A Diamond Pixel Detector for CMS Tracker Upgrade at Super-LHC

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Abstract

The proposed LHC luminosity upgrade, referred to as Super-LHC (sLHC), will push the luminosity up to $10^{35} \text{cm}^{-2}\text{s}^{-1}$ placing several challenges mainly for the expected high radiation levels. In this scenario, the CMS Silicon Pixel Detector close to the interaction region needs to withstand particle fluences of up to $\sim 10^{16} n_{eq}\text{cm}^{-2}$, and the low radiation tolerance of the present available Silicon sensor technology becomes an issue requiring to design and test new radiation-hard sensors. Among the proposed candidates, the 3D Silicon Sensors and the Diamond Sensors seem to be the more promising.

This thesis work is focused on the investigation of the performance of two detectors, a single-crystal and a polycrystal Diamond, tested this year on the proton beam of the Test Beam Facility (FTBF) of the Fermi National Accelerator Laboratory.

In the introductory chapters I will present a description of the CMS experiment at LHC, with a particular attention to the Pixel Detector and its related fundamental issues. Then, the beam-test setup is described in detail together with the alignment and track reconstruction procedure. At this point, I will give an overview of the dedicated software that I designed and implemented as general tool to efficiently analyze the beam-test data of any type of detector. Finally, in the last chapter, I will discuss the results of my analysis of the two Diamond beam-test data, highlighting their performance for a possible employ in the CMS Pixel Upgrade.
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Chapter 1

The CMS experiment at the Large Hadron Collider

1.1 The Large Hadron Collider

The Large Hadron Collider is a proton-proton and heavy ion collider located at CERN, in Geneva (Switzerland), in the already existing 27-km-long LEP collider tunnel. The machine is designed to produce head-on collisions of two proton (ion) beams each accelerated up to 7 $TeV$ with a design luminosity of $10^{34} cm^{-2}s^{-1}$. The two proton beams travel in opposite directions around the ring in two separate beam pipes, which intersect at four points where the highest luminosity is achieved.

The prime motivation of the LHC accelerator is the investigation of the electroweak symmetry breaking for which the Higgs mechanism is presumed to be responsible. Furthermore the experimental study of the Higgs mechanism can also shed light on the mathematical consistency of the Standard Model at energy scales above about 1 $TeV$. The LHC will also provide high-energy heavy-ion beams allowing us to further extend the study of QCD matter under extreme conditions of temperature and density. Finally there are high hopes for discoveries that might open a window onto physics beyond the Standard Model, and these discoveries could take the form of supersymmetry or extra dimensions [1].

The physics at the LHC is exploited by four main experiments which are located at the four intersection points where the two proton beams are brought into collision (see Fig. 1.1), whereby the particles are generated and detected.
1.1. The Large Hadron Collider

These main experiments are:

**CMS and ATLAS**: general purpose detectors whose main aims are the searches for the Higgs boson and for new physics beyond the Standard Model;

**ALICE**: exploiting lead ions collisions it investigates Quark-Gluon-Plasma, a state of matter wherein quark and gluons are deconfined;

**LHCb**: specialized b-physics experiment aimed at studying CP violation in the interactions of b-hadrons.

![The LHC scheme together with its injection chain and the locations of the four main experiments ATLAS, CMS, LHCb and ALICE.](image)

**Figure 1.1**: The LHC scheme together with its injection chain and the locations of the four main experiments ATLAS, CMS, LHCb and ALICE.
1.2 The CMS detector

The CMS experiment is a general-purpose high energy physics detector located at one of the four interaction points of the LHC near the village of Cessy in France [1, 2]. It has been designed to exploit the different properties of the wide range of particles and phenomena produced in high-energy collisions in the LHC.

Experimental challenge

The goal of the LHC physics programme of exploring new energy domain and searching for rare decay require high centre of mass energy and high luminosity, therefore a very careful design of the detectors and the necessity of developing tools able to reconstruct high-level physics objects and perform the physics analyses. The requirements put by these tasks represent an unprecedented challenge from the point of view of costs, technologies and human resources involved.

The total proton-proton cross-section at $\sqrt{s} = 14 \text{ TeV}$ is expected to be about 100 $mb$ which means that at design luminosity the detector will observe an event rate of about $10^9$ inelastic events/s. Furthermore the short time between bunch crossings, 25 ns, leads to a mean of about 20 inelastic collisions which will be superimposed on the event of interest so that the products of an interaction under study may be confused with those from other interactions in the same bunch crossing. In order to reduce this pile-up effect, fast time response and high-granularity detectors with good time resolution are required. Moreover, the large flux of particles coming from the interaction region leads to high radiation levels, requiring radiation-hard detectors and front-end electronics.

The requirements put by the new accelerator machine on the detectors can be summarised as follows:

- a high performance system to detect and measure muons over a wide range of momenta and angles and the ability to determine unambiguously the charge of muons;
- a high resolution method to detect and measure electrons and photons (an electromagnetic calorimeter);
- a high quality central tracking system to give accurate momentum measurements;
- good missing-transverse-energy resolution, requiring hadron calorimeters with a large hermetic geometric coverage to entirely surround the collision and prevent particles from escaping.

The design of CMS, detailed in next sections, meets these requirements.
1.2. The CMS detector

Coordinate system

The coordinate system adopted by CMS has the origin centered at the nominal collision point inside the experiment, the y-axis pointing vertically upward, the x-axis pointing radially inward toward the center of the LHC and the z-axis points along the beam direction. The azimuthal angle \( \phi \) is measured from the x-axis in the x-y plane. The polar angle \( \theta \) is measured from the z-axis. Pseudorapidity is defined as \( \eta = -\ln \tan \theta/2 \). Thus, the momentum and energy measured transverse to the beam direction, denoted by \( p_T \) and \( E_T \), respectively, are computed from the x and y components.

General concept

The overall layout of CMS is shown in Fig. 1.2. The detector is built in a cylindrical structure composed of a barrel in the center and endcaps at both sides. This structure is 21.6-m-long, 14.6-m in circumference and 12500-tons heavy.

![CMS detector layout in a tridimensional view. The various sub-detectors are shown.](image)

The detector design and layout was driven by the choice of the magnetic field configuration for the measurement of the momentum of muons. To fulfill the requirements of a momentum resolution less than 1% even for high \( p_T \) particles, a strong magnetic field is needed. Within the CMS detector this is achieved by a superconducting solenoid with a length of 12.9 m and an inner diameter of 5.9 m which generates a magnetic field of 4 Tesla. The bore of the magnet coil is large enough to accommodate in a cylindrical
1.2. The CMS detector

game around the beam line several sub-detectors. In fact, from inside out, CMS consists of:

- Silicon Tracker: to reconstruct the trajectories of all charged particles
- Electromagnetic Calorimeter (ECAL): to measure the energies of photons and electrons
- Hadron Calorimeter (HCAL): to measure the energies of hadrons
- Muon chambers: to measure the momenta of muons

The tracker and calorimeter detectors (ECAL and HCAL) fit inside the magnet coil while outside the magnet are the large muon detectors, which are inside the return yoke of the magnet.
The tracking volume is given by a cylinder of length 5.8 m and 2.6 m diameter. It consists of 10 layers of Silicon microstrip detectors and 3 layers of Silicon pixel detectors placed close to the interaction region to improve the measurement of the impact parameter of charged-particle tracks and the position of secondary vertices.
The Electromagnetic Calorimeter (ECAL) uses lead tungstate (PbWO$_4$) crystals with coverage in pseudorapidity up to $|\eta| < 3.0$. The scintillation light is detected by Silicon avalanche photodiodes (APDs) in the barrel region and vacuum phototriodes (VPTs) in the endcap region. A preshower system is installed in front of the endcap ECAL for $\pi^0$ rejection.
The ECAL is surrounded by the Hadron Calorimeter (HCAL), a brass/scintillator sampling calorimeter with coverage up to $|\eta| < 3.0$. The scintillation light is converted by wavelength-shifting (WLS) fibres embedded in the scintillator tiles and channeled to photodetectors via clear fibres. This light is detected by hybrid photodiodes (HPDs) that can provide gain and operate in high axial magnetic fields. Coverage up to a pseudorapidity of 5.0 is provided by an iron/quartz-fibre forward calorimeter. The Cherenkov light emitted in the quartz fibres is detected by photomultipliers. The forward calorimeter ensures full geometric coverage for the measurement of the transverse energy in the event.
The thickness of the detector in radiation lengths is greater than 25 $X_0$ for the ECAL, and the thickness in interaction lengths varies from 7-11$\lambda_f$ for the HCAL depending on $\eta$.

A more detailed description of all sub-detectors will be given in the following.
1.2.1 The Silicon Tracker

Immediately around the interaction point the tracker detector identify the tracks of individual particles and match them to the vertices from which they originated. The curvature of charged particle tracks in the magnetic field allows their charge and momentum to be measured. The high luminosity and the short time between bunch crossings requires a high granularity of the detector as well as a fast readout and radiation-hard sensors. This leads to a full Silicon detector design with decreasing granularity from inside out.

Considering the expected charged particle flux at various radii at high luminosity three regions can be delineated:

- Closest to the interaction vertex where the particle flux is the highest ($\approx 10^7/s$ at $r \approx 10\ cm$), pixel detectors are placed. The size of a pixel is $100 \times 150\ \mu m^2$, giving an occupancy of about $10^{-4}$ per pixel per LHC crossing.

- In the intermediate region ($20 < r < 55\ cm$), the particle flux is low enough to enable use of Silicon microstrip detectors with a minimum cell size of $10\ cm \times 80\ \mu m$, leading to an occupancy of $\approx 2-3\%$ per LHC crossing.

- In the outermost region ($r > 55\ cm$) of the inner tracker, the particle flux has dropped sufficiently to allow use of larger-pitch Silicon microstrips with a maximum cell size of $25\ cm \times 180\ \mu m$, whilst keeping the occupancy to $\approx 1\%$.

![Diagram of Silicon tracker layout in a tridimensional view.](image-url)

**Figure 1.3:** Silicon tracker layout in a tridimensional view. The various components are shown with different colours.
1.2. The CMS detector

The layout of the tracker detector is shown in Fig. 1.3 and 1.4. The outer radius extends to nearly 110 cm, and its total length is approximately 540 cm providing coverage up to $|\eta| < 2.5$. The properties of the various parts of the tracker are summarized in Table 1.1.

![Schematic cross section through the CMS tracker.](image)

**Figure 1.4:** Schematic cross section through the CMS tracker. Each line represents a detector module. Double lines indicate back-to-back modules which provide a measurement of the second coordinate.

At radii of 4.4, 7.3 and 10.2 cm, three cylindrical layers of hybrid pixel detector (Tracker Pixel Barrel) modules surround the interaction point. They are complemented by two disks of pixel modules (Tracker Pixel Endcaps) on each side placed at $\pm 34.5$ and $\pm 46.5$ cm from the interaction point, and covering the radial region between 6 and 15 cm. The size of the pixels is 100 $\mu$m $\times$ 150 $\mu$m $\times$ 300 $\mu$m. In total the pixel detector covers an area of about 1 m$^2$ and has 66 million pixels.

The radial region between 20 cm and 116 cm is occupied by the Silicon strip tracker which is composed of three different subsystems. The Tracker Inner Barrel and Disks (TIB/TID) extend in radius between 20 and 55 cm. The former is composed of 4 layers at radial distances of 25.5, 33.9, 41.9 and 49.8 cm covering the region $|z| < 65$ cm, whilst the latter is composed of 3 disks at each end covering the region $80 < |z| < 90$ cm. The Silicon micro-strips are 320-$\mu$m-thick, 20-cm-long and oriented parallel to the beam axis in the barrel and radial on the disks. The strip pitch is 81 $\mu$m on layers 1 and 2 and 118 $\mu$m on layers 3 and 4 in the TIB, leading to a single point resolution of 23 $\mu$m and 34 $\mu$m, respectively. In the TID the mean pitch varies between 97 $\mu$m and 143 $\mu$m.

The TIB/TID is surrounded by the Tracker Outer Barrel (TOB), which extends radially between 55 and 116 cm covering the region $|z| < 118$ cm. It
1.2. The CMS detector

consists of 6 layers at radial distances of 60.8, 69.2, 78, 86.8, 96 and 108 cm. The Silicon strips are 500-µm-thick, 25-cm-long and oriented parallel to the beam axis. The strip pitch is 183 µm on the first 4 layers and 122 µm on layers 5 and 6 leading to a single point resolution of 53 µm and 35 µm, respectively.

Finally the Tracker Endcaps (TEC) extends radially between 22.5 and 113.5 cm and covers the region 124 < |z| < 282 cm. Each TEC is composed of 9 disks, carrying up to 7 rings of Silicon micro-strip detectors (25-cm-long, 320-µm-thick on the inner 4 rings, 500-µm-thick on rings 5-7) with radial strips of 96 µm to 183 µm average pitch.

In addition, the modules in the first two rings and layers, respectively, of TIB, TID, and TOB as well as rings 1, 2, and 5 of the TEC carry a second micro-strip detector module which is mounted back-to-back with a stereo angle of 100 mrad in order to provide a measurement of the second coordinate (z in the barrel and r on the disks).

The CMS Silicon strip tracker has a total of 9.3 million strips and 198 m² of active Silicon area.

To avoid a too high leakage current, which is induced by bulk damage inside the sensor, the whole tracker is operated at a temperature of -10° C.

<table>
<thead>
<tr>
<th>tracker part</th>
<th>thickness (µm)</th>
<th>pitch (µm)</th>
<th>resolution (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>r-φ</td>
<td>z</td>
</tr>
<tr>
<td>TPB/TPE</td>
<td>300</td>
<td>100 × 150</td>
<td>10</td>
</tr>
<tr>
<td>TIB</td>
<td>320</td>
<td>81/118</td>
<td>23-34</td>
</tr>
<tr>
<td>TID</td>
<td>320</td>
<td>97/128/143</td>
<td>23-34</td>
</tr>
<tr>
<td>TOB</td>
<td>500</td>
<td>122/183</td>
<td>35-52</td>
</tr>
<tr>
<td>TEC(rings 1-4)</td>
<td>320</td>
<td>96/126/128/143</td>
<td>23-34</td>
</tr>
<tr>
<td>TEC(rings 5-7)</td>
<td>500</td>
<td>143/158/183</td>
<td>35-52</td>
</tr>
</tbody>
</table>

The main goals of the tracking system are a precise measurement of charged particle trajectories and reconstruction of secondary vertices, which requires a good position and momentum resolution, and a high reconstruction efficiency. For high momentum tracks (100 GeV) the efficiency for all transverse momenta of the muons is close to 100% over almost the full η-range whilst the resolution is around 1-2% up to |η| ≈ 1.6, beyond which it degrades.
1.2. The CMS detector

1.2.2 The Electromagnetic Calorimeter (ECAL)

The goal of the electromagnetic calorimeter is to measure precisely the energy of electrons and photons which generate electromagnetic showers inside it. ECAL is a hermetic, homogeneous calorimeter comprising 61200 lead tungstate (PbWO₄) crystals mounted in the central barrel part, closed by 7324 crystals in each of the 2 endcaps providing coverage up to $|\eta| < 3.0$. The high density (8.28 g/cm³), short radiation length (0.89 cm) and small Molière radius (2.2 cm) result in a high stopping power, fine granularity and so a compact calorimeter able to fit inside the solenoid. Furthermore, the radiation hardness and the fast light response (80% of the light is emitted within 25 ns) make them an appropriate choice for operation at LHC. However, the relatively low light yield (30 γ/MeV) requires use of photodetectors with intrinsic gain that can operate in a magnetic field. Silicon avalanche photodiodes (APDs) are used as photodetectors in the barrel and vacuum phototriodes (VPTs) in the endcaps. In addition, the sensitivity of both the crystals and the APD response to temperature changes requires a temperature stability.

![Figure 1.5: Schematic cross section of ECAL showing the locations of the barrel calorimeter (EB), endcap (EE) and preshower detector.](image)

A schematic cross section of ECAL is shown in Fig. 1.5.

The Barrel ECAL (EB) extends radially between 129 and 175 cm covering the region $|z| < 3.05 m$ and $0 < |\eta| < 1.479$. The crystals have a front face cross-section of $\approx 22 \times 22 \text{ mm}^2$ and a length of 230 mm (25.8 $X_0$). They are organised in 36 identical supermodules, 18 in each half barrel, each covering $20^\circ$ in $\phi$. The crystals are contained in a thin-walled glass-fibre alveola structures ("submodules") with $2(\phi) \times 5(\eta)$ crystals per each resulting in a granularity 360-fold in $\phi$ and (2×85)-fold in $\eta$.

The Endcaps ECAL (EE), at a distance of 314 cm from the vertex, extends radially between 3.16 and 17.11 cm covering the region $1.479 < |\eta| < 3.0$. They are each structured as 2 “Dees”, consisting of semi-circular alve-
1.2. The CMS detector

Minium plates from which are cantilevered structural units of 5×5 crystals, known as “supercrystals”. The crystals have a front face cross section of 28.6×28.6 mm² and a length of 220 mm (24.7 X₀).

The energy resolution of a calorimeter is often parametrised as:

\[ \left( \frac{\sigma}{E} \right)^2 = \left( \frac{S}{\sqrt{E}} \right)^2 + \left( \frac{N}{E} \right)^2 + C^2 \]  (1.1)

The first term, with coefficient S, is the stochastic term, arising from fluctuations in the number of signal generating processes (such as photo-electron statistics in a photodetector). The second term, with coefficient N, is the noise term and includes noise in the readout electronics and fluctuations in pile-up. The third term, with coefficient C, is the constant term and arises from imperfections in calorimeter construction, non-uniformities in signal collection, channel to channel inter-calibration errors, fluctuations in longitudinal energy containment and fluctuations in energy lost in dead material before or within the calorimeter. The goal of calorimeter design is to find, for a given application, the best compromise between the contributions from the three terms.

A best fit for ECAL of the energy resolution function in Equation 1.1, for incident electrons as measured in a beam test gives \( S = 2.8 \% \, (GeV^{1/2}) \), \( N = 0.12 \, GeV \) and \( C = 0.3\% \).

The Preshower Detector

One way the Higgs boson might decay is into high-energy photons and detecting them is one of the ECAL’s main tasks. However, neutral pions, also produced in collisions, can mimic high-energy photons when they decay into two closely-spaced lower energy photons. In the endcap regions, where the angle between the two emerging photons from the decay of a neutral pion is likely to be small enough to cause this problem, the Preshower detector is placed in front of the ECAL to prevent such false signals.

The Preshower is a sampling calorimeter which extends radially between 45.7 and 123 cm covering the region 298.5 < |z| < 316.5 cm and 1.653 < |\( \eta \) < 2.6.

It is composed of interlaced layers of two lead radiators plane (1.75 and 0.77 cm) which initiate electromagnetic showers from incoming photons/electrons and two plane of Silicon strip sensors placed after each radiator which measure the deposited energy and the transverse shower profiles. The orientation of the strips in the two planes is orthogonal. The total thickness of the Preshower is 20 cm.

1The energy is measured in a cluster of 3×3 crystals with an electron impacting the central crystal. Events are taken restricting the incident beam to a narrow (4×4 mm²) region.
1.2.3 The Hadron Calorimeter (HCAL)

The purpose of the Hadron Calorimeter (HCAL) is both to measure the energy of individual hadrons produced in each event, and to be as near to hermetic around the interaction region as possible to allow events with missing energy to be identified. It is a sampling calorimeter composed of layers of brass (30%Zn and 70% Cu) absorber interlaced with tiles of plastic scintillators as active material to detect the showers generated by the hadrons in the brass. The energy released in the scintillator tiles causes them to emit blue-violet light, a fraction of which is absorbed and re-emitted by embedded wavelength-shifting fibres (Ø= 0.94 mm) in the green region of the spectrum. The green light is then carried by special fibre-optic waveguides to the readout system. The photodetection readout is based on multi-channel hybrid photodiodes (HPDs), photodetectors configured especially for CMS that can provide gain and operate in a high magnetic field.

Figure 1.6: Schematic cross section of the HCAL detectors showing the locations of the hadron barrel (HB), endcap (HE), outer (HO) and forward (HF) calorimeters.

Figure 1.6 shows a schematic cross section of the HCAL detectors. The Hadron Barrel (HB) and Endcaps (HE) calorimeters sit behind the tracker and the electromagnetic calorimeter as seen from the interaction point. The HB is radially restricted between the outer extent of the electromagnetic calorimeter ($r = 1.77 \, m$) and the inner extent of the magnet coil ($r = 2.95 \, m$). This constrains the total amount of material which can be put in to absorb the hadronic shower. Therefore, an Outer Hadron (HO) calorimeter or tail catcher is placed outside the solenoid complementing the barrel.
1.2. The CMS detector

calorimeter. Beyond $|\eta| = 3$, the Hadron Forward (HF) calorimeter placed at
11.2 m from the interaction point extends the pseudorapidity coverage down
to $|\eta| = 5.2$.

The **Hadron Barrel** calorimeter is built in 2 half barrels covering the pseudorapidity region $|\eta| < 1.3$. Each half barrel is organized in 18 identical azimuthal wedges made of flat brass absorber plates aligned parallel to the beam axis. Each wedge is segmented into four azimuthal angle sectors while the plastic scintillator is divided into 16 $\eta$ towers, resulting in a segmentation $(\Delta \eta, \Delta \phi) = (0.087, 0.087)$. The wedges are bolted together in order to minimize the crack between the wedges to less than 2 mm. There are 14 brass plates, each with a thickness of about 5 cm, plus 2 external stainless steel plates for mechanical strength. Interlaced with them are 17 active plastic scintillator tiles with a thickness of 9 mm for layers 0 and 16 rather than 3.7 mm for the other ones. The total absorber thickness at 90° is 5.82 interaction lengths ($\lambda_I$). The HB effective thickness increases as $1/\sin \theta$, resulting in 10.6 $\lambda_I$ at $|\eta| = 1.3$.

Each **Hadron Endcap** consists of 13 $\eta$ towers covering the region $1.3 < |\eta| < 3.0$. For the 5 innermost towers (1.3 < $\eta$ < 1.74) the $\phi$ segmentation is $5^\circ$ and the $\eta$ segmentation is 0.087. For the 8 outermost towers (1.74 < $\eta$ < 3.0) the $\phi$ segmentation is $10^\circ$, whilst the $\eta$ segmentation varies from 0.09 to 0.35 at the highest $\eta$. The brass plates are 79-mm-thick interlaced with 9-mm-thick scintillator tiles for layer 0 and 3.7-mm-thick for layers 1-17. The outer layers are fixed to a 10-cm-thick stainless steel support plate.

In the central pseudorapidity region, the combined stopping power of EB plus HB does not provide sufficient containment for hadron showers. To ensure adequate sampling depth for $|\eta| < 1.3$, the hadron calorimeter is extended outside the solenoid with the **Outer Hadron** calorimeter. The HO uses the solenoid coil as an additional absorber to identify late starting showers and measure the the energy deposited after HB. The magnetic field is returned through an iron yoke organised in five rings ($\pm 2$, $\pm 1$ and 0) placed at distances of $\pm 5.342$, $\pm 2.686$ and 0 m from the interaction point. The HO represents the first sensitive layer in each of these five rings. Each ring covers 2.5 m in $z$ and has 12 identical azimuthal sectors separated by 75-mm-thick stainless steel plates. Each sector is divided in 6 azimuthal slices, while the $\eta$ sectors are 5, 6 and 8 for rings $\pm 2$, $\pm 1$ and 0, respectively, so following HB tower geometry with a segmentation $(\Delta \eta, \Delta \eta) = (0.087, 0.087)$. Since at $\eta = 0$, HB has the minimal absorber depth, the central ring (ring 0) has two 10-mm-thick layers of scintillators on either side of a 19.5-mm-thick piece of iron at radial distances of 3.850 m and 4.097 m. All other rings have a single scintillator layer at a radial distance of 4.097 m. The total depth of the calorimeter system is thus extended to a minimum of 11.8 $\lambda_I$.

Coverage in the region of $\eta$ between 3.0 and 5.0 is provided by the steel/quartz-fibre **Hadron Forward** (HF) sampling calorimeter. The signal is generated
when charged shower particles above the threshold generate Cherenkov light in the quartz fibres, thereby rendering the calorimeter mostly sensitive to the electromagnetic component of showers. The fibres measure $600 \pm 10 \ \mu m$ in diameter for the fused-silica core, $630^{+10}_{-10} \ \mu m$ with the polymer hard-cladding, and $800 \pm 30 \ \mu m$ with the protective acrylate buffer. Only light that hits the core-cladding interface at an angle larger than the critical angle ($71^\circ$) contributes to the calorimeter signal which is then channeled by the fibres to photomultipliers. The forward calorimeter is essentially a cylindrical steel structure with an inner radius of $12.5 \ cm$ and an outer radius of $130.0 \ cm$. The structure is $1.65 \ m$ deep and its front face is located at $11.2 \ m$ from the interaction point. The calorimeter consists of a steel absorber structure that is composed of $5-mm$-thick grooved plates. The quartz fibres, which run parallel to the beam line, have two different lengths (namely $1.43 \ m$ and $1.65 \ m$) and they are inserted into these grooves, creating 2 effective longitudinal samplings. There are 13 towers in $\eta$, all with a size given by $\Delta \eta \approx 0.175$, except for the lowest-$\eta$ tower with $\Delta \eta \approx 0.1$ and the highest-$\eta$ tower with $\Delta \eta \approx 0.3$. The $\phi$ segmentation of all towers is $10^\circ$, except for the highest-$\eta$ one which has $\Delta \phi = 20^\circ$.

