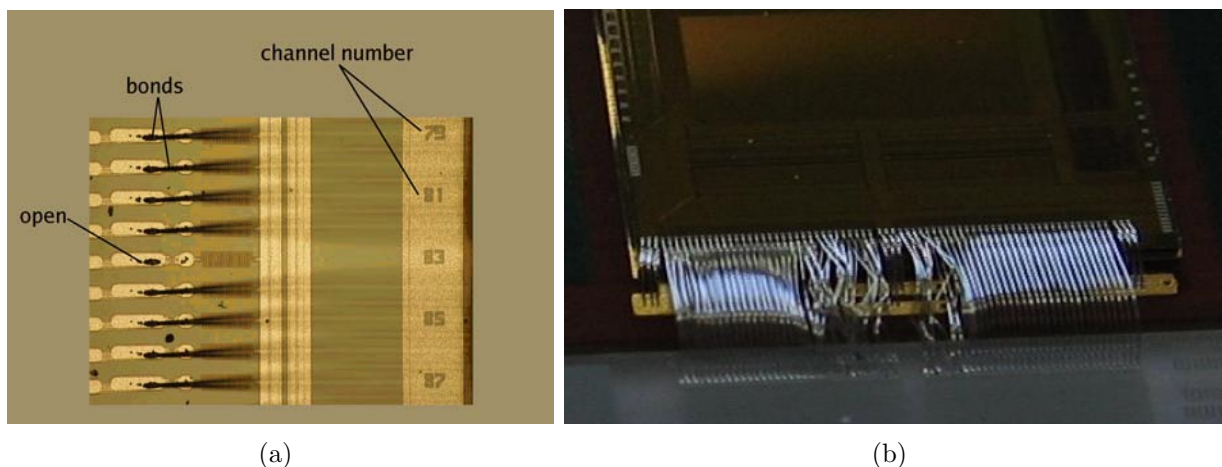


Figure 3.4: (a) Microscopic view of a missing bond at the sensor. (b) Photograph of destroyed APV bonds.

Sensor-Sensor open

A sensor-sensor open exists only for modules with two sensors (rings 5 to 7). In this case strips of the 'near sensor' are still operational. Usually the reason is a destroyed bond due to mishandling (Fig. 3.6).

Mid sensor open

As the name indicates the problem lies somewhere in the middle of a sensor. In Fig. 3.7 for example the source is a scratch on the sensor surface. A part of a strip is disconnected from the readout system.

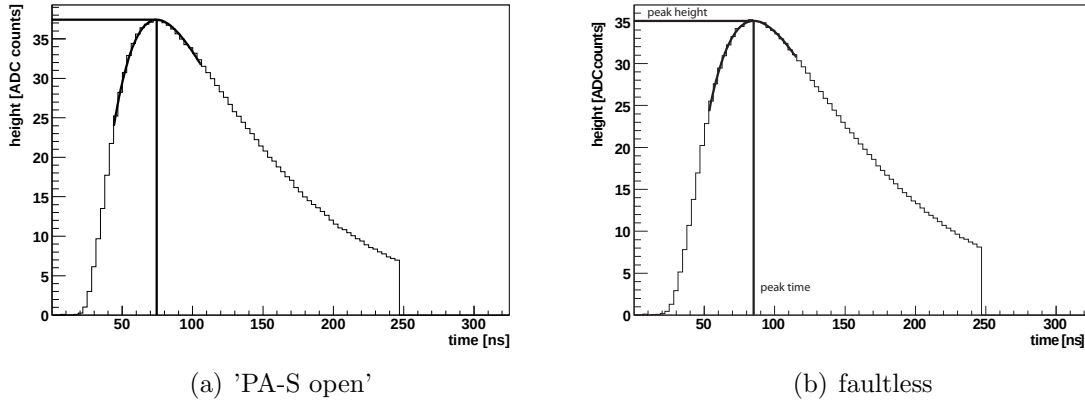


Figure 3.5: Calibration profile of a 'PA-S' open (a) and a faultless channel (b). The 'PA-S open' has compared to the faultless channel an earlier peak time and a raised peak height.

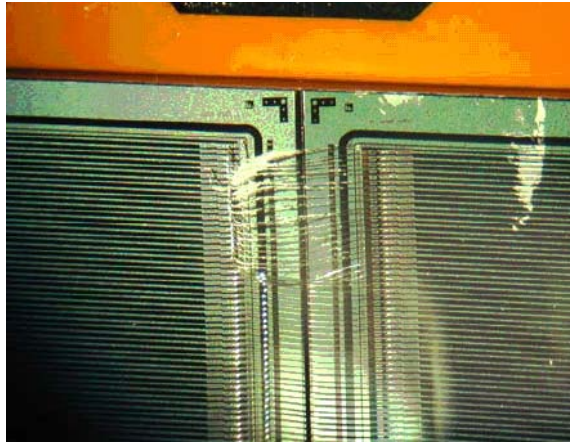


Figure 3.6: Photograph of touched and destroyed bonds between two sensors.

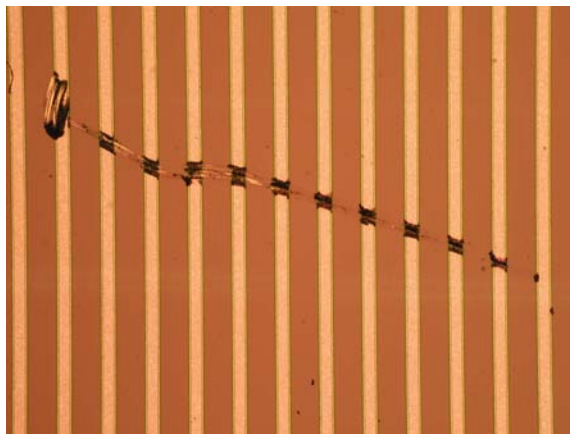


Figure 3.7: Microscopic view of a scratch on the sensor surface. [29]

3.3.2 Saturated channel

A strip affected by this defect shows always a saturated signal height. The origin is a defective chip on the hybrid. No traversing particle can be measured by this channel. Due to the fact that the channel is always saturated no variation can be measured. Furthermore the peak during the CalProf test is very small. Consequently noise and peak height are very low (Fig. 3.8).

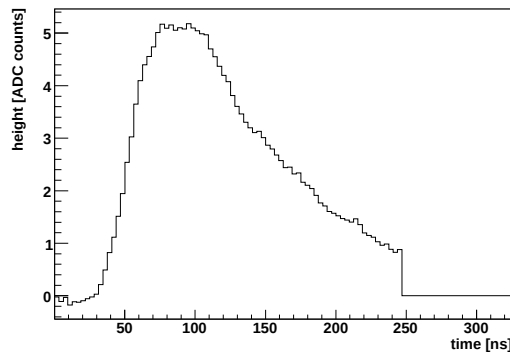


Figure 3.8: Calibration pulse of a saturated channel. Peak height is very low. For comparison see Fig. 3.2.

3.3.3 Short

This defect type occurs when two channels are connected (Fig 3.9(a)). The reason could be again a scratch on the sensor surface or some sort of pollution. The consequence is a lower peak height as the capacitance at the amplifier is higher (Fig. 3.9(b)). If exactly two strips are connected the capacitance is doubled and therefore the height is halved (Eq. 3.8) otherwise it is respectively lower.

3.3.4 Noisy channel

This is one of the 'harmless' problems. The channel behaves normal, just the noise of the strip is slightly higher. It is a bit more difficult to distinguish between signal and noise because the signal to noise ratio is reduced. The reasons for a noisy strip are various and were never investigated in detail. For APV edge strips it is known that the increased noise can be reduced by a optimized grounding scheme.

A more detailed explanation of these defect types and sources and of other defect classes can be found in [23, 33].

3.3.5 ARC test procedure and defect classification

The minimum set of tests performed by ARC to find strip defects are the noise measurements (in all four APV modes), the calibration profile runs (in all four APV modes) and some other

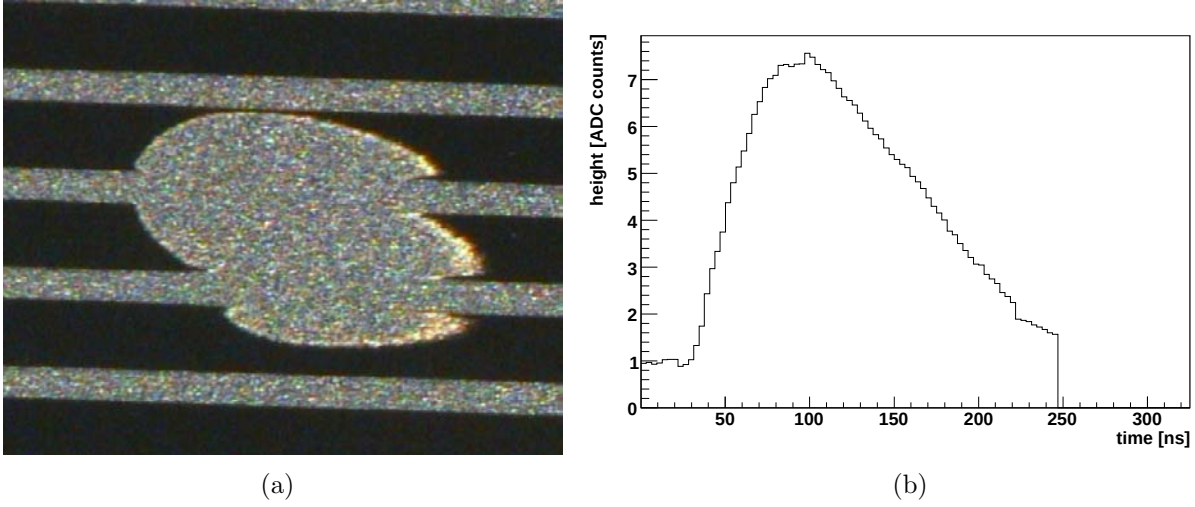


Figure 3.9: (a) Microscopic view of two connected strips. [23] (b) Calibration pulse of a 'short' strip. The peak height is very low. More than two strips are connected. For comparison see Fig. 3.2.

tests not explained in this thesis as not necessary to understand the final strip flagging. For each test and module geometry cuts are defined. Depending on the test result a classification of the strip is performed. This classification is done by the fault finding algorithm presented in [23]. From the eight tests the following quantities were used for this classification: common mode subtracted noise, relative height of the calibration pulse to the APV median and absolute deviation of the calibration pulse peak time to the median of the calibration group. Every quantity is cutted into different regions, e.g. the peaktime is splitted into five regions:

$$LC_3 < LC_2 < LC_1 < \text{range of normal channels} < HC_1 \quad (3.9)$$

where LC_x denotes low cuts and HC_x denotes high cuts. Each measurement gets a corresponding flag. The results of the quantities in the different APV modes are combined in a logical OR (see Tab. 3.1).

Example for the flag combination					
	dec inv.on	dec inv.off	peak inv.on	peak inv.off	combined flag
below LC_3	no	no	no	yes	yes
between LC_3 and LC_2	yes	no	yes	no	yes
between LC_2 and LC_1	no	yes	no	no	yes
above HC_1	no	no	no	no	no

Table 3.1: Example of the combination of flags for the fault finding algorithm. Though only one cut can be set for a single APV mode, several flags can be set in the combined flag [23].

These combined flags are transferred to the analysis procedure of the algorithm. The analysis is performed in several steps. A short summary of the analysis is given here:

- The channel is set to *unknown faulty* if it is flagged in only one test.
- If the noise of a channel (APV edge channel) passes the HC_1 cut (HC_2 cut) the channel is set to *noisy*. Module edge channels will not be marked.
- A noise below LC_1 combined with a peak height below 10 ADC counts indicates a *saturated channel*.
- A noise below LC_1 in addition to a LC_1 flag of the peaktime indicates an *open between two sensors*.
- If the LC_2 flag of the peaktime is set and one of the low noise flags the channel is marked as an *open between pitch adapter and sensor*.
- If one of the high noise flags is set and one of the low peak time flags the channel is marked as *mid-sensor-open*.
- If the LC_1 and LC_2 flag of the peaktime are set and in addition the low noise flag it indicates an open. The position of this open is determined to be a PA-S **and** S-S open which couldn't be realized, hence the flag *open with conflicting location results* is set.
- A low or high noise in one of two neighboring channels in addition to a LC_1 flag of the pulse height in both channels leads to the flag *short*

As an example the cut values for Ring 1 can be found in Tab. 3.2

Ring 1						
test	APV mode	very very low cut LC_3	very low cut LC_2	low cut LC_1	high cut HC_1	very high cut HC_2
noise [ADC]	dec inv.on	0.80	1.10		1.74	1.86
	dec inv.off	0.80	1.10		1.74	1.86
	peak inv.on	0.55	0.79		1.31	1.48
	peak inv.off	0.55	0.77		1.30	1.50
peak height[%]	dec inv.on	-	85		113	-
	dec inv.off	-	85		113	-
	peak inv.on	-	87		108	-
	peak inv.off	-	87		108	-
peak time [ns]	dec inv.on	-6.5	-2.7		1.5	
	dec inv.off	-6.5	-2.7		1.5	
	peak inv.on	-10.0	-5.0		3.0	
	peak inv.off	-10.0	-5.0		3.0	

Table 3.2: Cut values for the fault identification on TEC ring 1 modules [23].

Chapter 4

Long term test

After the assembly of the modules to the petals a test was performed. This test was designed to inspect the petal before installing it into the TEC and to ensure that all components are in a good state, this implies that an optical inspection shows no mechanical problems and that the petal is electrical fully functional. Special attention was paid to the simulation of LHC running conditions. This includes the simultaneous readout of all modules and an ambient temperature of -20°C as this temperature was supposed to ensure a silicon temperature below -10°C , the temperature at which the sensors should be operated to keep the impact of radiation damage small. Several cooling cycles should give information if the petal could withstand ten years LHC in which it will be cooled down often. The test was further designed to find single strip defects and to ensure that this amount is below 1% of all strips. In particular it is the first test which allows to test the cooperation of all components like module, ICB and AOH. As the whole test program needs a lot of time this test is called long term test (*LT test*). The data of the test allows a grading of the petal. By that a decision is made if the petal can be used for the TEC.

To speed up the assembly and the testing of the petals, the components (i.e. petal bodies, modules, etc.) were distributed to six Petal Integration Centers (*PICs*) which allowed to assemble and test the petals in parallel. A summary of major problems found by this test as also which problems were found with the setup in Aachen will be given in Chap. 5.

4.1 General setup

The main parts of the LT-setup are a cooling plant, a refrigerator, a rack with the necessary electronics, and two PC's for slow control and DAQ (Fig. 4.1 and 4.2). The functionality of the different parts will be described in the next subsections.

4.2 Communication

The communication during the longterm test with the petal works via a token ring like protocol. A FEC¹-card inside the DAQ-PC translates the commands of the PC into the token ring protocol with LVTTL² signals. An FEC adapter card, designed and build in Karlsruhe,

¹Front End Controller[40]

²Low Voltage Transistor Transistor Logic

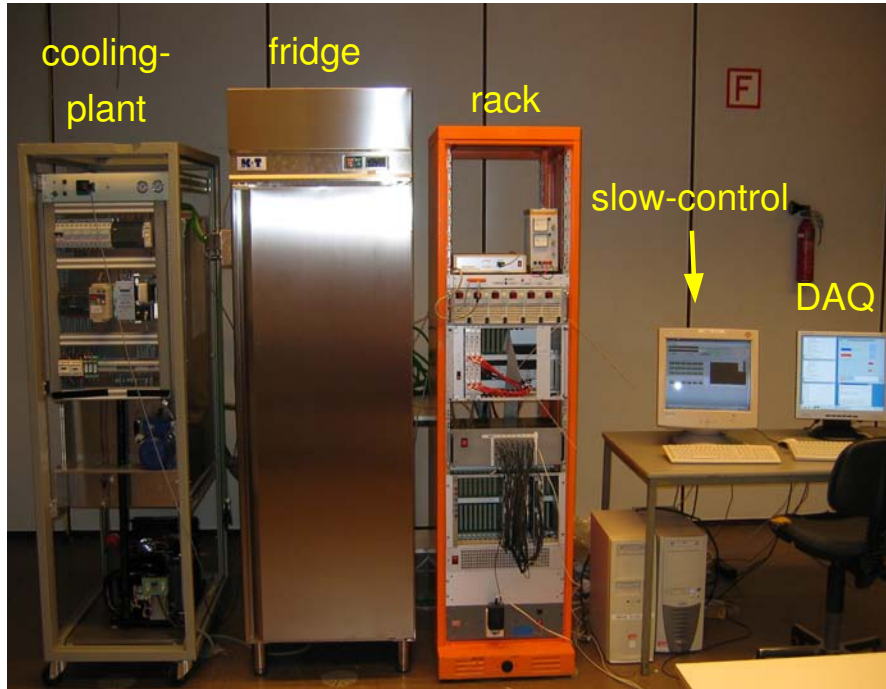


Figure 4.1: The long term test setup at Aachen. Left: the cooling plant for active cooling of a petal; middle: the fridge for passive cooling. The petal is placed inside the fridge . On the right side the rack with all electronics and the PCs for data recording are placed.

converts the LVTTTL into LVDS³. In addition to this conversion the adapter card was designed to filter noise from the power supply used for the control ring on the petal. Via a shielded twisted pair cable the CCUs on the petal get these commands, translate them into the I²C⁴ protocol and route them to the different modules and AOHs. The response of the components returns on the same path to the computer (see also Fig. 4.3).

4.3 Readout

In case of a positive trigger decision, the FEC sends the readout signal to the modules. Trigger and clock are generated inside the TSC⁵, a PCI computer card steered by the DAQ software. The modules send their data to the AOHs where it is converted into analog optical signals. The next step in the readout chain is the OFED⁶ housing the OECs⁷. Here the analog optical signal is transformed back into an analog electrical signal. In total there are six OEC, one for each multi ribbon cable. In principle it would now be possible to go directly to the FED⁸, a PCI card within the computer. This card converts the analog signals to digital signals with

³Low Voltage Differential Signal

⁴I²C stands for Inter-Integrated Circuit and is a multi-master serial computer bus invented by Philips [42]

⁵Trigger Sequencer Card [41]

⁶Optical Front End Driver, a VME crate card developed by CERN in collaboration with IIHE-Brussels

⁷Optical Electrical Converter, a chip, developed by CERN in collaboration with IIHE-Brussels, which converts analog optical in to analog electrical signals.

⁸Front End Driver

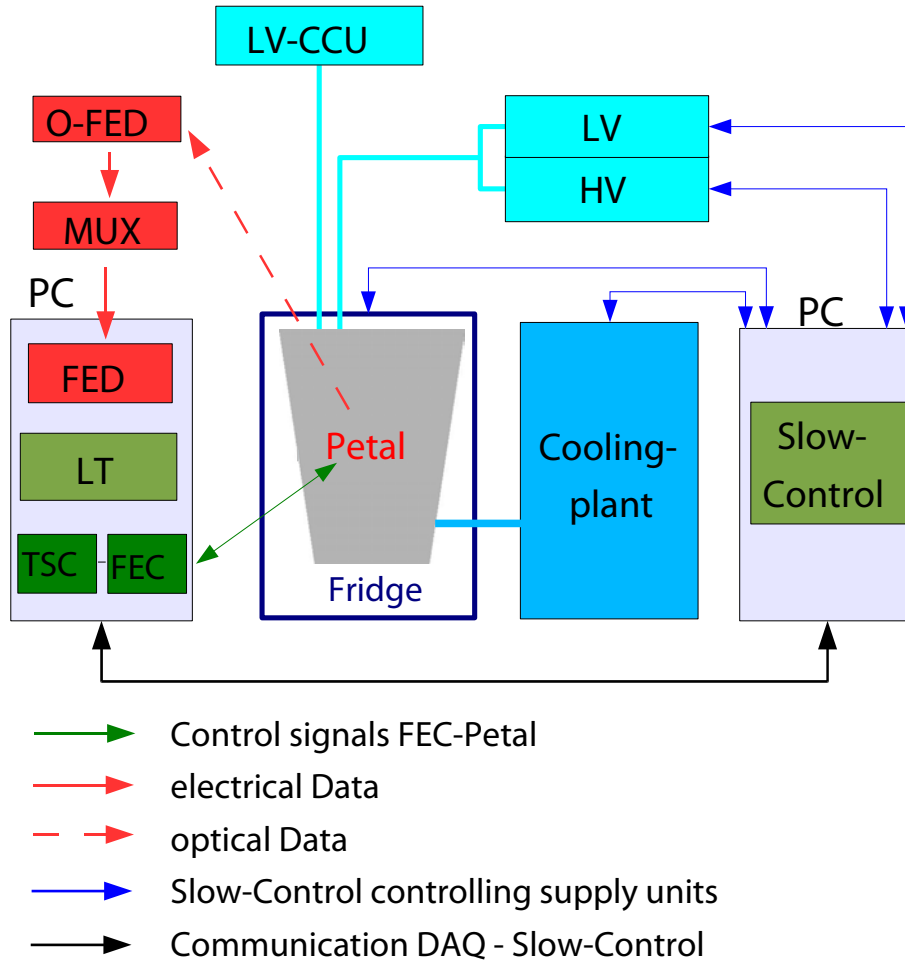


Figure 4.2: Schematic view of a longterm test station.

help of an 9 Bit ADC⁹. Unfortunately the FED has only eight input channels and not 68 as needed. To solve this problem a switch (K-MUX¹⁰) allowing to switch between eight times ten channels is used. A schematic view of communication and read out can be found in Fig. 4.3.

4.3.1 K-MUX

The K-MUX allows to change the readout between different modules. It consists of 80 input channels that are arranged in 8 units of each 10 input channels ('column'). Each unit allows to link one of the 10 input channels to a single output channel. The readout happens row-wise. For sake of efficiency and to avoid systematics by reordering the cables, it is desired to keep one unique mapping for front and back petals. Fig. 4.4 shows a photo of a fully cabled K-MUX. The only constraint to the mapping is to always read out complete modules. It can be shown that there is no common mapping which matches this constraint for front and back petals at the same time. Interchanging two complete ribbons solves this problem. In this case just one

⁹Analog Digital Converter

¹⁰Karlsruhe-Multiplexer

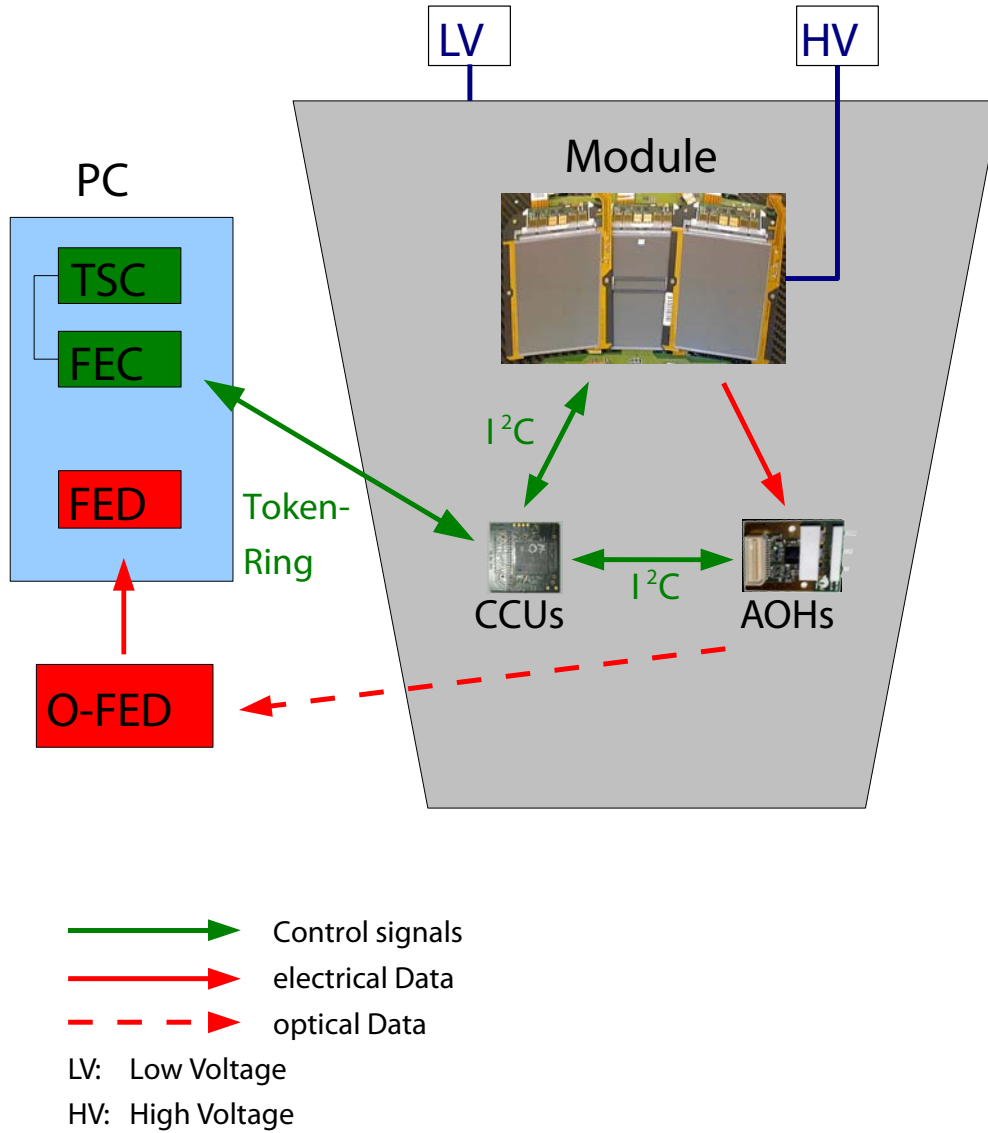


Figure 4.3: Schematic view of the communication and readout of a petal.

connection has to be redone as it is possible to interchange two ribbons directly. Details on the final mapping can be found in App. B.