1.2.4 The Muon System

As the name of the experiment suggests, the detection of muons plays an important role in CMS. Since many events of mainly interest have muons in their final state the CMS muon system has been designed to have the capability of reconstructing the momentum and charge of muons over the entire kinematic range of the LHC. CMS uses 3 types of gaseous particle detectors for muon identification: Drift Tubes (DTs), Resistive Plate Chambers (RPCs) and Cathode Strip Chambers (CSCs).

A schematic cross section of the CMS system of muon detectors is shown in Fig. 1.7. In the barrel region, where the neutron-induced background is small, the muon rate is low, and the 4-T magnetic field is uniform, Drift Chambers with standard rectangular drift cells are used covering the pseudorapidity region $|\eta| < 1.2$. The barrel drift tube chambers are organised in 5 wheels (YB±2,YB±1,YB0). Each wheel is divided into 12 sectors, each covering a $30^\circ$ azimuthal angle. In each of the 12 sectors there are 4 stations per wheel which are concentric around the beam line and separated by the iron return yoke. These stations are labeled MB1, MB2, MB3, and MB4 and are placed at radial distances of 4.0, 4.9, 5.9 and 7.0 $m$, respectively. The first 3 stations each contain 8 chambers, which measure the muon coordinate in the $r$-$\phi$ bending plane, and 4 chambers which provide a measurement in the $z$ direction, along the beam line. The fourth station does not contain the $z$-measuring planes.
1.2. The CMS detector

Figure 1.7: Schematic cross section of the CMS system of muon detectors showing the locations of Drift Tubes (DTs), Resistive Plate Chambers (RPCs) and Cathode Strip Chambers (CSCs).

In the two endcap regions of CMS, where the muon rates and background levels are high and the magnetic field is large and non-uniform, **Cathode Strip Chambers** are used with their fast response time, fine segmentation, and radiation resistance, covering the pseudorapidity region between 0.9 and 2.4. Each endcap consists of 4 stations of chambers, labeled ME1 to ME4 in order of increasing distance from the collision point, which are mounted on the disks enclosing the CMS magnet, perpendicular to the beam direction. In each disk the chambers are divided into 2 concentric rings around the beam axis (3 for ME1 station). Each CSC is trapezoidal in shape and consists of 6 gas gaps, each gap having a plane of radial cathode strips and a plane of anode wires running almost perpendicularly to the strips. All CSCs, except those in ME1/3, are overlapped in $\phi$ to avoid gaps in the muon acceptance. There are 36 chambers in each ring of a muon station, except for the innermost rings of ME2-ME4 which have 18 chambers. The gas ionization and subsequent electron avalanche caused by a charged particle traversing each plane of a chamber produces a charge on the anode wire and an image charge on a group of cathode strips. Thus, each CSC measures the space coordinates ($r$, $\phi$, $z$) in each of the 6 layers.

**Resistive Plate Chambers** has been added in both the barrel and endcap regions to provide a fast, independent, and highly-segmented trigger over a large portion of the rapidity range ($|\eta| < 1.6$) of the muon system. They
produce a fast response, with good time resolution (\(\sim 2\, \text{ns}\)) but coarser position resolution than the DTs or CSCs. The CMS RPC basic double-gap module consists of 2 gaps, hereafter referred as up and down gaps, operated in avalanche mode with common pick-up read-out strips in between. The total induced signal is the sum of the 2 single-gap signals. This allows the single-gaps to operate at lower gas gain (lower high voltage) with an effective detector efficiency higher than for a single-gap.

The muon system and the inner tracker provide independent muon momentum measurements. Due to multiple-scattering in the detector material before the first muon station, the best momentum resolution up to \(p_T\) values of \(\sim 200\, \text{GeV}/c\), is given by the resolution obtained in the Silicon tracker. The momentum measurement using only the muon system is essentially determined by the muon bending angle at the exit of the 4 T coil. For \(p_T\) values above 200 \(\text{GeV}/c\) the chamber spatial resolution dominates and can be improved when combining the inner tracker and muon detector measurements. The achievable resolutions using the tracking system only, the muon system only and the combination of both are shown in Fig. 1.8.

**Figure 1.8**: Muon momentum resolution in the central detector region \((0 < |\eta| < 0.2)\) as a function of the momentum using the tracking system only, the muon system only and the combination of both.
Chapter 2
Semiconductor Detectors

2.1 General properties

A semiconductor material is a crystalline material whose periodic lattice establishes allowed energy bands for electrons that exist within that solid. The lower band, called the *valence band*, corresponds to those electrons that are parts of the covalent bonding that constitute the interatomic forces within the crystal. The next higher-lying band is called the *conduction band* which contains electrons that are free to migrate through the crystal. Electrons in this band contribute to the electrical conductivity of the material. The two bands are separated by the *band gap*, the size of which determines whether the material is classified as a semiconductor or insulator. For insulator, the band gap is usually 5 eV or more, whereas for semiconductors, the band gap is considerably less. Among the class of semiconductors, Silicon has a band gap of 1.12 eV at 300 K.

At any nonzero temperature, some thermal energy is shared by the electrons in the crystal. It is possible for a valence electron to gain sufficient thermal energy to be elevated across the band gap into the conduction band. Physically, this process represents the excitation of an electron that is normally part of a covalent bond such that it can leave the specific bonding site and drift throughout the crystal. The excitation process not only creates an electron in the otherwise empty conduction band, but it also leaves a vacancy, called a *hole*, in the otherwise full valence band, representing a net positive charge. The combination of the two is called an *electron-hole pair* and is the fundamental information carrier of a solid state device.

After their formation, both electrons and holes take part in a random thermal motion that results in their diffusion away from their point of origin. This diffusion leads to a broadening distribution of charges as a function of time. A cross-section through this distribution can be approximated by a Gaussian function with standard deviation
2.1. General properties

\[ \sigma = \sqrt{2Dt} \quad (2.1) \]

where \( D \) is the diffusion coefficient and \( t \) the elapsed time. Values for \( D \) can be predicted from the Einstein relation

\[ \mu = \frac{e}{kT} D \quad (2.2) \]

where \( \mu \) is the mobility of the charge carriers, \( k \) the Boltzmann constant, and \( T \) the absolute temperature. If an electric field is applied, electrons and holes will tend to move in opposite directions. The motion will be a combination of a random thermal velocity and a net drift velocity parallel to direction of the applied field. At low to moderate values of electric field intensities, the drift velocity \( v_{e,h} \) for both electrons and holes, is proportional to the applied field according to

\[ v_{e,h} = \mu_{e,h} E \quad (2.3) \]

where \( E \) is the electric field intensity, \( \mu_e \) and \( \mu_h \) the mobilities of electrons and holes respectively.

At higher electric field intensities the charge carriers acquire a higher acceleration, but since the mean free path is not altered by the field, the number of random collision per unit time becomes higher. This counterbalances a further acceleration and finally leads to a saturation of the drift velocity at saturation values \( v_{s,e} \) and \( v_{s,h} \). This effect of velocity saturation is also referred to as “mobility degradation” and can be described by parametrizing the mobility as a function of the electric field as reported in [3]. The mobilities of electrons and holes according to this model are plotted in Fig. 2.1.

In addition to their drift, the charge carriers will also undergo the influence of diffusion mentioned before. Without diffusion, all charge carriers would travel to the collecting electrodes following exactly the electric field lines. The net effect is to introduce some spread in the arrival position with standard deviation

\[ \sigma = \sqrt{\frac{2kTx}{eE}} \quad (2.4) \]

where \( x \) represent the drift distance.

The motion of either electrons or holes constitutes a current that will persist until those carriers are collected at the electrodes placed at the boundaries of the active volume. Since both electrons and holes contribute to the conductivity (or the resistivity) of a semiconductor, the total measured current will be the sum of two separate contributions: the current \( I_h \) due to the flow of holes and that due to the flow of electrons, \( I_e \). Therefore, given a bulk of semiconductor with thickness \( t \), surface area \( A \) and carriers density \( n \), the current \( I \) that will flow when a voltage \( V \) is applied across the thickness is
2.1. General properties

Figure 2.1: Mobility as function of the electric field according to [3].

\[ I = I_e + I_h = Ane(v_e + v_h) = Ane \frac{V}{t}(\mu_e + \mu_h) \] (2.5)

Since electrons mobility in Silicon is much higher than for holes (\( \mu_e = 1350 \text{ cm}^2/(\text{Vs}) \) and \( \mu_h = 480 \text{ cm}^2/(\text{Vs}) \) at 300 K), the resulted drift velocity is much higher for electrons, so that the current is practically dominated by these carriers type contribution.

In a completely pure semiconductor, when the e-h pairs are caused by thermal excitation, each electron must leave a hole behind. Under these conditions the number of electrons in the conduction band must exactly equal the number of holes in the valence band:

\[ n_i = p_i. \] (2.6)

Such material is called an *intrinsic* semiconductor and the quantities \( n_i \) and \( p_i \) in Eq. 2.6 are known as the intrinsic carrier densities. In Silicon the intrinsic hole or electron densities at 300 K is \( 1.45 \times 10^{10} \text{cm}^{-3} \). Inserting this values in the following equation

\[ \rho = \frac{AV}{It} = \frac{1}{en_i(\mu_e + \mu_h)} \] (2.7)

we obtain that an intrinsic Silicon has a resistivity of 230,000 Ω · cm at room temperature.

The material used for semiconductor devices is in most cases not intrinsic but doped with a very small concentration of impurities to alter its conductivity. In this case the semiconductor is called *extrinsic*. During doping,
impurity atoms of a different element than the host atoms are introduced to an intrinsic semiconductor changing the electron and hole carrier concentrations at thermal equilibrium. Dominant carrier concentrations in an extrinsic semiconductor classify it as either an \textit{n}-type or \textit{p}-type semiconductor.

\textbf{\textit{n}-type semiconductors}

An \textit{n}-type semiconductor is a type of extrinsic semiconductor where the dopant atoms have one more valence electron than the host atoms. The most common example is atomic substitution in group IV solids (Silicon, Germanium) by group V elements (Phosphorus, Arsenic). The extra-electron left over after all covalent bonds have been formed, will have an energy near the top of the gap. The energy spacing between this energy level and the bottom of the conduction band is sufficiently small so that the probability of thermal excitation is high enough to ensure that a large fraction of the impurities are excited. Impurities of this type are referred to as \textit{donor} impurities because they are capable to provide extra conduction electrons. Practically, at room temperature all donor states are ionized and the concentration of electrons equals the concentration of donor atoms. The net effect of \textit{n}-doping is therefore to create a situation in which the number of conduction electrons is much greater and the number of holes much smaller than in the pure material. The electric conductivity is then determined almost exclusively by the flow of electrons, and holes play a very small role. In this case, the electrons are called the \textit{majority carriers} and the holes the \textit{minority carriers}.

\textbf{\textit{p}-type semiconductors}

In the \textit{p}-type semiconductors the dopant atoms have one less valence electron than the host atoms. An example of this type of doping is the addition of a trivalent impurity such as an element from group III (such as Boron) of the periodic table to a Silicon lattice. In this case one covalent bond of the impurity atom is left unsaturated and when an electron is captured to fill this vacancy, it will have an energy near the bottom of the gap. Since the energy difference between this energy level and the top of the valence band is small, a large fraction of electrons in the valence band will be excited to this level leaving a large number of holes in it. Impurities of this type are referred to as \textit{acceptor} impurities, because they create electron sites within the normally forbidden energy gap. At room temperature practically all acceptor atoms are ionized and the acceptor and hole concentrations are almost equal. In \textit{p}-type material, holes are the majority carriers and dominate the electrical conductivity.
2.2 The ionizing radiation

When a charge particle passes through a semiconductor the overall significant effect is the production of many electron-hole pairs along its track. When radiation interacts in a semiconductor, the energy deposition always leads to the creation of equal numbers of holes and electrons, whether the semiconductor is intrinsic or doped. The number of pairs $n$ depends on the total energy loss $E_{\text{loss}}$ and the ionization energy $\varepsilon$, which is the average energy expended by the charged particle to produce one pair, so that

$$n = \frac{E_{\text{loss}}}{\varepsilon}.$$  (2.8)

For Silicon, the average energy used for the creation of one e-h pair is $3.6 \; eV$ (at $300 \; K$), about three times larger than the band gap of $1.12 \; eV$, since part of the deposited energy is used to generate phonons, which will dissipate as thermal energy.

The average energy loss $dE$ of a charged particle traversing a length $dx$ in a medium (usually called the stopping power of the material) is described by the Bethe-Bloch formula:

$$-\langle \frac{dE}{dx} \rangle = 4\pi N_A r_e^2 m_e c^2 z^2 \frac{Z}{A} \beta^2 \left[ \frac{1}{2} \ln \left( \frac{2m_e c^2 \beta^2 \gamma^2 T_{\text{max}}}{I^2} \right) - \beta^2 - \delta(\gamma) \right] \quad (2.9)$$

In this formula $z$ is the charge of the incident particle, $T_{\text{max}}$ the maximum kinetic energy which can be imparted to a free electron in a single collision, $I$ the mean excitation energy, $Z$ the atomic number, $A$ the atomic mass, $N_A$ the Avogadro’s number, $m_e$ the electron mass, $c$ speed of light, $r_e$ classical electron radius, $\beta = v/c$, $\gamma = 1/(1 - \beta^2)^{1/2}$ and $\delta$ density effect correction.

For low energy the $1/\beta^2$ term in Eq. 2.9 is dominant and the stopping power decreases with increasing energy. At a particle velocity $\beta$ of about 0.96 ($\beta \approx 3$) a broad minimum is reached. At higher energies the logarithmic term leads to a slow rise again, which is eventually canceled by the density correction. A particle with an energy loss in the minimum of Eq. 2.9 is called a minimum ionizing particle (MIP).

It is important to mention that the energy loss in a finite medium is subject to statistical fluctuations well described by a Landau distribution. Therefore, if a particle is not stopped in the medium, the energy loss (and the number of charge carriers as a consequence) varies around the peak of the distribution. In rare but measurable cases, called $\delta$-rays or $\delta$-electrons, the transferred energy is large, so that these cases are responsible for the asymmetric long tail towards high charge deposits. Due to this tail the most probable value of energy transfer is about 30% lower than the average value. For a MIP the most probable number of electron-hole pairs generated in $1 \; \mu m$ of Silicon is
2.2. The ionizing radiation

76, while the average is 108. This means that a MIP generates a signal of about 22,500 electron-hole pairs = 0.7×108×300 (most probable value). A resulting Landau distribution is shown in Fig. 2.2.

![Signal distribution in 300µm silicon](image)

Figure 2.2: Measured MIP signal distribution in a Silicon detector of 300 µm thickness

In an intrinsic Silicon substrate there are \( \sim 10^9 \) thermally generated free charge carriers (leakage current) but only \( \sim 2 \times 10^4 \) electrons generated by an ionizing particle. The resulting charge signal would be negligible, so that the free charge carriers must be reduced by several orders of magnitude in order to detect the transit of the particle. This could be achieved by cooling to very low temperatures or by depleting the Silicon volume of free charge carriers using \( p \)- and \( n \)-type Silicon in a reverse-biased \( p-n \) junction configuration which is described in the next section.
2.3. The $p$-$n$ junction

![Diagram of a $p$-$n$ junction with plots for charge density, electric field, and voltage.]

Figure 2.3: Schematic representation of a $p$-$n$ junction together with plots for the charge density, the electric field, and the voltage.

A $p$-$n$ junction is formed when an $n$-type region in a Silicon crystal is put adjacent to a $p$-type region in the same crystal. In practice, such a junction is built by diffusing acceptor or donor impurities into an $n$-type or a $p$-type Silicon crystal, respectively. In this case, diffusion of electrons from $n$-type material into $p$-type material and diffusion of holes from $p$-type to $n$-type material, occur as a consequence of the motion of carriers from regions of high concentration to regions of low concentration. The result is the existence of a space charge region with two zones of non-zero electric charge, one of which is made of filled electron acceptor sites not compensated by holes and the other one, made of positively charged empty donor sites not compensated by electrons. The accumulated space charge creates an electric field (described by the built-in voltage) that, at equilibrium, prevent further diffusion across the junction, and a steady-state charge distribution is established. The region
over which the charge imbalance exists is called the *depletion region* because it is depleted from free charge carriers. If the concentrations of donors on the \( n \) side and acceptors on the \( p \) side are equal, the depletion region extends at equal distances into both sides. If the donor concentration in the \( n \)-type material is much higher than that of acceptor atoms in the \( p \)-type \((p-n^+)\) junction, the electron diffusing across the junction will tend to travel a greater distance into the \( p \)-type material before recombination with holes, so that the depletion region would extend farther into the \( p \) side. In the opposite case \((p^+-n)\) junction, the depleted region would extend farther into the \( n \) side.

A schematic representation of a \( p-n \) junction is shown in Fig. 2.3 together with plots for the charge density, the electric field, and the voltage.

**Reverse Bias**

The depletion region is a suitable medium for the detection of radiation. Free charges can be generated in excess of the equilibrium in the depletion region by ionizing particles traversing the junction. The charges produced by ionization in the depletion zone are separated and induce an electron and a hole signal. The interest of the junction structure for particle detection is the possibility to polarize it by applying a bias voltage.

The \( p-n \) junction are such that it will readily conduct current when voltage is applied in the “forward” direction, but it will conduct very little current when biased in the “reverse” direction. A schematic representation of a biased junction is shown in Fig. 2.4.

![Schematic representation of a biased p-n junction.](image)

**Figure 2.4:** Schematic representation of a biased \( p-n \) junction.

Applying a positive voltage to the \( p \) side with respect to the \( n \) side, the natural potential difference across the junction is reduced by an amount equal to the bias voltage. This is the direction of *forward biasing*. In this case the potential will tend to attract conduction electrons from the \( n \) side as well as
holes from the \( p \) side across the junction. Being these the majority carriers of both sides, conductivity is greatly enhanced.

If the situation is reversed, and the \( p \) side is made negative with respect to the \( n \) side, the junction is reverse biased. In this case, the natural potential difference across the junction is enhanced and the minority carriers (holes on the \( n \) side and electrons on the \( p \) side) are attracted across the junction. Since their concentration is relatively low, the reverse current across the junction is quite small.

The width of the depletion zone, the electric field, and the potential \( \phi \) as function of the applied voltage can be calculated by solving the one-dimensional Poisson’s equation

\[
\frac{d^2 \phi}{dx^2} = -\frac{\rho(x)}{\varepsilon}
\]  

where \( \varepsilon \) is the dielectric constant of the material, and \( \rho \) the charge density. For an abrupt \( p-n \) junction with constant doping concentrations on both sides, the total width \( d \) of the depletion region is

\[
d = x_n + x_p = \sqrt{\frac{2\varepsilon}{e} \left( \frac{1}{N_A} + \frac{1}{N_D} \right) (V + V_{bi})} \quad (2.11)
\]

where \( x_n \) and \( x_p \) are the parts of \( d \) on the \( n \) and \( p \) side with concentrations \( N_D \) and \( N_A \) respectively, \( V \) the externally applied voltage, and \( V_{bi} \) the built-in voltage.

For a \( p^+-n \) junction (\( N_A > 10^{18} \text{ cm}^{-3}, N_D \approx 10^{12} \text{ cm}^{-3} \)), the term \( 1/N_A \) in Eq. 2.11 can be neglected, meaning that the space charge region is extending much deeper into the lower doped side of the junction. Furthermore, the built-in voltage is small compared to typical operation voltages and can therefore be neglected. With these assumptions

\[
d \approx x_n \approx \sqrt{\frac{2\varepsilon}{eN_D} V} \quad (2.12)
\]

Many semiconductor detectors are operated with sufficient reverse bias voltage so that the depletion region extends through the full wafer thickness, creating a fully depleted detector. The full depletion voltage \( V_{dep} \) is obtained replacing \( x_n \) in Eq. 2.12 with the detector thickness \( t \)

\[
V_{dep} = \frac{eN}{2\varepsilon} t^2 \quad (2.13)
\]

where \( N \) is the dopant concentration on the side of the junction that has lower dopant level. The full depletion voltage is an important parameter of the sensor since it defines the minimum operating voltage. If the applied bias exceeds the full depletion voltage, the device is said to be overdepleted.
2.4 Pixel detectors

To obtain unambiguous two-dimensional information a charge-sensistive detector must provide fine segmentation in both dimensions. The detector electrodes can be segmented to form strips or pixels. In a strip detector only one spatial coordinate per layer is measured, therefore to obtain both coordinates from the same detector, both sides have to be segmented. Pixel detectors in contrast measure both spatial coordinates on the same side of the sensor, so that segmentation is necessary only on one side of the sensor.

In segmented planar detector the highly doped electrodes are introduced by implantation or diffusion through a mask to form the strip or pixel electrodes each of them forming a \( p-n \) junction.

The most common choices in segmented detector fabrication are \( n^+ \) or \( p^+ \) doped collection electrodes on \( n \)-type substrate material. Fabrication of semiconductor devices is a complex technology that uses many different techniques. Some key steps of semiconductor processing are schematically represented in Fig. 2.5.

![Figure 2.5: Main steps in the fabrication of a \( p^+\text{-in-}n \) planar pixel detectors.](image)

The starting point is a high-purity Silicon wafer that is mildly \( n \)-type, due to residual donors. After the wafer has been polished and cleaned, the surface is passified through the creation of a thin oxide layer. Usually Silicon Dioxide (\( \text{SiO}_2 \)) is used, which is very stable and chemically inert. It is a near-perfect dielectric and one of the best insulators, with an extremely high breakdown field strength. For tracking sensors it serves mainly as coupling capacitor oxide as well as protective layer and as a mask for implantation. Oxides can be thermally grown or deposited by a process called chemical vapor deposition and in both instances the wafers are exposed to gaseous ambients in high temperature furnaces.
After passivation, the technique of photolithography is used to remove selected areas of the oxide layer and pattern it to open windows to the Silicon substrate for subsequent doping. A photo-sensitive material (“photoresist”) is applied and distributed across the wafer surface by spinning. The photoresist is illuminated with a short wavelength in the UV range through a mask that is transparent in the areas that are to be removed. The illumination changes the structure of the photoresist, so that when immersed in a developer solution the exposed areas dissolve. The unmasked areas of the oxide layer are therefore removed by etching, leaving entrance windows for the introduction of dopants into the bulk. Dopants can be introduced either by diffusion or ion implantation. In doping by diffusion the wafer is exposed to a gaseous ambient of the desired dopant at temperatures of 800-1000°. The technique of ion implantation is today the most commonly used, as it allows more precise control of doping levels and depth. Accelerators are used to bombard the wafers with the desired dopant ions at energies ranging from keV to MeV. This technique may damage the crystal, therefore it is usually followed by annealing at elevated temperature. With the same technique the rear surface of the wafer is converted into $n^+$ material in order to create a blocking contact, used to suppress the leakage current due to minority carrier motion across the junction. Finally, ohmic electrical contacts at the front and rear surfaces are created through metallization. Aluminum is commonly used in Silicon detectors that is applied either by thermal evaporation or through sputtering, where atoms are ejected from a cathode through bombardment by inert energetic ions (typically Argon).

### 2.5 Induced charge (Ramo’s theorem)

The electrical signal used for the particle detection is generated on the collecting electrodes by the drift of the signal charge in the electric field. Hence a signal is already detectable when the charge starts to move and not only when it arrives at the collecting electrode. The general method to calculate induced charge on electrodes makes use of Ramo’s theorem [4]. The theorem (see Appendix A for demonstration) states that the instantaneous current induced on an electrode by the motion of a charge $q$ with drift velocity $\vec{v}$ is given by

$$i = - q \vec{v} \cdot \vec{E}_w$$

(2.14)

where $\vec{E}_w$ is called the weighting field. To calculate the charge $Q$ induced on the electrode by the charge $q$ drifting in the time interval $[t_1, t_2]$ from position $\vec{x}_1$ to $\vec{x}_2$, one has to integrate Eq. 2.14 over the time of charge collection:
2.5. Induced charge (Ramo’s theorem)

\[ Q = \int_{t_1}^{t_2} i(t)dt = q[\phi_w(x_1) - \phi_w(x_2)] = q\Delta \phi_w \]  \hspace{1cm} (2.15)

where \( \phi_w \) is the weighting potential.

The weighting potential as a function of position is obtained by solving the Laplace equation

\[ \nabla^2 \phi_w = 0 \]  \hspace{1cm} (2.16)

with some artificial boundary conditions:

- the voltage on the electrode for which the induced charge is to be calculated is set equal to unity
- the voltages on all other electrodes is set to zero

The weighting potential is not the actual electric potential in the detector but instead is an artifice that allows simple determination of the induced charge on the electrode of interest by taking differences in the weighting potential at the start and at the end of the carrier motion. The path of the carrier must still be determined from the actual electric field lines.

\[ \text{Figure 2.6: A planar detector configuration with a continuous electrode on the bottom surface and a pixelated surface on the top.} \]

The Ramo’s theorem can be easily applied to the case of a pixelated detector as the one sketched in Fig. 2.6, where the size of the collecting electrode is smaller than the wafer thickness. For simplicity, it can be assumed that the dimensions of the detector are large compared to the detector thickness, so that edge effects can be neglected. Furthermore, if a common voltage is applied on all the pixel electrodes, then the effects of the small gap between them are negligible. In this case we can assume that the electric field is uniform across the detector thickness and that the potential changes linearly. In order to predict the induced charge on the pixel of interest, the Laplace equation must be solved with boundary conditions that set the potential of
that pixel to unity, and the potential of all other pixels and the electrode on the opposite surface to zero. The results are plotted in three dimensions in Fig. 2.7, while Fig. 2.8 shows cuts through the weighting potential along the center of the signal pixel and the neighbor pixel.

Figure 2.7: Weighting potential($\times 10^3$) for a 250 $\mu$m thick pixel detector. The weighting potential of the pixel of interest only is plotted and set equal to unity at the center of the pixel [5].