4.4 Cooling

To cool down the petal, a combination of an active and a passive cooling system is used. For the latter a fridge, which allows to cool down the ambient temperature to -30°C , is used. The fridge is equipped with an input for dry air. This allows to dry the air to a dew point of -40°C . A system of five temperature and two humidity sensors allows to monitor the atmosphere inside the fridge. The active cooling is performed by a cooling plant. It circulates the cooling fluid (C_6F_{14}) through the petal and cools down the fluid to -25°C . Two temperature probes,

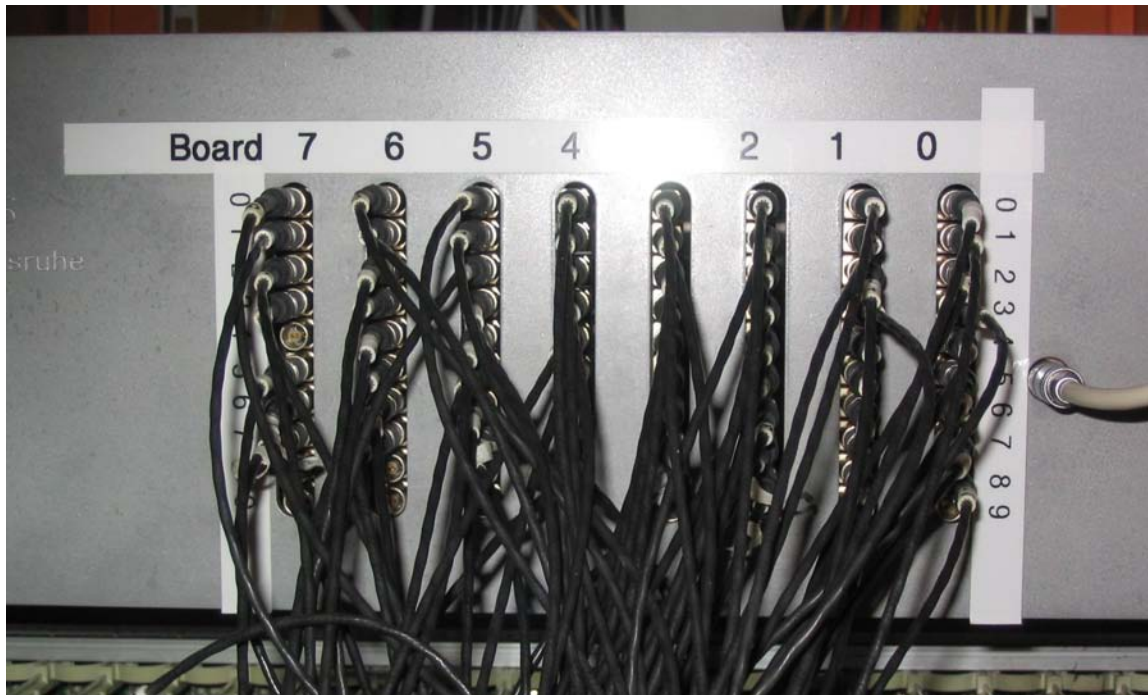


Figure 4.4: Photograph of a full cabled K-MUX.

glued to the cooling tube, monitor the input and output temperature of the fluid. The cooling plant was designed to run the system between 17°C and -25°C .

4.5 Slow control

The slow control [43], steers the environment of the system. It measures the temperature of the cooling plant, the fridge and of the sensors mounted in the fridge and on the cooling pipes. Further it measures currents and voltages of LV and HV circuits every 30 seconds. It controls the voltages and temperature of the cooling plant and the fridge. During the long term test the slow control was controlled remotely by the DAQ software. Nevertheless the slow control is able to take precautions if the dew point or the currents are too high. In this case the slow control initiates a shutdown of the system. The same happens if the readout fails for more than 2 minutes or if the fridge-door is opened. In Figs. 4.5 and 4.6 two screen shots of the slow control software are shown. As every PIC uses slightly different power and monitoring systems an adaption to the locally circumstances has to be done by each PIC itself. In case of the PIC Aachen the cooling of the fridge, and the read out of the temperature probes have to be adapted to the software. Both steps were performed with help of the Cooli [44]. In addition the controlling and monitoring of the HV provided by depp-boards [45] have to be implemented.

4.6 DAQ

The DAQ software [47] is the control center for the test. It controls the readout of the petal and the tests which should be performed. It sends commands to the slow control to change



Figure 4.5: Screen shot of the slow control software. On this tab the monitoring of the temperature is shown [43].

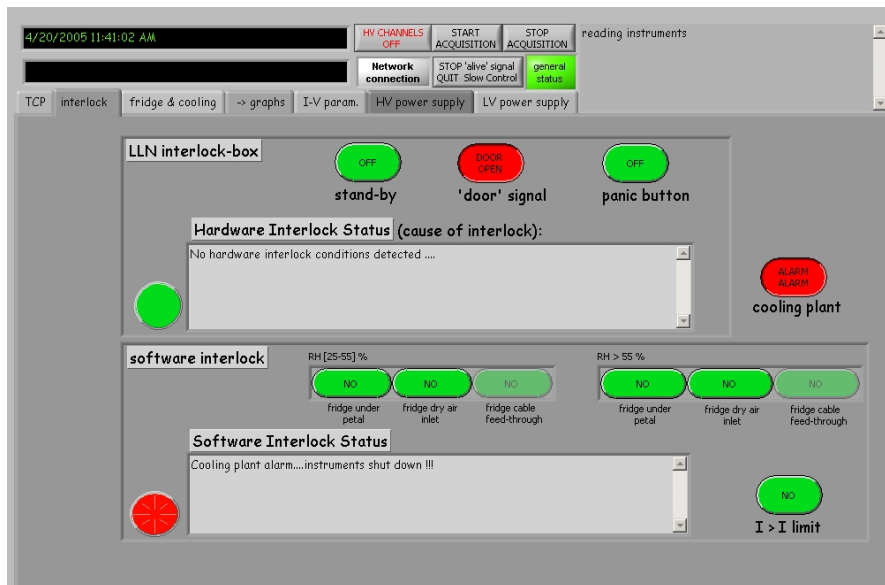


Figure 4.6: Screen shot of the slow control software. On this tab the interlock status is shown [43].

temperature and voltages (Fig. 4.7). The complete long term test of one petal needs two to three days, depending on the petal and scenario. To give the user the possibility to change the order of tests or to add some additional tests a scenario file can be loaded. The standard scenario can be found in App. C. The main parts of the scenario are pedestal and cal prof tests in different APV-modes and at different temperatures. To perform these tests in a proper way the parameters of the AOHs need to be optimized and the signal latency must be tuned.

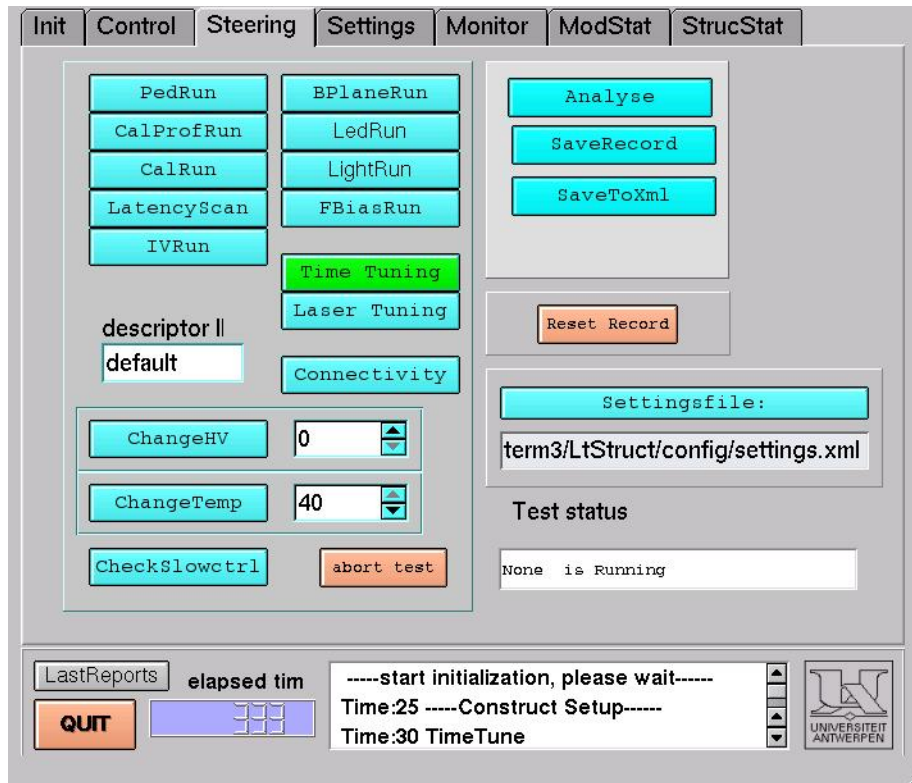


Figure 4.7: Screen shot of the DAQ software. On this tab the manual steering of the test is shown [47].

4.7 Test procedure

The standard long term test scenario can be split into three parts. Starting in warm conditions going to cold and back to warm conditions. The results of the test performed during each part are stored in a ROOT¹¹-file. Each part is saved into an own directory inside the ROOT-file: secltfirst, secltcold and secltlast. This single cooling cycle and the tests are mandatory for a LT test. Two further cooling cycles and tests are added but not analyzed (see Fig. 4.8). During the transition the temperature of the cooling liquid is changed between 17°C and -25°C. The fridge is off or on, respectively.

At each temperature an opto scan run, timing run, four pedestal runs (one per APV mode) and one calibration profile run are performed (Fig. 4.9). These tests are used to find strip errors. Additionally in the first and last part an extended I-V test and in the first part a pedestal test without HV are performed.

¹¹An Object-Oriented Data analysis framework, Copyright by Rene Brun & Fons Rademakers

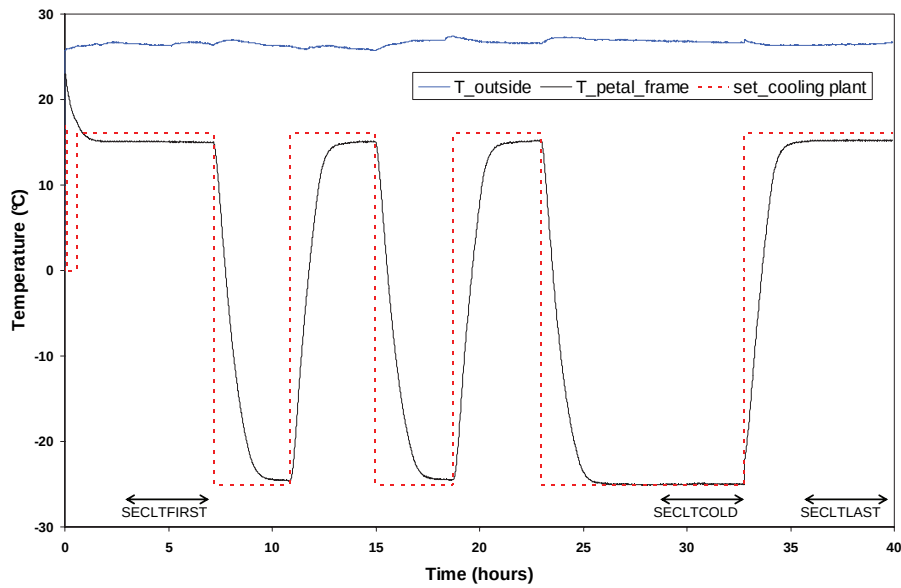


Figure 4.8: Temperature profile of a long term test with three cold phases.

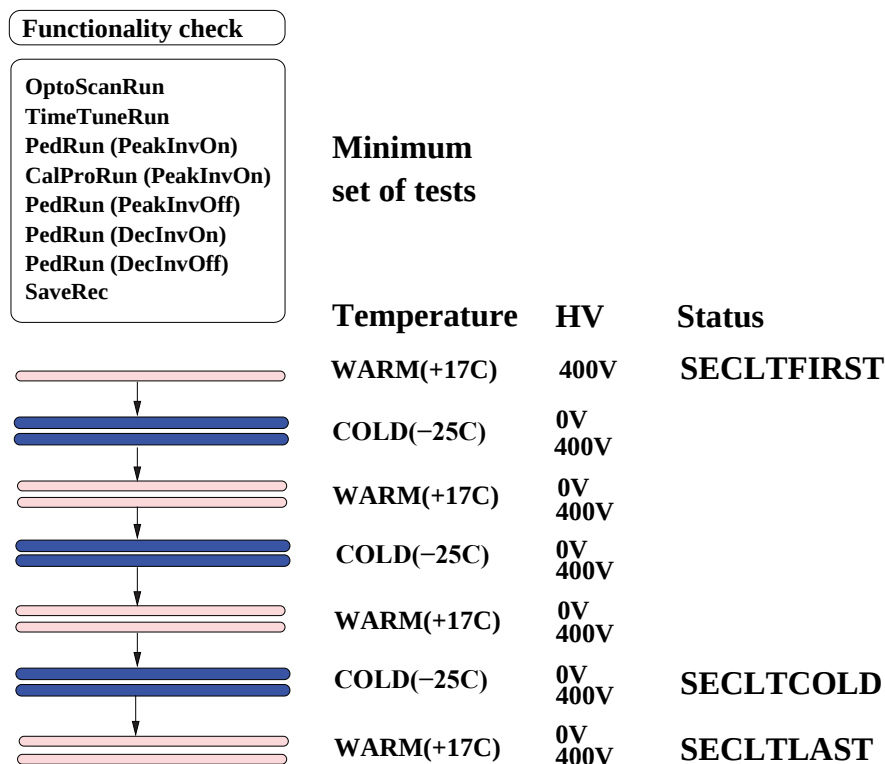


Figure 4.9: Structure of a long term test scenario [48].

With these tests more general sensor problems can be found. In the following sections opto scan run, timing run and the extended I-V run will be explained. Pedestal run and calibration profile run are already explained in Chap.: 3. A comparison of pedestal test with and without HV allows to determine if the HV reaches the sensors.

4.7.1 Timing run

The complete readout is time critical. The timing is different for each module, because the optical and electrical paths are different for each module. So an optimization is done at the modules and not at the FED, the timing run. During the timing or time tune run each APV sends every 3200 ns a logical one (tick). This signal can be delayed within the TPLL¹² in 24 steps of 1.04 ns. The FED reads every 25 ns. In Fig. 4.10 and Fig. 4.11 the result of such a run can be seen. As the tick of one APV has a duration of 25 ns and two ticks of two APVs are multiplexed together the duration of the tick in the plot is 50 ns. A good value for timing is in the center of the first 25 ns of the plotted tick as this is the most stable position [32]. It must be pointed out that each laser has its own timing run but the chosen delay is used per module.

In addition this test allows to measure the height of the tick h_{tick} and therefore to check if the optical connection is in a good state, i.e. if enough light is transmitted from the lasers. In case of a bad transmission (tick height is less than 100 ADC counts) the optical connections had to be checked and cleaned from dust. If no tick above 100 ADC counts could be reached the AOH had to be exchanged. Reasons for such a low tick are often a kink in the fragile fibers.

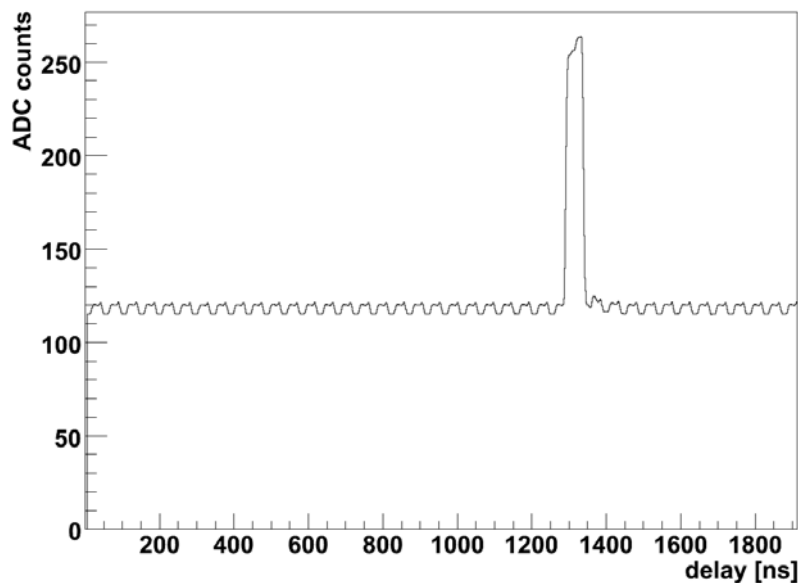


Figure 4.10: Time tune run for one Laser.

¹²Tracker Phase locked loop

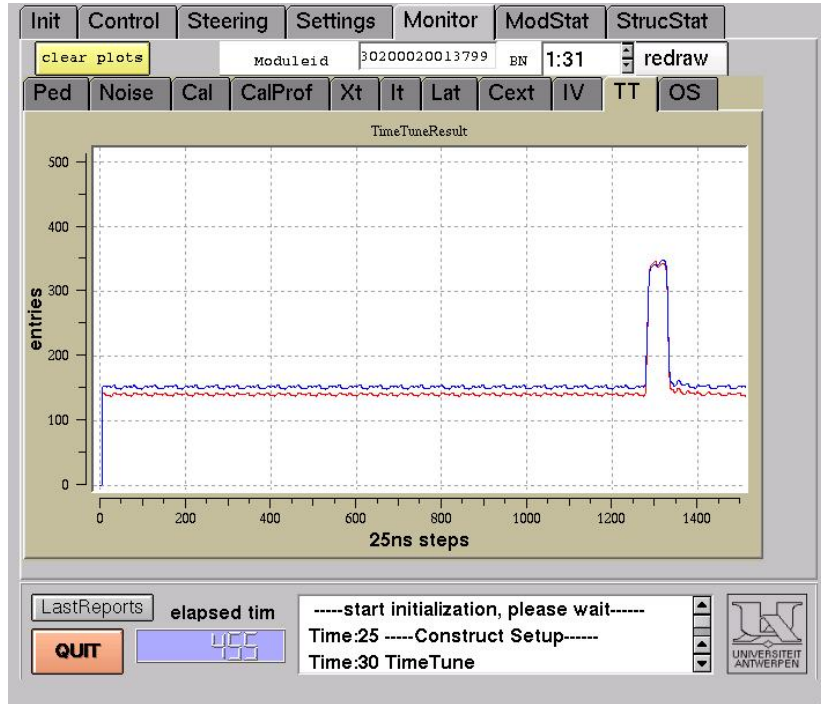


Figure 4.11: Screen shot of DAQ. On this tab the result of a time tune for a ring 3 module is shown.

4.7.2 Opto scan run

Every AOH has two or three lasers. These lasers can be operated in four gain settings (gain0 to gain3). Gain0 means minimal, gain3 maximal amplification. A second tuning parameter is the bias current of the laser which is regulated between 10mA and 40mA. This is a fine tuning parameter for the intensity of light. The opto scan run varies these parameters for the logical zero and one of each APV. In Fig. 4.12 and Fig. 4.13 the result for one APV in one gain setting is shown. The optimum is a maximal differential signal between logical one and zero for one bias and gain setting without saturation within the ADC of the FED. Per default gain2 is used in all tests as this should work for all lasers.

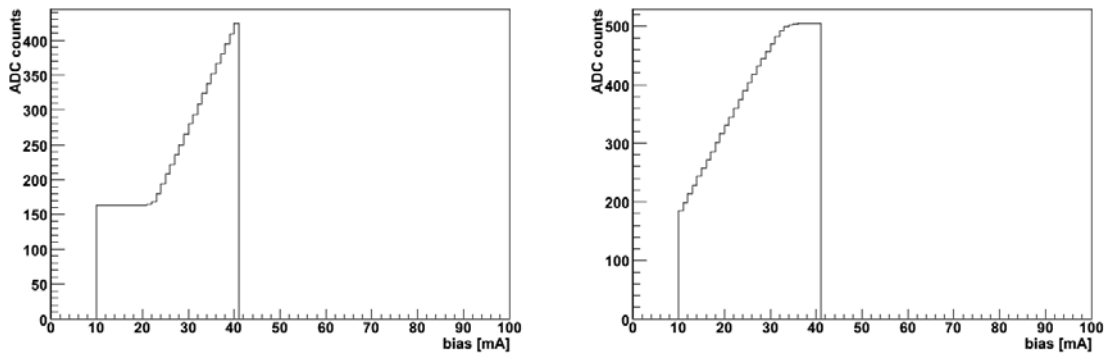


Figure 4.12: Opto scan run for one APV in gain3. Left: logical zero; right: logical one.