The shape of the weighting potential shows a gradient that becomes steeper at distances that are closer to the pixel electrode. Since the induced charge is proportional to the difference in weighting potential between the point of origin and collection, two consequences can be delineated:

- most of the signal is induced in the last part of the charge drift path close to the pixel electrode

- charge carriers drifting toward the backplane do not contribute significantly to the signal for events over most the detector volume

These consequences are often called small pixel effect and become more pronounced as the pixel dimensions decreased compared with the detector thickness.

In detector with segmented electrodes such as the configuration of Fig. 2.6, a signal is induced by a moving charge on the measurement electrode even if the charge is collected by an adjacent pixel. This is illustrated in Fig. 2.9. The weighting potential for the measurement electrode starts from zero at the beginning of the charge path, then rises and passes through a maximum before dropping to zero at the pixel surface. Therefore a transient signal is induced on that pixel electrode even though the charge never reach its...
2.5. Induced charge (Ramo’s theorem)

Figure 2.8: Cuts of the weighting field through the center of a pixel electrode and through the neighboring electrode.

surface. The induced current in this case will have a bipolar shape which integrates to zero giving a net zero induced charge. Practical semiconductor crystals suffer from imperfections introduced during crystal growth, during device fabrication, or by radiation damage. Defects in the crystal such as impurity atoms, vacancies, and structural irregularities introduce states into the crystal that can trap charge (see Section 2.6.1). In this case, charge is trapped before inducing a significant fraction of its signal on the collecting electrode and a different from zero induced signal on the adjacent pixels.

Figure 2.9: The weighting field in a pixel detector. The induced current is shown for a charge terminating on the measurement electrode (right) and the neighbor electrode (left).
2.6 Radiation damage

Particle irradiation affects Silicon sensors response in various ways. It is common practice to divide radiation-induced effects damage into surface and bulk damages.

2.6.1 Bulk Damage

![Diagram of some radiation-induced defects.](image)

The most fundamental type of bulk radiation damage is the Frenkel defect, produced by the displacement of an atom of the semiconductor material from its normal lattice site. The vacancy left behind, together with the original atom now at an interstitial position, constitutes a trapping site for normal charge carriers. These are sometimes called point defects to distinguish them from more complex “cluster” of crystalline damage (di-vacancies, triple-vacancies, or even di-interstitials) that are formed along the track of a primary “knock-on” atom if sufficient energy is transferred. A diagram of some bulk damage defects is shown in Fig. 2.10.

The primary defects caused by irradiation, silicon vacancies, and interstitials are not stable but able to move through the crystal. As result of this diffusion process, there is the possibility of

- Frenkel pair recombination
- vacancy and interstitial combination
- combination of more complex defects
2.6. Radiation damage

where the former types are short-range and very mobile processes and therefore occur with a shorter time constant, while the latter occurs with a longer time constant. The whole process is called annealing with a beneficial part reducing the damage and a reverse one degrading macroscopic sensor properties. In fact, the diffusion processes are naturally temperature dependent and some effects, can even be frozen out at temperatures below 0°C. The formation of complex defects produces new energy states in the band gap, some of which can be electrically charged, changing the electric properties of the material. There are mainly three macroscopic manifestations of the defects in reverse biased Silicon detectors:

- increase of the leakage current
- changes in doping concentration
- charge trapping

**Leakage current**

The formation of mid-gap states facilitates the transition of electrons from the valence to the conduction band leading to an increase of the leakage current in the depletion region. As shown in Fig. 2.11, the current variation $\Delta I$ normalized to the sensitive volume $V$ is strictly proportional to the irradiation fluence $\Phi$ according to

$$\frac{\Delta I}{V} = \alpha \Phi$$ (2.17)

where $\alpha$ is the current-related damage rate, which is independent on material type and resistivity.

As the leakage current is strongly temperature dependent according to

$$I \propto T^2 \exp \left( -\frac{E_g}{2kT} \right)$$ (2.18)

where $E_g$ is the band gap and $k$ the Boltzmann constant, irradiated sensors have to be cooled during operation.

After irradiation damage, the increased current also changes with time: during beneficial annealing, with a time constant of a few days at room temperature, the leakage current decreases, while later it rises due to reverse annealing process until it finally saturates at a value which is significantly above the initial level. At -10°C however, both effects are virtually frozen, so the detector current remains constant. Thus, irradiated detectors in general should be operated and stored at low temperature, while it is favorable to shortly expose them to room temperature to take advantage of the beneficial annealing.
2.6. Radiation damage

Doping concentration

With irradiation, both donors are removed and acceptor-like defects with a negative space charge are generated throughout the bulk leading to variations in the effective doping concentration

\[ N_{\text{eff}} = |N_D - N_A|. \] (2.19)

The fluence dependence of \(N_{\text{eff}}\) and of the full depletion voltage are plotted in Fig. 2.12(a). Starting with an \(n\)-doped material the effective doping concentration decreases up to a fluence \(\phi \sim (2-5) \times 10^{12} \text{cm}^{-2}\) at which equal number of donors and acceptors are reached and a type-inversion occurs. At the inversion point the effective doping concentration is zero and the Silicon behaves as if it were intrinsic. With further irradiation, the acceptors begin to dominate, and the bulk material is now effectively of \(p\)-type. As a consequence of this space charge sign inversion, the \(p-n\) junction moves from the \(p^+\) side of the sensor to the \(n^+\) side and the depletion zone grows from there. As the depletion voltage scales with the bulk doping concentration (Eq. 2.13), the bias voltage has to be adjusted during the irradiation process to ensure full depletion. Initially, the depletion voltage decreases to theoretically zero at the inversion point, and then rises with the effective bulk doping concentration.

The fluence needed for inversion depends on the initial doping concentration. High-resistivity sensors have a low initial donor density and reach the inversion point with less fluence than those of low resistivity. Fig. 2.13(a) shows the fluence dependence of the depletion voltage and effective doping concentration for Silicon detectors of various initial resistivities and manufacturers.
The effective doping concentration displays a complex annealing behavior shown in Fig. 2.12(b), commonly described by the Hamburg model [6]. After irradiation the effective doping concentration decreases to a minimum reached after about one week at room temperature (beneficial annealing) and slowly increases afterwards (reverse annealing). In order to slow down this increase, irradiated detectors have to be kept cool also outside running periods.

Extensive work has been done to evaluate whether the post-irradiation properties can be affected by specific impurities other than Boron, Phosphor or Arsenic. It was found that an enrichment of the Silicon substrate with Oxygen, which is believed to capture vacancies in stable and electrically neutral point defects, leads to a superior post-irradiation performance for samples irradiated with charged hadrons. The increase of the full depletion voltage after irradiation induced space charge sign inversion is reduced by about a factor of 4 compared to non-oxygenated float zone material. Furthermore reverse annealing is slowed down by a factor of two and its amplitude is reduced.

As the main fluence in the innermost part of the experiments at hadron colliders, where pixel detectors are commonly located, is due to charged pions, the use of oxygenated material is recommended there. The comparison of the doping concentration development between standard Silicon and oxygen enriched material is shown in Fig. 2.13(b).
2.6. Radiation damage

Figure 2.13: Left: variation of the inversion point with initial Silicon bulk resistivity. Right: fluence dependence of the the depletion voltage and \(N_{\text{eff}}\) for standard and oxygen enriched Silicon [8].

Charge trapping

The energy levels associated with the crystal defects are not only filled by charge carriers from the generation-recombination current (leakage current) but also by carriers produced by traversing particles. If these carriers are trapped for a time longer than the signal collection time they do not contribute to particle detection and are de facto lost leading to a reduction in the charge collection efficiency (CCE). After the generation of a free electron-hole pair, the electron moves to the positive electrode while the hole moves to the negative. If no charges are trapped, the sum of the distance they travel equals the detector thickness. After heavy irradiation however the mean travel distance shrinks and the actual distance \(d_C\) traveled by the charges, usually called charge collection distance (CCD), is given by

\[
d_C = \mu \tau E
\]

where \(E\) is the electric field intensity, \(\mu\) is the sum of electron and hole mobilities

\[
\mu = \mu_e + \mu_h
\]

and \(\tau\) is given by

\[
\frac{1}{\tau} = \frac{1}{\tau_e} + \frac{1}{\tau_h}
\]

with \(\tau_e\) and \(\tau_h\) the trapping lifetimes of electrons and holes respectively. The charge \(Q_{\text{coll}}\) collected at the electrodes is given by

\[
Q_{\text{coll}} = Q_0 \frac{d_C}{t}
\]
2.6. Radiation damage

where $t$ is the detector thickness and $Q_0$ represents the total charge produced by the radiation. The ratio $Q_0/t$ represents the generated charge per unit length ($q_p$), so that the above equation can be written as

$$Q_{coll} = q_p d_C , \quad (2.24)$$

and therefore the CCD is given by

$$d_C = \frac{Q_{coll}}{q_p} . \quad (2.25)$$

As already mentioned in Sec. 2.2, the charge produced by ionizing radiation is subject to statistical fluctuations, therefore $Q_{coll}$ has to be replaced by the mean value $\langle Q \rangle$ of the Landau distribution. Since the charge collection efficiency of a detector is defined as the ratio of the total charge observed to the actual deposited charge, using the above equation the CCE can be written as

$$\eta = \frac{Q_{ind}}{Q_0} = \frac{d_D}{t} . \quad (2.26)$$

Trapping can be reduced by collecting electrons instead of holes, because they have a higher mobility and are less prone to trapping. In addition, the charge collection efficiency can be partially restored by applying a higher bias voltage, which results in longer collection distances. While the efficiency curve of non irradiated detectors reaches its plateau at the full depletion voltage, irradiated sensors need considerable “overbiasing” beyond this voltage. In practice, the efficiency in that case never fully saturates, since the operational voltage is limited by high voltage breakthrough.

2.6.2 Surface Damage

In Silicon the surface region is also sensitive to radiation. The term surface damage summarizes all defects in the covering dielectrics as the Silicon Dioxide and the interface between the Silicon and the dielectric. As the crystal structure of SiO$_2$ is highly irregular, displacement of single atoms due to irradiation does not lead to macroscopic changes. Ionization in the oxide however is not fully reversible and may cause steady changes of the interface properties. One consequence of ionization in the oxide is the build up of a positive fixed oxide charge that saturates after some kGy at a value of about $3\times10^{12} \text{ e/cm}^{-2}$. This oxide charge changes the electric field in the Silicon bulk close to the surface and may lead to electric breakdown. A further effect of radiation is the generation of interface states leading to a surface generated current when the space charge region reaches the surface. This contribution to the dark current is proportional to the area not covered by the pixel implants.
Chapter 3

The CMS Pixel Detector

The extremely high particle fluxes at small distances from the interaction point requires the innermost tracking layers to be composed of pixel devices able to deliver high resolution track hits information in three dimensions. Over the full acceptance of the CMS detector the pixel system (see Fig. 3.1) allow precise measurement of the tracks close to the interaction region, which is essential for the identification of secondary vertices and for tagging long-lived objects, like $b$ or $c$ quarks and $\tau$-leptons in order to distinguish them against a large background of light quark and gluon jets. For detecting Higgs or SUSY particles $b$-tagging in particular will play an important role.

Figure 3.1: Layout of the CMS pixel detector with three barrel layers (green) and four forward disks (red).
3.1. Pixel sensors

With increasing luminosities the pixels will help greatly in pattern recognition of the many tracks present in one bunch crossing. The pixel detectors will confirm or reject track segments proposed by the outer tracker layers. Once a track has been successfully followed to the pixel layers, the two pixel hits will be crucial to extrapolate this track to the vertex with high precision. Reducing the size of the sensor elements also mitigates the problems of radiation damage of the sensors. Smaller detector capacitance permits high signal-to-noise ratios even when charge collection degrades. Extremely short strips or pixels are therefore an inevitable choice for a vertex detector at the LHC.

In the previous chapter some basic features of semiconductor detectors were summarized (more about this argument can be found for instance in [9, 10]). In this chapter the properties and design of the CMS pixel sensors are described in detail together with a discussion around the radiation damage of the sensors.

3.1 Pixel sensors

3.1.1 General properties

The sensors for the CMS pixel detector are planar Silicon detectors built with the n⁺-in-n technique [11, 12]: pixels consist of high dose n-implants introduced into a highly resistive n-substrate (see Sect. 2.4). The backside of the substrate is p⁺-doped, therefore the junction is placed on this side of the sensor (see Fig. 3.3(d)). A schematic layout of the sensors is shown in Fig. 3.2.

![Schematic layout of the n⁺-in-n technology for construction of CMS pixel sensors. Inter pixel isolation techniques is also represented.](image)

**Figure 3.2:** Schematic layout of the n⁺-in-n technology for construction of CMS pixel sensors. Inter pixel isolation techniques is also represented.
The requirements of the LHC experiments in terms of radiation hardness cannot be fulfilled by the standard $p^+\text{-}in\text{-}n$ sensors. At the end of the targeted lifetime of the detector, a full depletion voltage of more than 1000 V is expected. As the maximum bias voltage foreseen is in the order of 600-700 V, an under-depleted operation of the sensors is required for a significant part of their lifetime. In fact, an effect known as type inversion is usually observed to occur in high resistivity Silicon bulk after prolonged exposure to high fluences of radiation. The effective concentration of impurities gradually decreases with exposure, until a transition to the other type material behavior occurs (see Sect. 2.6.1). In an unirradiated $p^+\text{-}in\text{-}n$ device, the depletion zone grows from the higher doped $p^+$-side into the lower doped $n$-bulk (see Fig. 3.3(a)) and the sensor can be operated partially depleted. While, after type inversion, the depletion region grows from the non-pixelated bottom (see Fig. 3.3(b)). Since in $n^+\text{-}in\text{-}n$ sensors the depletion region grows from the electrode pixel side after type inversion (see Fig. 3.3(e)), the device can be be operated partially depleted if full depletion cannot be reached anymore. Extremely high operating voltages can therefore be avoided, reducing the problems of leakage currents and high voltage breakdowns. Furthermore, the double-sided processing of $n^+\text{-}in\text{-}n$ detectors allows a guard ring concept which keeps all sensor edges at ground potential and avoids the risk of disruptive discharges to the very closely spaced front-end chip. In comparison with standard $p^+\text{-}in\text{-}n$ sensors, $n^+\text{-}in\text{-}n$ devices are roughly twice as expensive due to the need for double sided processing and inter pixel isolation.
3.1.2 Inter pixel isolation

In the fabrication of planar Silicon detectors the surface of the bulk material is passified through the creation of an oxide layer. This layer represents a positive charge density, which, if sufficiently large, causes an electron accumulation on the Si/SiO$_2$ interface. In contrast to the $p^+\text{-}in\text{-}n$ case, where the isolation of the adjacent $p^+$-implants is provided by this electron accumulation layer, exactly this accumulation layer electrically connects the $n^+$-implants of the pixel side if no precautions are taken. Isolation is usually provided by a $p$-type Boron implant between the pixels, forming a lateral $p\text{-}n$ junction. Two inter-pixel isolation techniques were evaluated with good results. Open $p$-stops [13] were selected for the endcap disks and moderated $p$-spray [14] for the barrel detector (see Fig. 3.2 and 3.4).

![Diagram](image)

**Figure 3.4:** Photo of four pixel cells with moderated p-spray (a) and open p-stop design (b). The pixel size is 100µm×150µm.

The $p$-stops are open rings of high dose $p^+$-implants ($\sim 10^{14}$ Boron ions/cm$^2$) surrounding the pixels that interrupt the conducting layer. This is done by an additional photolithographic step. The alignment of the $p$-stop mask with respect to the $n^+$-pixels is critical as an overlapping of the two high dose implants would result in an electrical breakdown.

The value of the oxide charge increases after a small irradiation dose to a saturation value which is in the order of $3\times 10^{12}$ cm$^{-2}$. If the dose of the Boron implant is matched to the saturation value, the concentration is small enough that an overlap of the Boron implant with the $n^+$-implant does not lead to breakdown, in such a way that the photoligraphic step with the mask can be avoided. This technique is called $p$-spray isolation.

In unirradiated $p$-stops devices the lowest electric field is reached, but after a sufficient irradiation dose an accumulation of electrons close to the surface caused an increased of the electric field between the isolating $p$ layer and the $n^+$ pixel implants. This means that the breakdown voltage of devices
3.1. Pixel sensors

featuring p-stops decreases with irradiation. The opposite scenario holds for p-spray devices. In this case the unirradiated device displays the highest electrical field and therefore the lowest breakdown voltage in its lifetime. With the increase of the oxide charge to its saturation value the electric field decreases and the lowest electric field is reached when the Boron implant matches exactly the saturation value of the oxide charge. This means that the devices have a better high voltage performance after irradiation than before.

In order to improve the pre-radiation high voltage stability of p-spray devices while keeping their good post-radiation behavior, the so-called moderate p-spray technique has been developed. The Boron dose in the middle of the gap between two pixels can be chosen high enough to ensure interpixel isolation, for instance twice the expected saturation value of the surface charge. At the same time the Boron dose in the surrounding of the lateral p-n junction can be optimized for the best high voltage performance which is reached if the dose is close to the expected saturation value of the surface charge [15].

3.1.3 Spatial resolution

A central decision in the development of the CMS pixel detector was to exploit charge sharing among pixels to improve the position resolution. The position resolution of single-pixel hits for a pixel sensor with pitch $p$ centered around 0 is easy to determine with the following assumptions:

- the threshold is adjusted in such a way that only one pixel per particle track fires;
- only particles hitting the detector between $-p/2$ and $p/2$ trigger a signal in the pixel;
- the detector is hit by a uniform density of particles, $D(x) = 1$.

Then the average difference between the “real” impact position $x_r$ and the measured impact position $x_m = 0$ is given by

$$\sigma_x^2 = \frac{\int_{-p/2}^{p/2} (x_r - x_m)^2 D(x_r) dx_r}{\int_{-p/2}^{p/2} D(x_r) dx_r} = \frac{\int_{-p/2}^{p/2} x_r^2 dx_r}{\int_{-p/2}^{p/2} dx_r} = \frac{p^2}{12}$$

so that

$$\sigma_x = \frac{p}{\sqrt{12}}$$

is the expected resolution.

Actually, the threshold of the readout electronics is set as low as possible without getting a too high rate of noise hits. This means that two (or more)
3.1. Pixel sensors

pixels can be triggered by the same particle if the signal charge is shared between the pixels. The group of pixels showing a signal from the same particle is called *cluster* and is usually created when the track passes close to the pixels divide. The spatial resolution for events triggering two pixels whose divide is centered in 0 can be calculated assuming that the cluster occurs if the track impact point is comprised in the charge sharing region \([-s/2, s/2]\). The expected spatial resolution is then \(s/\sqrt{12}\) and for events triggering one pixel is \((p - s)/\sqrt{12}\). Therefore the occurrence of clusters with more than one pixel improves the resolution.

The analogue readout of the CMS pixel detector (see Sect. 3.3.3) allows an additional improvement of the spatial resolution since it delivers a signal proportional to the collected charge. In the region where both pixel cells show a signal, interpolation algorithm can be used, as for instance the so-called \(\eta\)-function [16]. If \(Q\) is the charge deposited in two adjacent pixels (left \((L)\) and right \((R)\)), the \(\eta\)-function is defined as the fraction of charge deposited in, say the right pixel

\[
\eta = \frac{Q(R)}{Q(R) + Q(L)} .
\]

In CMS significant charge sharing is a consequence of the Lorentz drift in the strong magnetic field of 4 T. Charge carriers released by the ionizing particle in the sensor do not follow the electric field lines to the collection electrodes, but are deflected by the Lorentz force (see Fig. 3.5). This effects influenced the choice of the barrel pixels size in order to achieve the optimal spatial resolution. Since division of the signal charge among more than two pixels increases the data rate and reduces the signal charge per pixel without an improvement of the resolution, an ideal choice of the pixel size in the direction perpendicular to the magnetic field \((r\phi)\) is therefore given
by the length over which charges are spread when they reach the surface of
the sensor. For the usual $\approx 300\mu m$ sensor thickness and the electron Lorentz
angle of $25^\circ$ this amounts to $\approx 140\mu m$. However, the pixel dimension was
chosen to be $100\mu m$, since due to threshold effects in the readout, three-pixel
clusters will still be negligible.

Little charge sharing is expected in the end disks since the electric and mag-
netic fields are parallel, and most tracks are close to normal incidence. There-
fore charge sharing is obtained by rotating the detector blades by $20^\circ$ away
from the $r\phi$-plane in order to introduce an angle between electric
and magnetic field and hence Lorentz drift.

### 3.2 Module

The CMS pixel system will have three barrel layers and two end disks on
each side of the barrel. The layers are composed of modular detector units.

#### 3.2.1 Pixel barrel detector module

The pixel barrel module consist of a thin, segmented sensor plate with highly
integrated readout chips (ROCs) connected to them using the bump bonding
technique with Indium solder (see Fig. 3.6).

The modules of the pixel barrel are shown in Fig. 3.7. A full mod-
ule consists of two rows of 8 readout chips connected to one sensor, has
a size of $66.6 \times 26 mm^2$ and weights $3.5 g$. To put the two half shells of
the detector together without a gap, two kind of half modules are neces-
sary, containing half of the channels of a full module ($1 \times 8$ ROCs). Ta-
ble 3.1 gives the number of full and half modules on the three different
detector layers.

Each ROC read an array of $52 \times 80$
pixels and is connected through bond
wires to an hybrid circuit (High Den-
sity Interconnect) glued onto the backside of the sensor. The HDI is equipped
with a module controller chip, called Token Bit Manager (TBM), which con-
trols the readout of the ROCs, as well as it receives all external control signals
and distributes them to the chips. The sensor elements at the chip boundaries
have twice the normal width to avoid dead regions between ROCs. Pixels

---

1For an unirradiated sensor at a bias voltage of $150 \, V$ [17].
in the corners are four times larger. The chips extend 0.8 mm beyond the sensor edge allowing access to the wire-bond pads. Base-strips are glued underneath the readout chips allowing the module to be mounted on the barrel mechanics. The base-strips are made of Silicon nitride (Si$_3$N$_4$) with a thickness of 250 $\mu$m. Kapton cables connected to the hybrids transmit the signals to and from a periphery situated at the outer region of the pixel system frame where detector control chips and electro-optical converters for optical signal transmission are located. The modules are attached to cooling frames, with the cooling tubes being an integral part of the mechanical structure. The module is powered via 6 copper coated aluminium wires of 250 $\mu$m diameter.

![Components of the CMS pixel barrel modules.](image)

**Figure 3.7:** Components of the CMS pixel barrel modules.

**Table 3.1:** Number of modules, readout chips (ROCs) and pixels on the three detector layers.

<table>
<thead>
<tr>
<th>radius (cm)</th>
<th>full modules</th>
<th>half modules</th>
<th>ROCs</th>
<th>pixels ($10^6$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.4</td>
<td>128</td>
<td>32</td>
<td>2304</td>
<td>9.6</td>
</tr>
<tr>
<td>7.3</td>
<td>224</td>
<td>32</td>
<td>3840</td>
<td>16</td>
</tr>
<tr>
<td>10.2</td>
<td>320</td>
<td>32</td>
<td>5376</td>
<td>22.4</td>
</tr>
<tr>
<td>Total</td>
<td>672</td>
<td>96</td>
<td>11520</td>
<td>48</td>
</tr>
</tbody>
</table>
3.2.2 Forward pixel detector plaquette

Each disk of the endcap detector has 24 wedge shaped in blades. Figure 3.8(a) displays the configuration of the blades arranged in a ‘turbine’ geometry. The blades extend from 6 cm to 15 cm in radius and have a width between 3 cm and 5 cm. The basic unit of construction for the forward pixel detector is the plaquette. A plaquette consists of a single pixel sensor bump-bonded to an appropriate number of ROCs (see last section) and wire-bonded to a very-high-density-interconnect (VHDI) that provides power, control, and data connections. The connection of the pixel sensors to the ROC is achieved by fine-pitch bumping using Pb/Sn solder.

![Figure 3.8:](image)

(a) (b)

**Figure 3.8:** *Left:* a pixel endcap half-disk with 12 blades. *Right:* sketches of the two types of FPix panels showing the different sizes and numbers of the plaquettes on each.

In order to cover the trapezoidal or pie-shaped panels without leaving cracks, five different sizes of plaquettes are needed. These are respectively 1×2, 2×3, 2×4, 1×5, 2×5, where the first digit refers to the number of rows and the second to the number of columns of read-out chips that are attached to a given sensor. The largest plaquette, the 2×5, has dimensions of 16×35 mm².

A blade consists of the cooling channel with two panels mounted on either sides such that each one covers the insensitive regions of the other. The two types of panels are shown in Fig. 3.8(b). The panels on the side of the cooling channel closest to the IP contain 1×2, 2×3, 2×4, and 1×5 plaquettes or a total of 21 ROCs. The panels on the side of the cooling channels farthest from the IP contain 2×3, 2×4 and 2×5 type plaquettes with a total of 24 ROCs. From the point of view of readout and control, a panel is the equivalent of a barrel module with one TBM. The four disks are made of 96 panels populated by 672 plaquettes.
3.3 The Readout Chip

The front-end chip [12] is a key component of the pixel detector and its development accounts for a large fraction of the detector R&D. The ROCs have to record position and charge for all hit pixels with a time resolution of 25 $ns$, which is the time between two LHC bunch crossings. These information have to be stored on-chip during the CMS Level-1 trigger latency of 3.2 $\mu s$ after which they are either read out or discarded.

Figure 3.9: Schematic view of the Pixel Unit Cell.

A schematic view of the pixel readout is shown in Fig. 3.9. Each pixel sensor is connected via a bump bond to its own readout circuit on the readout chip (Pixel Unit Cell, PUC). Two PUC columns form a double column, which represents an independent readout unit controlled by a circuit sitting
in the *column periphery* from where the PUC is controlled, where data is buffered and global functions common to all pixels are located. Local bus lines connect all PUCs of a double column with the column periphery, one of them being the Column OR which combines all PUCs in the double column into a global OR.

The PUC can be divided into an analog part and the digital logic. The signal from the sensor enters a two stage charge sensitive pre-amplifier/shaper system. The shaper is a band-pass filter that limit the bandwidth of the preamplifier output signal. This is beneficial for a reduction of high- and low-frequency noise contributions introduced in particular by the sensor leakage current and by the input device.

The pre-amplifier input is DC coupled to the sensor pixels. Its feedback must absorb the expected sensor leakage current of 10 $nA$ per pixel. This introduces a DC-offset at the preamplifier output bringing the circuit out of its operation regime. A globally programmable current source at the input node compensates for sensor leakage current.

In order to verify the correct operation of the PUCs and to calibrate the pixels an electrical signal can be injected and delayed for a certain time. After, the shaper zero suppression of the signal is performed through a comparator. It compares the shaper output to a threshold value which is distributed globally to all pixels. Since variations of the threshold of the individual pixels caused by transistor mismatch, voltage drops or preamplifier gain variations can lead to an increased noise hit rate or to a reduced sensitivity, each pixel has a 4-bit DAC to trim the threshold. Furthermore, a mask bit allows to disable noisy pixels.

When the rising edge of the signal has passed the threshold, the signal height is sampled after some delay and stored in the sample-and-hold capacitance until the readout mechanism is started from the periphery. During this time the pixel becomes insensitive.

To control and optimize the readout, 26 DACs (Digital to Analog Converters) and 3 registers can be adjusted [18].

### 3.3.1 Column drain architecture

Since the Level-1 trigger latency time in CMS is 3.2 $\mu s$ (128 bunch crossings), the information of a hit pixel, including the associated bunch crossing number information and the analog pixel signal, can not be kept on the pixel itself during this time without introducing a significant inefficiency. In the architecture chosen for the CMS pixel readout (Column Drain Architecture), the basic idea is to copy all pixel hits occurring in a pixel double column into the column periphery as soon and as fast as possible in order to free the pixels for the next hit. In this case the probability of having a second hit in the pixel during the latency is significantly reduced.
Each double column is equipped with a global OR which informs the column periphery immediately of any hits that occur in the double column sending to the periphery a current with adjustable intensity. If more than one pixel is hit in a double column at the same time the currents are added. This OR signal starts a column drain cycle and must be fast enough to associate the hits uniquely to the correct bunch-crossing. A timestamp is created in the column periphery, which hosts a circular buffer for time-stamping the hits with an 8-bit bunch-crossing number through a local bunch-crossing counter running at 40 MHz (Write Counter).

Upon receipt of an OR signal, the column periphery initiates a token scan of the double column, which basically passes a token from cell to cell. Once the hit pixel is found, in the readout block of the PUC the token signal initiates the transfer of pixel address and analog signal, which are stored in a data buffer located in the periphery waiting for the Level-1 trigger. The hit pixels remain inactive until their hit information has been transferred. While still copying the hits of the previous time stamp into the data buffer, the architecture allows the recording of one more time-stamp caused by new hits arriving later in other pixels of the same-double column. These new hits will be copied into the data buffer in a subsequent column drain.

The verification of all active time-stamps in each column is based on a second bunch-crossing counter (Search Counter) at the chip periphery. This counter is running concurrently with the actual time-stamp counter (Write Counter) but delayed by the trigger latency time. For each bunch crossing the search counter value is compared with the stored time-stamps in each column. If a coincidence is detected, this time-stamp is eliminated from the list. However, if in addition a Level-1 trigger is present for this bunch crossing a readout sequence is started.

3.3.2 The Token Bit Manager

The readout of several chips on a module is controlled by the Token Bit Manager (TBM) chip [19]. This chip sends a token flag in a fixed order from chip to chip. The chip that has the token transmits all hits for a given trigger and then passes the token to the next chip. Every readout chip starts sending a three cycle header when it receives the readout token. While the header is transmitted, the token is passed through the chip looking for a double-column with validated hits belonging to that token. The length of the header is sufficient for the token to skip all 26 double-columns if no triggered hits were present and to be passed on to the next chip with the right timing.

Triggers and readout tokens are both counted and hits are only read out when the token number matches the readout number. It must be ensured that exactly one token for every trigger is issued and that there is never more
than one token. For every Level-1 trigger the TBM sends a token to the first chip and waits until the token returns from the last chip in the chain. It keeps track of triggers arriving while the readout is still busy with a FIFO. The TBM adds a header with an event number and a trailer with status information to each readout. The most important status information during data-taking is token FIFO overflow warning. A loss of a token destroys the synchronization between module and data-acquisition, effectively leading to the loss of all subsequent data. The trigger counter is used to verify the correct synchronization.

3.3.3 The Analogue Readout

An example for the analog readout of a module where one pixel on ROC 0 has been activated is shown in Fig. 3.10. The TBM header starts with three ultra black levels (UBL). An UBL is simply a large negative signal level well outside of the range of pixel data. The three UBLs are followed by a black level, which defines the zero level of the differential analogue signal. The four remaining clock cycles encode an 8-bit event number. The minimal readout of each ROC starts with an UBL, a black level and a level called last DAC which represents the value of the most recently programmed DAC. This sequence unambiguously identifies the beginning of a new chip in a sequence of analog levels. No further chip ID is present in the data stream. The chip number is simply incremented for each ultra black signal recorded. Each hit adds a block of six clock cycles to the analogue readout: 2 for the double-column address, 3 for the row address, and one for the pulse-height. The pixel addresses are not binary coded, but use a set of 6 discrete analog levels (≈ 2.5 bits/clock) as shown in Fig. 3.10. The readout is terminated by the TBM trailer, containing two UBLs, two black levels, plus four clock cycles with the TBM status information.

![Figure 3.10: Analogue readout of a pixel module with one hit in ROC 0.](image)
Chapter 4

The CMS Tracker Upgrade

All the different parts of the CMS detector were designed and optimized in order to face the physics requirements and the technological challenges put by the nominal LHC. To extend significantly the physics potential of the collider, a luminosity upgrade is already under study [20]. An increased luminosity will improve the accuracy in the determination of Standard Model parameters, as well as extend the discovery reach in the high-mass region and the search for rare processes. The first increase of the luminosity by a factor of 2 (Phase I) will be obtained by pushing the current accelerator capabilities to its ultimate with hardware changes only in the LHC insertions and/or in the injector complex. For the second upgrade (Phase II), referred to as Super-LHC (sLHC), new accelerator magnets will push the luminosity up to $10^{35} \text{cm}^{-2}\text{s}^{-1}$. In this scenario sLHC would accumulate $\sim 2500 \text{fb}^{-1}$ of integrated luminosity after five years of operation. Under these conditions the CMS tracker system performance, and mainly the pixel detectors one, will be dramatically affected by radiation damage caused by the immense particle fluxes to which it will be exposed. Furthermore, the increase in the track density requires faster detectors with finer granularity. This means for example that the pixel detectors will have to cover the tracking volume to higher radii pushing the microstrip detector system further outside. The microstrip detectors themselves will have to be reduced in strip size making the difference between microstrip and pixel detectors less and less distinct. These tasks are even more complicated by the fact that the existing power cables, optical fibers and cooling tubes cannot be changed for the upgraded system and by the need to keep the costs as low as possible.

In this chapter a particular attention is given to the inner pixel detector limitations in terms of radiation hardness and to the two main candidates for a future replacement, which are 3D Silicon Sensors and Diamond Sensors.
4.1 The Pixel Detector Upgrade

At full LHC luminosity the innermost layer will be exposed to a particle fluence of $3 \times 10^{14} \text{n}_{eq}\text{cm}^{-2}\text{yr}^{-1}$, the second and third layer to about $1.2 \times 10^{14} \text{n}_{eq}\text{cm}^{-2}\text{yr}^{-1}$ and $0.6 \times 10^{14} \text{n}_{eq}\text{cm}^{-2}\text{yr}^{-1}$, respectively. All components of the current generation of Silicon pixel detectors are designed to operate up to a total fluence of $6 \times 10^{14} \text{n}_{eq}\text{cm}^{-2}$. This implies that the 2nd layer will have to be replaced once after about 7 yr (4 with reduced and 3 with full luminosity), while the innermost layer will probably be replaced every 1-2 yr of full luminosity equivalent. The total fluences of photons, neutrons and charged hadrons expected in the CMS experiment over the scheduled 10 years of LHC operation is shown in Fig. 4.1.

For the sLHC upgrade the presently available Silicon detector technology cannot match the extreme requirements with respect to the necessary radiation tolerance. As shown in Fig. 4.2(a), decreasing fast hadron fluences in the range $16-2.3 \times 10^{15} \text{cm}^{-2}$ are expected at distances from 4 cm to 11 cm from the beam interaction point, after 2500 $fb^{-1}$ of integrated luminosity.

The effects caused by radiation damage are explained in detail in Sect. 2.6. When radiation fluence increases, Silicon detectors suffer from signal degradation with a consequent decreasing of the signal collected and an increasing of the background noise. Figure 4.2(b) shows the degradation of the collected signal with increasing luminosity.
4.1. The Pixel Detector Upgrade

Figure 4.2: Left: radiation fluence as a function of the radius in sLHC scenario extrapolated from simulations for the CMS detector. Right: Signal degradation as a function of fluence.

Semiconductor detectors seem the best option for vertex sensors also in the next generation of colliders, provided that their radiation hardness is significantly improved. Two main research lines have been identified: Material Engineering, with the aim of producing more radiation-hard semiconductor material, and Device Engineering, to develop a more radiation-tolerant detector geometry. Among the several proposed solutions, Diamond and 3D Silicon Sensors, seem to be two of the most promising tracking detector candidates. A comparison between these two solutions and the actual planar technology is shown in Fig. 4.3, where the signal efficiency and the collected signal are plotted as a function of fluence.

Figure 4.3: Comparison of the measured signal (left) and signal efficiency (right) between Diamond, 3D Silicon Sensors and the actual planar technology [21].
4.2 3D Silicon Sensors

The 3D technology was first proposed by Parker and Kenney [22] in 1997 to solve the problem of charge loss in gallium arsenide detectors. In contrast to the planar technology used for construction of the standard Silicon pixel sensors, in which the electrodes are parallel to the surface of the bulk, the 3D architecture presents electrodes perpendicular to the bulk surface, extend partially or completely through the volume of the wafer. A schematic view of a full 3D sensor is shown in Fig. 4.4.

**Figure 4.4:** Three-dimensional view of a 3D sensor showing the electrodes penetrating the substrate.

Both planar and 3D Silicon sensors are reversely biased, with several advantages of the latter with respect to the traditional planar design [23]. Fig. 4.5 compares the way in which charges are collected by the two sensor geometries. Since in 3D sensors the electric field is parallel, rather than orthogonal, to the detector surface, the depletion region proceeds laterally.
4.2. 3D Silicon Sensors

Figure 4.6: Layout proposed for the double sided 3D detectors by CNM.

in between columnar electrodes, rather than vertically, so that the charge carriers created by passing-through particles move to the electrodes following parallel directions. Since the interelectrode distance can be made one order of magnitude smaller than the detector thickness, the charge collection distance can be several times shorter, the collection time considerably faster and the full depletion voltage an order of magnitude smaller (see Tab. 4.1). Furthermore, thanks to the short interelectrode distance, the ability of the detector to operate in the presence of severe bulk radiation damage is greatly increased. In fact, the charge carriers generated by ionizing radiation can be collected within a time smaller than the trapping time of the induced defects.

3D technology is very interesting for the possibility of obtaining the so-called active edges. Planar detectors need multiple guard ring structures at the cutting edge of the Silicon in order to prevent high leakage currents coming from the edge of the sensor flowing into the active area, to smooth electric field from the active region to the edge and for the confinement of the depleted region (sensitive area). Guard ring structures should be at least as wide as the detector thickness to be effective, so the dead zone is on average a few hundred microns. In 3D devices this can be avoided by micro-machined trenches filled with a suitable dopant to define the potential in the Silicon very close to the cut edge, resulting in a thin dead zone.

The first 3D sensor concept has been the Full-3D detector with active edges fabricated at the Stanford Nano Fabrication Facility, California, U.S.A. In this configuration the electrodes pass through the whole detector thickness (see Fig. 4.4). Besides this standard design, other modified 3D detectors have so far been proposed by other research groups. Double-sided 3D detectors have been proposed by CNM [24] (Centro National de Microelectronica,
Barcelona, Spain) and FBK [25] (Fondazione Bruno Kessler, Trento, Italy) independently, with few differences in the fabrication process. In this configuration columns of one doping type are etched from the front side of the device, and the other type from the back side. Neither set of columns passes through the full thickness of the Silicon substrate, as shown in Fig. 4.6. Further details about the construction and fabrication of 3D Silicon sensors can be found in [26].

Table 4.1: Comparison between 3D and planar detector design parameters for a 300-μm-thick Silicon substrate. The depletion voltage quoted is for a detector prior to irradiation [21].

<table>
<thead>
<tr>
<th></th>
<th>3D</th>
<th>Planar</th>
</tr>
</thead>
<tbody>
<tr>
<td>Depletion Voltage</td>
<td>&lt; 10 V</td>
<td>70 V</td>
</tr>
<tr>
<td>Collection length</td>
<td>≈ 50 μm</td>
<td>300 μm</td>
</tr>
<tr>
<td>Charge collection time</td>
<td>1-2 ns</td>
<td>10-20 ns</td>
</tr>
<tr>
<td>Edge sensitivity</td>
<td>&lt; 10 μm</td>
<td>≈ 300 μm</td>
</tr>
</tbody>
</table>

4.3 Diamond Sensors

Figure 4.7: A schematic view of a Diamond detector.

Figure 4.7 shows the basic principle of the use of Diamond as a charged particle detector. A voltage is applied across a layer of Diamond a few hundred microns thick. When a charged particle traverses the Diamond, atoms in the crystal lattice sites are ionized, promoting electrons into the conduction band and leaving holes in the valence band. On average, 3600 electron-hole
pairs are created per 100 $\mu m$ of Diamond traversed by a minimum ionizing particle. These charges drift across the Diamond in response to the applied electric field producing a signal that can be measured.

### 4.3.1 General properties

Table 4.2 [27] summarizes the properties of Diamond (and for comparison Silicon) that are of interest when considering this material for use as a particle detector. Diamond is intrinsically a radiation hard material thanks to its high bonding strength and stable lattice of Carbon atoms. Because of its large bandgap (5.5 eV), Diamond is an excellent insulator with a high breakdown voltage, allowing the application of a large electric field to attain a saturated drift velocity while maintaining a very low leakage current. Thus there is no need, as in the case with Silicon, for reversed biased $p$-$n$ junction to prevent large leakage currents whose fluctuations would dominate the signal. It is also extremely fast to read out thanks to the high electron and hole mobilities. In a Diamond detector with thickness of a few hundred microns, all of the charge can be collected within 1 ns.

Table 4.2: The physical properties of Diamond and Silicon at 293 $K$.

<table>
<thead>
<tr>
<th>Property</th>
<th>Diamond</th>
<th>Silicon</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bandgap [eV]</td>
<td>5.5</td>
<td>1.12</td>
</tr>
<tr>
<td>Breakdown field [V/cm]</td>
<td>$10^7$</td>
<td>$3 \times 10^5$</td>
</tr>
<tr>
<td>Resistivity [$\Omega$cm]</td>
<td>$&gt; 10^{11}$</td>
<td>$2.3 \times 10^5$</td>
</tr>
<tr>
<td>Intrinsic carrier density [cm$^{-3}$]</td>
<td>$&lt; 10^3$</td>
<td>$1.5 \times 10^{10}$</td>
</tr>
<tr>
<td>Electron mobility [cm$^2$V$^{-1}$s$^{-1}$]</td>
<td>1800</td>
<td>1350</td>
</tr>
<tr>
<td>Hole mobility [cm$^2$V$^{-1}$s$^{-1}$]</td>
<td>1200</td>
<td>480</td>
</tr>
<tr>
<td>Saturation velocity [km/s]</td>
<td>220</td>
<td>82</td>
</tr>
<tr>
<td>Dielectric constant</td>
<td>5.7</td>
<td>11.9</td>
</tr>
<tr>
<td>Thermal expansion coefficient [K$^{-1}$]</td>
<td>$0.8 \times 10^{-6}$</td>
<td>$2.6 \times 10^{-6}$</td>
</tr>
<tr>
<td>Thermal conductivity [Wm$^{-1}$K$^{-1}$]</td>
<td>1000-2000</td>
<td>150</td>
</tr>
<tr>
<td>Energy to create e-h pair [eV]</td>
<td>13</td>
<td>3.6</td>
</tr>
<tr>
<td>Ave number of e-h pairs/100$\mu$m [e]</td>
<td>3600</td>
<td>9200</td>
</tr>
</tbody>
</table>

This material has two additional properties that are of interest. Its small dielectric constant yields, for a given geometry, a low detector capacitance and thereby, low-noise performance of the associated front-end electronics. In addition, even though Diamond is an electrical insulator, it is an excellent thermal conductor with a thermal conductivity exceeding that of copper by a factor of five at room temperature. This is important since a common problem with large detector systems is the management of the thermal load generated by the on-detector electronics used in the detector readout. The
handling of this thermal load would be simplified if the detectors were con-
structed from Diamond since it would act as a heat spreader.
Although Diamond appears ideal in many respects it does have a limitation: 
the large bandgap which produces many of its outstanding properties also 
means that its signal size is less than half that of Silicon.

4.3.2 Chemical Vapor Deposition
The Diamond crystals for particle detector applications are grown through 
the Chemical Vapor Deposition (CVD) process [28]. A small fraction of 
hydrocarbon gas, such as Methane, is mixed with molecular Hydrogen and 
Oxygen. The gas mixture is then excited by an energy source and brought 
into contact with a heated (600°-1000° C) substrate, usually Silicon or Molyb-
denum, where carbon-based radicals are reduced and the carbon atoms link 
together forming graphite (sp$^2$ hybridized orbitals) and diamond (sp$^3$ hy-
bridized orbitals) lattice. Graphite usually deposits much faster than Dia-
mond, however, it is etched by hydrogen and oxygen atoms and OH radicals 
while Diamond is comparatively inert. Under several conditions (tempera-
ture, pressure and gas mixture) any deposited Graphite will be etched while 
Diamond continues to be deposited. The growth speed is typically about 
1 $\mu$m/h. There are several types of CVD reactors, which differ in the way 
the gas is excited; for instance, this is done by microwaves or by a hot fila-
ment. After the growth process, the substrate is etched from the diamond 
film, which is then cut and cleaned.

Figure 4.8: Schematic section (left) and SEM photograph (right, 
scale 10 $\mu$m) [29] of a grown diamond film showing the columnar grain 
structure due to the growing process.

At the beginning of the growing process there is a large number of small 
crystal seeds on the substrate, each oriented individually. As deposition 
continues, the grains grow together, forming columnar single-crystals with
4.3. Diamond Sensors

grain boundaries between. Because of that, this type of Diamond is usually called polycrystal (pCVD). On the substrate side the grain size is very small (in the order of micrometers), while the size continuously increases in the growth direction, reaching a diameter in the order of 100 \( \mu m \) with a diamond film thickness of 500 \( \mu m \). The section of a CVD grown Diamond, representing this grain structure, is shown schematically in Fig. 4.8(a) and as a SEM (scanning electron microscopy) photograph in Fig. 4.8(b). The different grain sizes of substrate and growth sides are clearly visible with the SEM photographs in Fig. 4.9. The grain size expands from approximately 2 \( \mu m \) at the substrate side to about 80 \( \mu m \) at the growth side of a 415-\( \mu m \)-thick CVD Diamond.

![Grain structure image](image-url)

**Figure 4.9:** Grain structure at the substrate (left, scale 2 \( \mu m \)) and growth (right, scale 100 \( \mu m \)) sides of the same diamond sample (415-\( \mu m \)-thick)[29].

For the detector application, the diamond film is equipped with contacts on either side. First a Chromium layer of typically 50 \( nm \) is sputtered onto the sample, which forms a carbide with the diamond, providing an ohmic contact. Then, a Gold layer (typically 200 \( nm \)) is sputtered to prevent oxidation and to provide a surface suitable for wire-bonding. Besides this standard contact, also a Ti/Au combination was used. For the Indium bump bonding of pixel detectors, Cr/Ni/Au and Ti/W techniques were developed.

4.3.3 Charge collection properties

The grain boundaries of pCVD Diamond provides charge trapping and recombination centers resulting in a charge collection quality gradient along the depth coordinate. The CCD is very short on the substrate side, where the grain size is at its minimum resulting in a large amount of traps. With ascending depth coordinate the single-crystal volumes expand, causing the trap density to shrink and the CCD to increase linearly. In Fig. 4.10(a) the CCD of a Diamond sample is plotted as a function of the material thickness removed from the substrate side showing the linear relationship mentioned.
4.3. Diamond Sensors

The sample was lapped three times by about 60 µm at each step [29]. For the application as a tracking detector the target is to achieve the maximum collected signal, which is a function of the CCD only (see Eq. 2.24). However, with thicker films more charge is generated, thus more charge is collected. The solution is to grow a rather thick diamond film and then remove, by lapping, material from the substrate side, where the CCD is very low.

Natural diamond has a charge collection distance of about 30 µm. In the early 1990s, the CCD of pCVD Diamond was far below this value, but in the following years was permanently improved by refining the manufacturer’s growth process.

![Graphs showing CCD vs. thickness and CCD vs. electric field](image)

**Figure 4.10:** Left: CCD as a function of the material removed from the substrate side [29]. Right: collected charge signal vs. electric field from a pCVD Diamond sample measured using a 90Sr source. The saturation of the collected charge occurs at an electric field of 1 V/µm [30].

The CCD increases with the electric field until a saturation is reached, following the behaviour of the charge carriers drift velocity as described in Sec. 2.1. In Fig. 4.10(b) the dependence of the CCD and of the collected charge (mean value) on the applied electric field is plotted for a pCVD Diamond, showing a saturation at a value of ∼ 1 V/µm. The distribution has been obtained using a 90Sr source: the Diamond has been metalized with solid electrodes on each side, an external voltage has been applied across the Diamond and the collected charge measured. The CCD is then computed through Eq. 2.25.

In late 2002 a single-crystal Diamond (scCVD) has also been produced by the CVD process for the first time [31]. The samples has been synthesized with a microwave plasma-assisted CVD reactor using a specially prepared
4.3. Diamond Sensors

oriented single-crystal synthetic diamond substrate. This material removes many of the issues of pCVD material. In particular there should be no grain boundaries and therefore none of the defects and traps associated with grain boundaries. In Fig. 4.11(a) the most probable charge observed in scCVD Diamond using a $^{90}$Sr source is plotted versus thickness of the material showing a larger signal compared to pCVD Diamonds. In Fig. 4.11(b) the dependence of the CCD on the applied electric field is plotted for a 480-$\mu$m-thick scCVD Diamond showing that this material collects all the charge at an electric field value $\sim 0.2$ V/$\mu$m, well below the value obtained for pCVD Diamonds. From these results, this material appears ideal in many respect, although only small (0.1-0.2 cm$^2$ in area) scCVD Diamonds has been produced so far due to the extremely difficult growth process.

![Graphs](image.png)

(a) Most Probable Charge  
(b) Charge Collection Distance

**Figure 4.11:** scCVD Diamond properties. *Left:* the most probable pulse height versus thickness [32]. *Right:* CCD vs. electric field [30].

4.3.4 Radiation hardness

The damage produced to solid state material by particle irradiation has already been described in Sec. 2.6. It has been shown that high energy particles displace atoms in the lattice producing vacancies and interstitial that change the electrical properties of the material, leading to two primary consequences. On one hand, there is the increase in leakage current and therefore an increase in noise and, on the other hand, the reduction in the amount of collected charge, and thus a smaller signal. However, thanks to its electrical properties, Diamond has a reputation of being quite insensitive to radiation. The radiation-induced defects produce in Silicon new levels with energies within the band gap. These sites act as current generation centers emitting electrons into the conduction band and holes into the valence band which are immediately swept out of the depletion region by the applied field contribut-
ing to the signal. As Diamond has a very large band gap and defect energy levels are lower than half the gap, the radiation-induced leakage current remains negligible. The lattice defects are also responsible for charge trapping in the bulk material causing a decrease in the observed pulse height. Thanks to its large cohesive energy and tightly bound lattice structure Diamond is more resistant than Silicon to this mechanism.

Pumping effect

A Diamond detector that has never been irradiated before is in a virgin state, called “unpumped”. With moderate irradiation fluence, the signal output, or charge collection distance, increases significantly. It is due to very long trapping times of the trap centers caused by non-diamond atoms in the bulk. These sites are typically located deep in the band gap such that thermal emission is very unlikely. Once filled with signal charges the centers are made inactive and no longer able to absorb further electrons or holes. When all such traps are passivated, the diamond is called “pumped” and this state is conserved until the diamond is exposed to UV light. By UV absorption, the trapped charges are released again, resetting the Diamond to its original, or unpumped state. This procedure is fully reversible and there is no limitation in the number of pumping unpumping cycles. The pumping transition occurs with all types of particles and needs a radiation fluence of approximately $10^{10}$ particles/cm$^2$.

Figure 4.12: The pumping effect during exposure of a Diamond sample to a $^{90}$Sr source [29].