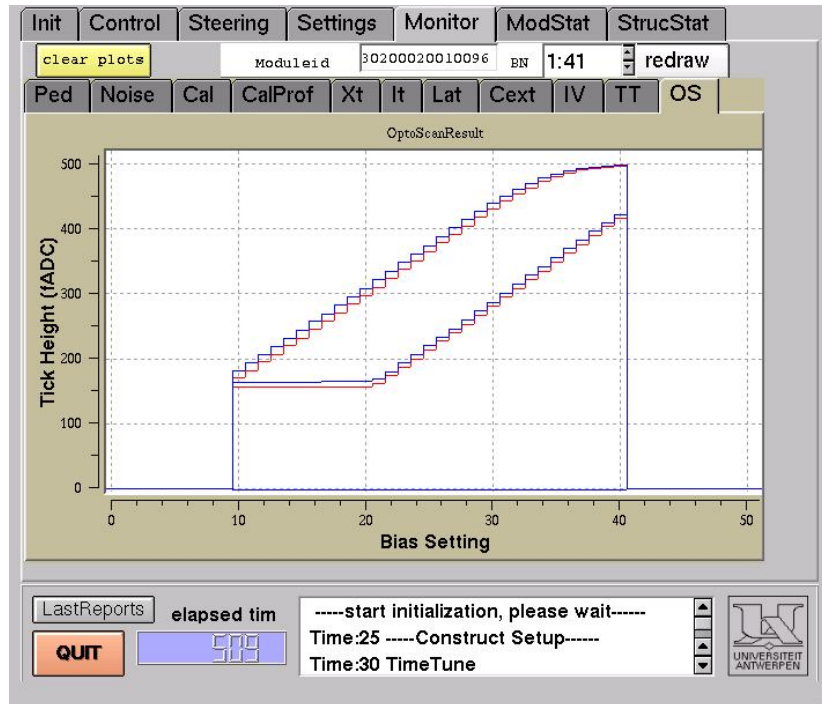


Figure 4.13: Screen shot of the DAQ. An opto scan run (in gain2) for a ring 4 module is shown. Logical one and zero for both lasers are plotted into one diagram.

4.7.3 Extended I-V run

In the extended I-V run a current voltage curve (bias current against depletion voltage) per module is taken. Measurements are done up to 450 V in steps of 50 V. A high current indicates that the module has a problem even if the detector performance is not disturbed by this. As the leakage current of each module will increase during LHC running (see Sec. 2.4.2) this problem could also be one for the power supplies. They won't be able to deliver the necessary current for this module and so the module has to be cut from the power system without being exchanged. Therefore sensors with a leakage current above $10\mu\text{A}$ per sensor at 400 V are rejected. A normal current at this voltage is below $1\mu\text{A}$. Such a high current ($>10\mu\text{A}$) was found for approximately ten modules out of 6600 modules. These modules were disassembled and replaced by other modules.

Chapter 5

Problems found with long term test

This chapter gives a summary of problems found during the LT tests with the Aachen setup. There are three locations where problems can occur: the test stand setup, defect components of the petal and problems of the petal design itself.

5.1 LT test setup

Before testing each petal, the setup itself had to be set into operation and tested. The hardware part was done with the help of the mechanical and electronics engineer¹. The software part had to be adapted to the local conditions in Aachen. This was done² without bigger problems as the software was very modular and therefore only few changes were needed.

The commissioning of the setup with help of a test petal was not that easy. It was found that the communication of the software with the petal was very instable: In most cases the token ring could not be established, otherwise it was lost after few minutes. A deeper investigation with the electronics engineer showed that the FEC adapter card³, used by all test centers, was misdesigned. Ground and hence the reset line were not under control. This leads to the fact that the communication with the petal was sometimes possible but very instable. After correction of the adapter card it was possible to establish a stable communication.

During the LT test phase several software problems were found like tick marks which were not saved, incorrect I_{leak} measurement or slow test routines. Most of those problems lead to an reinstallation of the software. As we updated our software regularly we had the role of a beta tester and run often into such software problems. Obvious problems were reported directly to the responsible persons and corrected.

5.2 Defective components

Out of 297 petals 51 were tested in Aachen. Due to a design problem (not enough clearance between ICB and sensor) some of those petals were rebuilt later and retested mainly in Strassbourg [22]. In addition petals which were disassembled from the TEC at CERN were retested

¹mechanical: D. Jahn and electronics engineer: F. Beissel

²with the help of Th. Hermanns and W. Beaumont

³the card which translates LVTTTL into LVDS

later at CERN, petals exchanged from the TEC in Aachen were retested in Aachen. Therefore Aachen did the final test for 32 petals. In total there were eight production and test setups: in Aachen, Brussels, CERN, Louvain, two in Karlsruhe and two in Strassbourg. It is worth mentioning that CERN could test six petals in parallel with one setup which implies that there were 13 testing lines in total. At the end of this chapter a list of the defect components and the reason why they were exchanged is given (Tab. 5.4). To understand this list it is necessary to understand the grading of a petal.

5.2.1 Petal grading

For the grading of a petal the quality of each module was used. The grading of each module can be found in Tab. 5.1 and Tab. 5.2. The grading of the whole petal is described in Tab. 5.3. Only grade A and B petals were accepted to be built into the TEC. Hence petals with grade C or D had to be repaired which implies to exchange the defective modules. A module is also exchanged if an optical inspection shows that bonds are bended or damaged or some other problems are found. This inspection is done before and after the LT test. Normally such problems imply that a module would be graded as C as a lot of channels are lost by those problems. Even if a module would pass the LT test it is not desired to have bended bonds inside the tracker as it is unknown if they still have the necessary stability or if they could introduce some shorts.

Parameter	Min. Value	Max. Value	Type of cut
Normalised common mode subtracted noise	-10%	+10%	Percentage
Normalised Pulse Height	-20%	+20%	Percentage
Peak Time Average Subtracted	-15	15	Absolute [ns]

Table 5.1: Valid ranges for module test parameter values [48]. Modified in Chap. 6.

Grade	Bad channels	I_{leak}
A	$n \leq 1\%$	$\leq 3\mu\text{A}/\text{sensor}$
A_F	$n \leq 1\%$	$> 3\mu\text{A}/\text{sensor}$
B	$1\% < n \leq 2\%$	$\leq 3\mu\text{A}/\text{sensor}$
B_F	$1\% < n \leq 2\%$	$> 3\mu\text{A}/\text{sensor}$
C	$n > 2\%$	
C		$> 10\mu\text{A}/\text{sensor}$

Table 5.2: Module grading criteria as a function of the number of bad channels n and the sensor leakage current I_{leak} [48].

5.2.2 List of exchanged components and their defects

In the following a short summary of the components exchanged in Aachen is given (Tab. 5.4). The reason why the modules were exchanged can be found in Tab. 5.5, the reasons for the

Grade	Total bad channels	Module quality	Total I_{leak}
A	$N \leq 0.5\%$	$< 25\%$ of B modules, no C module	$\leq N_{\text{sensors}} * 3\mu\text{A}$
A.F	$N \leq 0.5\%$	$< 25\%$ of B modules, no C module	$> N_{\text{sensors}} * 3\mu\text{A}$
B	$0.5\% < N \leq 1\%$	$< 50\%$ of B modules, no C module	$\leq N_{\text{sensors}} * 3\mu\text{A}$
B.F	$0.5\% < N \leq 1\%$	$< 50\%$ of B modules, no C module	$> N_{\text{sensors}} * 3\mu\text{A}$
C	$1\% < N \leq 1.5\%$	1 C module with $< 2.5\%$ of bad channels	
D	Any other combination		

Table 5.3: Petal grading criteria as a function of the total number N of bad channels in a petal, the module quality and the total sensor leakage current I_{leak} [48].

AOHs in Tab. 5.6. The reasons for the exchange of modules are touched bonds, I2C problems i.e. inter chip communication problems during the LT test, modules graded as C by LT or damaged during the rework of the petal (clearance problem [22]), the insertion into TEC+ at the Tracker Integration Center (TIC) or the preparation for the LT test. The categorie 'other' includes scratches on the sensor surface or broken carbon fibre frames. The defects that occur most are touched bonds. After a training and learning phase this defect type could be avoided. For the AOHs the defect classes are: no signal (most probably a broken fibre), I2C problems, damage found during petal insertion (TIC) and unknown. For the unknown one it is only known that this AOH was exchanged. The full list and description can be found in [46].

	CCUs	AOHs	Modules
#	2	14	48

Table 5.4: Amount of exchanged components in Aachen [46].

Reason	touched bonds	Grade C	rework	I2C	TIC	preperation for LT	other
#	22	4	8	3	4	5	2

Table 5.5: Reasons for module exchange [46].

Reason	no signal	I2C	TIC	unknown
#	6	2	5	1

Table 5.6: Reasons for AOH exchange [46].

5.3 Petal design

During the LT test phase it was discovered that in a few cases the communication with some AOHs was lost during the cold phase but working again during the warm phase. This

behaviour was reproducible and occurred for each AOH at its individual temperature. A deeper investigation showed, that removing the screw with which the AOH is mounted to the petal body solves this problem. The connection of the AOH to the petal can be seen in Fig 5.1. As removing the screw solves this problem it is assumed that the real problem is mechanical stress between the ICB and the AOH inside the connector.

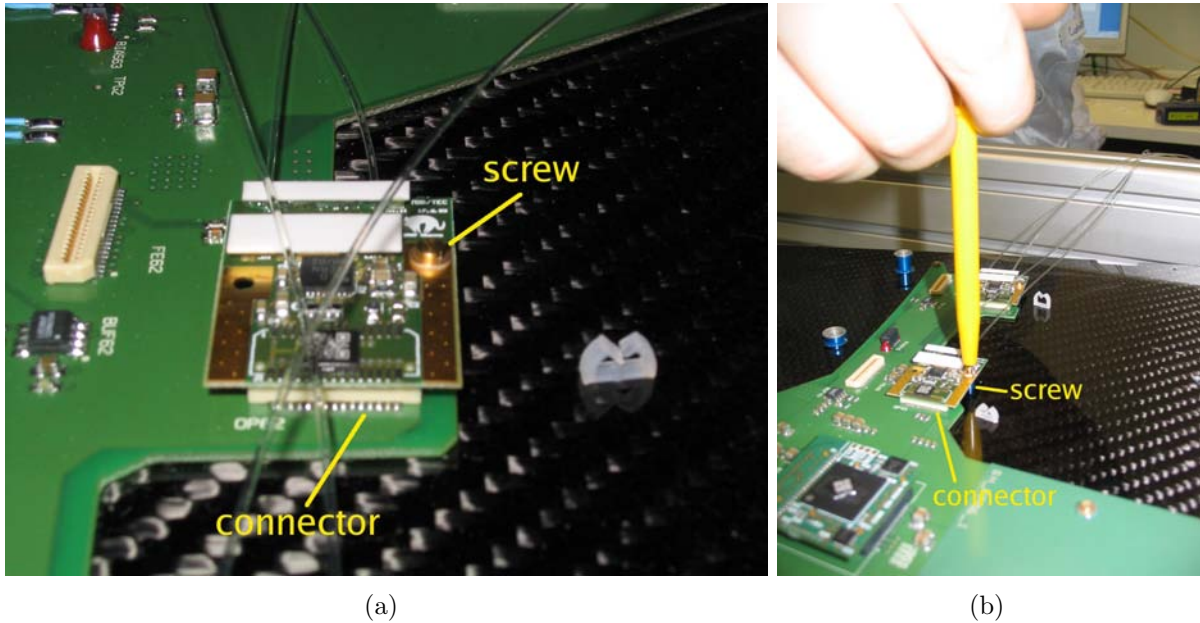


Figure 5.1: AOH on an ICB. Marked are the screw which connects the AOH to the petal body and the connector with which the AOH is plugged to the ICB.

The AOH is connected to the ICB and to the petal body. Petal body and ICB have different thermal expansion coefficients. Cooling the petal causes a shear force inside the connector and hence increases the chance to lose the electrical connection between AOH and ICB. This problem was found approximately ten times and could always be solved by removing the screw. Usually a redesign of the petal mechanics would have been necessary but as this problem was found at the end of the production phase it was not possible to reprocess all petals and even not to remove all screws. In addition removing the screws introduces the risk that an AOH gets completely loose and scratches over the modules.

The amount of AOHs which will lose their communication due to this problem during normal operation of the tracker is hard to predict as it is unknown at which temperature exactly the tracker will be operated and how the temperature distribution inside the tracker will be. Hence it was decided to remove the screws only if the problem was found. In later tests of the TECs this problem was found for about ten AOHs again. Until today it is unclear how large the impact of lost AOHs due to the shearing forces will be.

Chapter 6

Analysis of LT measurements

This chapter gives a detailed analysis of the measurements of the LT test. Therefore the LT test data of all petals are used. A strategy to find defects is developed using the ARC test results. At the end, the results of the different test systems will be compared.

6.1 Pedestal test: defect detection

Every defect which can be detected by the LT test has a noticeable signature in the pedestal run of the LT test. In the following two subsections it is shown that the analysis of these runs flag roughly the same amount of strips as the ARC test (see Chapter 6.1.1). Furthermore, it is shown that this test is reproducible (see Chapter 6.1.2). This means that most defects are found in every pedestal run.

6.1.1 Defect rate

To determine the defect rate the distribution of the 'common mode subtracted noise' (see Sec. 3.1) during one pedestal test is used. The noise is normalized to the APV average. Strips with a noise which vary more than 10% w.r.t. the mean of the corresponding APV are flagged by the LT test as 'bad' (Fig. 6.1). The 10% were chosen because they are roughly the same amount of deviation as allowed during the ARC test [54] (ARC used absolute cuts per ring). The amount of 'bad' strips is used as a reference value and adds up to 1.44% for all 297 petals (Fig. 6.1(a)). This amount differs from the amount of 0.14% of all strips that were not accepted by the ARC test by one order of magnitude. Excluding APV edge strips¹ improves the ratio between channels flagged by the LT and ARC test to a factor of 3 (0.32% by LT (Fig. 6.1(b)) and 0.13% by ARC). This exclusion is motivated by the fact that these channels have a higher noise level than the other channels ([14, 23]).

A dedicated investigation shows, that a better agreement of these two numbers can be reached by splitting the data into petals tested with the CERN LT setup and petals tested at the other setups (Chap. 4) (Fig. 6.2). Obviously the amount of strips outside the 10% region is much higher for petals tested at CERN than for those tested at the other test centers. There are several explanations for this, the most probable is the fact that CERN used a different DAQ software than the other five PICs and tested up to six petals simultaneously which might introduce additional noise. Unfortunately assembly and test of the petals was done under

¹APV channels 1, 2, 127 and 128

high pressure of time. This lead to the fact that no investigation of the CERN setup and its high noise was done. This course of action was accepted by all decision-makers.

The petals not tested at CERN have roughly the same amount of strips outside the 10% region compared to the ARC test (0.11% by the LT test, 0.13% by the ARC test). A complete set of all noise distributions is included in App. D. The further analysis for the defect detection will exclude APV edge strips. The plots will be shown separately for petals tested at CERN and petals tested at the other PICs.

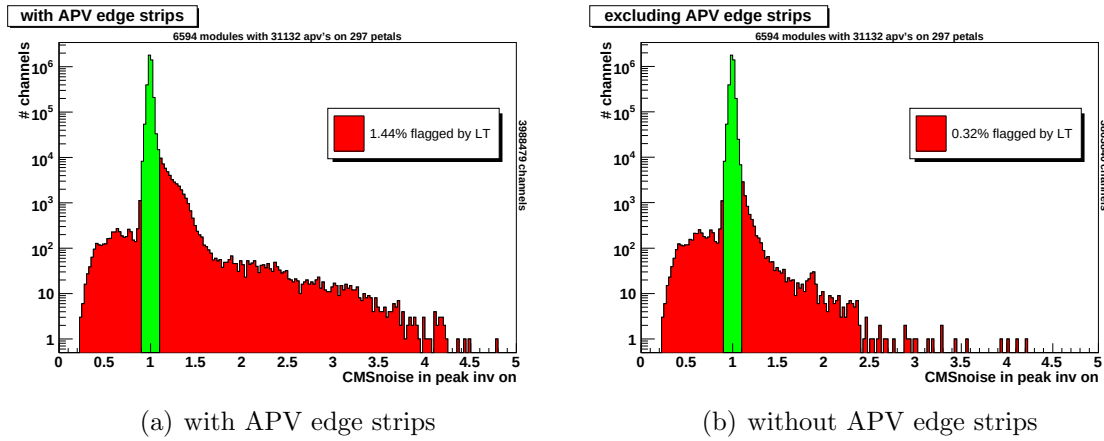


Figure 6.1: Noise distribution taken during the cold phase. The noise is normalized to the APV average. The APV mode is 'peak inverter on'. In red channels are marked with a noise which deviates more than 10% from the APV average. Those channels are declared as 'bad' and hence flagged by LT. All 'good' channels are plotted in green [51].

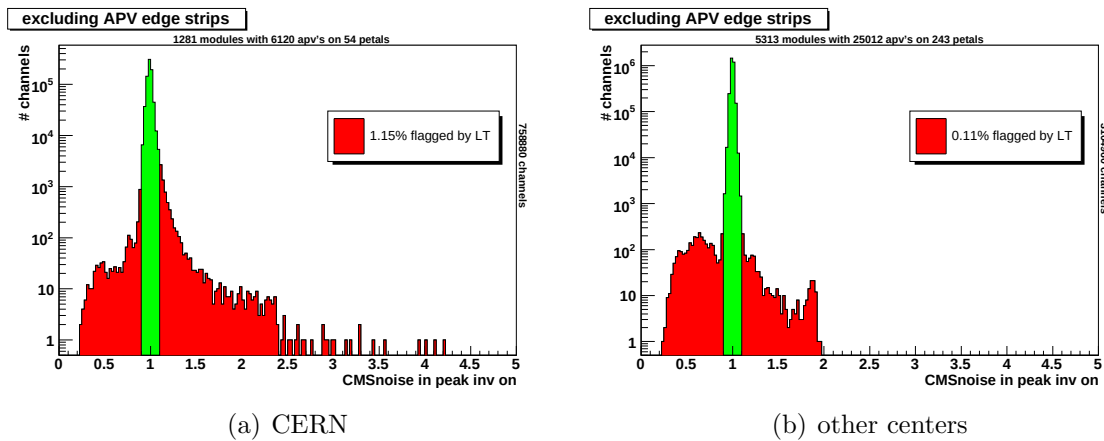


Figure 6.2: Noise distribution taken during the cold phase. The noise is normalized to the average. The APV mode is 'peak inverter on'. APV edge strips are excluded. In red channels are marked with a noise which deviates more than 10% from the APV average. Those channels are declared as 'bad'. All 'good' channels are plotted in green [51].

6.1.2 Reproducibility

As shown above, every noise test flags around 0.1% of all strips, except for APV edge strips and the CERN setup. The total amount contains no information about the reproducibility of a single test i.e. if the same strips are flagged in all pedestal runs. In total twelve noise tests are performed. If the flagging was totally random, approx. 1% ($1 - 0.999^{12} \approx 12 \cdot 0.1\%$) of all strips would be flagged at least once and the test would not be very reliable. Therefore it is interesting to analyze how often a strip is flagged in all noise tests. This can be seen in Fig. 6.3². The color code is given by the ARC test results. Concentrating on the petals not tested at CERN and using the information from the ARC test it can be said that a defective strip is flagged at least six times or never. Intact strips are normally flagged never or only a few times (<6).

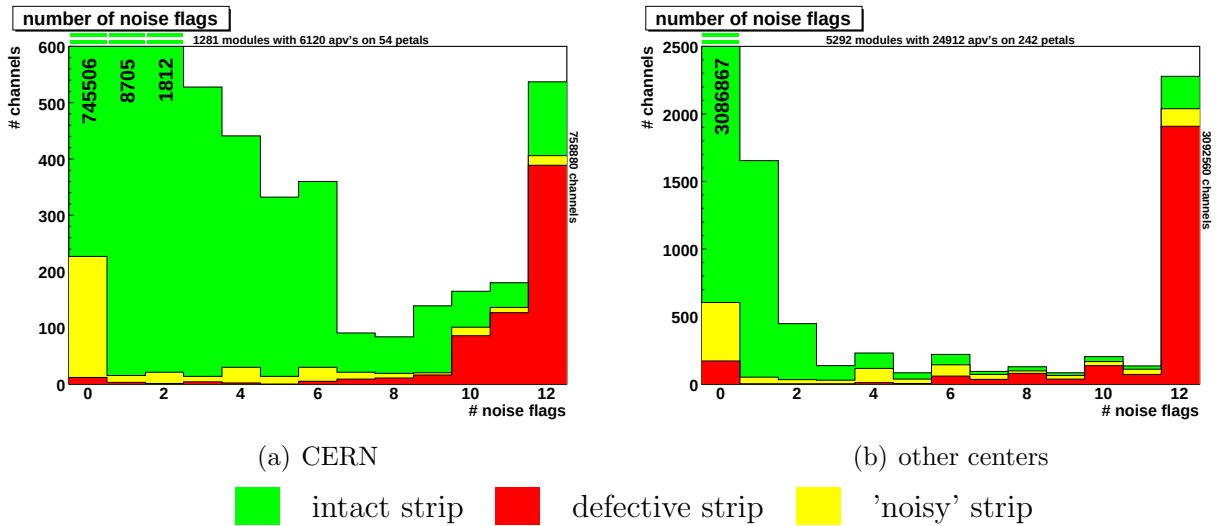


Figure 6.3: Number of flags after noise tests. Colors indicate the ARC test results.

This is similar for petals tested at CERN but the correlation is not as high due to the problematic noise behaviour. The range up to 10,000 channels (the height of bin 1) can be found in App. E. Thus a 10% deviation in at least six noise tests is a good criterion to find defective strips without flagging too many good strips, especially for the CERN setup. A lot of strips which would be flagged by the CERN setup via a simple 10% cut are rejected by requiring a misbehavior in at least six tests. The performance of this method can be seen in Fig. 6.4 and Fig. 6.5. APV edge strips are now included.

Fig. 6.4 shows that the amount of flagged strips (by the LT test) drops from approx. 24,000 channels to roughly 5,000 channels (from 0.6% to 0.12%). Most channels are flagged by both ARC and LT test³. In Fig. 6.5 the number of defective strips per APV channel for ARC and LT test are shown. A good agreement between ARC and LT test for all petals can be seen. Apart from the edge channels only some APV channels show a different behavior e.g. channel 8 in Fig. 6.5(a). This can be improved by excluding 'noisy' strips from ARC and LT test. Therefore a definition of 'noisy' in the LT test is needed. This will be done in Sec. 6.2.2.

²The petal with ID: 30250400000095 was excluded from the analysis due to a corrupt dataset.

³Fluctuating numbers due to slightly varying statistics.

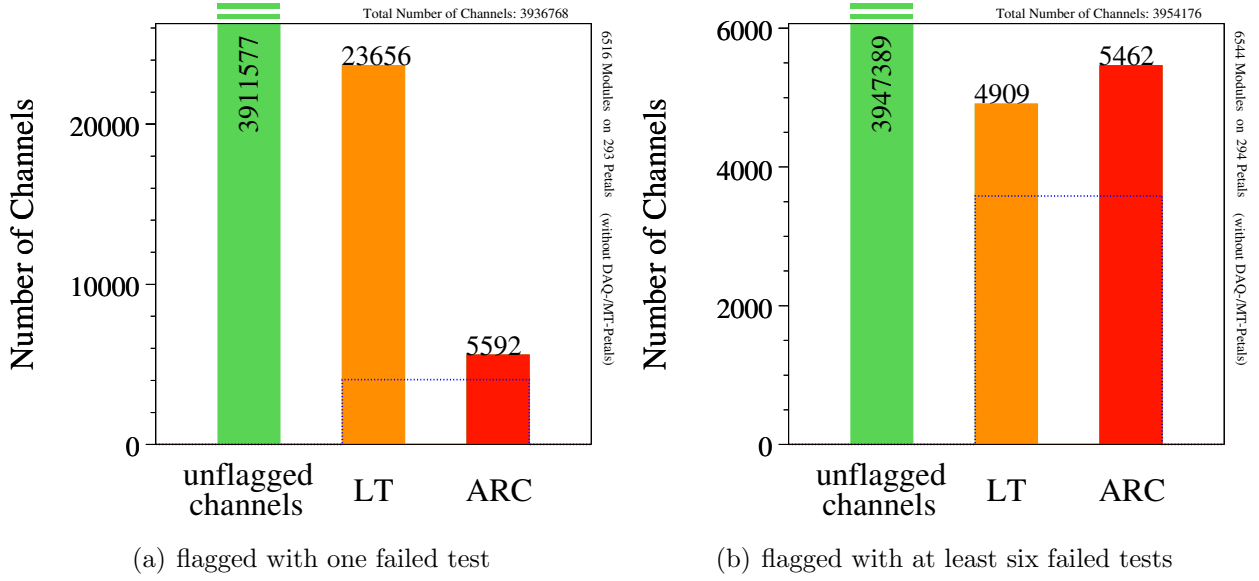


Figure 6.4: The first column shows the amount of good strips, the second those which are flagged by LT and the third those flagged by ARC. The dashed line shows the amount of strips flagged by both test systems [51].

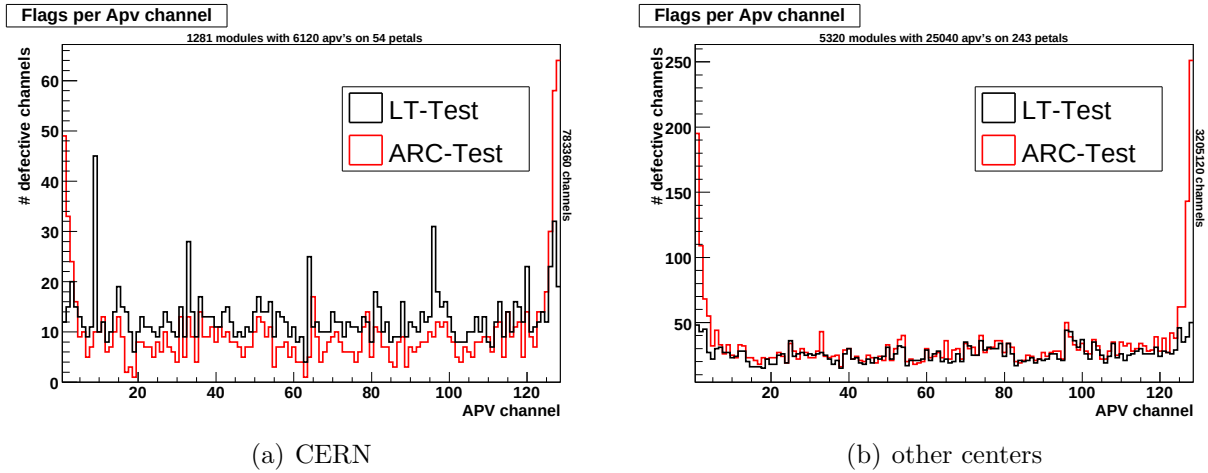


Figure 6.5: Number of defective strips per APV channel seen by the ARC and the LT test. A defective strip for the LT test implies that the strip failed at least six tests [51].

6.2 Calibration pulse test: defect declaration

After the identification of defective strips it is necessary to classify the kind of defect for each strip. Some types of defective strips may still be used afterwards, e.g. 'shorts' and 'S-S opens' still deliver some signal, while 'PA-S open' or 'saturated' channels are 'dead'. Also noisy strips are flagged as defective though they are functioning with only an increased noise level. They can be excluded from the set of defective strips. All information about the strips is stored in a database. The reconstruction algorithms are able to use this information and hence the

nominal reconstruction capability of the CMS detector is improved.

This classification is possible with the help of the calibration pulse test, (see Chap. 3 and Fig. 6.6). Every defect has a unique signature in the peak time versus peak height plane. The ARC test results are used again (Chap. 6.2.2) to assign signatures to the defect classes. It is necessary to transform peak time and peak height of different modules to a common standard (see next section), to be able to compare them.

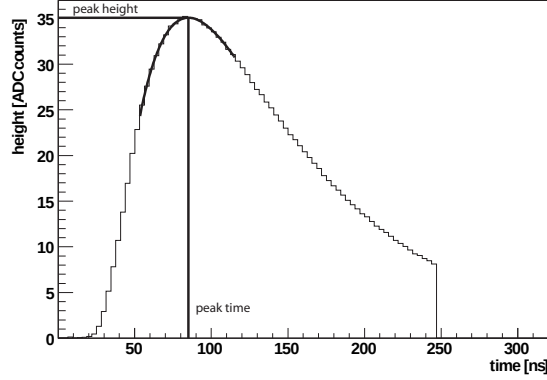


Figure 6.6: Example of a pulse with a peak time of 85 ns and a height of 35 ADC counts. Fit based on the CRRC function (see Chap. 3 and Eq. 3.8).

6.2.1 Normalization of the discriminating variables

In [23, 29] it is shown that instead of peak time t_p and peak height h_p , the difference to the calibration group median $\bar{t}_p$, $\bar{h}_p$ should be used (Eq. 6.1). This method removes uncertainties in the signal propagation delay as this is the same for the whole calibration group. The error onto the rise time (time between the points where the peak has a height of 10% and 90% of its maximum) is much larger and therefore not a good quantity to be measured. So these Δt_p and Δh_p values will be discussed.

$$\Delta t_p = t_p - \bar{t}_p, \quad \Delta h_p = h_p - \bar{h}_p \quad (6.1)$$

The measured Δh_p is a abstract function (Eq. 6.2) of the quality of the strip q_{strip} and the tick height h_{tick} (the logical one see Sec. 4.7.1) as each signal measurement scales with the tick height. Normalizing Δh_p to h_{tick} removes this dependance. As the height of a tick is in the order of 100 ADC counts the outcome of this division is scaled by this factor (Eq. 6.3). h_{p_used} is the value used in the later analysis. In principal Δh_p depends also on the sensor geometry but this variation is negligible.

$$\Delta h_p = f(q_{\text{strip}}, h_{\text{tick}}) = f(q_{\text{strip}}) \cdot h_{\text{tick}} \quad (6.2)$$

$$h_{p_used} = \frac{100 \text{ ADC} \cdot \Delta h_p}{h_{\text{tick}}} = f(q_{\text{strip}}) \cdot 100 \text{ ADC} \quad (6.3)$$

This is different for Δt_p . It scales directly with the strip length of the sensors (Eq. 6.4 and Eq. 2.2). Because the median subtracted value of an intact strip peaks around zero this effect

is visible only for defective channels as they differ from zero. The 'PA-S open' strips provide a good signature for the dependency on the strip length. In Fig. 6.7 the correlation between the Δt_p of 'PA-S open' and the strip length is shown. The distribution of Δt_p per ring can be found in App. F. Due to this behavior and the fact that a strip length is of the order of 10 cm [14] Δt_p is scaled to this length (Eq. 6.5).

$$\Delta t_p = f(q_{\text{strip}}) \times \text{striplength} \quad (6.4)$$

$$t_{p\text{-used}} = \frac{10 \text{ cm} \cdot \Delta t_p}{\text{striplength}} = 10 \text{ cm} \cdot f(q_{\text{strip}}) \quad (6.5)$$

$t_{p\text{-used}}$ is the value used in the later analysis. In the following the terms 'peak time' and 'peak height' indicate the scaled values $t_{p\text{-used}}$ and $h_{p\text{-used}}$.

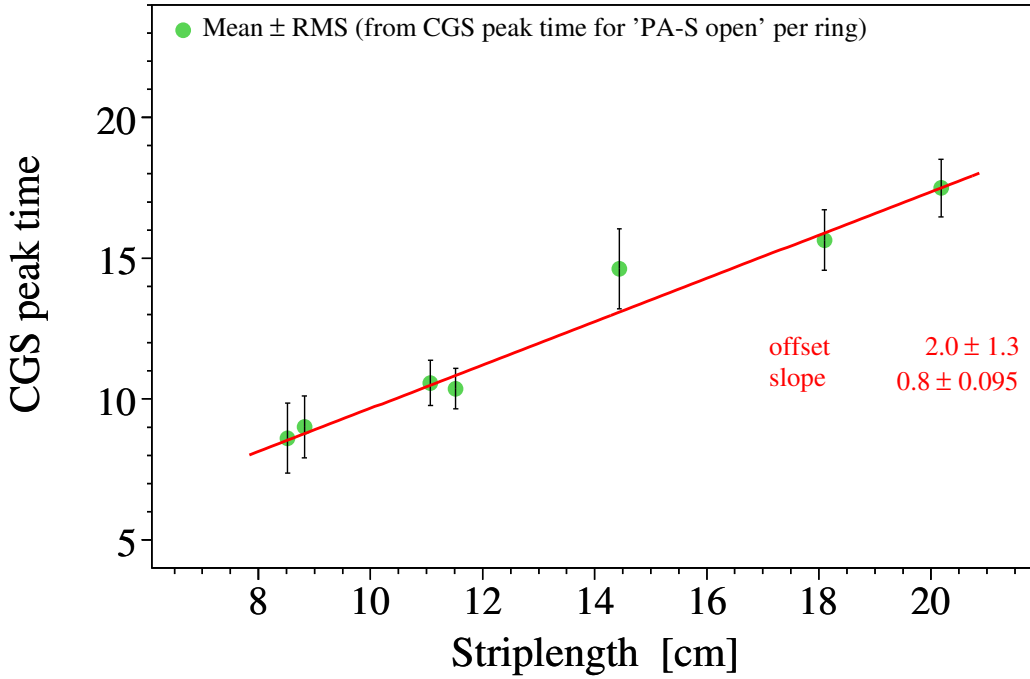


Figure 6.7: Line fit through the 'calibration group subtracted' (CGS) peak time per ring for 'PA-S opens'.

6.2.2 Classification of defect types

As described above, the scaled peak height and peak time of all defects allow to classify the type of defect. Fig. 6.8 shows the LT calibration pulse test results of peak height versus peak time as a scatter plot for channels identified as defective by ARC and LT (six failed noise tests). The classification of a defective channel is given by the ARC test results (see Chap. 3). This distribution allows to distinguish between the different defect types. In Fig. 6.9 the same plot is split up into the five classification types.

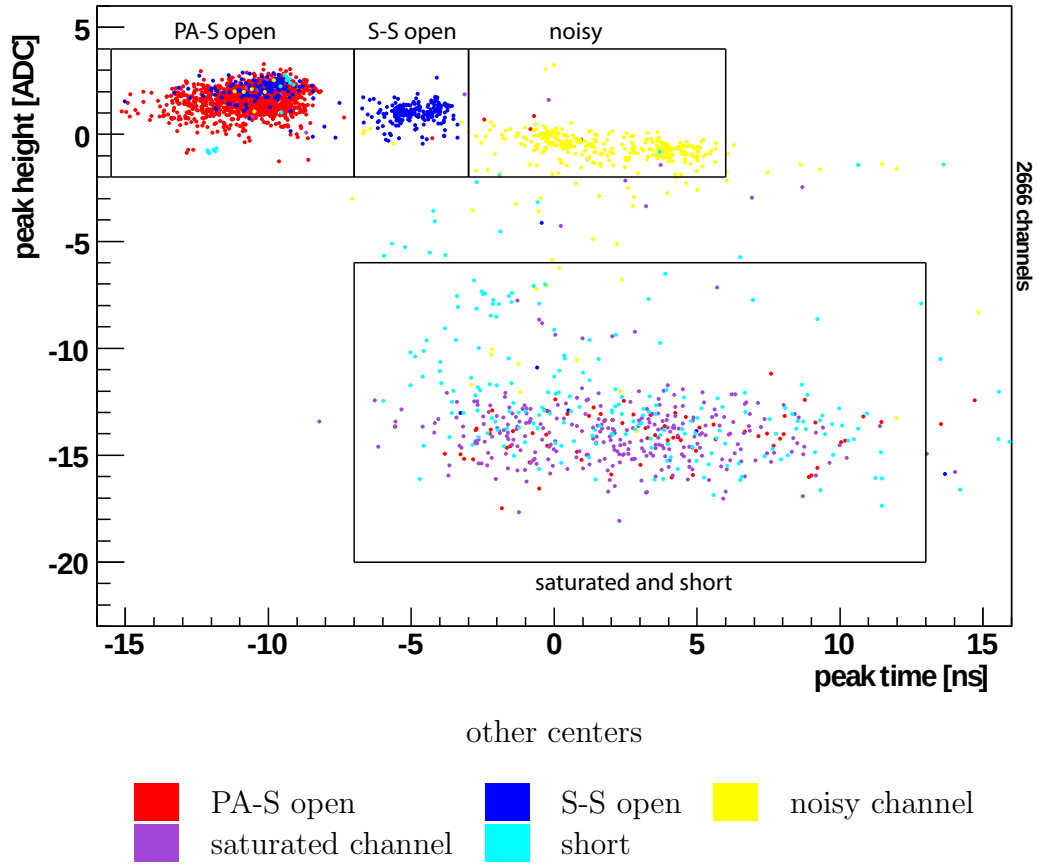


Figure 6.8: Peak height versus peak time. Only channels identified as defective by ARC and LT are taken into account. Categories are defined as in the ARC test.

other	peak time [ns]		peak height [ADC]	
PA-S open	> -15.5	< -7	> -2	< 4
S-S open	> -7	< -3	> -2	< 4
noisy channel	> -3	< 6	> -2	< 4
saturated channel and short	> -7	< 13	> -20	< -6

Table 6.1: Definition of the four regions: 'PA-S open', 'S-S open', 'noisy channel' and 'saturated channel and short'.

All channels flagged as 'PA-S open' or 'likely PA-S open' in the ARC test are marked in red (upper left), channels with 'S-S open', 'likely S-S open' and 'mid sensor open' flag are marked in blue (upper right). In yellow those channels are marked which are 'noisy' (middle left). 'Shorts' are marked in light blue (middle right) and 'saturated' channels in purple (lower one). In the peak height/peak time plane the different types split-up into four areas (Tab. 6.1). The plots and results for the CERN center are shown at the end of this section.

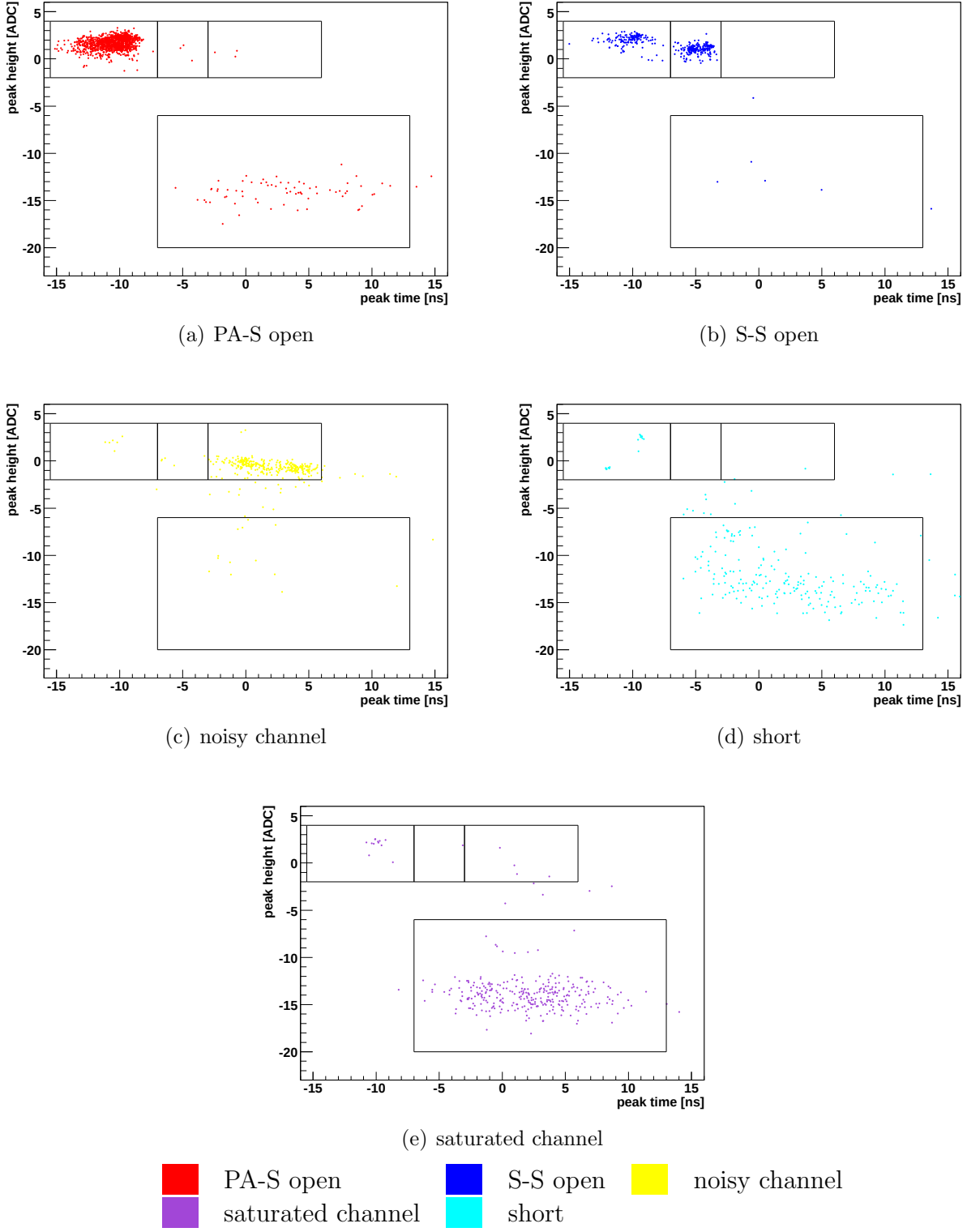


Figure 6.9: Scaled peak height versus peak time. Plots are separated into the different defect types of ARC. Only channels identified as defective by ARC and LT are taken into account.

The upper and lower bounds of 'PA-S open', 'S-S open' and 'noisy' are chosen to keep areas small and hence achieve a high purity. The same argument is true for the left border of 'PA-S open' and the right of 'noisy'. The position of each inner line separating two areas of defect classes is chosen based on the purity p (Eq. 6.6) of the corresponding samples (Fig. 6.10). $def1_{A1}$ denotes the amount of strips in area 'A1' with defect '1' (i.e. assigned correctly) and Sum_{A1} the total amount of strips in A1 and analog for '2'

$$p = \frac{def1_{A1} + def2_{A2}}{Sum_{A1} + Sum_{A2}} \quad (6.6)$$

The cut is chosen to give an almost constant purity under slight variation. Using the cut values shown in Tab. 6.1 a purity for these three regions in the order of 90% is achieved. For some of the strips classified differently in ARC and LT test it is known that the ARC test has declared them as 'S-S open' but visual investigation showed that the real defects are 'PA-S open' [39]. ARC is a very precise test system with low noise but there are still some misidentifications and -classifications. Unfortunately the real amount of those misidentifications and -classifications is unknown. Some other differently classified strips can be explained by the fact that the DAQ software had some problems in the start-up phase of the LT test (software bugs) which lead to a wrong peak time and peak height.

Obviously shorts and saturated channels cannot be distinguished that easily. To distinguish

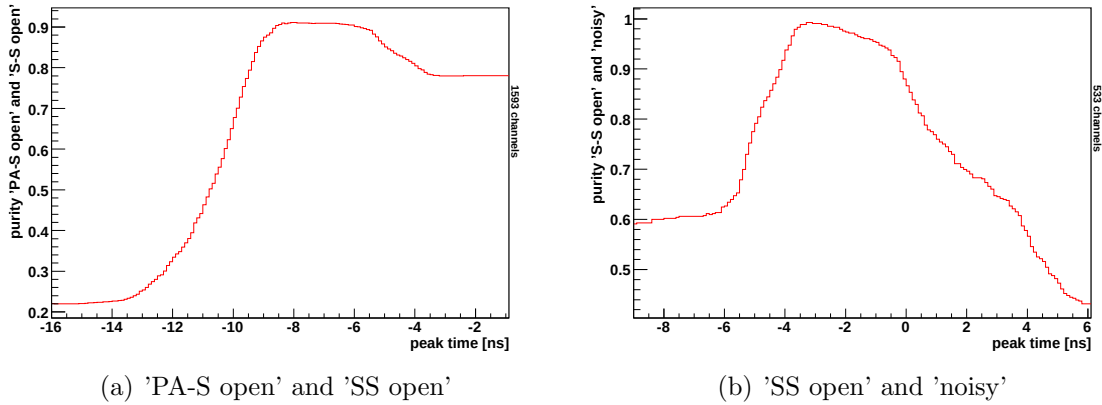


Figure 6.10: Purity as given by Eq. 6.6. 'PA-S open' and 'S-S open' define the two areas (a) and 'S-S open' and 'noisy' (b) respectively.

between them the scaled⁴ noise⁵ APV average subtracted of those channels can be used (see Fig. 6.11). This is possible because 'saturated' channels should have a low noise, because they are always saturated and do not show any variation. It can be seen that this variable has a discriminating power.

The same investigation can be done for the CERN setup (see Fig. 6.12 and Fig. 6.13). The data differs from the test data of the other centers even if is also discriminating. This deviation is as understood as the deviation in the noise data. In Tab. 6.2 the resulting cut definitions are listed for each defect class.

⁴scaled to strip length and same tick height

⁵mean of all tests in peak mode

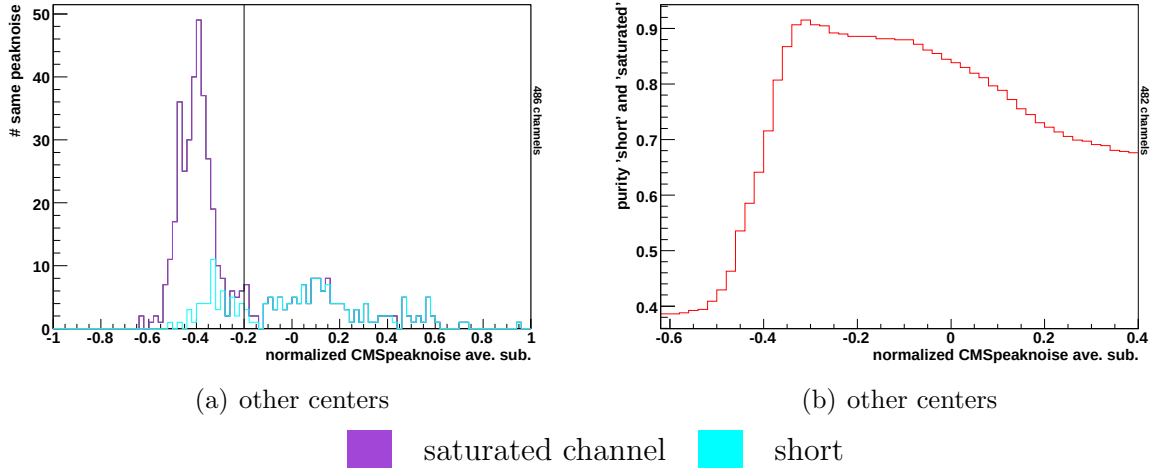


Figure 6.11: (a) Noise distribution of 'short' and 'saturated' channels. The noise is scaled and the average is subtracted. (b) Purity as given by Eq. 6.6. 'Short' and 'saturated' channels define the two areas.

OTHERS	peak time [ns]		peak height [ADC]		peak noise
short	> -7	< 13	> -20	< -6	> -0.2
saturated channel	> -7	< 13	> -20	< -6	< -0.2
PA-S open	> -15.5	< -7	> -2	< 4	-
S-S open	> -7	< -3	> -2	< 4	-
noisy channel	> -3	< 6	> -2	< 4	-
unknown	everything else				

CERN	peak time [ns]		peak height [ADC]		peak noise
short	> -10	< 0	> -22	< -10	> -0.2
saturated channel	> -10	< 0	> -22	< -10	< -0.2
PA-S open	> -11.5	< -1.5	> -8	< 5.5	-
S-S open	> -5	< -1.5	> -1	< 5.5	-
noisy channel	> -1.5	< 6	> -6	< 3	-
unknown	everything else				

Table 6.2: Upper and lower bound of the classification for each defect class and testing center. S-S open overrule PA-S open definition.