Fig. 4.12 shows a measurement of the charge collection distance of a Diamond sample as a function of time [29]. The electron flux from the 37 MBq $^{90}$Sr source was constant and therefore the time coordinate in the figure is
4.3. Diamond Sensors

proportional to the absorbed dose from the source. It can be seen that the charge collection distance increased in time from a value of (50 ± 5) µm to (87 ± 3) µm as a consequence of the pumping effect. Furthermore, Fig. 4.13(a) shows two “pump-up” curves of the collected charge during exposure to electrons from the ⁹⁰Sr source for the same Diamond sample [29]. The upper curve is before pion irradiation while the lower one is after pion irradiation. A comparison between the two curves shows that the charge saturation value is higher before irradiation compared to after irradiation. In addition, it can be seen that the time constant required to reach the saturation value before irradiation is lower compared to after irradiation leading to the conclusion that the fluence needed for complete pumping increases after intense irradiation, because of an increased number of traps in the diamond bulk. A linear relationship between pumping time and irradiation fluence can be seen from plot in Fig. 4.13(b) [29].

Figure 4.13: Left: collected charge and CCD as a function of time during exposure to electrons from ⁹⁰Sr for a pCVD before (upper) and after (lower) pion irradiation. Right: pumping time as a function of the pion fluence from several pCVD samples [29].
Chapter 5

Beam-test Setup

The last chapter was focused on the limitations in terms of radiation hardness of the present Silicon sensor technology for particle tracking in high-energy collider experiments. This subject becomes even more sensitive when dealing with the future LHC luminosity upgrade, that leads to the need for designing and testing new radiation-hard sensors. For this purpose, several prototypes of 3D and Diamond pixel sensors have been tested on beam at the Test Beam Facility (FTBF) of the Fermi National Accelerator Laboratory (FNAL) in Batavia, Illinois (USA) [33]. The collaboration goal is to compare the performances of the prototypes before and after irradiation, in order to understand if the proposed technologies are capable of resisting the high fluences expected at the sLHC with the required design specifications.

![Diagram of beam delivery to Fermilab Test Beam Facility](image_url)

**Figure 5.1:** Scheme of the 120 GeV proton beam delivery to Fermilab Test Beam Facility.

The MTest is the primary beamline of the FTBF and consists of a beam of 120 GeV protons at moderate intensities (∼ 1-300 kHz). In Fig. 5.1 a scheme of the beam delivery to FTBF is shown and can be summarized in few processes:
1. Negative Hydrogen ions with energy of 750 keV are extracted from the source into the Linac.

2. Electrons are stripped off the $H^-$ leaving $400 MeV$ protons in the Booster.

3. The Booster captures the protons into 84 bunches (1 batch) and accelerates them to $8 GeV$. Each of these bunches is 19 ns long.

4. A fraction of the bunches (8-30) are extracted to Main Injector that accelerates the beam to $120 GeV$.

5. The beam is finally resonantly extracted in a slow spill for each Main Injector rotation delivering a single 4.2-s-long spill per minute.

## 5.1 The Pixel Telescope

The beam-test setup has been chosen in order to fully characterize the Detector Under Test (DUT) as far as efficiency, spatial resolution and charge collection are concerned. For this purpose a CMS pixel based detector telescope has been built to provide precision tracking [34].

![Pixel Telescope Setup](image)

**Figure 5.2:** *Left:* 2×4 CMS PSI46.v2 plaquette. *Right:* telescope mechanical structure together with its components.

The telescope is placed along the MTest beamline and consists of 8 detector planes each with a plaquette leftover from the CMS Forward Pixel detector production (see Sec. 3.2.2). Four of the 8 telescope planes use plaquettes composed of 6 (2×3) PSI46.v2 ROCs while the remaining four planes are equipped with a 2×4 plaquette each. One of the 2×4 plaquettes is shown in Fig. 5.2(a). Each ROC reads an array of 52×80 pixel cells with size of...
5.1. The Pixel Telescope

100 \mu m \times 150 \mu m \times 285 \mu m each (except for the ROC border columns and upper row with size of 300 \mu m and 200 \mu m, respectively). The planes are arranged in 2 stations with 2 DUTs placed between them. The DUTs form a separate station itself. The two telescope stations are identified by their position relative to the DUTs: one placed upstream of the DUT station with the other one placed downstream of it. Each detector is glued to a carbon fiber support layer. Heat is dissipated through the carbon fiber and hence no cooling is required. For each station, the detectors are grouped in two pairs and for each pair, they are mounted together on an aluminium support then screwed on the carbon fiber box. As illustrated in Fig. 5.2(b), the mechanical structure of the telescope is of modular design: there are three basic cells, one for each station, built with carbon fiber tubes with dimensions of 17.0 cm \times 17.0 cm \times 34.0 cm. After complete assembly, the telescope is covered by a Mylar, anti-static layer (see Fig. 5.9).

Figure 5.3: Schematic three-dimensional view of the pixel telescope.

A three-dimensional schematic view of the telescope detector planes is presented in Fig. 5.3 where the laboratory coordinate system is also indicated. In this reference frame the Z axis is along the beam direction with +Z pointing downstream, Y axis is perpendicular to the beam with +Y pointing upwards and X axis is the horizontal axis with positive direction given by the right-hand rule. The coordinate system origin is placed between the two stations so that each plane of upstream and downstream station has negative and positive Z coordinate, respectively.

In order to exploit the improvement in the spatial resolution deriving from charge sharing between adjacent pixels (see Sec. 3.1.3), the planes are tilted by 25 degrees as follows:
5.2. The Data Acquisition System

- four planes (2x4 detectors) tilted around the X axis with the small pixel side oriented in the Y direction;
- four planes (2x3 detectors) tilted around the Y axis with the small pixel side oriented in the X direction.

In the first case the best measurement precision is achieved in the Y coordinate, while in the second case is the X coordinated that is measured with higher resolution. The configuration of each telescope plane is reported in Tab. 5.1.

Table 5.1: Configuration of the pixel telescope planes.

<table>
<thead>
<tr>
<th>Station</th>
<th>Detector ID</th>
<th>ROCs</th>
<th>Z position (cm)</th>
<th>Rotation axis</th>
<th>Rotation angle</th>
</tr>
</thead>
<tbody>
<tr>
<td>Downstream</td>
<td>0</td>
<td>2x4</td>
<td>46.5</td>
<td>x</td>
<td>-25°</td>
</tr>
<tr>
<td>Downstream</td>
<td>1</td>
<td>2x4</td>
<td>42.7</td>
<td>x</td>
<td>-25°</td>
</tr>
<tr>
<td>Downstream</td>
<td>2</td>
<td>2x3</td>
<td>29.7</td>
<td>y</td>
<td>25°</td>
</tr>
<tr>
<td>Downstream</td>
<td>3</td>
<td>2x3</td>
<td>25.9</td>
<td>y</td>
<td>25°</td>
</tr>
<tr>
<td>Upstream</td>
<td>0</td>
<td>2x3</td>
<td>-24.9</td>
<td>y</td>
<td>25°</td>
</tr>
<tr>
<td>Upstream</td>
<td>1</td>
<td>2x3</td>
<td>-28.7</td>
<td>y</td>
<td>25°</td>
</tr>
<tr>
<td>Upstream</td>
<td>2</td>
<td>2x4</td>
<td>-39.2</td>
<td>x</td>
<td>-25°</td>
</tr>
<tr>
<td>Upstream</td>
<td>3</td>
<td>2x4</td>
<td>-43</td>
<td>x</td>
<td>-25°</td>
</tr>
</tbody>
</table>

A scintillator detector placed downstream behind the telescope generates the trigger signal that opens a small time window in which the data acquisition system collects and sends to computer the data from the detectors. The data from each ROC are marked with a time-stamp (see Sec. 3.3.1), so that data recorded from all the detectors and marked with the same time-stamp, is identified as an event that is essentially the collection of hits that constitutes a particle track.

5.2 The Data Acquisition System

5.2.1 The DAQ: hardware

The Data Acquisition (DAQ) hardware is based on the CAPTAN system developed at Fermilab [35]. The CAPTAN (Compact And Programmable daTa Acquisition Node) is a flexible and versatile data acquisition system designed to meet the readout and control demands of a variety of pixel and strip detectors for high energy physics applications. The system is characterized by three key architectural features: a vertical bus that allows the
5.2. The Data Acquisition System

(user to stack multiple boards, a Gigabit Ethernet Link (GEL) that permits high speed communications to the system, and the core boards that provide specific capabilities for the system.

The system is based on core elements known as system nodes. A node is a stack of boards connected together by the vertical bus. There are no limits to the number of nodes that can work together in a system; the only limits are for the number of boards that a stack contains. The CAPTAN architecture supports two types of data paths, namely, the intra-node and the inter-node data paths. The intra-node communication is achieved by means of the vertical bus that connects all the boards in the same node. The inter-node communications are realized by two different paths, the horizontal bus and the GEL. Another key feature of the architecture is the existence of core or primary boards providing the backbone of the node system forming the central part of the hardware.

Each telescope station (upstream, downstream and DUT station) is provided with a node that consists of two octogonal primary boards:

- **Data Conversion Board (DCB)** provided with a 12-bit MAX1438 Analogue to Digital Converter (Fig. 5.4(b));

- **Node Processing and Control Board (NPCB)** provided with a Virtex-4 Field Programmable Gate Array (FPGA) (Fig. 5.4(a)).

The two boards are stacked together as in Fig. 5.5. Each NPCB is connected to the computer placed in the FTBF control room through a Ethernet cable, where a graphical user interface (see below) allows to set up the DACs and registers of the ROCs through the FPGA on the NPCB, as well
5.2. The Data Acquisition System

Figure 5.5: Scheme of the CAPTAN stack used for telescope data acquisition.

as control it and the DCB. The trigger signal from the scintillator arrives over LEMO cable to the NPCB of the central DUT station node from which it is distributed over SATA cables to the outer station nodes. The external Main Injector clock (53 MHz) for synchronization of the stations follows the same path. For each station, the data from ROCs are received by the DCB, digitized by the ADC and sent to the FPGA. The formatted data are then transfer to the control room PC via Ethernet at a Gigabit per second. The diagram in Fig. 5.6 shows schematically the full readout system.

Figure 5.6: Scheme of the telescope readout system based on CAPTAN hardware.
5.2. The Data Acquisition System

The data from each individual telescope plane are stored in its own directory. Within each directory, the runs are segmented into many partial-run files where the binary data resides. Files from different directories are then sequentially scanned and all temporally correlated data from every pixel plane (marked with the same time-stamp started by the trigger) are pulled from the file and merged to build what represents an event. A single binary file, containing the merged hits data information organized by time-stamp, is then created for each run.

5.2.2 The DAQ: software

Figure 5.7: A diagram illustrating the CAPTAN software topology.

A complete software solution for interfacing with the CAPTAN system has been designed for Microsoft Windows using Microsoft Visual C++ 2008 [36]. The diagram in Fig. 5.7 shows schematically the CAPTAN software topology. The building blocks of the software are the Global Master (GM), the CAPTAN Controller (CC), a Graphical User Interface (GUI) and the CAPTAN Analysis and Display (CAD).

The GM is the server for the entire system. It passes commands from the user to the CAPTAN system and, in the other direction, it forwards data from the system to the user for interpretation. The CC provides the basic connection between a CAPTAN stack and the GM so that there is a CC for each of the three stations. Each CC receives messages from the GM and forward them to its associated CAPTAN and handles the data coming from the stack either storing it on disk or handing it off to the GM which in turn sends it to the GUI. The GUI initiates all writes and reads to and from the
5.2. The Data Acquisition System

CAPTAN. It allows to set up the readout chips, trigger and clock system, run calibration procedures, as well as start or stop data acquisition. It also cues the CC to begin storing data to disk. The final block of the software architecture is represented by the CAD which allows the user to immediately visualize the telescope merged data in three dimensions as shown in Fig. 5.8. This allows to check almost on-line the quality of the data taken. For instance, it makes possible to recognize immediately if the beam is centered or not on the detectors and in the latter case a table control software installed on the computer allows remote mechanical translations of the telescope while the beam is active.

In Fig. 5.10, a picture of the various CAPTAN sofware blocks, are reported, while Fig. 5.9 illustrates the overall telescope assembly.

**Figure 5.8:** Three-dimensional data visualization with the CAPTAN software.

**Figure 5.9:** The CAPTAN pixel telescope final assembly with all its components.
5.2. The Data Acquisition System

(a) Global Master

(b) CAPTAN Controller

(c) GUI

Figure 5.10: Screenshots of the CAPTAN software blocks.
Chapter 6
Telescope Tracking and Alignment

The main goal of the beam-test project is to study the performance of the Detectors Under Test placed in the middle of the pixel-based telescope planes. For this purpose the telescope has been designed to achieve an optimal resolution for the reconstructed tracks, in order to obtain the best precision of the telescope track projections on the DUTs. The track reconstruction has been performed by means of the C++ package Monicelli, developed at the Università degli Studi di Milano-Bicocca (Milan, Italy) [37]. A correct track reconstruction requires a suitable alignment of the telescope planes. For this purpose, this powerful software provides the user with a complex interactive GUI to manually handle an appropriate iterative procedure. This feature makes the software relatively simple so that a large base of users can benefit from its functionalities. Furthermore, each step of the procedure produces a large number of distributions to control its progress and status, therefore the software is equipped with efficient interactive tools allowing the user to browse, examine, print and save these distributions in real-time. The track reconstruction and iterative alignment operations represent the preliminarily step of the subsequent analysis on DUTs. Since the analysis results are appreciably affected by the accuracy of this early setting up, a particular attention is reserved in this chapter to an overview of the main operations of the procedure. Finally, in the last section the results of an accurate alignment performed on a particular Run are shown.

6.1 Track Reconstruction

The first step of the track reconstruction process consists of the event building from raw data: Monicelli reads the merged binary data file together with an XML geometry file describing the overall configuration and the geometrical details of the telescope detectors for that particular Run. This file is editable
6.1. Track Reconstruction

by the user by means of an easy editor included in the package. To understand how this editor works a screenshot is reported in Fig. 6.1 where the labels Station 0, Station 1 and Station 2 refer to downstream, DUTs and upstream station, respectively. Then for each station the detectors are identified by the numbers from 0 to 3 (0 and 1 for the two DUTs). The geometrical details of each plane are set indicating the space coordinates and rotation angles in the laboratory frame, as well as the number and orientation of ROCs and for each ROC, the number of columns and rows together with their pitch.

Figure 6.1: Screenshot of the XML editor tool included in the Monicelli package.

In the event reconstruction process, the information contained in the binary file are decoded: for each event, the ADC value of every hits is associated with a row and a column to its own detector according to the telescope information provided by the XML file. Two output files are created on disk: one with decoded events data and the other one with the associated geometry. In addition, a scatter plot filled with the hits accumulated by each pixel in that Run is generated for each detector to graphically represent the beam-spot on it (see Fig. 6.2). These histograms allow users to cross-check the geometry information provided to the program as well as to check that the beam is roughly centered on all the detectors.

The next step in the reconstruction process is to compute the hit space coordinates on each detector by first organizing the adjacent fired pixels into clusters. No limits are imposed on cluster size and shape so that all types of clusters are built and stored in the output file with the associated space
6.1. Track Reconstruction

coordinates. However, since the telescope detectors are tilted by 25 degrees around X or Y axis, only hits involving one pixel, two adjacent pixels and four adjacent pixels (2×2) are interesting, while some other cluster types arising from a variety of reasons (dead pixels, threshold issues, δ-rays, etc) are considered unphysical or irrelevant and therefore discarded for alignment and analysis purposes. When a single pixel only is fired, the space coordinates associated with that hit are those of the geometrical center of the cell with a resolution given by $p/\sqrt{12}$, where $p$ is the pixel pitch (see Sec. 3.1.3). If a cluster with size larger than 1 is created, the hit coordinate is determined by weighing the collected charge between the cells considering the expected track impact angle $\beta$. For instance, for a cluster of size 2 where pixels are arranged horizontally, the hit coordinate is computed as

$$x = \frac{\left( x_e^{(1/2)} - I(\beta) \right) \cdot C^{(1)} + \left( x_e^{(1/2)} + I(\beta) \right) \cdot C^{(2)}}{C^{(1)} + C^{(2)}} \quad (6.1)$$

where $C^{(n)}$ is the charge collected in the pixel $n$, $x_e^{(1/2)}$ is the coordinate of the common edge between the cells and

$$I(\beta) = \begin{cases} +\frac{1}{2} t \tan \beta & x_e^{(1)} < x_e^{(2)} \\ -\frac{1}{2} t \tan \beta & x_e^{(1)} > x_e^{(2)} \end{cases}$$

where $t$ is the sensor thickness and $x_e^{(n)}$ is the center of the pixel cell $n$. In this case, the expected resolution associated with the computed hit position is not trivial to be determined a-priori. A resolution of $\sim 15 \, \mu m$ has been associated to this type of clusters as a result of a study based on pulls unitarity [37].

The next step in the track reconstruction procedure consists of finding track candidates. The strategy employed here starts by looping through every combination of hit pairs between the first and the last detector. A line is then traced connecting these two points and a user adjustable window is opened for every intersection of the line on each intermediate plane. The nearest hit on every plane within this window is then selected and associated to the track candidate.

Finally, the last step of track reconstruction consists of fitting each set of aligned hits found, exploiting the least-squares method to compute the track parameters. The reader can find the calculation details in Appendix B.1.
Figure 6.2: Beam spot on each telescope detector.
6.2 Alignment Procedure

The following describes the final strategy that has been successfully adopted to align telescope detectors with beam-test data. The alignment results obtained with Monicelli for this procedure will be subsequently discussed in the last section.

1. The track reconstruction algorithm described in the last section considers a track as a collection of hits lying on a straight line. This requires a fairly accurate estimate of the relative positions of the detectors to start with. Since preliminarly laboratory measurements of the positions within the telescope constitute rough estimations, a preliminarly raw alignment has to be performed. A crude, first approximation is obtained in Monicelli by aligning the shape of the beam on each detector. The X and Y projections of the beam spot are fit with a gaussian function to obtain the space coordinates of the beam spot centers in each telescope detector.

2. An initial suitable sample of tracks is found through a “road search” as described in the previous section, performed with large enough window tolerances (usually 1000 $\mu$m large) and without any cuts.

3. A finer translation alignment can be achieved analyzing, for each plane, the $X$ and $Y$ residual distributions. The detector residual is defined as the difference between the coordinate of the measured hit and the coordinate of the predicted track impact point. The mean values or the fit peaks (at this stage off from zero by a few hundred microns) of the residual spectra, give an estimate of the detector shifts in X and Y directions. With this operation the X and Y detector positions in the geometry file are automatically updated with these translation corrections.

4. A new “road search” is then performed with a thinner fiducial window (usually 250 $\mu$m large) and a better sample of tracks is obtained as indicated by the $\chi^2/DoF$ distribution whose peak is reduced to well below 20. At this stage some cuts can be applied requiring, for instance

- $\chi^2/DoF < 10$
- 8 hits per track
- 1 cluster hit per plane

With these cuts, a further look at X and Y residual distributions will give at this stage a detector translation shifts of few microns in both directions, therefore point (3) can be eventually iterated again and a new sample of tracks can be found with the same cuts as above.
5. At this stage alignment conditions are good to proceed with the fine alignment iterative algorithm that exploits a least-squares minimization, to compute the 1st-order roto-translation corrections, as explained in details in Appendix B.2. A sample made of tracks with 8 hits of maximum size 2 is selected to compute and minimize the X and Y unconstrained residuals. In this first iterative minimization run the first and the last detector along Z direction, because of the longest lever arm, are used as reference for other planes translations and rotations. They are considered in the fit phase to compute unconstrained residuals, but are fixed (none of their parameters is going to be minimized) through all iterations until the end of the minimization procedure. Furthermore, if the angular dispersion of the beam tracks is smaller than $\sim 1 \text{ mrad}$, the minimization algorithm loses precision in the resolving power of the Z position correction, resulting in a progressive run-away divergence of the procedure. Hence, in order to obtain convergence of the minimization algorithm it is necessary to fix the position along Z of all the telescope planes. The number of iterations is set by the user (usually 10 iterations) as well as the $\chi^2/\text{DoF}$ cut (for instance, $\chi^2/\text{DoF} < 10$). At the end of this process pull, unconstrained residual and correlation distributions are produced showing the alignment results.

6. A new “road search” is now performed with the updated geometry and more events with good tracks are found, as shown by the $\chi^2$ distribution improvement. Furthermore, it is observed an increase in the number of tracks reconstructed that satisfy the quality requirements put by the cuts.

7. Point (5) and (6) can be iterated several times until a satisfactory result is obtained.

8. Finally, a complete iterative minimization is executed releasing the first and last planes and fixing only Z positions for all the telescope planes. Usually 10 iterations are set with a $\chi^2/\text{DoF}$ cut of 10. This is followed by a new road search and the same minimization computed again until a satisfactory result is achieved.
6.3 Alignment Results

Applying the previously outlined alignment procedure, convergence has been reached with all the data collected with the present beam-test setup. An example of the final result is shown here for a particular data Run. The following distributions have been created for a sample of tracks satisfying some requirements:

- $\chi^2/\text{DoF} < 10$
- 1 cluster hit on each of the 8 planes
- 1 track per event
- a maximum cluster size of 2

Figure 6.3 shows the X and Y residual distributions after a complete alignment for each telescope plane. The unconstrained residuals are defined on each detector as the distances between the coordinates of the measured hit and the coordinates of the predicted point on that plane obtained by the fit of all other hits associated to that track. This means that, when computing the residual on a detector, its hit is removed from the track fit. As shown in Fig. 6.3, the residual spectra for each detector show both a larger, non-gaussian shape along the non-tilted coordinate ($\text{pitch} = 150 \, \mu m$) and a narrow shape along the tilted one ($\text{pitch} = 100 \, \mu m$). The former shape is caused by the most probable single-hit events, resulting in distributions with RMS of about $150/\sqrt{12}$. In the second case the distribution is dominated by charge sharing between adjacent pixels along the coordinate that is measured with the best resolution, resulting in distributions with RMS of about $22 \, \mu m$.

Figure 6.4 shows the X and Y pull distributions after a complete alignment for each telescope detector. Pull $(p_{x,i}, p_{y,i})$ on a detector $i$ is defined as the unconstrained residual normalized to the square-root of the sum between the squared error associated to the measured hit coordinates ($x_{m,i}, y_{m,i}$) and the squared error of the impact point ($x_{p,i}, y_{p,i}$) predicted by the track fit obtained excluding the hit on that plane:

$$p_{x,i} = \frac{x_{m,i} - x_{p,i}}{\sqrt{\sigma^2_{x_{m,i}} + \sigma^2_{x_{p,i}}}} \quad p_{y,i} = \frac{y_{m,i} - y_{p,i}}{\sqrt{\sigma^2_{y_{m,i}} + \sigma^2_{y_{p,i}}}}$$  \hspace{1cm} (6.2)

The X and Y pull distributions are plotted in Fig. 6.4 showing the unitarity expected if the initial estimate for different hit resolutions is correct.
Figure 6.3: The X and Y residual distributions for each detector after a complete alignment.
Figure 6.4: The X and Y pull distributions for each detector after a complete alignment.
Figure 6.5: Plots of the correlations between unconstrained residuals and impact point coordinates for each downstream station detector after a complete alignment.
Figure 6.6: Plots of the correlations between unconstrained residuals and impact point coordinate for each upstream station detector after a complete alignment.
6.3. Alignment Results

The precision of the alignment is further investigated studying the plots of Figures 6.5 and 6.6 showing the correlations between the unconstrained residuals and the impact point coordinates on the detector. For instance, the need for a further rotation of a detector around the Z axis should show up as a correlation in the plot of the distributions of the X(Y) residuals against the Y(X) associated coordinates. On the other hand, correlations in the distributions of X residuals against X coordinates and Y residuals versus the Y coordinates highlight the need for a further rotation of a detector around the Y and the X axis, respectively. As the alignment procedure goes ahead the correlation plots are flattening and becomes as in the figures.

The shape of the fitted track $\chi^2/DoF$ distribution in Fig. 6.7 shows the quality of the tracks reconstructed with this alignment, highlighting the efficiency of the alignment procedure.

**Figure 6.7:** The track $\chi^2/DoF$ distribution after a complete alignment.

Fig. 6.8 reports the X and Y slope distributions of the 120 GeV proton tracks showing a very small angular dispersion ($\sim 10^{-4}$), that results in a low resolving power for the determination of Z position corrections.

Finally, errors extrapolation at DUT Z position ($Z \approx 0$) is plotted in Fig. 6.9. It turns out that the best achievable telescope resolutions on DUT is as small as 5.5 $\mu m$ in both X and Y coordinates, and that the bulk of tracks give resolutions better than 8 $\mu m$. 
6.3. Alignment Results

Figure 6.8: The slope distributions of the 120 GeV proton tracks.

Figure 6.9: Extrapolated error distributions at the DUT Z position (Z ≈ 0) after a complete alignment.
Chapter 7

Beam-test Data Analysis

7.1 Diamond Detectors Under Test

The purpose of this thesis work is to investigate the performance as tracking sensors of two Diamond materials characterized by two different crystalline structures (see Sec. 4.3):

- **LC500**: a 500 $\mu m$ pCVD Diamond with a CCD of 172 $\mu m$ (measured at Colorado University)
- **PLT S32A**: a 500 $\mu m$ scCVD Diamond with a CCD of 508 $\mu m$ (measured at Rutgers University)

Both crystals were grown by Element-6 [38], polished by Diamond Detector Ltd [39] and bump-bonded at Princeton University. The LC500 is Indium bumped to the full PSI46.v2 ROC, while the PLT is bumped to an array of 21(columns)×39(rows) pixels covering an area of 3.15 × 3.9 $mm^2$ (see Fig. 7.1).

*Figure 7.1:* Picture of the PLT S32A sensor. The single-crystal covers a ROC area of 3.15 × 3.9 $mm^2$. 