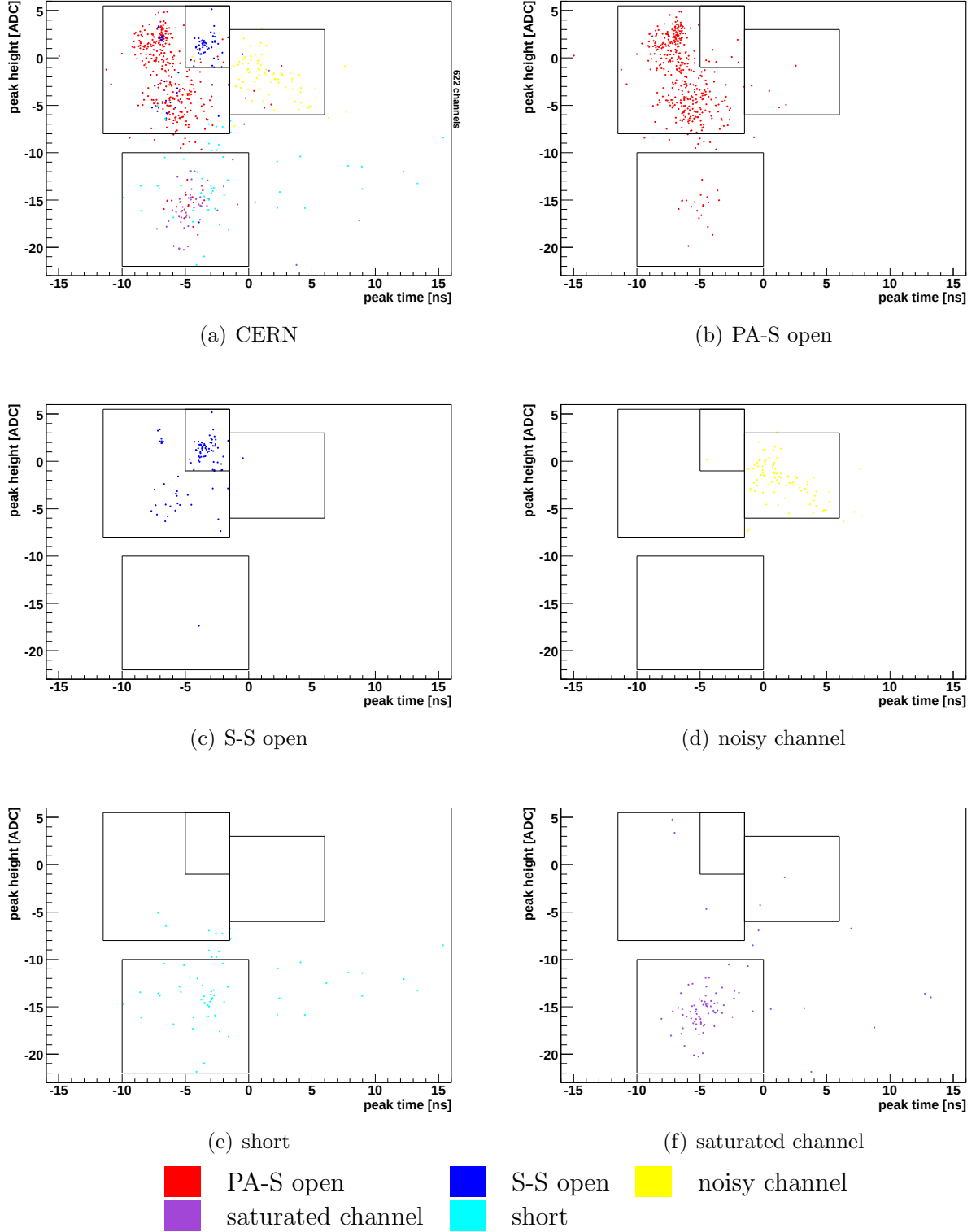


Figure 6.12: Scaled peak height versus peak time for petals tested at CERN.

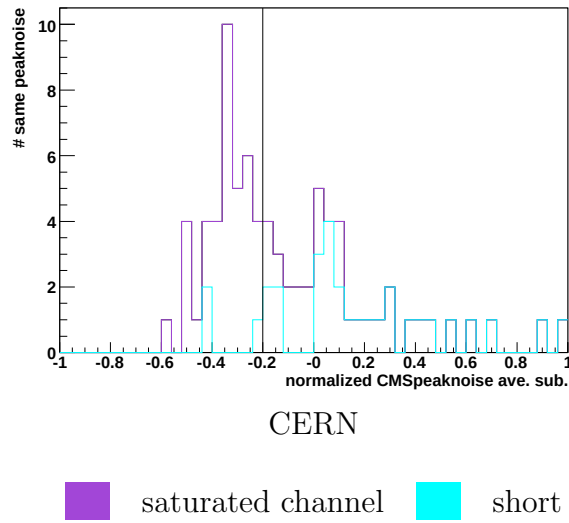


Figure 6.13: Noise distribution of shorts and saturated channels.

6.3 Comparison between ARC and LT test

Using the classification scheme that has been presented above, it is possible to compare ARC and LT test results without counting 'noisy' channels to the defective channels. In Fig. 6.14 the number of defect strips per APV channel is shown. Fig 6.15 shows the difference between the ARC test and the LT test results. As noisy channels are still operational they are excluded. For most channels a good agreement of the amount of flagged channels between the ARC and the LT test result is visible for all test centers. A strip by strip comparison will be shown later in this section. The first two APV channels show an enhanced defect rate in the ARC test results compared to the LT test results. The expected shape should be flat as one would expect every channel to show the same rate of defects. The LT test results indicate such a flat distribution except for channels 127 and 128, while the ARC test results show an unexpected enhancement of the edge channels. The fact that the ARC setup does not combine several tests to classify a defect, but uses just the worst test of all could be an explanation for the increased rate.

A detailed look into the ARC data shows (Fig. 6.16), that the surplus of defective strips mainly has the flag 'short' and affects mostly the APV channels 1 and 2, or rather module channels 1 and 2 not shown in this plot. To explain this behaviour in Fig. 6.17 the peak height distribution of one module is shown as an example. The first two channels of this module are flagged as 'short'. This distribution obviously shows that the defect is not a problem of the strip but a problem of the classification scheme [23]. The reference of the classification scheme is a flat distribution of the peak height for each APV. A channel is flagged if the deviation from the median exceeds a certain value. But the peak height distribution versus the channel number is not always flat for an APV and even not linear. Therefore, the channels 1 and 2 are flagged more often than the other channels as the deviation to the expected reference value is largest for those channels, even larger than for channel 129 and 130. The classification scheme of LT is different as it needs more than one test to declare a channel to be defective and uses only noise tests.

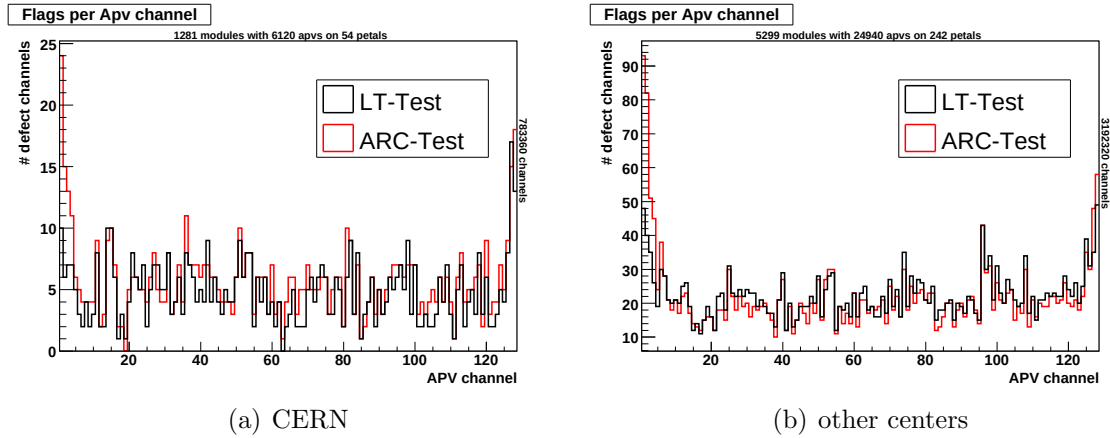


Figure 6.14: Number of defective strips per APV channel for ARC and LT. Noisy channels are excluded [51].

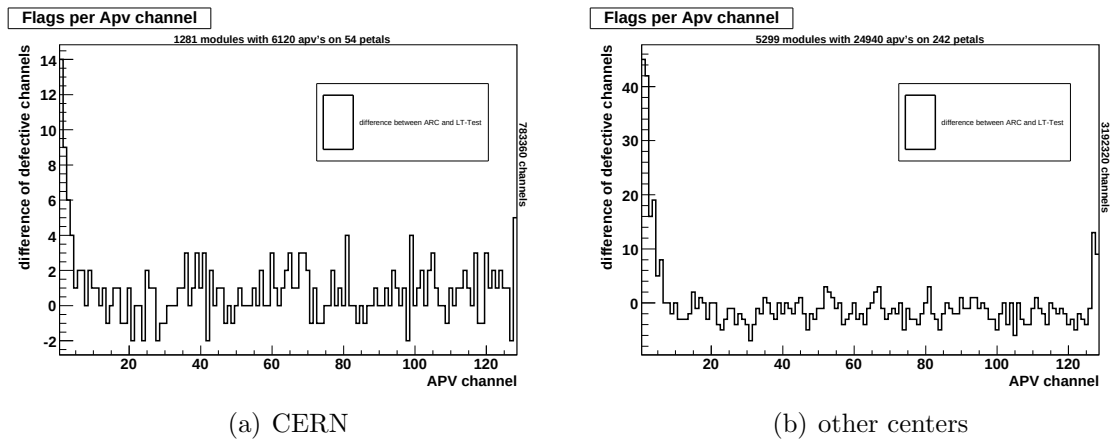


Figure 6.15: Difference of defective strips per APV channel between ARC and LT (ARC-LT). Noisy channels are excluded [51].

Another way to compare the ARC test with the LT test is to investigate how many strips are flagged by the two tests (Fig. 6.18). This plot shows the amount of strips flagged by both test systems (upper dashed line) and how many of these have the same classification (lower dashed line). In Fig. 6.18(a) it can be seen that 88% of all strips flagged by the ARC test are also flagged by the LT test and that in this case $76\% \pm 1\%$ have the same classification. The error is determined by varying the width and height of the different areas of each defect type simultaneously by 10%. The borders in 6.11 and 6.13 are varied 0.05 counts which is roughly 10% of the width of the peak at a height of 10%.

As the channels 1 and 2 are flagged by the ARC test disproportionately high, Fig. 6.18(b) shows the same numbers excluding both channels. Here 92% of the channels flagged by the ARC test are found by the LT test and $77\% \pm 1\%$ have the same classification. It is worth mentioning, that the LT test flagged 204 channels as unknown, because there is no information about the height of their tick mark due to a software bug. This was discovered so lately that

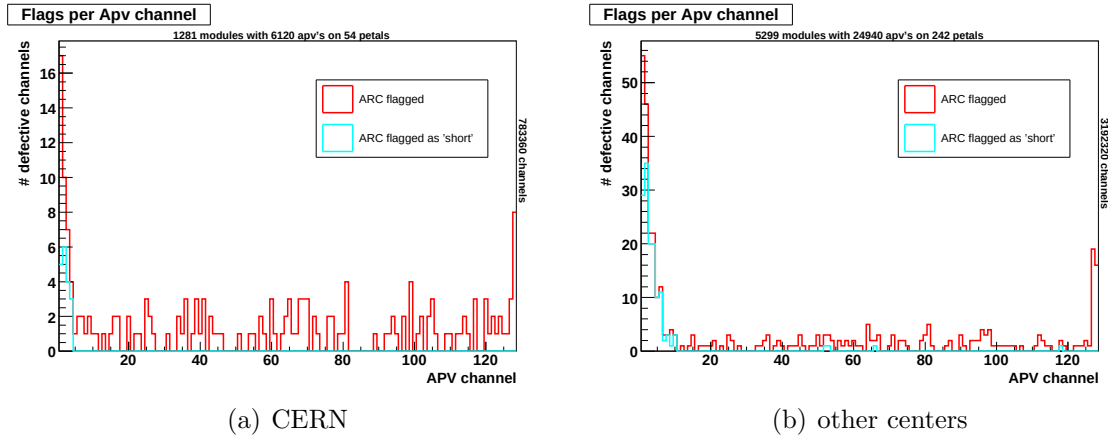


Figure 6.16: Only channels flagged just by ARC are counted. Noisy channels are excluded.

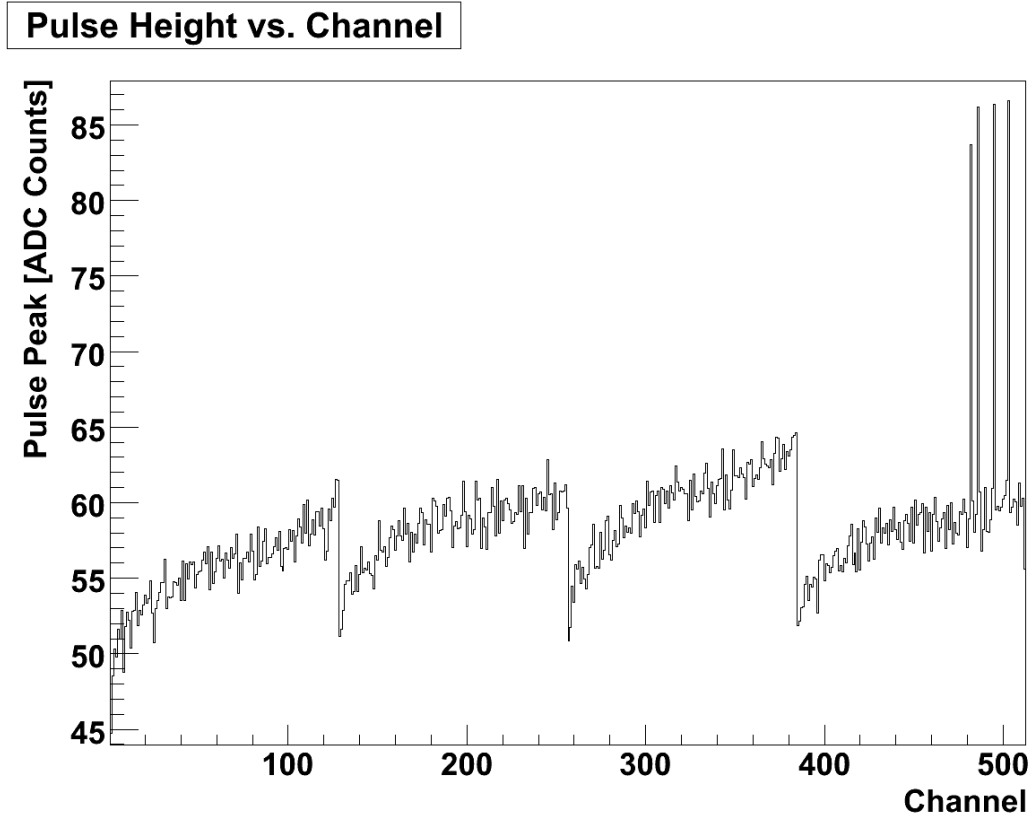


Figure 6.17: Peak height (Pulse Peak) versus channel number. The channels 482, 486, 495 and 503 have a strongly increased peak height. These channels are also suspicious in other tests. Channels 1 and 2 have a small peak height which differs only slightly from the distribution which has a slope between 0.5 and 1.0 ADC count per channel. But as the deviation from the median is taken into account these channels are flagged as shorts. Using other tests for the same strips does not indicate defects.

reprocessing the petals was not an option. This prevents a correct classification (see prev. section). The corrected amount of strips flagged identically by the ARC and LT test is around $82\% \pm 1\%$. A scenario in which all strips flagged by the ARC and LT test are bad, results in a defect rate of 0.09% (excluding APV edge strips⁶ and noisy channels). For TIB and TID together this number adds up to 0.07%, for TOB to 0.13% [53, 52]. So the 0.09% of TEC (LT) are in a comparable range. Unfortunately TIB, TID, TOB and TEC have different defect declaration methods and a different noise level so that the relevance of this comparison is not clear.

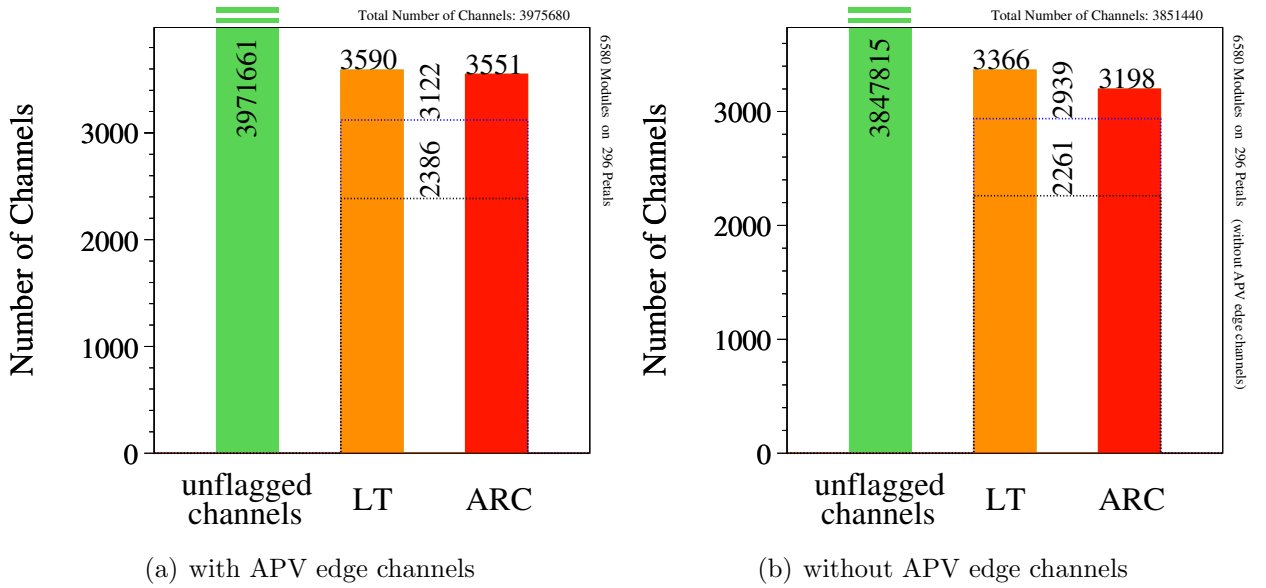


Figure 6.18: Number of channels flagged during LT and ARC tests. The upper dashed line gives the number of channels flagged in both test systems, the lower one the number of same flags [51].

Fig. 6.19 shows the number of flagged channels split into channels flagged only by the LT test, only by the ARC test or by both setups. From Fig. 6.19(a) and Fig. 6.19(b) it can be derived that around 40% of the channels flagged only by ARC are edge channels. In contrast the number of channels flagged only by the LT test are similar in both plots. Channels flagged only by LT are channels which are probably affected during assembly of the petals. A misclassification of those channels by LT or ARC is possible as well. The truth can eventually revealed by an optical inspection of the corresponding channels which is in general not possible anymore.

6.4 Comparison between LT and sector test

After the LT test all petals have been assembled into both TECs. A pedestal run in peak and deconvolution mode has been performed [30]. In this section the data taken with TEC+ in deconvolution mode is compared to the LT test data.

⁶APV channels 1, 2, 127 and 128

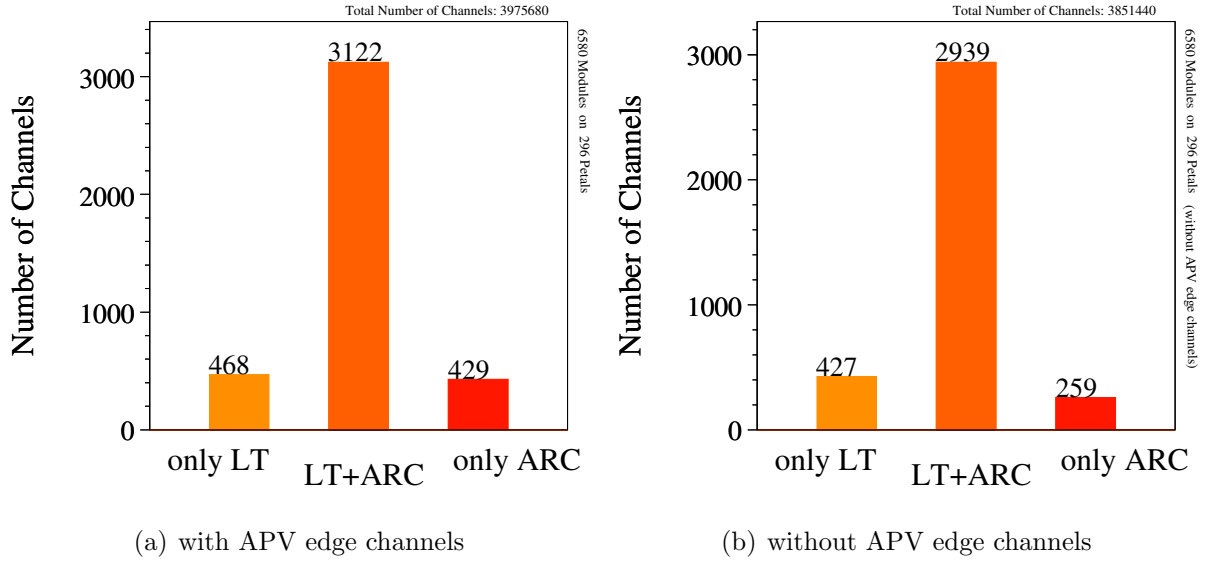


Figure 6.19: Number of channels flagged during LT and ARC test, split into channels flagged only by LT and ARC or by both test systems [51].

In Fig. 6.20 the noise distribution of the TEC+ petals (in deconvolution mode) can be found. It is split into the rings 1 to 4 and 5 to 7. The red histogram indicates strips, which are

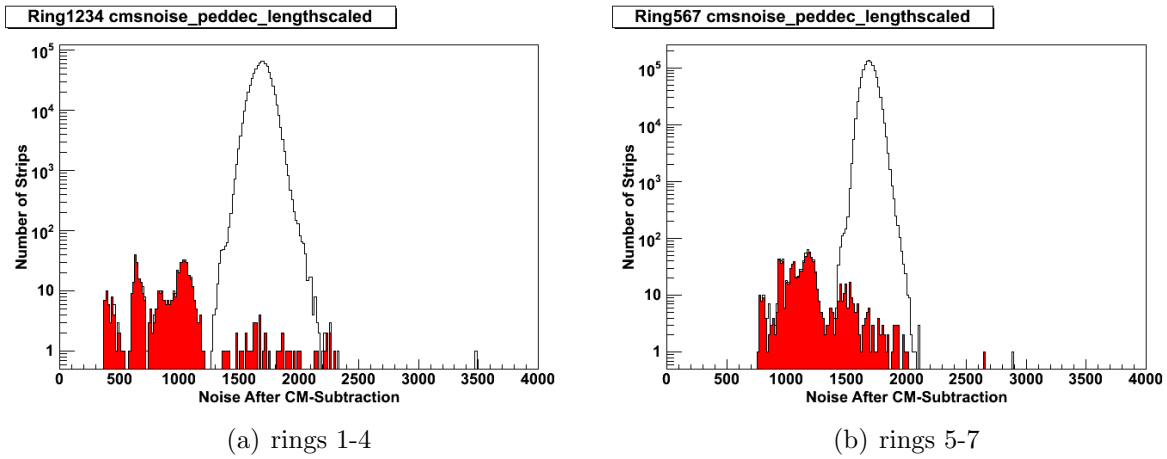


Figure 6.20: Scaled noise distribution measured in TEC+. Channels flagged by the LT test are marked in red. APV edge channels and bad APVs are excluded [30, 31].

classified as defect by the LT test. Noisy channels are not labeled. APVs which are known to be defect [30] and APV edge channels are excluded. Taking these distributions it can be seen that defective and good strips separate well for the rings 1 to 4 but not for the rings 5 to 7. Therefore, the channels of rings 5 to 7 which cannot be separated are investigated in more detail.

One difference between rings 1 to 4 and 5 to 7 is that the latter contain only 'two sensor modules' and only strips of such modules can have the defect 'S-S open'. Strips with a 'S-

'S open' have a higher noise than strips with other defects (see Chap. 3). This explains that channels do not separate. Another reason are channels flagged as 'unknown'. Their real defect is unknown, part of them should be 'noisy' and hence do not separate.

Due to these facts the defective channels are grouped into three classes: 'unknown', 'S-S open' and the rest is gathered as 'defect'. Fig. 6.21 shows the result of this classification. Indeed most channels which do not separate are 'S-S opens' and 'unknown' channels. The same plot can be done for ring one to four, see Fig. 6.22.

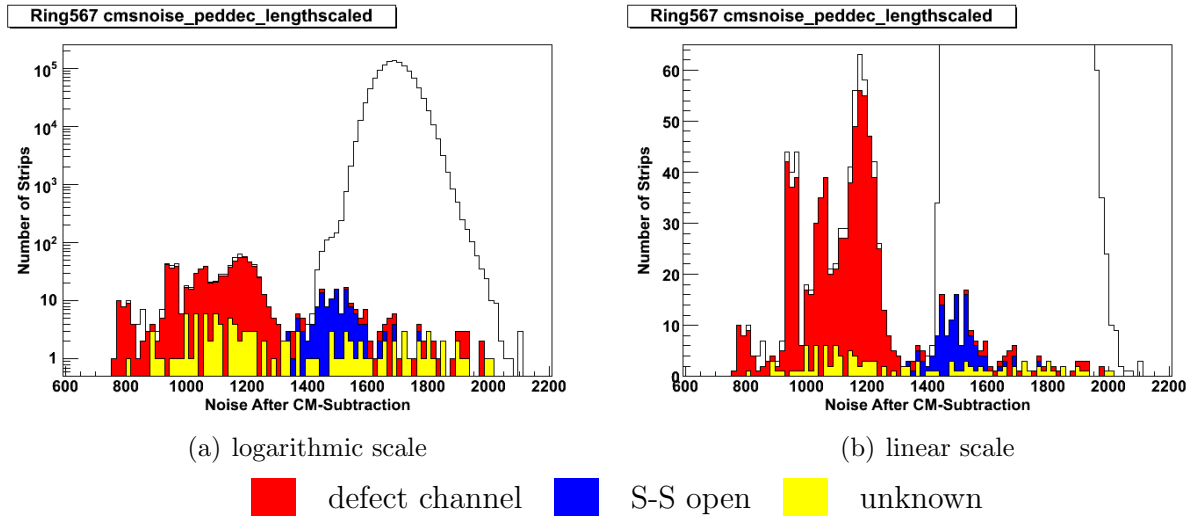


Figure 6.21: Scaled noise distribution of ring five to seven measured in TEC+. Categories are defined as in the LT test. APV edge channels and bad APVs are excluded [30, 31].

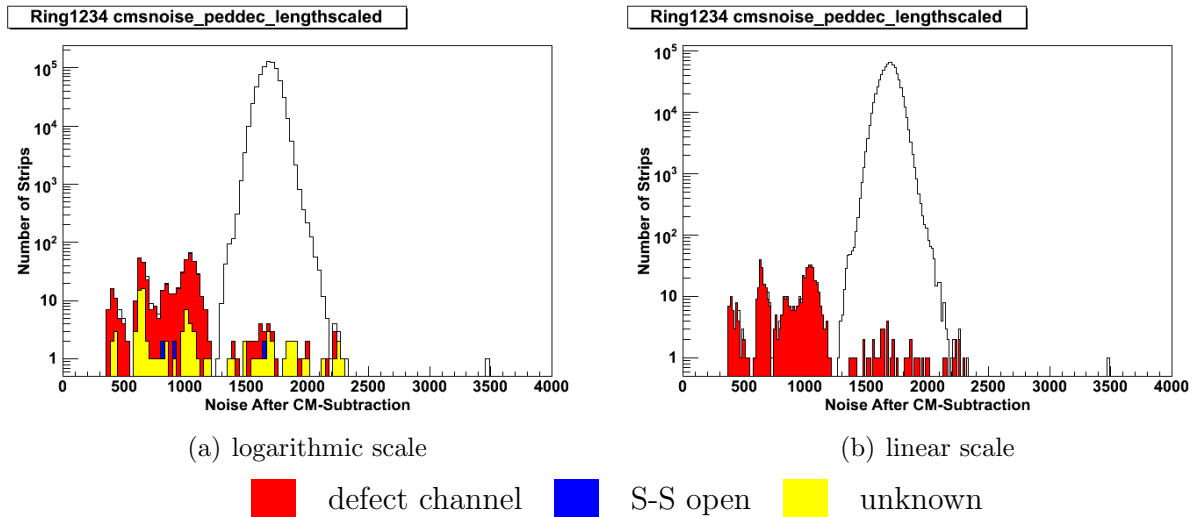


Figure 6.22: Scaled noise distribution of ring one to four measured in TEC+. Categories are defined as in the LT test. Channels marked in blue are 'mid sensor open' as they are counted to 'S-S open'. APV edge channels and bad APVs are again excluded [30, 31].

The distributions in Fig. 6.20 are used to define defective channels in the TEC. The cut pa-

rameters are listed in Tab. 6.3. This results in the distributions Fig. 6.23 and Fig. 6.24 which are defined in analogy to Sec. 6.3.

TEC	Ring 1-4	Ring 5-7
dec noise	< 1250	< 1420

Table 6.3: In this table a definition of defect channels inside the TEC+ is given. Noise was taken in deconvolution mode (*dec mode*)

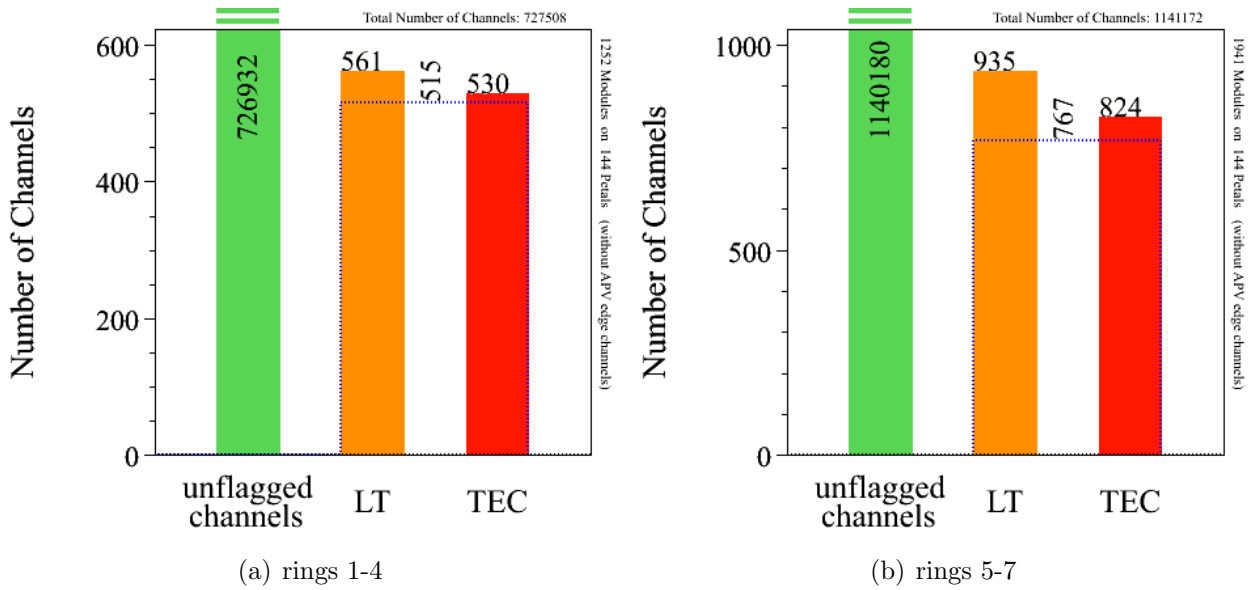


Figure 6.23: Number of channels flagged during LT and TEC+ (sector) test. APV edge channels and defective APVs are excluded [51, 30].

Finally 85% of all LT test flags can be reproduced by the sector test data. From the 214 channels flagged by LT and not flagged by TEC+ only 50 channels are not flagged as 'S-S-open' or 'unknown'. This implies that only 3.3% of channels flagged by LT are not found by TEC+ unexplained. In the noise region below 1250 for Ring 1 to 4 and 1420 for ring 5 to 7 (see Fig 6.20) less than 6% more channels are flagged from TEC+ than from LT. These two numbers (3.3% and 6%) show the high consistency between LT and TEC+ test and hence the consistency between ARC and TEC+.

Using also the ARC information for those 50 channels only 8 channels are just flagged by LT. Doing the same for the 214 channels just 28 channels are not flagged. These 28 channels are equal to 1.8% of all channels flagged by LT and those 8 are equal to 0.5%. This shows, that a channel flagged by LT is really defect in about 99% of all cases. Unfortunately this statement can not be proved as it is not possible to do an optical inspection of the modules after the petal assembly.

Since 34 APVs out of 15104 APVs are dead [30] (only TEC+) the defect rate here is 0.23%. Taking all defect channels from ARC, LT and TEC (including dead APVs) a defect rate of

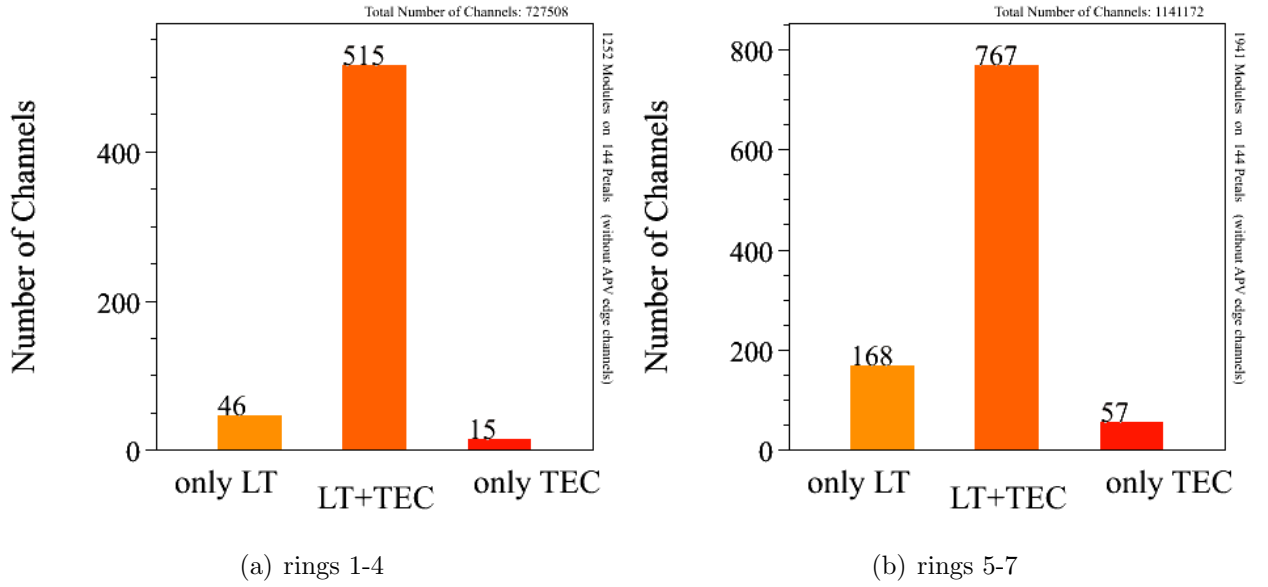


Figure 6.24: Number of channels flagged during LT and TEC+ (sector) test, split up into channels flagged by LT and TEC+ or by both test systems. APV edge channels and defective APVs are excluded [51, 30].

approx. 0.33% is estimated (excluding APV edge strips and noisy channels). This gives hope, that the design goal of less than 1% missing strips after the whole tracker insertion can be achieved.

Chapter 7

Summary

The focus of the present work is the longterm test of silicon strip modules. This test has been crucial for the production of the CMS tracker to guarantee the benchmark quality of the petals. Moreover in case of defect components it has been possible to exchange them or even to exchange the whole petal. Furthermore, the LT-test provides an important independent data set which allows to characterize each single module and extrapolate the final tracker performance before the start-up and final assembly of all detector components.

The presented results and methods have been elaborated during the time of the LT-test (2005-2007) and have influenced the final classification scheme. Here, the following results are summarized:

- The layout of the Si-strip detector is introduced and possible defect sources affecting single strips are presented.
- The LT test procedure and the importance of it is described [48].
- The data acquisition of the LT test is introduced. For efficient data taking the MUX-mapping has been developed in the context of the presented work (see App. B).
- A test setup has been set into operation with the help of F. Beissel and D. Jahn. The DAQ-software and slow control has been ported to the test system in Aachen with the help of W. Beaumont and Th. Hermanns.
- Roughly 15% of the whole LT test data has been taken with the LT-test setup in Aachen [48].
- The whole data set of the LT test and TEC+ sector test is used for the present analysis [48, 49].
- The LT test data has been compared with the ARC test data. The knowledge gained from this comparison leads to a robust defect finding algorithm [48]. The efficiency to find a defect that has already been noticed by the ARC setup is at 92% (see Fig. 6.18(b) and Fig. 6.19(b)). 13% of all channels flagged as defect by the LT test have not been

noticed to be defect by the ARC test. Reasons therefore could be the assembly of the modules onto the petals as also a bad identification of defects in ARC or LT.

- A further comparison of ARC and LT test leads to a defect classification algorithm based on a simple cut strategy. For those strips, that have been noticed defect by both, ARC and LT setup, the classification indicates in 83% the same kind of defect. The combination of the defect identification and classification algorithm shows an efficiency to classify a defect found by ARC with the same defect with LT to 76%.
- The combination of defects seen by LT and ARC test yields in a defect rate of 0.09%.
- Shells and discs of TIB and TID have a single strip defect rate of 0.07% and the rods of TOB a defect rate of 0.13% [53, 52]. So the result of the LT test is in the same range.
- Results have been cross-checked with the results of TEC+ sector test data to verify and to validate the presented method. 95% of the strips, that are declared as defect based on the LT test results, have also been identified as defect based on the sector test data. About 0.002% strips have been noticed as defect based on the sector test data and thus not flagged before. This indicates the high accuracy of the presented algorithms.
- A further 0.23% of all APVs have been excluded from the analysis of the sector test data due to defects which are supposed to be caused during the integration of the petals into the TEC [30].
- The combination of ARC, LT and sector test results of TEC+ yields a final defect rate of 0.33%.

The determined defect rate of 0.33% for strips inside TEC+ is far below the benchmark rate of 1% and so a very promising result as the performance of the tracker and therefore physics analyses are not harmed by those defects [22]. This lets us eagerly await the first physics run at LHC to see 'new' physics.

Appendix A

Fiber Mapping

ribbon/ch	1	2	3	4	5	6	7	8	9	10	11	12
1	430	432	440	442	610	612	620	622	630	632	640	642
2	420	422	410	412	330	332	320	322	310	312	—	—
3	240	241	242	230	231	232	220	221	222	210	211	212
4	140	141	142	130	131	132	120	121	122	110	111	112
5	750	752	740	742	540	541	542	530	531	532	730	732
6	720	722	520	521	522	510	511	512	710	712	—	—

Table A.1: Mapping of AOH-Fibers to long ribbon cables (given for a frontpetal). The First position in this table is 430. This means AOH on ring 4, position 3, fiber 0 has to be plugged on longribbon cable 1 channel 1.

Appendix B

K-Mux Mapping

KMUX (back petal)		for a front: petal change shortribbon 1 against 5						
ch\group	7	6	5	4	3	2	1	0
0	5.12	5.11	2.6	2.5	2.4	2.3	2.2	2.1
1	2.12	2.11	2.10	2.9	2.8	2.7	1.12	1.11
2			1.10	1.9	1.8	1.7	1.6	1.5
3	3.6	3.5	3.4	3.3	3.2	3.1	1.4	1.3
4	3.12	3.11	3.10	3.9	3.8	3.7	1.2	1.1
5	4.12	4.11	4.10	4.9	4.8	4.7	5.10	5.9
6	4.6	4.5	4.4	4.3	4.2	4.1	5.8	5.7
7	6.10	6.9	5.6	5.5	5.4	5.3	5.2	5.1
8	6.8	6.7	6.6	6.5	6.4	6.3	6.2	6.1
9								

Figure B.1: Mapping of long ribbon cables to K-MUX. The mapping is given for a back petal. In row 0 column 7 the entry is 5.12. This means that channel 12 of longribbon 5 has to be plugged in slot 7 row 0. To switch from back to front petal the blue have to be exchanged against the green ones. This can be done by changing just one whole ribbon, which means one connection.

Appendix C

Scenario-File

Each line of the scenario-file represents one command for the DAQ-software and each command can be split into four parts. The first part is the information when the command should be executed, positive numbers are absolute times in second, negative values represent a relative time to wait, e.g. 1 means: to be executed at the second 1 of the longterm test and -600 means: wait 600 seconds after finishing the last test. The second part of the line is the main command which should be executed by the DAQ software. In addition to this command two parameters can be transferred. These are the third and fourth part of the command. In most cases this are just dummy text. A complete documentation of the commands can be found in [50] and [48].

1 Start longterm test	-2 PedRun i2cpeak _pp
-2 SetDt 600000 _noslctrl	-2 I2cDump dummy dummy
-2 ChangeHV 0 _hv0	-2 SaveRec 1 no
-2 I2cDump dummy dummy	-2 PedRun i2cdec _pd
-2 PiaReset pllinit dummy	-2 I2cDump dummy dummy
-2 ChangeCool 16 _t16	-2 SaveRec 1 no
-2 ChangeCool 16 _t16	-2 PedRun i2cdecinv _pdi
-60 TempReached 16 _tr	-2 I2cDump dummy dummy
-600 I2cDump dummy dummy	-2 CheckEnv dummy _d
-2 CheckEnv dummy _d	-60 I2cDump dummy dummy
-60 OptoScanRun i2cpeak fast	-2 SaveRec 1 no
-2 I2cDump dummy dummy	-2 ChangeHV 400 _hv400
-2 CheckEnv dummy _d	-2 I2cDump dummy dummy
-60 I2cDump dummy dummy	-2 PiaReset pllinit dummy
-2 TimeTuneRun i2cpeak _ts	-2 CheckEnv dummy _d
-2 PedRun i2cpeakinv _ppi	-60 OptoScanRun i2cpeak descibl=fullscan
-2 ConnectivityRun i2cpeakinv dummy	-2 TimeTuneRun i2cpeakinv _ts
-2 PedRun i2cpeakinv _ppi	-6 PedRun i2cpeakinv _ppi
-2 I2cDump dummy dummy	-2 I2cDump dummy dummy
-2 CalRun i2cpeakinv _cpi	-2 CalProfRun i2cpeakinv _cfpi
-2 I2cDump dummy dummy	-2 I2cDump dummy dummy
-2 CheckEnv dummy _d	-2 CheckEnv dummy _d
-60 I2cDump dummy dummy	-60 I2cDump dummy dummy
-2 SaveRec 1 no	-2 SaveRec 3 SECLTFIRST

```

-2 PedRun i2cpeak _pp
-2 I2cDump dummy dummy
-2 SaveRec 3 SECLTFIRST
-2 PedRun i2cdec _pd
-2 I2cDump dummy dummy
-2 SaveRec 3 SECLTFIRST
-2 PedRun i2cdecinv _pdi
-2 I2cDump dummy dummy
-2 SaveRec 3 SECLTFIRST
-2 CheckEnv dummy _d
-60 I2cDump dummy dummy
-2 SaveRec 3 SECLTFIRST
-2 ChangeHV 0 _hv0
-2 ExtIvRun i2cdecinv _iv
-20 HardReset pllinit recover_iv
-2 I2cDump dummy dummy
-2 PiaReset pllinit dummy
-2 ChangeHV 0 _hv0
-2 I2cDump dummy dummy
-2 PiaReset pllinit dummy
-2 CheckEnv dummy _d
-60 SaveRec 3 SECLTFIRST
-2 ChangeHV 0 _hv0
-2 I2cDump dummy dummy
-2 PiaReset pllinit dummy
-2 CheckEnv dummy _d
-60 ChangeCool -25 _t-25
-30 ChangeCool -25 _t-25
-120 TempReached -23 _tr
-1800 I2cDump dummy dummy
-2 PiaReset pllinit dummy
-2 I2cDump dummy dummy
-2 ChangeHV 400 _hv400
-2 I2cDump dummy dummy
-2 PiaReset pllinit dummy
-2 CheckEnv dummy _d
-60 I2cDump dummy dummy
-2 OptoScanRun i2cpeak descbl=fullscan
-2 I2cDump dummy dummy
-2 TimeTuneRun i2cpeak _tt
-2 I2cDump dummy dummy
-2 PedRun i2cpeakinv _ppi
-2 I2cDump dummy dummy
-2 CalProfRun i2cpeakinv _cfpi
-2 I2cDump dummy dummy
-2 CheckEnv dummy _d
-60 I2cDump dummy dummy
-2 SaveRec 17 SECLTLAST
-2 PedRun i2cpeak _pp
-2 I2cDump dummy dummy
-2 LatRun i2cpeak _lp
-2 I2cDump dummy dummy
-2 SaveRec 17 SECLTLAST
-2 PedRun i2cdec _pd
-2 I2cDump dummy dummy
-2 CheckEnv dummy _d
-60 I2cDump dummy dummy
-2 SaveRec 17 SECLTLAST
-2 PedRun i2cdecinv _pdi
-2 I2cDump dummy dummy
-2 SaveRec 17 SECLTLAST
-2 ChangeHV 0 _hv0
-2 I2cDump dummy dummy
-2 SaveRec 14 SECLTCOLD
-2 PedRun i2cdec _pd
-2 I2cDump dummy dummy
-2 SaveRec 14 SECLTCOLD
-2 PedRun i2cdecinv _pdi
-2 I2cDump dummy dummy
-2 SaveRec 14 SECLTCOLD
-2 CheckEnv dummy dummy
-60 I2cDump dummy dummy
-2 SaveRec 14 SECLTCOLD
-2 ChangeHV 0 _hv0
-2 PiaReset pllinit dummy
-2 I2cDump dummy dummy
-30 ChangeCool 16 _t16
-30 ChangeCool 16 _t16
-600 TempReached 16 _tr
-3600 I2cDump dummy dummy
-2 CheckEnv dummy _d
-60 I2cDump dummy dummy
-2 ChangeHV 400 _hv400
-2 PiaReset pllinit dummy
-2 I2cDump dummy dummy
-2 CheckEnv dummy _d
-60 OptoScanRun i2cpeak descbl=fullscan
-2 I2cDump dummy dummy
-2 TimeTuneRun i2cpeak _tt
-2 I2cDump dummy dummy
-2 PedRun i2cpeakinv _ppi
-2 I2cDump dummy dummy
-2 CalProfRun i2cpeakinv _cfpi
-2 I2cDump dummy dummy
-2 CheckEnv dummy _d
-60 I2cDump dummy dummy
-2 SaveRec 17 SECLTLAST
-2 PedRun i2cpeak _pp
-2 I2cDump dummy dummy
-2 LatRun i2cpeak _lp
-2 I2cDump dummy dummy
-2 SaveRec 17 SECLTLAST
-2 PedRun i2cdec _pd
-2 I2cDump dummy dummy
-2 CheckEnv dummy _d
-60 I2cDump dummy dummy
-2 SaveRec 17 SECLTLAST
-2 PedRun i2cdecinv _pdi
-2 I2cDump dummy dummy
-2 SaveRec 17 SECLTLAST
-2 ChangeHV 0 _hv0

```

-2 ExtIvRun default _iv	-2 I2cDump dummy dummy
-20 HardReset pllinit recover_iv	-2 CheckEnv dummy _d
-2 PiaReset pllinit dummy	-60 SaveRec 17 SECLTLAST
-2 SaveRec 17 SECLTLAST	-2 Stop 0 _stop
-2 ChangeHV 0 _hv0	
-2 PiaReset pllinit dummy	

Appendix D

Noise distribution

On the following pages the common mode subtracted noise distribution of the LT setup in peak and deconvolution mode with inverter on or off is shown. The plots are separated into the three phases (first warm, cold and last warm), with and without APV edge channels and with and without petals tested at CERN as well as petals only tested at CERN.