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Table 7.1: DAC setting of the two Diamond Detectors.

<table>
<thead>
<tr>
<th>DAC</th>
<th>PLT S32A</th>
<th>LC500</th>
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<td>6</td>
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<tr>
<td>VIbias_roc</td>
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<tr>
<td>VsunCol</td>
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</tr>
<tr>
<td>WBC</td>
<td>113</td>
<td>113</td>
</tr>
</tbody>
</table>

Bias Voltage (V) 500 500

The LC500 performance have been studied with data taken in January 2012 beam-test run, while for the PLT the data from April 2012 run have been used. Data used in this analysis refers to runs in which the sensors were placed orthogonal to the beam trajectory.

A proper threshold for pixels output signal is usually introduced in order to suppress the equivalent noise charge (ENC) that depends on the thermal noise of the bias resistors $R$, the leakage current $I$ and the sensor capacitance $C_d$:

$$ ENC \propto C_d \cdot \sqrt{I} \cdot \sqrt{\frac{k_B T}{R}} $$

90
Each ROC is characterized by a single threshold value, that can be globally set for all the pixel cells before data taking. A low threshold is clearly preferred to minimize charge losses in adjacent pixels as much as possible. Nevertheless, a very low threshold value cannot be set for optimum ROC operation, so that a minimum value exists that represents a compromise between the two considerations.

Quick threshold and bias scans are usually preliminarily performed in order to define the DUT working conditions that give the maximum efficiency. This operation consists in taking data for a minute for each bias and threshold value. The merged data file is then processed by Monicelli for a preliminarily and approximate alignment. Finally, the Monicelli output file containing the reconstructed tracks is analyzed with the software described in Sec. 7.4 to obtain the DUT efficiency. The threshold ($V_{cThr}$) and bias voltage chosen with this procedure for both the sensors are reported in Tab. 7.1 together with the DAC settings of the two ROCs[18]. The threshold is expressed in DAC units and can be converted in electrons units by means of the calibration procedure described in Sec. 7.2.

### 7.2 Calibrations

![Figure 7.2: The sampled pulse height as a function of the amplitude of the injected signal.](image)

As already mentioned in Sec. 3.1.3, the spatial hit resolution can be improved by using the analogue information instead of the binary one. This is possible thanks to PSI ROC which features an analogue readout giving the possibility of measuring the pulse height of the induced signal. To exploit this advantage, it is very important to know exactly what ionization
charge a measured pulse height corresponds to. Therefore a precise calibration of the pixel cells, gain and threshold, is needed. To this extent, the PSI ROC is provided with an internal circuit which injects a signal charge in each preamplifier. The signal amplitude is controlled by the \( V_{\text{cal}} \) register, an 8-bit register that can be varied between 0 and 280 mV in the low range or between 0 and 1800 mV in the high range. A signal amplitude in the high range is about seven times higher than in the low range for the same DAC value. The signal from the sensor or the internal calibration circuit first passes the preamplifier and the shaper. At this stage, if the amplitude exceeds the set threshold, a comparator fires and a hit is generated, and the analogue signal is stored for the final read out. Both the Diamond sensors have been calibrated in the high range. The conversion factor of \( V_{\text{cal}} \) units in electrons can only be determined with an absolute calibration with an external source. A conversion factor of 421 \( \pm \) electrons per \( V_{\text{cal}} \) unit is often used as measured in [40].

The calibration operations are accomplished through the CAPTAN GUI where a hit map is created showing the fired pixels for each signal injection and therefore giving the possibility to check online the calibration status. An ASCII file is generated with calibration data that is then read and decoded by Monicelli where calibration curves are produced and fit. A typical pulse height calibration curve is shown in Fig. 7.2. The curve is linear over a limited charge range and then reaches the saturation. The measured pulse height curve is fit with a four parameter hyperbolic tangent function:

\[
y = p_0 + p_1 \tanh(p_2 x + p_3)
\]  

(7.1)

The fit parameters are saved in Monicelli output file and read during cluster building to convert the collected charge from ADC units to electrons units and compute the hit coordinates through Eq. 6.1. In the same way, once the threshold has been set, it is possible to perform a threshold scan to measure its value.

### 7.3 DUT Alignment

Once the telescope alignment is performed and the obtained geometry is saved, the reconstructed tracks with this optimized geometry are then used by Monicelli to obtain predicted impact points on the DUT after a proper alignment with the telescope. The DUT alignment procedure follows the same steps described in Chapter 6: clusters are built with calibration data and associated to telescope tracks (but not included in track fit); then a preliminarily alignment with residuals is performed and finally the iterative

\[\text{As we will see in Sec. 8.3.1 this conversion factor is overestimated for the single-crystal ROC.}\]
minimization algorithm is applied selecting a set of telescope tracks satisfying the following requirementes:

- $\chi^2/\text{DoF} < 10$
- 1 cluster hit on each of the 8 telescope planes
- 1 track per event
- a maximum cluster size on telescope and DUT planes of 2

The beam spots on both the Diamond detectors are shown in Fig. 7.3: the single-crystal covers only a fraction of the ROC area and a dead column is clearly visible; on the contrary the polycrystal covers all the ROC area but with poor bump-bonding in part of it. Furthermore, the polycrystal was well centered in the proton beam while the single-crystal captured only a part of it.

Since the detectors were placed orthogonally to the beam and the tracks are practically parallel to the $Z$ axis (see Fig. 6.8), the alignment algorithm is not sensible to small rotations around the $X$ and $Y$ axis and the $Z$ position. Therefore, the $Z$ position and those two angles were fixed.

The obtained distributions of unconstrained residuals, pulls and correlations are reported in Fig. 7.4 for both the Diamond detectors after a complete alignment.

![Figure 7.3](image_url)

**Figure 7.3:** Beam spots on the single-crystal (left) and the polycrystal (right) Diamond sensors.
Figure 7.4: The residual, pull and correlation distributions for the single-crystal (left) and polycrystal (right) Diamond sensors after a complete alignment.
7.4 Analysis Program

The beam-test data for polycrystal and single-crystal Diamond detectors collected in January and April 2012 have been analyzed through a dedicated software that I designed and developed considering the following requirements:

- Since DUTs are usually single-chip sensors, the majority of tracks reconstructed by the telescope fall outside their area, therefore the software must be able to quickly handle a large amount of data in order to achieve a good statistics on DUT.

- Analysis results are appreciably affected by event selections and a proper understanding of collected data usually requires to test and study different cuts. Hence, a system able to easily create and/or modify selections must be included in the software: the ideal choice is represented by the XML document format where selections, together with further configuration information, can be saved and loaded again at later times.

- A large base of users should have the chance to perform an analysis on the interesting data collected during the beam-test runs, thus it is preferred to provide the software with a simple to use graphical interface.

- A histogramming package to handle analysis results together with an interactive browser that gives the possibility to quick check the effect of the chosen event selections on the produced distributions is considered of great help and has thus been included.

- A simple architecture is required, so that a user could create preferred distributions and plots different from those already present, easily applying changes to the code without dealing with the overall software structure.

I defined and used these requirements as guidelines towards the implementation of the analysis program Chewie for the DUT data collected at the FTBF. The software features a simple GUI where the user can choose the studies to be performed on DUT (see Fig. 7.5), such as charge-collection, efficiency and spatial resolution ones, as well as study parameters and errors of the fits of the reconstructed telescope tracks. This is accomplished in the “Run” tab of the Chewie GUI as reported in Fig. 7.5. The “Run Analysis” button starts the chosen studies, automatically preceded by few operations where a fiducial window on DUT surface is prepared filling a 2-D histogram with the hits accumulated by pixel cells. The events falling outside
this window will be discarded in the analysis that follows. The limits of the window in terms of columns and rows, are decided by the user in the “Pre Analysis” tab of the GUI (see Fig. 7.6) where, furthermore, the user can also decide to remove particular cells from the window chosen. This is useful when it is preferred to exclude some detector dead parts or noisy pixels that can affect the analysis results. As shown in Fig. 7.7, the GUI also presents a dedicated tab for each of the studies mentioned above, where the event selections are written down in the appropriate line by checking the boxes on the right corresponding to the event parameters on which the desired cut must be applied. The full configuration chosen through the GUI, including for instance the fiducial window limits, the removed pixels or the selections, can be saved in an XML file that must be loaded each time an analysis is performed.
7.4. Analysis Program

Figure 7.6: Screenshot of the “Pre Analysis” tab of Chewie GUI where a fiducial window on detector surface can be decided as well as noisy pixels can be remove from it. The events falling outside the window will be discarded in the analysis that follows.

Figure 7.7: Screenshot of the “Charge” tab of Chewie GUI where the study of DUT charge sharing is performed. The string representing the desired event selections is automatically written down when checking the boxes on the right.
7.5 Code development

The analysis software code has been implemented in the C++ programming language and developed on a Linux platform using the Qt framework, a cross-platform framework with a rich C++ API [41]. It provides tools (Qt Designer) to design and build complex graphical user interfaces: the user can compose and customize graphical elements, such as widgets or dialogs, with different styles and resolutions and easily assign them behaviors using Qt’s signals and slots mechanism. Among all its functionalities, it also includes many useful library tools to manage multithreading systems and browse folder structures as well as a module (QtXml) that provides a stream reader and writer for XML documents. Its most attractive feature relies in its full compatibility with the ROOT library, an object oriented package developed at CERN in the C++ programming language and primarily designed for particle physics data manipulation [42]. It provides many useful C++ classes implemented to create and handle complex data structures with a large amount of information, as well as to handle many kind of distributions and plots with the possibility to display them with easy to use graphic utilities. Moreover, it includes the TThread class, developed to provide a platform independent interface to threads giving the possibility to build a multithreaded application that represents the immediate choice when it is required to control a large amount of data in a suitable lapse of time. A particular attention has been paid to decouple the code parts concerning graphical interface from the analysis parts. This choice allows in principle to use all the software functionalities in a separate program without Qt or graphic dependencies. This would allows to perform the analysis also over slow remote connections. In the following sections a description of the software architecture is presented.

7.5.1 The Threader Class

In order to allow users to process large amounts of data in a reasonably short time by running several sub-processes in parallel on distinct independent partitions of the data-set, the code has been designed from scratch to be able to handle concurrent processing. This idea can be accomplished through a multithreaded programming and execution model. This model has been implemented in Chewie exploiting the TThread class of ROOT. A thread is an independent flow of control that operates within the same address space as other independent flows of controls within a process. A process is a program that is loaded into memory and prepared for execution. It can be considered as an execution frame. Each process has a private address space. A thread is a sequence of instructions being executed in a process. A thread has a program counter and a private stack to keep track of local vari-
ables and return addresses. A multithreaded process is associated with one 
or more threads that execute independently and share the private address 
space of that process. This means that two pointers having the same value in 
two threads refer to the same data. Furthermore, if any thread changes one 
of the shared system resources, all threads within the process are affected. 

For example, if a thread closes a file, the file is closed for all threads. 
The true advantage of a multithreaded program is to operate faster on com-
puter systems that have multiple CPUs (multi-core system): the threads 
actually run at the same time, with each core running a particular thread. 

In Chewie, a class Threader is defined (see Listing C.1 and C.2) with a C++ 
vector of TThread pointers among the private variables:

```cpp
std::vector<TThread*> pThreads_;
```

The vector size, and therefore the number of threads to be run within 
the process, is set in the class constructor and can be chosen by the user 
through the software GUI. The class Threader has also a member function, 
Threader::thread0, that should run as one or more threads. For this pur-
pose the class provides the method Threader::startThreads(void) where, 
for each element of the pThreads vector, a thread instance is created calling 
the TThread constructor, and the function thread0 is started through the 
TThread::Run(void) method of the TThread class:

```cpp
for(int t=0; t<nOfThreads_; t++)
{
    pThreads_[t] = new TThread(threadName.str().c_str(),
                              thread0,
                              (void*) pThreadArgs_[t]);
    pThreads_[t]->Run();
}
```

The class Threader also includes the method Threader::join(void) 
whose function is to wait for all threads to be done before the method 
Threader::stopThreads(void) is called to stop the running threads calling 
the TThread::Delete(TThread*) of the TThread class. 

Therefore the required multithreaded process is created in Chewie calling 
just three consecutive methods:

Listing 7.1: The multithreaded process routine.

```cpp
startThreads(); ----> thread0(void*); ----> execute(int);
join();
stopThreads();
```

Hence, the main method of any inherited class (such as the Analysis 
and the EventConverter classes described below) will be represented by 
this routine. In addition, when the member function thread0 is started, it 
calls the virtual method Threader::execute(int) that represents the actual
function running within threads that must be implemented by a user in any inherited class.

### 7.5.2 The Event Converter

As already mentioned, two output files are created by Monicelli: the Event file and the Geometry file. The former is a ROOT file with a TTree containing the Event class. It is created during the parsing stage and it stores all data elaborated during the Monicelli track reconstruction and alignment processes. Due to the complexity of the Event class (see [37] for its definition) and to the requirement of building a relatively fast and maintainable software, the class EventConverter is defined in Chewie, as an inherited Threader class, to read and decode the Monicelli Event file from which several event information considered useful for the following analysis, are selected and stored in a TTree that is then saved in a new “converted” file. The creation and filling of this TTree is accomplished by the Data class: the addresses of this class private variables are associated to the TTree. The TTree name is CaptanTrack and is filled with one entry per track. For each entry 59 items of track information are stored. This means that the Data class has 59 private variables whose addresses are associated to the tree branches. The information contained in the CaptanTrack tree are listed and briefly described in Table D.1. There are three types of variables:

- variables with information concerning the track fit such as parameters and errors;
- 1-dimensional array variables of size 10 indexed by plane ID: 0-7 for telescope and 8-9 for DUTs;
- 2-dimensional array variables of size 4×10 indexed by plane ID (0-9) and by the hit ID (0-3) of clusters with maximum size 4

Several of these variables contain values defined in two reference frames:

- the local reference frame: it is the coordinate system of each detector, where the origin is defined from the beam spot centers on each plane; the long pitch is placed along the X axis (column direction) and the short one along the Y axis (row direction);
- the global reference frame: it is the coordinate system of the laboratory defined as in Fig. 5.3

Most of the variables are already contained in the Monicelli Event file and just copied in the CaptanTrack tree, while some of them require some calculations that are directly performed during conversion using the methods of the classes defined in the Monicelli Geometry file, that thus must be
loaded in Chewie together with the Event file when converting. Furthermore, the Geometry file also stores the calibration curve fit results that are of interest for the following analysis as well.

The EventConverter class includes a private variable defined as a vector of Event* pointers

```cpp
std::vector<Event> eventVector_;
```

whose size is defined in the class constructor and is equal to the number of threads chosen by the user through the GUI.

The reading of the input Event file, as well as the writing of data in the converted output file, is assigned to the EventManager class: it scrolls through all the Event tree entries and for each of them, the Event class is copied in the element of the EventConverter::eventVector assigned to the first “free” thread, in such a fashion that threads do not work simultaneously on the same object but each on a different memory allocation, avoiding any possible program crash. For the same purpose the Event tree reading is performed with the methods TThread::Lock() and TThread::Unlock() that prevent the threads to access simultaneously to the tree. Clearly, this “trick” can not be used frequently when dealing with threads if a real advantage in terms of program rapidity is desired.

The threads are started through the EventConverter::runConverter(void) main method that follows the same routine as in Listing 7.1. In this routine the virtual Threader::execute(int) is called and now implemented as follows:

```cpp
int EventConverter::execute(int threadNumber)
{
    TThread::Lock();
    int event = theEventManager_ -> getCurrentEvent(
                eventVector_[threadNumber]);
    TThread::Unlock();
    if(event >= 0)
        convert(eventVector_[threadNumber], event);
    return event;
}
```

Once the Event copy is performed as described above, each thread works independently and simultaneously with the others on its own copy of the Event: each thread runs the convert(Event&, int) method, where, after several calculations on the variables stored in the Event class, the CaptainTrack tree is filled through the Data class proper methods.

In the “Convert” tab of Chewie GUI (see Fig. 7.8) the user can load several Monicelli Event files to be converted consecutively. The Geometry file is automatically loaded. Furthermore, the number of threads to be started can be set as well as the number of events to be processed if the conversion of the full file is not desired.
7.5. Code development

Figure 7.8: Screenshot of the “Convert” tab of Chewie GUI where Monicelli Event files are loaded and consecutively converted in the CaptanTrack tree.

7.5.3 The Analysis Class

The Analysis class inherists from the Threader and its working principle is very similar to that of the EventConverter. A class AnalysisManager is also included in Chewie whose tasks are reading the input CaptanTrack tree, as well as writing the produced analysis histograms and distributions in a ROOT output file. The input tree is split in several parts whose number is equal to that of the threads, so that each thread can independently access to its own data set simultaneously with the other threads, therefore avoiding the lock/unlock traps mentioned in the last section. The AnalysisManager will scroll through the entries of each tree part and give a copy of the Data class to the corresponding thread when it is asked to. The threads are started by the Analysis::runAnalysis(void) main method that follows the same routine as in Listing 7.1. In this routine the virtual method Threader::execute(int) is called and now implemented as follows

```cpp
int Analysis::execute(int threadNumber)
{
    int entry;
    Data data = theAnalysisManager_ -> getCurrentData(&entry ,
              threadNumber);
    if(entry >= 0)
        analyze(data ,threadNumber);
```
7.5. Code development

```cpp
return entry;
}
```

Each thread runs the `Analysis::analyze(const Data&, int)` method which is virtual in the `Analysis` class and must be implemented in the appropriate inherited class. The routine that is executed each time the analysis is started, calls three consecutive methods:

**Listing 7.2:** The multithreaded analysis routine.

```plaintext
beginJob();
runAnalysis(); --> execute(int); --> analyze(const Data&, int);
endJob();
```

The first and the last method of the above routine are also declared virtual in the `Analysis` class and must be overridden. There are three inherited classes, each representing a study to be performed on DUT data: Efficiency, Charge, Resolution. In addition, there is a fourth Tracks class that produces the distributions of the track fit parameters and errors. In general, in the first method some class member initializations are performed and several ROOT histograms are booked; these histograms are then filled with the `Data` class variable values\(^2\) in the overridden `analyze(void)` function called by the second method. Each distribution is defined as a vector of histograms with size equal to the number of threads, so that each thread fills a separate histogram (to avoid a possible program crash). Then, in the third method, the histograms are added together to give the final distribution.

Once the number of threads has been set through the Chewie GUI, the analysis routine in Listing 7.2 is automatically started for each of the chosen studies by the “Run Analysis” button in the “Run” tab of the graphical interface (see Fig. 7.5). The event selection is performed using the `TTreeFormula` class of ROOT since it allows to apply cuts on tree variables by simply writing down a string. Since the words in the string must match the names of tree branches the GUI is equipped with check boxes corresponding to the event parameters on which the desired cut must be applied (see Fig. 7.7).

\(^2\)each time the `TTree::getEntry(int)` method is called, the addresses associated to tree branches are populated

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Chapter 8

Analysis Results

To better understand the results here reported and their implications, it is necessary to anticipate some general considerations about the expected behavior of the two detectors under test.

The single-crystal Diamond detector features a CCD practically identical to the sensor thickness, which means that all the charge carriers generated by the ionizing radiation are collected at the electrodes and none of them get trapped into the bulk. In this case, the signals on each electrode is given by the amount of charge actually collected on each of them only. Any possible signal induced on a non-collecting electrode during the drift of the carriers will be identically canceled by an opposite polarity signal in such a way that the net collected charge at the same electrode will be zeroed (see Sec. 2.5).

When such a detector is placed orthogonally to the beam, sharing of the same ionization charge among adjacent electrodes is therefore mainly driven by the carrier diffusion. Our measurements indicate an effective diffusion of the order of $10 \, \mu m$.

By way of contrast, the other detector we tested, the polycrystalline Diamond, exhibits a completely different behavior. In this case, indeed, the measured CCD is $\sim 170 \, \mu m$, well below the sensor thickness, and therefore only a small fraction of the ionization charge is collected at the electrodes. The resulting net charge-signal will be due to both induction during the carrier drift and real charge-collection at the electrodes. Sizable amount of induction is in fact measured on our detector. Charge can be shared even with electrodes (pixels) 50 microns away from the incoming track. This means that the signal always involves more than one pixel and the observed single hits are only due to the threshold cut, which for such small signals becomes severe.

Having said that, we expect an excellent performance of the single-crystal Diamond detector, fully comparable with that of an analogous state-of-art Silicon pixel detector, whereas a rather poor performance of the polycrystalline Diamond detector, which to be fully exploited certainly demands for a suitable readout chip capable to work at much lower threshold.
8.1 Analysis Procedure

The full data analysis procedure can be summarized in the following steps:

1. telescope alignment and track reconstruction operations are performed with Monicelli as described in Section 6.2;

2. once the correct telescope geometry is obtained will not be modified so that a correct telescope track sample is used at this stage to obtain projections on DUT for its alignment (see Sec. 7.3);

3. the DUT is now correctly aligned with telescope and the Monicelli Event and Geometry files are loaded in Chewie to be converted in a new file where event information are stored in a tree structure (see Appendix D);

4. the analysis is then executed on the converted file which is loaded in Chewie together with the XML file containing the configuration (selections, fiducial window limits, etc.) chosen by the user for the analysis.

In order to achieve a good statistics on DUT more than one data Run file must be loaded. The analysis routine has been designed to collect the events from several converted files. This means that the steps 1. and 2. must be executed for each data Run with the obvious requirement that the DUT operation conditions remained the same. However, if the data Runs were collected without changing anything in the geometry, like tilting or replacing the DUTs, the telescope and DUT alignment can be performed only for the first of these Runs. In fact, the obtained correct geometry can be loaded with the following Run binary files and Monicelli is then used for track reconstruction only.

8.2 Event Selection

The studies that follow use a clean sample of telescope tracks that are selected with the following quality requirements:

- \( \chi^2/\text{DoF} \leq 5 \) (see Fig. 6.7)
- 1 cluster hit on each of the 8 telescope planes
- 1 track per event (to avoid loss of precision due to wrong hit associations)
- clusters on telescope planes with a maximum size of 2 and diagonal clusters excluded
8.3. Single-crystal Diamond

- extrapolated track errors at DUT position ≤ 8 µm (see Fig. 6.9)

Only tracks satisfying these requirements are considered to study the DUT performance, while the other ones are discarded. Further requirements concerning the DUT hits are applied depending on the study. However, it is always required DUT fired cells to fall within a fiducial window:

\[
\begin{align*}
\text{single-crystal} & : & 19 \leq \text{column} \leq 33 \\
& & 42 \leq \text{row} \leq 76 \\
\text{polycrystal} & : & 29 \leq \text{column} \leq 42 \\
& & 29 \leq \text{row} \leq 58
\end{align*}
\]

The polycrystal fiducial window has been chosen in order to exclude the poor bump-bonded part of the ROC while covering the beam spot in Fig. 7.3(b). Fig. 7.3(a) shows that the single-crystal works well over the full ROC area covered by the crystal. However, in order to avoid the inclusion of events in which the adjacent hit missed because of a dead pixel or because of the crystal boundary, we prefer to exclude the boundary columns and rows and the three columns on the right.

The threshold used for single-crystal tests was about 3.5k electrons with a dispersion of about 2k electrons, whereas that for polycrystal tests was about 2.6k electrons with a dispersion of ∼ 500 electrons. The larger dispersion measured for the single-crystal is related to two quite different classes of calibration curves present on our ROC.

8.3 Single-crystal Diamond

8.3.1 Charge collection

The charge-collection properties of the single-crystal Diamond is first investigated studying the collected charge within a pixel cell as shown in Fig. 8.1. Here, the mean charge collected by the pixel pointed by the track is plotted as a function of the coordinates of the predicted track impact point on the 150 µm × 100 µm DUT pixel cell. The plot on the right is centered at the corner between four adjacent pixels. The figure shows that significant charge sharing is observed up to ∼ 20 µm away from the cell edges. This is due to the fact that intrinsic diffusion width combines in quadrature with the track resolution error giving a wider charge sharing region. It is worth noting that the fractions of signal collected at the pixel edges is ∼ 30% of that collected at the pixel centers.

The collected charge has been also measured considering two classes of events: events with only one fired pixel and those with two adjacent fired pixels. This
8.3. Single-crystal Diamond

Figure 8.1: *Left*: mean charge collected by the sole pixel pointed by the track as a function of the coordinates of the predicted track impact point on it. *Right*: mean charge collected by the sole pixel pointed by the track as a function of the coordinates of the track impact point centered at the corner between four adjacent pixels.

Last class is further divided in horizontal (2 columns and 1 row) and vertical clusters (2 rows and 1 column). The single-hit spectrum reported in Fig. 8.2(a)) shows the charge collected by the sole pixel pointed by the telescope track when the predicted impact point of the track on DUT is within the pixel cell boundaries by at least 20 $\mu$m in X and Y (see the scheme in Fig. 8.2(b)). This cut has been applied in order to minimize the inclusion of events where charge has been probably lost in adjacent pixels because of threshold cut. By way of contrast, whenever the track impact point is close to an edge by more than 20 $\mu$m in X or Y, but not simultaneously (see the schemes in Figures 8.3(c) and 8.3(d)), the sum of the charges collected by the pointed pixel and the adjacent one is plotted in Fig. 8.3. Figures 8.3(a) and 8.3(b) show the distributions of the sum of the charges collected by two adjacent pixels on the same row and on the same column, respectively.