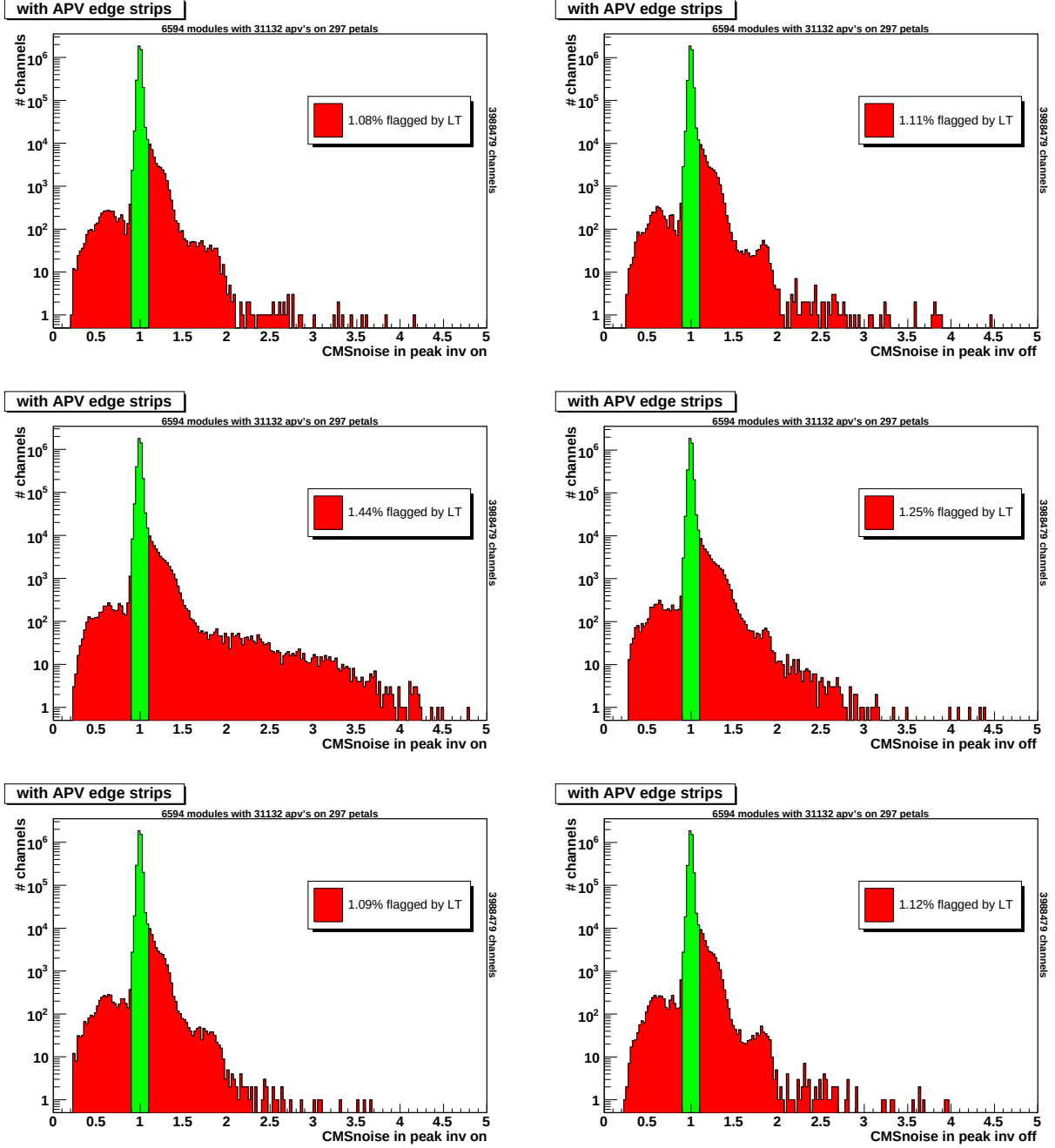


Figure D.1: Noise distributions taken in peak mode. The noise is normalised to the average (module-wise). First row is first warm phase, second row in cold phase and third row again in warm phase. All channels are included.

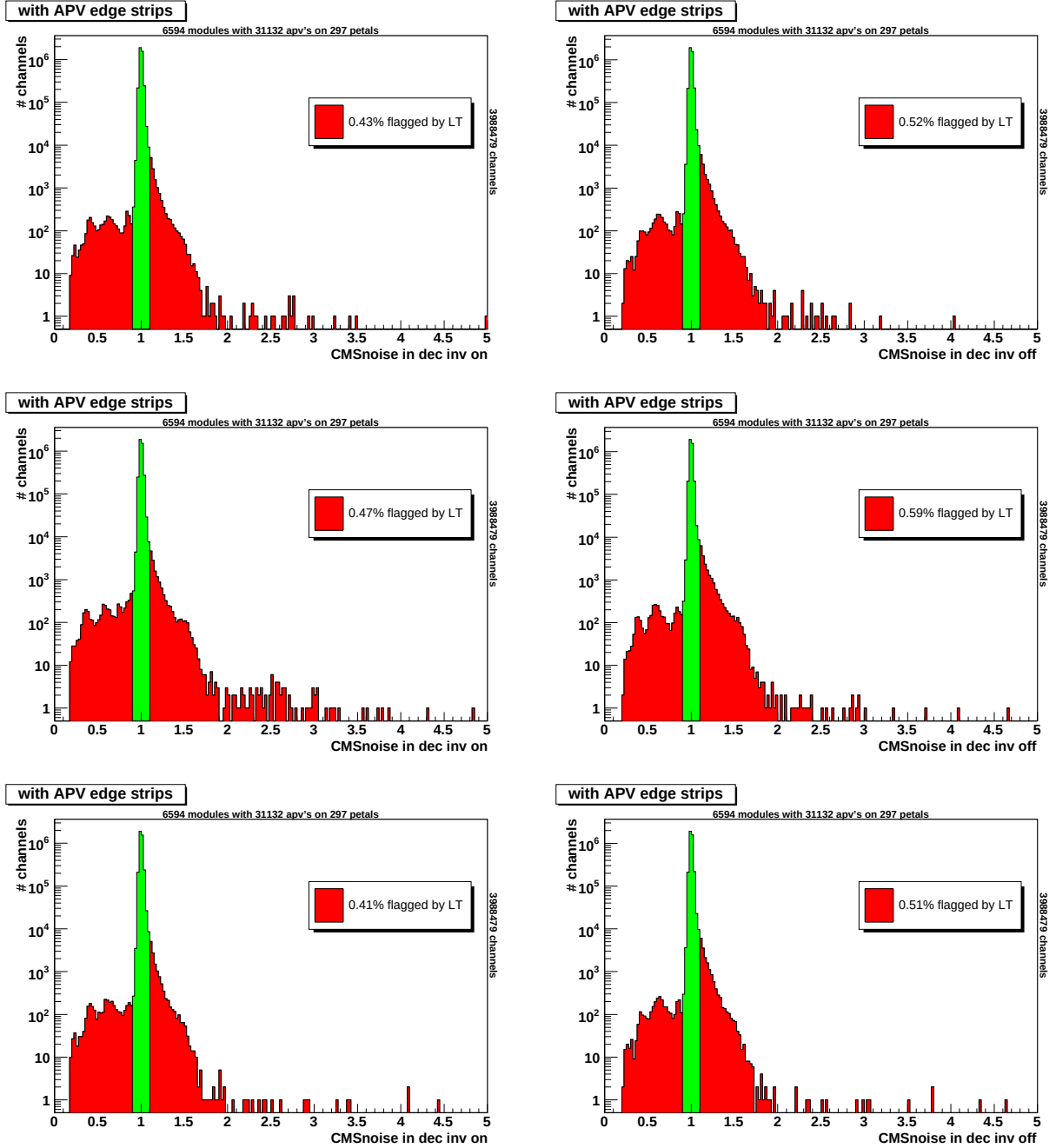


Figure D.2: Noise distributions taken in deconvolution mode. The noise is normalised to the average (module-wise). First row is first warm phase, second row in cold phase and third row again in warm phase. All channels are included.

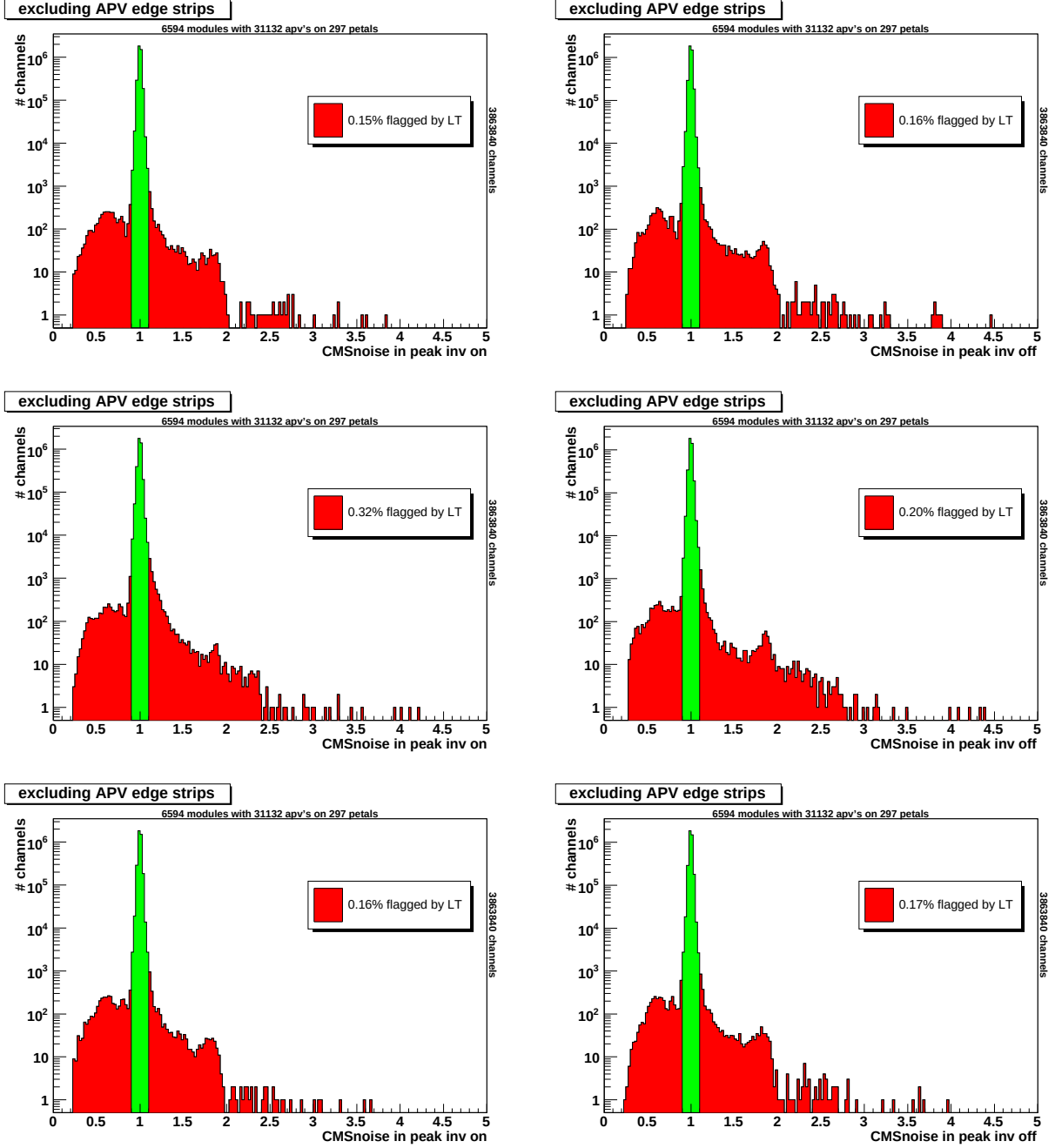


Figure D.3: Noise distributions taken in peak mode. The noise is normalised to the average (module-wise). First row is first warm phase, second row in cold phase and third row again in warm phase. APV edge strips are excluded.

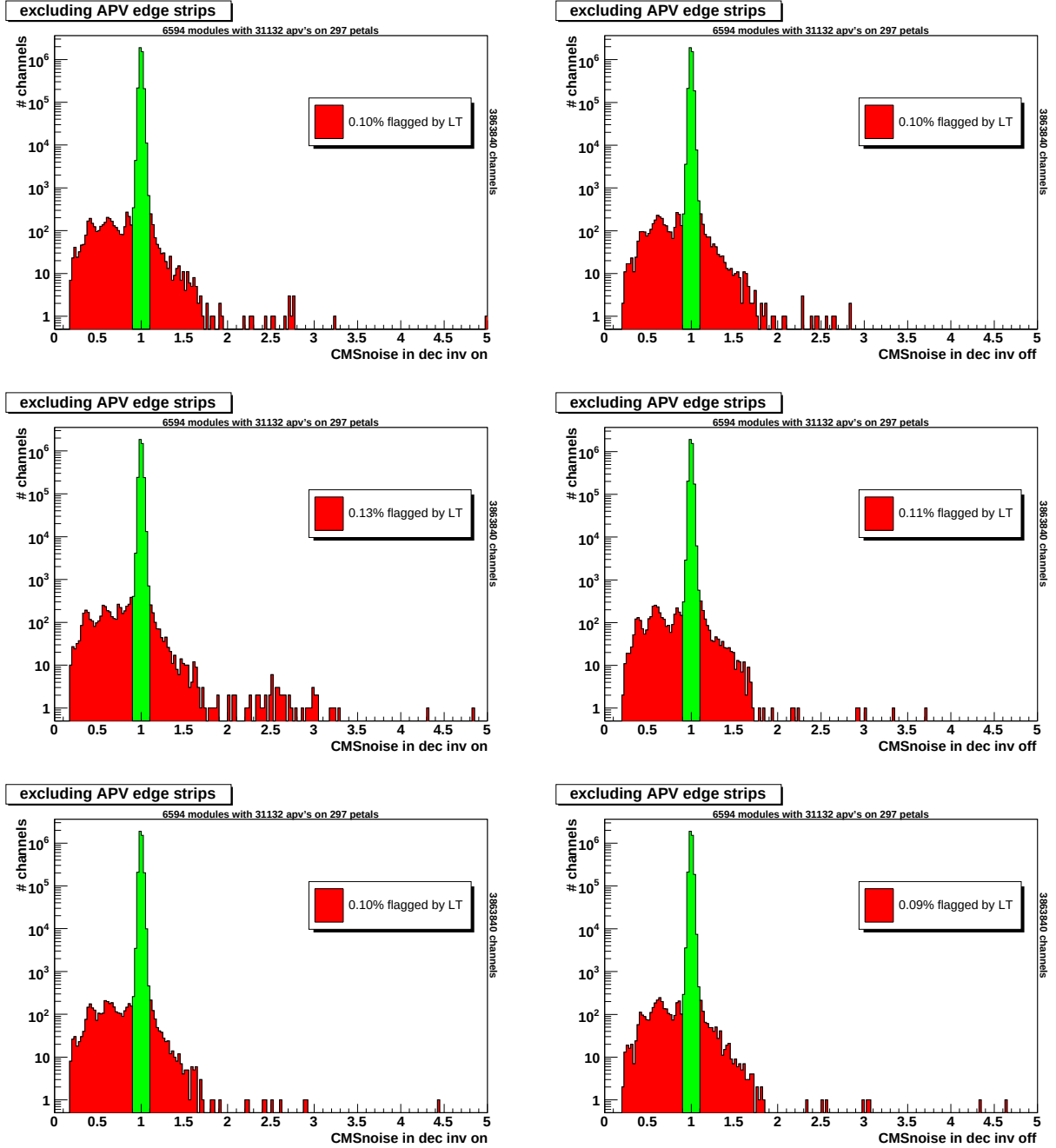


Figure D.4: Noise distributions taken in deconvolution mode. The noise is normalised to the average (module-wise). First row is first warm phase, second row in cold phase and third row again in warm phase. APV edge strips are excluded.

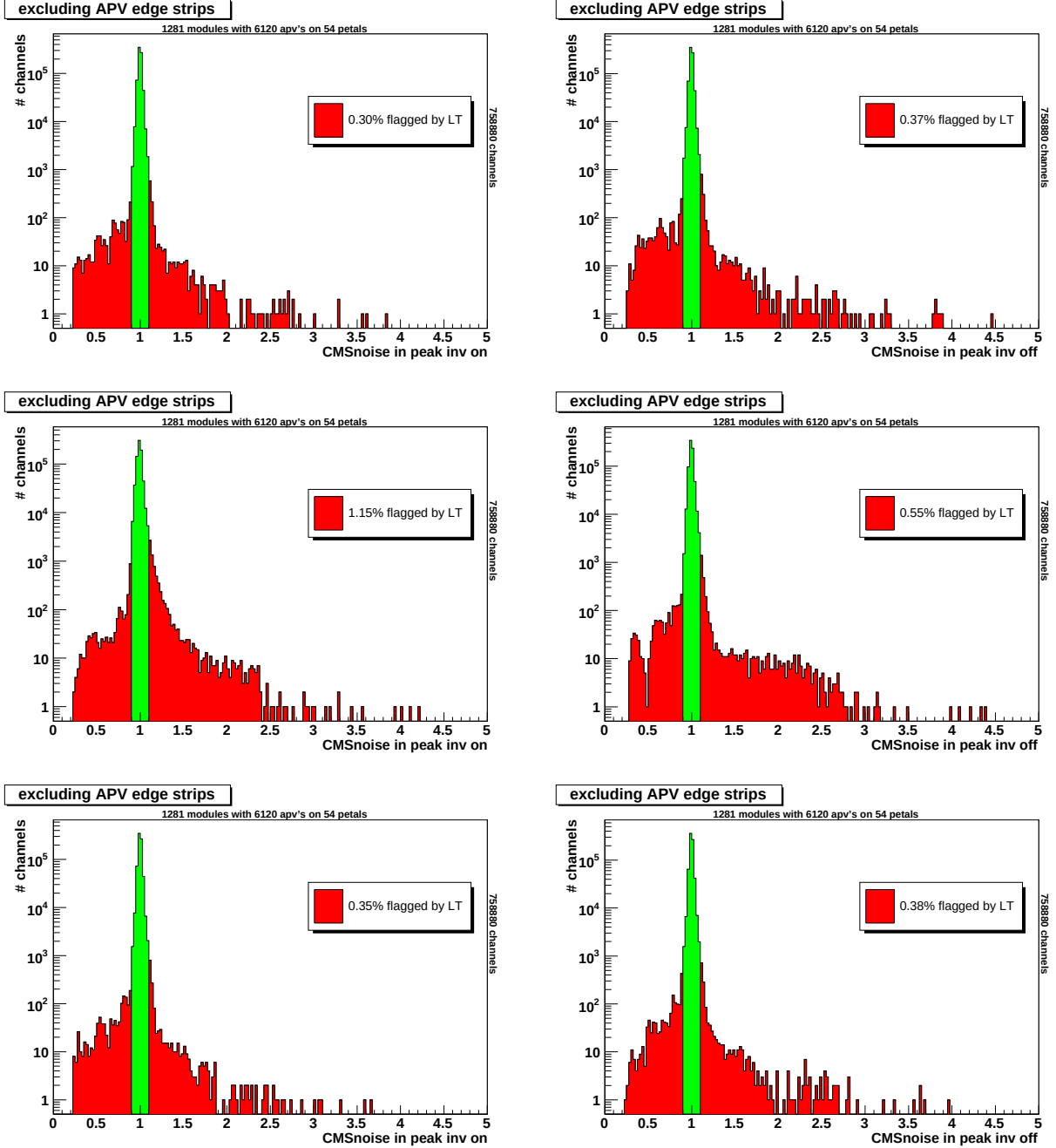


Figure D.5: Noise distributions taken in peak mode. The noise is normalised to the average (module-wise). First row is first warm phase, second row in cold phase and third row again in warm phase. APV edge strips are excluded. Only petals tested at CERN are taken into account.

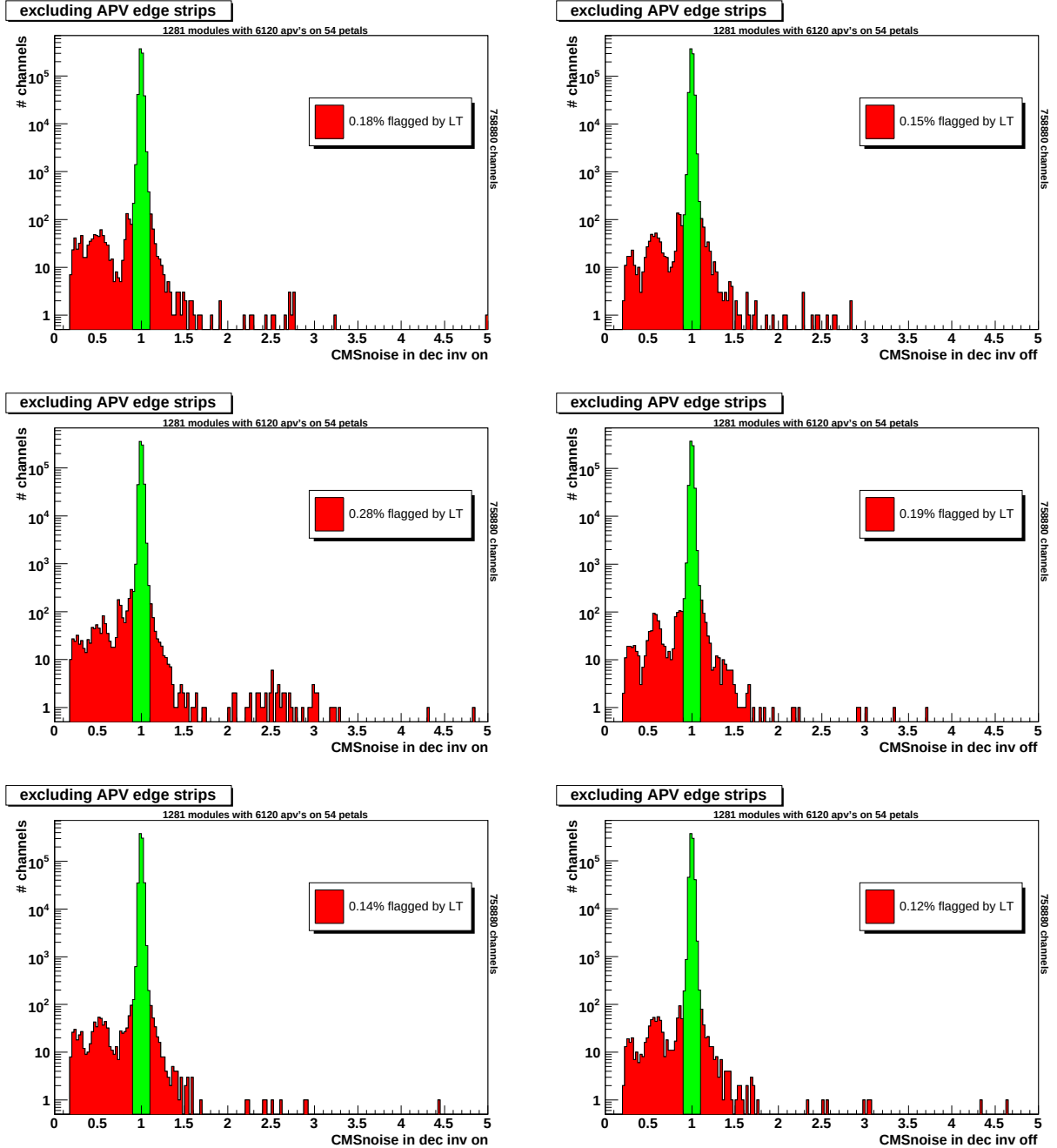


Figure D.6: Noise distributions taken in deconvolution mode. The noise is normalised to the average (module-wise). First row is first warm phase, second row in cold phase and third row again in warm phase. APV edge strips are excluded. Only petals tested at CERN are taken into account.