The measured data have been fit with a Landau distribution (see Sec. 2.2), convoluted with the normal distribution of the electronic noise and the intrinsic detector fluctuations, which both contributed in broadening of the pure Landau shape. The fit results are reported in Tab. 8.1. The expected mean charge signal for the measured single-crystal CCD of 508 $\mu$m is $508 \times 36 \approx 18.3$ $\text{k electrons}$ corresponding to a Most Probable charge signal of $0.7 \times 18.3 \approx 13$ $\text{k electrons}$. These values have to be compared with the measured mean of $\sim 23$ $\text{k electrons}$ and peak of $\sim 20$ $\text{k electrons}$. This means that the conversion factor of 421 $\text{electrons per Vcal}$ unit used in calibrations is overestimated for this ROC and should be lowered by $\sim 22\%$. However, we ignore this trivial rescaling since will not affect our considerations to any
8.3. Single-crystal Diamond

Figure 8.2: On the left is the single-hit spectrum of the charge collected by the sole pixel pointed by the telescope track when the predicted impact point (indicated by the red “P” on the right) is within the dashed region of the DUT cell scheme on the right. The distribution is peaked at $\sim 20k$ electrons.

Figure 8.3: Sum of the charges collected by two adjacent pixels on the same row (left) and on the same column (right) when the predicted impact point (indicated by the red “P” in the lower schemes) is within the dashed region of the corresponding scheme. Both the distributions are peaked at $\sim 20k$ electrons.
8.3. Single-crystal Diamond

Table 8.1: Results of the fits performed on the distributions of the charge collected by the single-crystal Diamond Detector. All the values are quoted in electron units.

<table>
<thead>
<tr>
<th>Event type</th>
<th>Histogram Mean</th>
<th>Landau MPV</th>
<th>Landau Width</th>
</tr>
</thead>
<tbody>
<tr>
<td>single-hit</td>
<td>22720</td>
<td>19710 ± 12</td>
<td>1033 ± 9</td>
</tr>
<tr>
<td>horizontal cluster</td>
<td>23820</td>
<td>19670 ± 222</td>
<td>1852 ± 198</td>
</tr>
<tr>
<td>vertical cluster</td>
<td>24120</td>
<td>19770 ± 48</td>
<td>1854 ± 75</td>
</tr>
<tr>
<td>Expected Values</td>
<td>18288</td>
<td>12802</td>
<td></td>
</tr>
</tbody>
</table>

extent. As reported in Tab. 8.1 the most probable signal collected by two adjacent pixels on either the same column or the same row is consistent with the value obtained for single-hit events, which means that the full particle signal charge is collected even in sharing cases. The observed slight increase of the mean value is expected as a bias introduced by the threshold cut.

Figure 8.4: The black points show the average collected charge by the sole pixel pointed by the track as a function of the distance of the track impact point from the boundary of two adjacent pixels on the same row (left) or on the same column (right). The red points show the average sum of charges collected by the pixel pointed by the track and the adjacent one on the same row (left) or on the same column (right).

The charge-collection features are further investigated in Fig. 8.4. Here, the average collected charge is plotted as a function of the distance of the track impact point from the boundary of two adjacent pixels on the same row (Fig. 8.4(a)) and on the same column (Fig. 8.4(b)). To avoid additional sharing with other pixels, the track impact point is required to stay well
within the row edges in the former case and the column edges for the latter. The same fiducial cuts of 20 \( \mu m \) in X or Y as mentioned above have been applied. The two types of data points refer to the mean charge collected by the sole pixel pointed by the track (black points) and the average sum of charges collected by two adjacent pixels (red points)\(^1\). It turns out that the total amount of charge collected is almost constant with a marginal deficit of few percent in crossing the region between two adjacent pixels due to threshold cut. The black points indicate a charge sharing region extending for \( \sim 20 \mu m \) away from the pixel edges, as already observed on the plots of Fig. 8.1.

### 8.3.2 Efficiency

We define the detector efficiency \( \varepsilon \) as the ratio between the number of tracks having an associated hit on the DUT plane and the total number of reconstructed tracks. The tracks must satisfy the selections in Sec. 8.2. A pixel hit on the DUT plane is associated to a track if and only if it is the pointed by the track or one of the eight nearby pixels. The complete two-dimensional point detection efficiency of the single-crystal is shown in Fig. 8.5. Here, the efficiency of the single pixel pointed by the track combined with the efficiency of the eight nearby pixels, is plotted as a function of the predicted track impact point on it. It turns out that the single-crystal efficiency is constant and practically 100% across the whole cell without showing any appreciable degradation even in the pixel edges.

\(^1\)A common saturation limit of 35k electrons was imposed on both single-hit and double-hit signal charge to obtain consistent and directly comparable average values.
8.3. Single-crystal Diamond

![Figure 8.6: One-dimensional detection efficiency of the single-crystal. The black points show the detection efficiency of the sole pixel pointed by the track as a function of the distance of the track impact point from the boundary of two adjacent pixels on the same row (left) and on the same column (right). The red points show the combined efficiency of the pixel pointed by the track and the adjacent one.](image)

The resulting average detection efficiency is

\[ \varepsilon = 0.998601 \pm 0.00006 \]

where the error is computed for the binomial distribution as

\[ \sigma_{\varepsilon} = \sqrt{\frac{\varepsilon(1 - \varepsilon)}{N_{\text{track}}}} \]  

(8.1)

The same conclusion is reached for the one-dimensional plots in Fig. 8.6 where the measured efficiency is shown as a function of the distance of the track impact point from the boundary of two adjacent pixels on the same row (Fig. 8.6(a)) and on the same column (Fig. 8.6(b)). In order to exclude additional sharing with other pixels, the track impact point is required to stay well within the row edges in the former case and the column edges for the latter. The same fiducial cuts discussed for double-hit studies in the previous section, of 20 µm in X or in Y was applied. In these plots the two types of data points refer to the sole efficiency of the pixel pointed by the track (black points) and the combined efficiency of two adjacent pixels (red points). As expected, the single-crystal combined efficiency is constant in both the views.
8.3.3 Spatial resolution

The best achievable spatial resolution in case of charge sharing between two adjacent pixels has been investigated studying the correlation between the position and the charge asymmetry $\eta$, defined as

$$\eta = \frac{Q_L - Q_R}{Q_L + Q_R}$$  \hspace{1cm} (8.2)

where $Q_L$ is the charge collected by the pixel on the left side and $Q_R$ that on the right side. The plots in Fig. 8.7 show the actual two-dimensional correlations (Figures 8.7(a) and 8.7(b)) and the average values computed for each bin of $\eta$ of the distance of the track impact point from the boundary of two adjacent pixels (Figures 8.7(c) and 8.7(d)). The usual fiducial cuts of 20 $\mu$m in X or Y have been applied. Energetic $\delta$ electrons, which could bias this correlation, are removed by rejecting events with a pulse height exceeding 30k electrons. The $\eta$-function completely characterized the charge division between adjacent pixels, and presents non-linearity at the ends due to the Gaussian shape of the diffusion cloud, as expected when the detector is orthogonal to the tracks. In the plots shown in Fig. 8.7 the curve does not reach the two extremes value of +1 and -1 just because of the threshold cut. The central part of the function can be assumed as linear and the coordinate $x_m$ of the measured hit can be computed as

$$x_m = p_0 + p_1 \eta$$  \hspace{1cm} (8.3)

where $p_0$ and $p_1$ are the intercept and the slope of the linear fit performed over the linear central region of the plots in figures 8.7(c) and 8.7(d). The obtained fit parameters are

<table>
<thead>
<tr>
<th>Clustering</th>
<th>$p_0$</th>
<th>$p_1$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Horizontal cluster</td>
<td>$1.4 \pm 0.2$</td>
<td>$-13.7 \pm 0.5$</td>
</tr>
<tr>
<td>Vertical cluster</td>
<td>$-0.6 \pm 0.1$</td>
<td>$-12.1 \pm 0.3$</td>
</tr>
</tbody>
</table>

It is worth noting that the two slopes are completely consistent and their possible difference can be for sure attributed to a residual tiny rotation angle error in the detector alignment.

Limiting ourselves to the linear portion of the $\eta$-curve and rejecting events with a pulse height exceeding 30k electrons, we can compute the coordinate of the measured cluster-hit and the residual with respect to the telescope track. The resulting X and Y unconstrained residuals are shown in Fig. 8.8 for double hits on the same row (Fig. 8.8(a)) and on the same column (Fig. 8.8(b)), respectively. To extract the resolution $\sigma_{DUT}$ of the DUT, the extrapolated error $\sigma_{tel}$ of the telescope track has to be subtracted in
8.3. Single-crystal Diamond

Figure 8.7: The upper plots show two-dimensional correlations between the position and the charge asymmetry $\eta$ for double hits on the same row (left) and on the same column (right). The lower plots show the average value for each bin of $\eta$ of the distance of the track impact point from the boundary of two adjacent pixels on the same row (left) and on the same column (right).

quadrature from the width $\sigma_M$ of the measured residual spectrum obtained from a fit with a gaussian distribution:

$$\sigma_{DUT} = \sqrt{\sigma_m^2 - \sigma_{tel}^2}$$

The X and Y telescope resolutions are 7.1 and 6.7 $\mu m$, respectively (mean values of the spectra in Fig. 6.9), resulting in the single-crystal resolution of $\sim 6 \mu m$ in both the coordinates as reported in Tab. 8.2.
8.4. Polycrystal Diamond

8.4.1 Charge collection

The same studies as in the previous sections have been carried out in order to investigate the charge-collection features of the polycrystal Diamond as well. In the first investigation we study the collected charge within a pixel cell as shown in Fig. 8.9. Here, the mean charge collected by the sole pixel pointed by the track is plotted as a function of the coordinates of the predicted track impact point on the 150 µm × 100 µm DUT pixel cell. The plot on the right is centered at the corner between four adjacent pixels. It turns out that sizable charge loss is observed up to ∼35 µm away from the cell edges where the fraction of signal collected by the pixel pointed by the track becomes ∼12% of that at the pixel center.

As suggested by the previous considerations, single-hit events are studied requiring the predicted track impact point on the cell to stay within the pixel cell boundaries by at least 35 µm in X and Y. The corresponding collected charge spectrum is shown in Fig. 8.10. On the other hand, whenever the

---

**Figure 8.8**: X (left) and Y (right) unconstrained residual spectra for double hits on the same row and on the same column, respectively. The spectra were fit with a gaussian distribution.

**Table 8.2**: Widths of the residual distributions resulted from the Gaussian fit, together with the corresponding DUT resolutions. The values are quoted in µm.

<table>
<thead>
<tr>
<th>Width</th>
<th>Resolution</th>
</tr>
</thead>
<tbody>
<tr>
<td>X</td>
<td>9.3</td>
</tr>
<tr>
<td>Y</td>
<td>9.2</td>
</tr>
</tbody>
</table>
8.4. Polycrystal Diamond

![Figure 8.9](image)

**Figure 8.9:** *Left:* mean charge collected by the sole pixel pointed by the track as a function of the coordinates of the predicted track impact point on it. *Right:* mean charge collected by the sole pixel pointed by the track as a function of the coordinates of the track impact point centered at the corner between four adjacent pixels.

A track impact point is close to an edge by more than 35 µm in X or Y, but not simultaneously, the sum of the charges collected by the pointed pixel and the adjacent one is plotted in Fig. 8.11 for horizontal- (Fig. 8.11(a)) and vertical-cluster 8.11(b) events. The measured data have been fit with a Landau distribution convoluted with a normal distribution as already done for the single-crystal. The fit results are reported in Tab. 8.3. Since the polycrystalline structure of this detector causes a large fraction of the released charge to be trapped, the mean collected charge at the center of the cell for single-hit events is peaked at the very low value of $\sim 3.8k$ electrons with a mean of $\sim 5.6k$ electrons. The expected mean collected signal for the measured polycrystal Diamond CCD of 172 µm is $172 \times 36 \approx 6.2k$ electrons corresponding to a Most Probable charge signal of $0.7 \times 6.2 \approx 4.3k$ electrons. The measured values are not far from the expected ones and become even closer if we consider that charge is on average spread over more than one pixel by induction. This issue is not present when measuring CCD with “infinite” parallel-plate electrodes. A similar bias effect is present when measuring double-hit signal. Because of the rather low signal and the threshold cut, events firing two discriminators are preferably characterized by a total charge higher than the average. This is clearly indicated by the measure MPV which is $\sim 1.8$ times higher. Just from these results one can argue about the need of a more suitable electronics with much lower and precise threshold. Obviously, our results and mainly those concerning spatial resolution are severely limited by this fact. Unfortunately, so far, such a readout chip is not available.
8.4. Polycrystal Diamond

Figure 8.10: Single-hit spectrum of the charge collected by the sole pixel pointed by the telescope track when the predicted impact point is within the pixel cell boundaries by at least 35 µm in X and Y. The distribution is peaked at \( \sim 3.8k \) electrons.

![Single-hit spectrum](chart1)

Figure 8.11: Sum of the charges collected by two adjacent pixels on the same row (left) and on the same column (right) when the predicted impact point is close to an edge by more than 35 µm in X and Y, respectively. Both the distributions are peaked at more than 6k electrons, which is twice the MPV obtained for the single-hit case.

![Sum of charges](chart2)

The significant presence of the induction is also evident in the 1-D charge plots in Fig. 8.12. Here, the average collected charge is plotted as a function of the distance of the track impact point from the boundary of two adjacent pixels on the same row (Fig. 8.12(a)) and on the same column (Fig. 8.12(b)). The same fiducial cuts of 35 µm in X or Y as mentioned before have been applied. The two types of data points refer to the mean charge collected by the sole pixel pointed by the track (black points) and the average sum of charges collected by two adjacent pixels (red points).\(^2\) It turns out that

\(^2\)A common saturation limit of 10k electrons was imposed on both single-hit and
charge is shared even at 50 microns away from the pixel edges for both the horizontal and vertical cases indicating a strong presence of induction effects.

Table 8.3: Results of the fits performed on the distributions of the charge collected by the polycrystal Diamond. All the values are quoted in electron units.

<table>
<thead>
<tr>
<th>Event type</th>
<th>Histogram Mean</th>
<th>Landau MPV</th>
<th>Landau Width</th>
</tr>
</thead>
<tbody>
<tr>
<td>single-hit</td>
<td>5625</td>
<td>3789 ± 13</td>
<td>838 ± 10</td>
</tr>
<tr>
<td>horizontal cluster</td>
<td>9033</td>
<td>6615 ± 42</td>
<td>594 ± 36</td>
</tr>
<tr>
<td>vertical cluster</td>
<td>8920</td>
<td>6386 ± 82</td>
<td>639 ± 72</td>
</tr>
<tr>
<td><strong>Expected Values</strong></td>
<td><strong>6192</strong></td>
<td><strong>4334</strong></td>
<td></td>
</tr>
</tbody>
</table>

Figure 8.12: The black points show the average collected charge by the sole pixel pointed by the track as a function of the distance of the track impact point from the boundary of two adjacent pixels on the same row (left) or on the same column (right). The red points show the average sum of charges collected by the pixel pointed by the track and the adjacent one on the same row (left) or on the same column (right).

double-hit signal charge to obtain consistent and directly comparable average values.
8.4.2 Efficiency

The complete two-dimensional point detection efficiency (already defined in Sec. 8.3.2) of the polycrystal is shown in Fig. 8.5. It turns out that efficiency begins to decrease already at \( \sim 35 \) microns from the pixel edges where a fraction of the signal begins to be lost because induction or diffusion and the charge signal easily falls below the threshold. This is also visible in the one-dimensional plots in Fig. 8.14 where the measured detection efficiency is shown as a function of the distance of the track impact point from the boundary of two adjacent pixels on the same row (Fig. 8.14(a)) and on the same column (Fig. 8.14(b)). In these plots the two types of data points refer to the sole efficiency of the pixel pointed by the track (black points) and the combined efficiency of two adjacent pixels (red points) when the track impact point is close to an edge by more than 35 \( \mu m \) in X or in Y.

The resulting average detection efficiency is

\[
\varepsilon = 0.638164 \pm 0.00051
\]

where the error is computed using the binomial distribution as in Eq. 8.1. It is clear that the polycrystal inefficiency is due to the fact that the threshold is too high to efficiently operate with polycrystal charge signal.

**Figure 8.13:** Two-dimensional detection efficiency of the polycrystal: the plot shows the detection efficiency of the single pixel pointed by the track combined with the detection efficiency of the eight nearby pixels as a function of the predicted track impact point on it.
8.4. Polycrystal Diamond

Figure 8.14: One-dimensional detection efficiency of the polycrystal. The black points show the detection efficiency of the sole pixel pointed by the track as a function of the distance of the track impact point from the boundary of two adjacent pixels on the same row (left) and on the same column (right). The red points show the combined efficiency of the pixel pointed by the track and the adjacent one.

8.4.3 Spatial resolution

As already carried out for the single-crystal the best achievable spatial resolution in case of charge sharing between two adjacent pixels is investigated studying the correlation between the position and the charge asimmetry $\eta$ defined as in Eq. 8.2. The plots in Fig. 8.16 show the actual two-dimensional correlations (Figures 8.16(a) and 8.16(b)) and the average values computed for each bin of $\eta$ of the distance of the track impact point from the boundary of two adjacent pixels (Figures 8.16(c) and 8.16(d)). The usual fiducial cuts of 35 $\mu$m in X or Y have been applied and energetic $\delta$ electrons are removed by rejecting events with a pulse height exceeding 10k $electrons$. The correlation results very weak meaning that the sharing of charge signal is over a wide region and certainly not due to the simple diffusion of carriers. Another effect, such as signal induction of carriers that are trapped in the bulk, should contribute and mask the diffusion. In addition, the errors on calibration, which become relatively more important for these small signals, increase the eta-dispersion. The measured correlation is about 1/2 that of single-crystal Diamond. The same linear algorithm described before for the single-crystal studies has been applied to compute the coordinate of the measured hit (see Eq. 8.3) and the corresponding unconstrained residuals. The parameters obtained from the fit of the central linear region of the $\eta$-curve are
8.4. Polycrystal Diamond

The resulting X and Y unconstrained residuals are shown in Fig. 8.15 for double hits on the same row (Fig. 8.8(a)) and on the same column (Fig. 8.15(b)), respectively. The detector resolution is computed as in Eq. 8.4 subtracting the extrapolated error of the telescope track from the width of the measured residual spectrum obtained from a fit with a gaussian distribution. The X and Y telescope resolutions are 7.1 and 6.7 $\mu$m, resulting in the resolutions of $\sim 32 \mu$m and $\sim 30 \mu$m in X and Y, respectively (see Tab. 8.4). The measured poor resolution is expected in this case since the correlation is very weak and dominated by the large fluctuations. To draw final conclusion about polycrystal Diamond an electronic capable to properly handle small signals is required and possibly a much thinner detector to contain induction effects is advisable.

![X and Y unconstrained residual spectra](image)

**Figure 8.15:** X (left) and Y (right) unconstrained residual spectra for double hits on the same row and on the same column, respectively. The spectra were fit with a gaussian distribution.

**Table 8.4:** Widths of the residual distributions resulted from the Gaussian fit, together with the corresponding DUT resolutions. The values are quoted in $\mu$m.

<table>
<thead>
<tr>
<th>Width</th>
<th>Resolution</th>
</tr>
</thead>
<tbody>
<tr>
<td>X</td>
<td>32.5</td>
</tr>
<tr>
<td>Y</td>
<td>30.0</td>
</tr>
</tbody>
</table>
8.4. Polycrystal Diamond

![Figure 8.16](image)

**Figure 8.16:** The upper plots show two-dimensional correlations between the position and the charge asymmetry, $\eta$ for double hits on the same row (left) and on the same column (right). The lower plots show the average value for each bin of $\eta$ of the distance of the track impact point from the boundary of two adjacent pixels for double hits on the same row (left) and on the same column (right).
Chapter 9

Conclusions

This thesis work has been focused on the characterization of a single-crystal and a polycrystal Diamond Detectors for the CMS Pixel Tracker Upgrade. The two detectors were tested on beam at the Test Beam Facility (FTBF) of the Fermi National Accelerator Laboratory within a project aimed to understand if new radiation-hard sensors are capable of resisting at the high fluences expected at the sLHC.

The Diamond Detectors under test were placed in the middle of a CMS pixel based detector telescope. A precision tracking and alignment of the telescope with the beam-test data was performed with the dedicated software Monicelli. Once a precise alignment is obtained, the reconstructed tracks were used to study charge-collection, spatial resolution and efficiency performance of the detector under test, through the analysis software Chewie, that I designed and developed for these purposes.

The results of the studies carried out on the two Diamond Detectors highlight their greatly different intrinsic natures. On one hand, the single-crystal CCD is sufficiently large to collect all the charge carriers generated by the ionizing radiation leading to practically 100% detection efficiency and to a precise spatial resolution of $\sim 6 \, \mu m$ for two adjacent hits. On the other hand, the polycrystal, that suffers from a large charge trapping, exhibits a small CCD resulting in a very low charge-signal affected by strong induction effects. It is clear from the results that the threshold cut severely affects the performance of this detector, even if the minimum achievable threshold by PSI ROC was used. A suitable readout chip capable to deal with low signals (order of a few thousands electrons) and to operate at much lower threshold (\(~ 1000\) electrons), is certainly needed to fully exploit the polycrystalline Diamond Detector. Furthermore, since a sizable fraction of the signal is spread over the nearby pixels by induction, thus lowering the signal on the central pixel, detectors much thinner than 500 $\mu m$ are suggested for this CCD value. A simple simulation shows that a detector with thickness 1.5 times the CCD, i.e. $172 \times 1.5 = 258 \, \mu m$, is sufficient to strongly limit the induction while
collecting \(~\sim\) 90\% of the signal delivered by a 500\textmu m thickness detector. However, although the single-crystal Diamond appears from these results ideal in many respects, is nowadays produced in small quantities and sizes (5\times5 \text{mm}^2) not certainly adequate for the construction of large size detectors as those required in CMS. The polycrystals, instead, are already available in 4” wafers and, therefore, represent the only conceivable solution for the CMS Upgrade.

Having said that, it is clear that the Diamond, thanks to its intrinsic radiation hardness, arises from these results as an excellent candidate for the future CMS Pixel Tracker Upgrade.

In conclusion my results demonstrate that Diamond, thanks to its intrinsic radiation hardness, is as an excellent candidate for the future CMS Pixel Upgrade.
Consider a mobile charge in the presence of any number of grounded electrodes, A, B, C, D. Surround the charge \( q \) with a small equipotential sphere. Then, if \( V \) is the potential of the electrostatic field, in the region between conductors

\[
\nabla^2 V = 0
\]

Call \( V_q \) the potential of the small sphere and note that \( V = 0 \) on the conductors. Applying Gauss' law yields

\[
\int \frac{\partial V}{\partial n} \, ds = 4\pi q .
\]

where \( \partial V/\partial n \) indicates differentiation with respect to the outward normal to the surface and the integral is taken over the surface of the sphere.