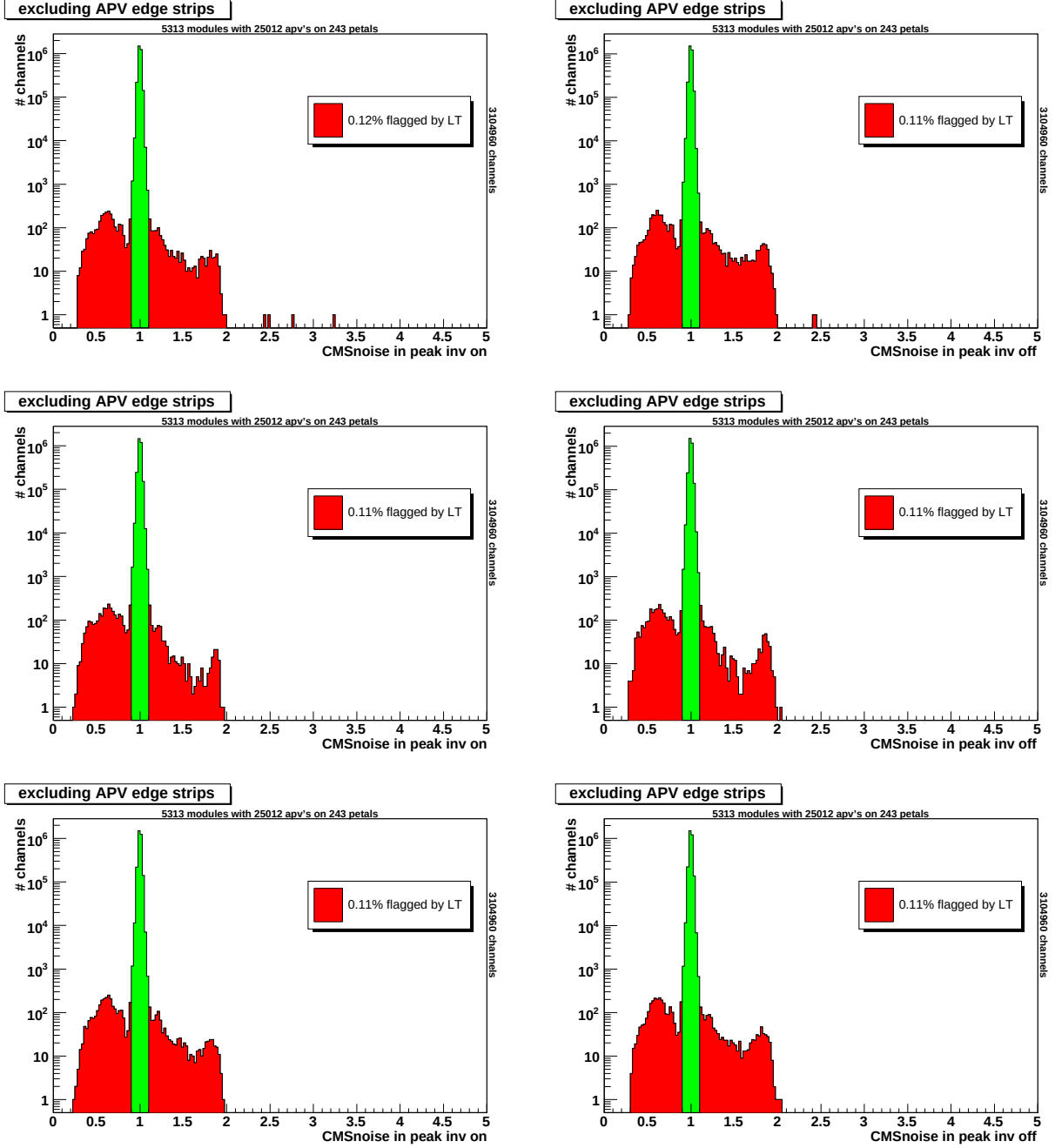


Figure D.7: Noise distributions taken in peak mode. The noise is normalised to the average (module-wise). First row is first warm phase, second row in cold phase and third row again in warm phase. APV edge strips and petals tested at CERN are excluded.

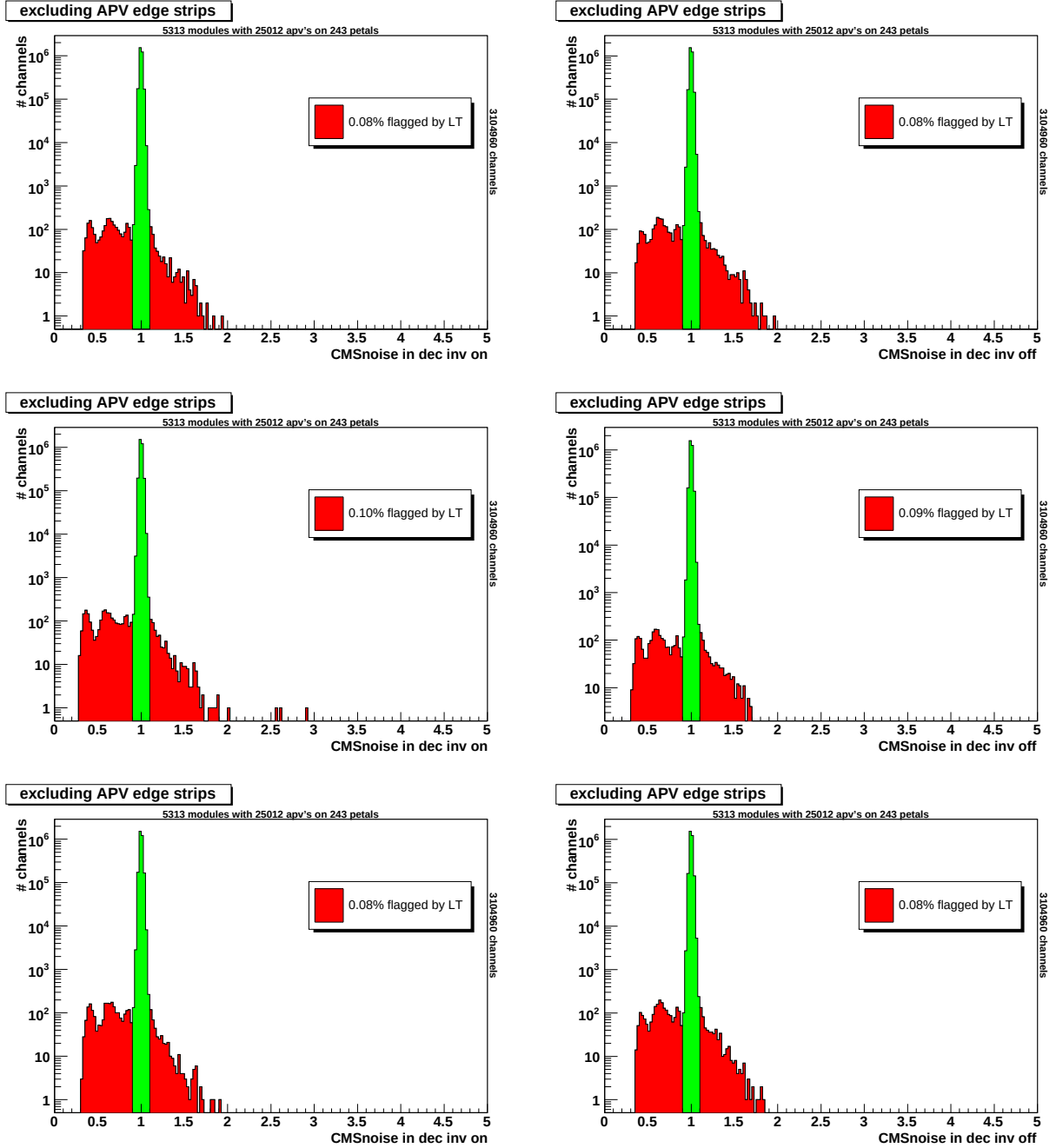


Figure D.8: Noise distributions taken in deconvolution mode. The noise is normalised to the average (module-wise). First row is first warm phase, second row in cold phase and third row again in warm phase. APV edge strips and petals tested at CERN are excluded.

Appendix E

Number of failed noise tests

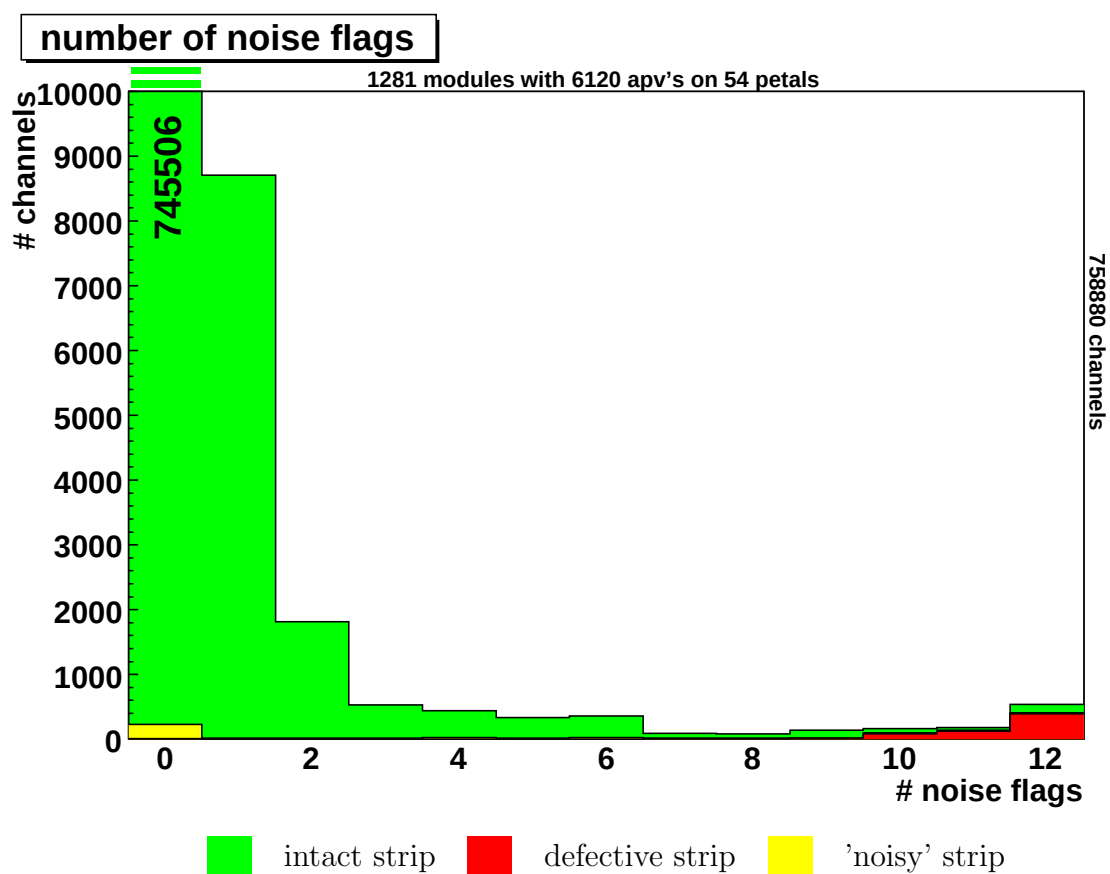


Figure E.1: Number of flags after noise tests. Colors indicate the ARC test results.

Appendix F

Calibration group subtracted peaktime

To show that the calibration group subtracted peaktime scales with the length of the modules, mean and RMS of it have to be determined. Results are used afterwards in a linear fit.

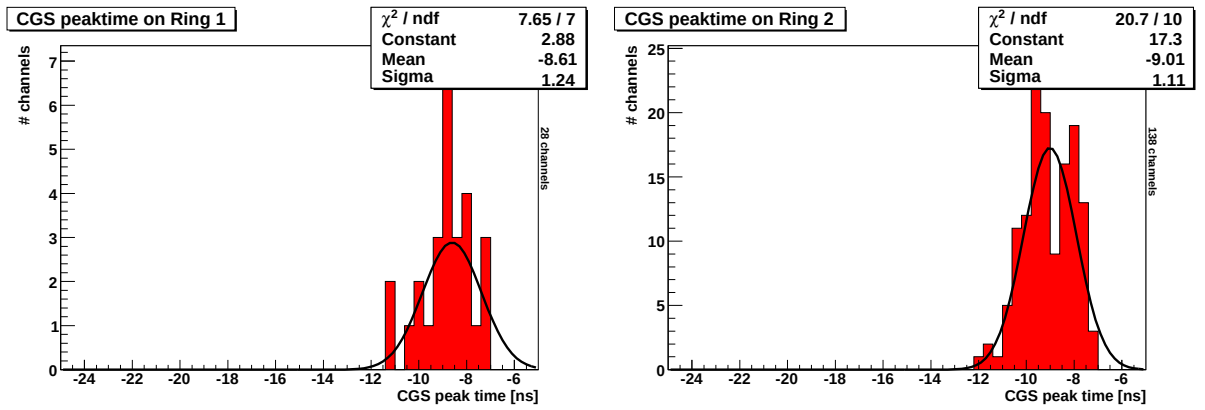


Figure F.1: Calibration group subtracted (*CGS*) peaktime for 'PA-S opens' in ring 1 (left) and ring 2 (right).

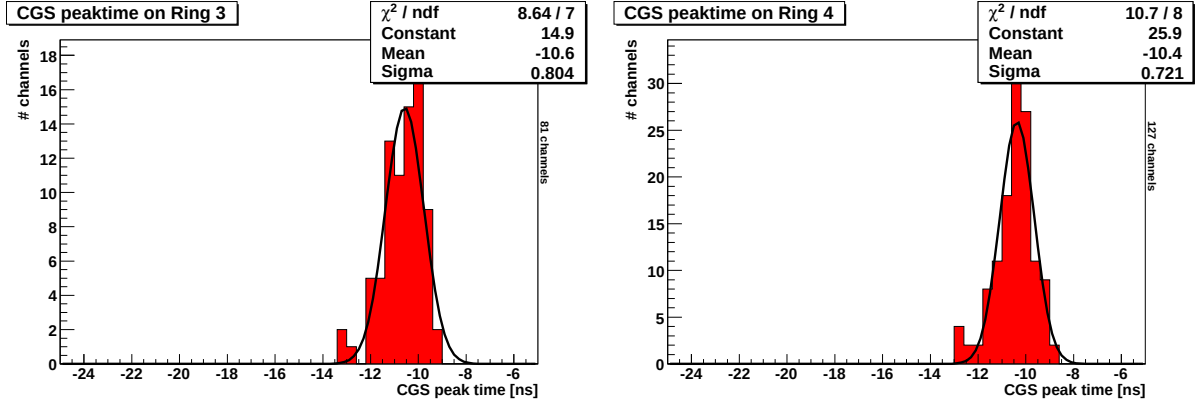


Figure F.2: Calibration group subtracted peaktime for 'PA-S opens' in ring 3 (left) and ring 4 (right).

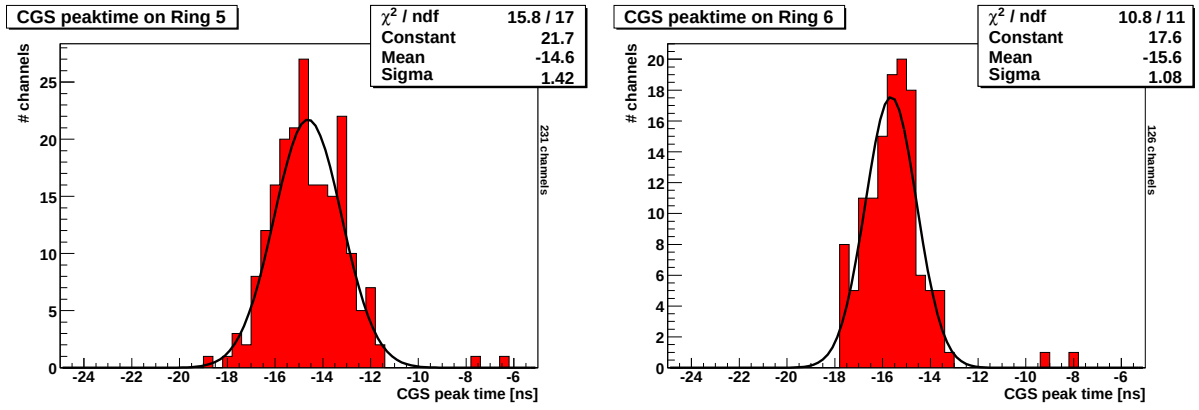


Figure F.3: Calibration group subtracted peaktime for 'PA-S opens' in ring 5 (left) and ring 6 (right).

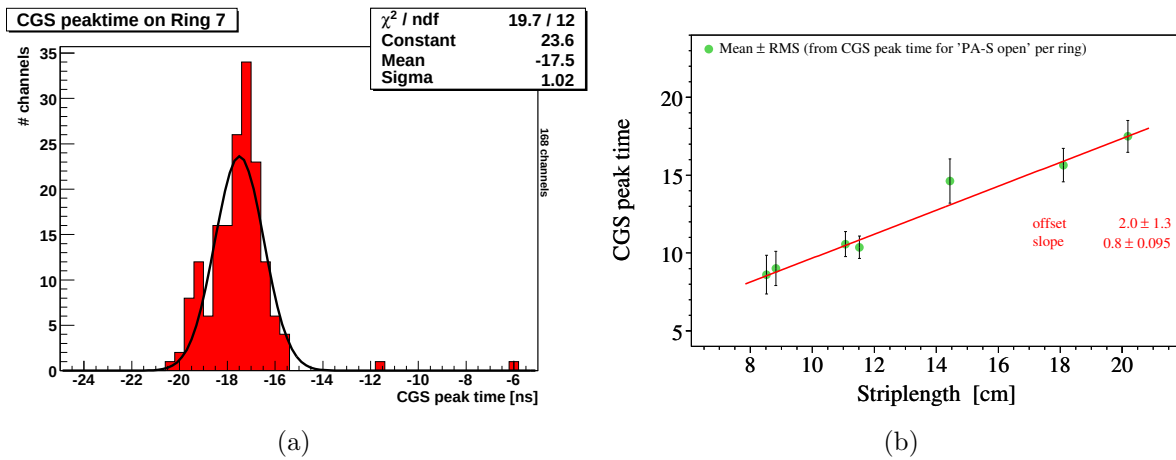


Figure F.4: (a) Calibration group subtracted peaktime for 'PA-S opens' in ring 7. (b) Linear fit through the calibration group subtracted peaktime per ring.

Glossary

SM Standard Model

LHC Large Hadron Collider

CERN Conseil Européen pour la Recherche Nucléaire

LEP Large Electron Positron collider

ALICE A Large Ion Collider Experiment

ATLAS A Toroidal LHC ApparatuS

CMS Compact Muon Solenoid

LHC-b Large Hadron Collider beauty Experiment

HCAL Hadron Calorimeter

ECAL Electromagnetic Calorimeter

TIB Tracker Inner Barrel

TID Tracker Inner Disc

TOB Tracker Outer Barrel

TEC Tracker End Cap

TPB Tracker Pixel Barrel

TPE Tracker Pixel End cap

TST Tracker Support Tube

CFC Carbon Fiber Composit

ICB Inter Connect Board

CCU Central Communication Unit

AOH Analog Opto Hybrid

APV Analogue Pipeline Voltage

ARC APV Readout Control

CalProf Calibration Profile

ADC Analoge Digital Converter

PA-S open Pitch Adapter-Sensor open

S-S open Sensor-Sensor open

PIC Petal Integration Center

LT Long Term

FEC Front End Controller

OFED Optical Front End Driver

OEC Optical Electrical Converter

K-MUX Karlsruhe Multiplexer

PLL Phase Lock Loop

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Persönliche Daten

Name: Dirk Heydhausen
Diplom-Physiker
Geburtsdatum/-ort: 20.03.1978 in Kempen
Familienstand: ledig
Staatsangehörigkeit: deutsch

Studium

seit 01/2005 Promotion am III. Physikalischen Institut B, RWTH Aachen
(„Analysis of Petal Longterm test data for the CMS-Experiment“)
10/2008 Abgabe der Doktorarbeit
11/2006 – 03/2007 Aufenthalt am CERN in Genf

1998-2004 Physikstudium (Diplom) an der RWTH Aachen
2003 – 2004 Diplomarbeit am II. Physikalischen Institut A, RWTH Aachen
2001 Vordiplom

Zivildienst

1997 – 1998 Haus Broich, Anrath

Schulische Ausbildung

1994 – 1997 LFS Mühlhausen (Abitur)
1988 – 1994 Joh. Kepler Realschule Süchteln
1984 – 1988 Katholische Grundschule Grefrath

Weitere Tätigkeiten während des Studiums

2001 – 2008	Anstellung als Übungsgruppenleiter für Mathematik I-IV und Physik I-III Betreuung von Versuchen im Fortgeschrittenenpraktikum Physik Vorbereitung von Versuchen für die Vorlesung Physik I
2006	Teilnahme an der „LHC School of Physics: theoretical tools and experimental challenges“ in Lecce, Italien
2005	Teilnahme an der „Joint Dutch Belgian German Graduate School“ in Texel, Niederlande
2002+2003	studentischer Vertreter in Berufungskommissionen
1999+2000	Leitung eines Tutoriums für Physik-Erstsemester

Außeruniversitäre Tätigkeiten und Hobbys

freiwilliger Helfer beim Weltjugendtag 2006, Organisation von Wallfahrten und Jugendfahrten, Betreuung von Messdienergruppen, Klettern, Wandern, Fussball, Musizieren

Computerkenntnisse

Linux, Windows (95, 98, 2000, NT, XP), DOS, Office (Excel, Word, Power Point), OpenOffice, TEX, Pascal, C/C++, Fortran, ROOT, MatLab, LabVIEW, Gimp, ...

Sprachkenntnisse

Englisch, Grundkenntnisse in Französisch und Hebräisch

Veröffentlichungen

Diplomarbeit: Untersuchung der Kopplung von phononischen und orbitalen Anregung mittels Raman-Streuung in $\text{La}_{1-x}\text{Sr}_{1+x}\text{MnO}_4$ (2004)
The CMS experiment at the CERN LHC, 2008 JINST 3S08004
Petal Integration for the CMS Tracker End Caps, CMS Note-2008/028
Integration of the End Cap TEC+ of the CMS Silicon Strip Tracker, CMS Note, to be published
Doktorarbeit: Analysis of Petal Longterm test data for the CMS-Experiment, to be published