Now consider the same set of conductors with the charge removed, conductor A raised to unit potential, and the other conductors grounded. Call the potential of the field in this case \( V' \), so that

\[
\nabla^2 V' = 0
\]

in the space between conductors, including the point where the electron was situated before. Call the new potential of this point \( V'_q \). Green's theorem states that

\[
\int (V'\nabla^2 V - V\nabla^2 V') \, dv = - \int \left(V'_q \frac{\partial V}{\partial n} - V \frac{\partial V'}{\partial n} \right) \, ds .
\]
Choose the volume to be that bounded by the conductors and the tiny sphere. Then the left-hand side is zero and the right-hand side may be divided into three integrals:

1. Over the surfaces of all conductors except $A$. This integral is zero since on these surfaces $V = V' = 0$.

2. Over the surface of $A$. As $V' = 1$ and $V = 0$ for conductor $A$ this reduces to

$$- \int_{\text{surface } A} \frac{\partial V}{\partial n} ds$$

3. Over the surface of the sphere. This becomes

$$- V' \int_{\text{sphere's surface}} \frac{\partial V}{\partial n} ds + V \int_{\text{sphere's surface}} \frac{\partial V'}{\partial n} ds$$

The second of the integrals in (3) is zero by Gauss’ law, since it is the negative of the charge enclosed, but in this case the charge is removed. Combining these three integrals yields

$$0 = - \int_{\text{surface } A} \frac{\partial V}{\partial n} ds - V' \int_{\text{sphere's surface}} \frac{\partial V}{\partial n} ds = 4\pi Q_A - 4\pi qV' \quad (A.5)$$

or

$$Q_A = qV' \quad (A.6)$$

If the charge $q$ moves in direction $x$, the current on electrode $A$ is

$$i_A = \frac{dQ_A}{dt} = q \frac{dV_q'}{dt} = q \left( \frac{\partial V_q'}{\partial x} \frac{dx}{dt} \right) \quad . \quad (A.7)$$

Since the charge’s velocity $v = dx/dt$, the induced current on electrode $A$ is

$$i_A = qv \frac{\partial V_q'}{\partial x} \equiv qv \frac{\partial \phi_w}{\partial x} \quad , \quad (A.8)$$

where $\phi_w$ is the weighting potential. The induced current can also be expressed in terms of the weighting field $E_w = -\partial \phi_w/\partial x$, so that

$$i_A = - q \frac{\partial E_w}{\partial x} \quad (A.9)$$
Appendix B

Track Fit and Alignment Algorithms

B.1 Track Fit

Hits associated to each track candidate are fitted with the least-squares method. Since there is no magnetic field, the particle trajectories should be fitted with straight lines that in the global telescope coordinate system are parametrized as:

\[
\begin{align*}
  x &= s_x z + q_x \\
  y &= s_y z + q_y
\end{align*}
\] (B.1)

The method consists of minimizing the residuals between the coordinates of the hit measured on the detector \(i\) and the ones of the point predicted by the track at the same \(Z\) position of the measured hit. Denoting the measured hit coordinates in the global reference frame as \((x_{m,i}, y_{m,i}, z_{m,i})\), and the predicted point ones as \((x_i, y_i)\), the residuals are defined as

\[
\begin{align*}
  x_{m,i} - x_i &= x_{m,i} - (s_x z_{m,i} + q_x) \\
  y_{m,i} - y_i &= y_{m,i} - (s_y z_{m,i} + q_y)
\end{align*}
\] (B.2)

The function to be minimized to compute track coefficients is

\[
\chi^2 = (\hat{y} - A\tilde{\vartheta})^T V^{-1} (\hat{y} - A\tilde{\vartheta})
\] (B.3)

where \(\hat{y}\) is the measurements array, \(\tilde{\vartheta}\) the parameters vector and \(A\) the \(N \times 4\) coefficients transport matrix, defined as
B.2. Alignment Algorithm

\[
\bar{y} = \begin{bmatrix} x_{m,1} \\ y_{m,1} \\ \vdots \\ x_{m,N} \\ y_{m,N} \end{bmatrix}, \quad \bar{\vartheta} = \begin{bmatrix} s_x \\ q_x \\ s_y \\ q_y \end{bmatrix}, \quad \mathcal{A} = \begin{bmatrix} z_{m,1} & 1 & 0 & 0 \\ 0 & 0 & z_{m,1} & 1 \\ \vdots & \vdots & \vdots & \vdots \\ z_{m,N} & 1 & 0 & 0 \\ 0 & 0 & z_{m,N} & 1 \end{bmatrix}
\] (B.4)

Furthermore, the error matrix \( \mathcal{V} \) is given by the cluster errors \( \sigma_{x_{m,i}} \) and \( \sigma_{y_{m,i}} \) in the global coordinate system. Since measured hits on each plane are assumed independent the \( \mathcal{V} \) matrix is represented by an \( N \times N \) block diagonal matrix with blocks holding the \( x-y \) correlations due to 3D plane rotations:

\[
\mathcal{V} = \begin{bmatrix} \sigma_{x_{m,1},x_{m,1}} & \sigma_{x_{m,1},y_{m,1}} & 0 & \cdots & 0 \\ \sigma_{x_{m,1},y_{m,1}} & \sigma_{y_{m,1},y_{m,1}} & 0 & \cdots & 0 \\ 0 & 0 & \ddots & \ddots & \vdots \\ 0 & 0 & \cdots & \sigma_{x_{m,N},x_{m,N}} & \sigma_{x_{m,N},y_{m,N}} \\ 0 & 0 & \cdots & \sigma_{x_{m,N},y_{m,N}} & \sigma_{y_{m,N},y_{m,N}} \end{bmatrix}
\] (B.5)

By putting the derivatives of \( \chi^2 \) with respect to \( \bar{\vartheta} \), we get the explicit solution of the minimization

\[
\bar{\vartheta} = (\mathcal{A}^T \mathcal{V}^{-1} \mathcal{A})^{-1} \mathcal{A}^T \mathcal{V}^{-1} \bar{y}
\] (B.6)

and the covariance matrix of the parameters vector \( \bar{\vartheta} \) is

\[
\mathcal{V}_{\bar{\vartheta}} = (\mathcal{A}^T \mathcal{V}^{-1} \mathcal{A})^{-1}.
\] (B.7)

B.2 Alignment Algorithm

Starting from the observation that the telescope detectors are slightly roto-translated from its supposed nominal position by an unknown quantity, a least-square minimization algorithm of the 1\textsuperscript{st}-order roto-translation corrections has been implemented. It consists of minimizing the unconstrained residuals defined as the distances between the measured hit associated with a track on the detector \( i \) and the predicted point on that plane given by the fit of all other hits associated to that track. This means that, when computing the residual on a detector, its hit is removed from the track fit. It is convenient to work in the local coordinate system in order to avoid dependence upon errors in the assumed roto-translation parameters and to exploit
the fact that the error matrix is diagonal. Denoting the measured hit coordinates in the local reference frame as \((x'_{m,i}, y'_{m,i})\), and the predicted point ones as \((x'_{p,i}, y'_{p,i})\), the X and Y residuals \(r_{x,i}\), \(r_{y,i}\) are defined as

\[
\begin{align*}
    r_{x,i} &= x'_{m,i} - x'_{p,i} \\
    r_{y,i} &= y'_{m,i} - y'_{p,i}
\end{align*}
\] (B.8)

For the plane \(i\), the 0th-order transformation from the global reference frame to the local one is

\[
\begin{bmatrix}
    x' \\
    y' \\
    z'
\end{bmatrix} = R
\begin{bmatrix}
x \\
y \\
z - z_0
\end{bmatrix}
\] (B.9)

where \(R\) is the 0th-order rotation matrix given by

\[
R = R_\alpha R_\beta R_\gamma
\] (B.10)

with

\[
R_\alpha = \begin{bmatrix}
1 & 0 & 0 \\
0 & \cos \alpha & \sin \alpha \\
0 & -\sin \alpha & \cos \alpha
\end{bmatrix}
\] (B.11)

\[
R_\beta = \begin{bmatrix}
\cos \beta & 0 & -\sin \beta \\
0 & 1 & 0 \\
\sin \beta & 0 & \cos \beta
\end{bmatrix}
\] (B.12)

\[
R_\gamma = \begin{bmatrix}
\cos \gamma & \sin \gamma & 0 \\
-\sin \gamma & \cos \gamma & 0 \\
0 & 0 & 1
\end{bmatrix}
\] (B.13)

Introducing the 1st-order roto-translation corrections, the transformation in Eq. B.9 becomes

\[
\begin{bmatrix}
    x' \\
    y' \\
    z'
\end{bmatrix} = \delta R \cdot R
\begin{bmatrix}
x \\
y \\
z - z_0
\end{bmatrix} + \begin{bmatrix}
\delta x' \\
\delta y' \\
\delta z'
\end{bmatrix}
\] (B.14)

where \(\delta R\) is the 1st-order Taylor expanded matrix of the 0th-order rotation matrix \(R\) and is given by

\[
\delta R = \delta R_\alpha \delta R_\beta \delta R_\gamma
\] (B.15)

with
\[ \delta R_\alpha = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & \delta \alpha \\ 0 & -\delta \alpha & 1 \end{bmatrix} \]  
(B.16)

\[ \delta R_\beta = \begin{bmatrix} 1 & 0 & -\delta \beta \\ 0 & 1 & 0 \\ \delta \beta & 0 & 1 \end{bmatrix} \]  
(B.17)

\[ \delta R_\gamma = \begin{bmatrix} 1 & \delta \gamma & 0 \\ -\delta \gamma & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \]  
(B.18)

The inverse transformation is

\[ \begin{bmatrix} x \\ y \\ z - z_0 \end{bmatrix} = \mathcal{R}^{-1}\delta R\mathcal{R}^{-1} \begin{bmatrix} x' - \delta x'' \\ y' - \delta y'' \\ z' - \delta z'' \end{bmatrix} \]

\[ = (\mathcal{R}_\alpha \mathcal{R}_\beta \mathcal{R}_\gamma)^{-1} \mathcal{R}(\delta \alpha, \delta \beta, \delta \gamma)^{-1} \begin{bmatrix} x' - \delta x'' \\ y' - \delta y'' \\ z' - \delta z'' \end{bmatrix} \]

\[ = \mathcal{R}_{-\gamma} \mathcal{R}_{-\beta} \mathcal{R}_{-\alpha} \mathcal{R}(-\delta \alpha, -\delta \beta, -\delta \gamma) \begin{bmatrix} x' - \delta x'' \\ y' - \delta y'' \\ z' - \delta z'' \end{bmatrix} \]  
(B.19)

The intersection of a track with a generic plane is

\[
\begin{cases}
x_p = s_x z + q_x = s_x(z - z_0) + q_x + s_x z_0 \\
y_p = s_y z + q_y = s_y(z - z_0) + q_y + s_y z_0
\end{cases}
\]  
(B.20)

Replacing Eq. B.19 in the last equation, the latter is then written in the local reference frame. Furthermore, demanding \( z' = 0 \) with \( R \equiv \delta R \cdot \mathcal{R} \), the following is obtained

\[
\begin{cases}
R_{1,1}^{-1}x_p' + R_{1,2}^{-1}y_p' - R_{1,3}^{-1}\delta z'' = s_x(R_{3,1}^{-1}x_p' + R_{3,2}^{-1}y_p' - R_{3,3}^{-1}\delta z'' + z_0) + q_x \\
R_{2,1}^{-1}x_p' + R_{2,2}^{-1}y_p' - R_{2,3}^{-1}\delta z'' = s_y(R_{3,1}^{-1}x_p' + R_{3,2}^{-1}y_p' - R_{3,3}^{-1}\delta z'' + z_0) + q_y
\end{cases}
\]  
(B.21)

with the replacement

\[
\begin{align*}
x_p' &\equiv x_p' - \delta x'' \\
y_p' &\equiv y_p' - \delta y''
\end{align*}
\]  
(B.22)

It is easy to verify that Eq. B.21 can also be written as
The function to be minimized is

\[ \chi^2 = \sum_{i=1}^{N} (\bar{r}_i - \mathcal{A}_i \delta \bar{\vartheta}_i)^T \mathcal{V}^{-1} (\bar{r}_i - \mathcal{A}_i \delta \bar{\vartheta}_i) \tag{B.25} \]

where

\[
\mathcal{A}_i = \begin{bmatrix}
\begin{bmatrix}
\cdots \\
1^{\delta \alpha} \\
1^{\delta \beta} \\
1^{\delta \gamma} \\
1^{\delta x} \\
1^{\delta y} \\
1^{\delta z}
\end{bmatrix} & \begin{bmatrix}
\cdots \\
\cdots \\
\cdots \\
\cdots \\
\cdots \\
\cdots
\end{bmatrix}
\end{bmatrix}
\]

\[
\bar{r}_i = \begin{bmatrix}
\begin{bmatrix}
\cdots \\
r_{x,i}^{1} \\
r_{y,i}^{1} \\
r_{x,i}^{M} \\
r_{y,i}^{M}
\end{bmatrix} & \begin{bmatrix}
\cdots \\
\cdots \\
\cdots \\
\cdots \\
\cdots
\end{bmatrix}
\end{bmatrix}
\]

and \( \mathcal{V} \) is the diagonal covariance matrix of the hit errors in the local coordinate system

\[
\mathcal{V}^{-1} = \begin{bmatrix}
\begin{bmatrix}
1/\sigma_{x,x}^{1} & 0 & 0 \\
0 & 1/\sigma_{y,y}^{1} & 0 \\
0 & 0 & \ddots
\end{bmatrix} & 0 & 0 \\
0 & 0 & 0 & \begin{bmatrix}
1/\sigma_{x,x}^{M} & 0 \\
0 & 1/\sigma_{y,y}^{M}
\end{bmatrix}
\end{bmatrix} \tag{B.27}
\]

Once the roto-translation parameters are minimized for all the planes on the same set of 0th-order tracks, the 0th-order geometry should be updated, the tracks refitted and another iteration of alignment retried for the updated set of tracks.
Appendix C

The Threader Class

Listing C.1: The Threader class header.

```cpp
#ifndef _Threader_h_
#define _Threader_h_

#include <Rtypes.h>
#include <vector>
#include <map>
#include "Data.h"

class TThread;

class Threader
{
public:
  Threader(int nOfThreads = 1);
  virtual ~Threader();

  static void* thread0(void* arg); // functions running as threads
  virtual int execute(int threadNumber); // user function called by thread0

  virtual int startThreads(); // launch all threads
  virtual int stopThreads(); // stop all threads
  virtual int join(); // wait for threads to be done

  void setNumberOfThreads(int numberOfThreads);

  bool getThreadsRun(){return threadsRun_;}

protected:
  int nOfThreads_; // flags for quick abort of loops within threads

  bool threadsRun_; // flags for quick abort of loops within threads

};
```

133
std::vector<TThread*> pThreads_; // Thread pointer
std::vector<ThreadArgs*> pThreadArgs_; // Thread arguments

/////////////////////////////////////////
class ThreadArgs
{
public:
  ThreadArgs(Threader* threader, int threadNumber) :
    theThreader_(threader),
    threadNumber_(threadNumber),
    funcRunning_(false) {}
  ~ThreadArgs(){};

  Threader* getThreader (void) { return theThreader_; }
  int getThreadId (void) { return threadNumber_; }
  bool getFuncRunning (void) { return funcRunning_; }
  void setFuncRunning (bool running){ funcRunning_ = running; }

private:
  Threader* theThreader_;
  int threadNumber_;   
  bool funcRunning_;   
};
#endif
Listing C.2: The Threader class methods implementation.

Threader::Threader(int n0fThreads) :
n0fThreads_(n0fThreads)
,threadsRun_(false)
{
    setNumberOfThreads(n0fThreads);
}

void Threader::setNumberOfThreads(int numberOfThreads)
{
    stopThreads();
pThreads_.clear();
pThreadArgs_.clear();
n0fThreads_ = numberOfThreads;
for(int t=0; t<n0fThreads_; t++)
{
    pThreads_.push_back(0);
pThreadArgs_.push_back(0);
}
}

int Threader::startThreads()
{
    threadsRun_ = true;

    for(int t=0; t<n0fThreads_; t++)
    {
        if(!(pThreads_[t]))
        {
            std::stringstream threadName;
            threadName << "Thread:" << t;
            // creating thread arguments instance
            pThreadArgs_[t] = new ThreadArgs(this,t);
            // creating thread instance
            pThreads_[t] = new TThread(threadName.str().c_str(),
                                      thread0,
                                      (void*) pThreadArgs_[t]);

            if(pThreads_[t])
                pThreads_[t]->Run();
            else
                return -1;
        }
    }
    return 0;
}
int Threader::join()
{
    for (int t=0; t<nOfThreads_; t++)
    if (pThreads_[t])
        pThreads_[t]->Join();
    return 0;
}

int Threader::stopThreads()
{
    if (!threadsRun_)
        return 0;

    threadsRun_ = false; // aborting flag

    for (int t=0; t<nOfThreads_; t++)
    {
        if (pThreads_[t])
        {
            int timeout = 0;
            while (pThreadArgs_[t]->getFuncRunning() && timeout < 240)
            {
                timeout++;
                gSystem->Sleep(500); // wait a while for threads to halt
            }
            TThread::Delete(pThreads_[t]);
            delete pThreads_[t];
            pThreads_[t] = 0;
            delete pThreadArgs_[t];
            pThreadArgs_[t] = 0;
        }
    }
    return 0;
}

void* Threader::thread0(void* arg)
{
    ThreadArgs* threadArgs = (ThreadArgs*) arg;
    Threader* inst = threadArgs->getThreader();
    threadArgs->setFuncRunning(true);
    while( inst->getThreadsRun() &&
        inst->execute(threadArgs->getThreadNumber()) >= 0){
    }
    threadArgs->setFuncRunning(false);
    return 0;
}
## Appendix D

### The Converted File

Table D.1: Event information contained in the CaptanTrack tree saved in the converted file.

<table>
<thead>
<tr>
<th>Parameter Name</th>
<th>Reference Frame</th>
<th>Units</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>eventNumber/I</td>
<td></td>
<td></td>
<td>Event ID</td>
</tr>
<tr>
<td>numberOfTracks/I</td>
<td></td>
<td></td>
<td>Number of tracks saved in this event</td>
</tr>
<tr>
<td>trackNumber/I</td>
<td></td>
<td></td>
<td>Track ID</td>
</tr>
<tr>
<td>ndof/I</td>
<td></td>
<td></td>
<td>Number of degree of freedom in track fit</td>
</tr>
<tr>
<td>chi2/F</td>
<td></td>
<td></td>
<td>$\chi^2$ of track fit</td>
</tr>
<tr>
<td>xIntercept/D</td>
<td>Global</td>
<td>$\mu m$</td>
<td>Track intercept on the X axis</td>
</tr>
<tr>
<td>yIntercept/D</td>
<td>Global</td>
<td>$\mu m$</td>
<td>Track intercept on the Y axis</td>
</tr>
<tr>
<td>sigmaXIntercept/D</td>
<td>Global</td>
<td>$\mu m$</td>
<td>Error on the track intercept on the X axis</td>
</tr>
<tr>
<td>sigmaYIntercept/D</td>
<td>Global</td>
<td>$\mu m$</td>
<td>Error on the track intercept on the Y axis</td>
</tr>
<tr>
<td>xSlope/D</td>
<td>Global</td>
<td>rad</td>
<td>Track slope along X axis</td>
</tr>
</tbody>
</table>
Table D.1: Event information contained in the *CaptanTrack* tree saved in the converted file.

<table>
<thead>
<tr>
<th>Parameter Name</th>
<th>Reference Frame</th>
<th>Units</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>ySlope/D</td>
<td></td>
<td>rad</td>
<td>Track slope along Y axis</td>
</tr>
<tr>
<td>sigmaXslope/D</td>
<td></td>
<td>rad</td>
<td>Error on the track slope along X axis</td>
</tr>
<tr>
<td>sigmaYslope/D</td>
<td></td>
<td>rad</td>
<td>Error on the track slope along Y axis</td>
</tr>
<tr>
<td>hasHit[10]/O</td>
<td></td>
<td></td>
<td>True if the plane has a hit associated to the track</td>
</tr>
<tr>
<td>isInDetector[10]/O</td>
<td></td>
<td></td>
<td>True if the predicted impact point on the plane is inside detector area</td>
</tr>
<tr>
<td>clusterSize[10]/I</td>
<td></td>
<td></td>
<td>Cluster size of the plane hit</td>
</tr>
<tr>
<td>numberOfCols[10]/i</td>
<td></td>
<td></td>
<td>Number of columns in the plane cluster hit</td>
</tr>
<tr>
<td>numberOfRows[10]/i</td>
<td></td>
<td></td>
<td>Number of rows in the plane cluster hit</td>
</tr>
<tr>
<td>clusterCharge[10]/I</td>
<td></td>
<td>electrons</td>
<td>Total charge of the cluster</td>
</tr>
<tr>
<td>meanCol[10]/F</td>
<td></td>
<td></td>
<td>Average column ID of the plane cluster hit</td>
</tr>
<tr>
<td>meanRow[10]/F</td>
<td></td>
<td></td>
<td>Average row ID of the plane cluster hit</td>
</tr>
<tr>
<td>colPredicted[10]/I</td>
<td></td>
<td></td>
<td>Column ID of the cell predicted by the track projection on the plane</td>
</tr>
<tr>
<td>rowPredicted[10]/I</td>
<td></td>
<td></td>
<td>Row ID of the cell predicted by the track projection on the plane</td>
</tr>
<tr>
<td>xPitchLocal[10]/F</td>
<td>Local</td>
<td>µm</td>
<td>Pitch along X axis of the cell predicted by the track projection on the plane</td>
</tr>
<tr>
<td>xPitchGlobal[10]/F</td>
<td>Global</td>
<td>µm</td>
<td>Pitch along X axis of the cell predicted by the track projection on the plane</td>
</tr>
<tr>
<td>yPitchLocal[10]/F</td>
<td>Local</td>
<td>µm</td>
<td>Pitch along Y axis of the cell predicted by the track projection on the plane</td>
</tr>
</tbody>
</table>

Following parameters are arrays indexed by plane ID: 0-7 for telescope, 8-9 for DUTs.
Table D.1: Event information contained in the CaptanTrack tree saved in the converted file.

<table>
<thead>
<tr>
<th>Parameter Name</th>
<th>Reference Frame</th>
<th>Units</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>yPitchGlobal[10]/F</td>
<td>Global</td>
<td>µm</td>
<td>Pitch along Y axis of the cell predicted by the track projection on the plane</td>
</tr>
<tr>
<td>xMeasuredLocal[10]/F</td>
<td>Local</td>
<td>µm</td>
<td>Measured X coordinate of the plane hit</td>
</tr>
<tr>
<td>xErrorMeasuredLocal[10]/F</td>
<td>Local</td>
<td>µm</td>
<td>Error on the measured X coordinate of the plane hit</td>
</tr>
<tr>
<td>xMeasuredGlobal[10]/F</td>
<td>Global</td>
<td>µm</td>
<td>Measured X coordinate of the plane hit</td>
</tr>
<tr>
<td>xErrorMeasuredGlobal[10]/F</td>
<td>Global</td>
<td>µm</td>
<td>Error on the measured X coordinate of the plane hit</td>
</tr>
<tr>
<td>yMeasuredLocal[10]/F</td>
<td>Local</td>
<td>µm</td>
<td>Measured Y coordinate of the plane hit</td>
</tr>
<tr>
<td>yErrorMeasuredLocal[10]/F</td>
<td>Local</td>
<td>µm</td>
<td>Error on the measured Y coordinate of the plane hit</td>
</tr>
<tr>
<td>yMeasuredGlobal[10]/F</td>
<td>Global</td>
<td>µm</td>
<td>Measured Y coordinate of the plane hit</td>
</tr>
<tr>
<td>yErrorMeasuredGlobal[10]/F</td>
<td>Global</td>
<td>µm</td>
<td>Error on the measured Y coordinate of the plane hit</td>
</tr>
<tr>
<td>xPredictedLocal[10]/F</td>
<td>Local</td>
<td>µm</td>
<td>X coordinate of the impact point predicted by the track projection on the plane</td>
</tr>
<tr>
<td>xPredictedGlobal[10]/F</td>
<td>Global</td>
<td>µm</td>
<td>X coordinate of the impact point predicted by the track projection on the plane</td>
</tr>
<tr>
<td>yPredictedLocal[10]/F</td>
<td>Local</td>
<td>µm</td>
<td>Y coordinate of the impact point predicted by the track projection on the plane</td>
</tr>
<tr>
<td>yPredictedGlobal[10]/F</td>
<td>Global</td>
<td>µm</td>
<td>Y coordinate of the impact point predicted by the track projection on the plane</td>
</tr>
<tr>
<td>xErrorPredictedLocal[10]/F</td>
<td>Local</td>
<td>µm</td>
<td>Predicted error on plane along X axis</td>
</tr>
<tr>
<td>xErrorPredictedGlobal[10]/F</td>
<td>Global</td>
<td>µm</td>
<td>Predicted error on plane along X axis</td>
</tr>
<tr>
<td>yErrorPredictedLocal[10]/F</td>
<td>Local</td>
<td>µm</td>
<td>Predicted error on plane along Y axis</td>
</tr>
<tr>
<td>yErrorPredictedGlobal[10]/F</td>
<td>Global</td>
<td>µm</td>
<td>Predicted error on plane along Y axis</td>
</tr>
<tr>
<td>xTrackResidualLocal[10]/F</td>
<td>Local</td>
<td>µm</td>
<td>Unconstrained residual on plane along X axis</td>
</tr>
</tbody>
</table>
Table D.1: Event information contained in the CaptanTrack tree saved in the converted file.

<table>
<thead>
<tr>
<th>Parameter Name</th>
<th>Reference Frame</th>
<th>Units</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>x(\text{TrackResidualGlobal}[10]/F)</td>
<td>Global</td>
<td>(\mu m)</td>
<td>Unconstrained residual on plane along X axis</td>
</tr>
<tr>
<td>y(\text{TrackResidualLocal}[10]/F)</td>
<td>Local</td>
<td>(\mu m)</td>
<td>Unconstrained residual on plane along Y axis</td>
</tr>
<tr>
<td>y(\text{TrackResidualGlobal}[10]/F)</td>
<td>Global</td>
<td>(\mu m)</td>
<td>Unconstrained residual on plane along Y axis</td>
</tr>
<tr>
<td>x(\text{PixelResidualLocal}[10]/F)</td>
<td>Local</td>
<td>(\mu m)</td>
<td>Residual between the X coordinates of the predicted cell center and of the predicted impact point</td>
</tr>
<tr>
<td>x(\text{PixelResidualGlobal}[10]/F)</td>
<td>Global</td>
<td>(\mu m)</td>
<td>Residual between the X coordinates of the predicted cell center and of the predicted impact point</td>
</tr>
<tr>
<td>y(\text{PixelResidualLocal}[10]/F)</td>
<td>Local</td>
<td>(\mu m)</td>
<td>Residual between the Y coordinates of the predicted cell center and of the predicted impact point</td>
</tr>
<tr>
<td>y(\text{PixelResidualGlobal}[10]/F)</td>
<td>Global</td>
<td>(\mu m)</td>
<td>Residual between the Y coordinates of the predicted cell center and of the predicted impact point</td>
</tr>
</tbody>
</table>

Following parameters are 2-D arrays indexed by plane ID (0-9) and by cluster pixels (max size 4):

<table>
<thead>
<tr>
<th>Parameter Name</th>
<th>Reference Frame</th>
<th>Units</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>cluster\text{HitRow}[4][10]/I</td>
<td></td>
<td></td>
<td>Rows of the cluster pixels</td>
</tr>
<tr>
<td>cluster\text{HitCol}[4][10]/I</td>
<td></td>
<td></td>
<td>Cols of the cluster pixels</td>
</tr>
<tr>
<td>cluster\text{HitCharge}[4][10]/I</td>
<td></td>
<td>electrons</td>
<td>Charges of the cluster pixels</td>
</tr>
<tr>
<td>cluster\text{PixelCenterLocalX}[4][10]/F</td>
<td>Local</td>
<td>(\mu m)</td>
<td>X coordinate of the cluster pixels’ center</td>
</tr>
<tr>
<td>cluster\text{PixelCenterGlobalX}[4][10]/F</td>
<td>Global</td>
<td>(\mu m)</td>
<td>X coordinate of the cluster pixels’ center</td>
</tr>
<tr>
<td>cluster\text{PixelCenterLocalY}[4][10]/F</td>
<td>Local</td>
<td>(\mu m)</td>
<td>Y coordinate of the cluster pixels’ center</td>
</tr>
<tr>
<td>cluster\text{PixelCenterGlobalY}[4][10]/F</td>
<td>Global</td>
<td>(\mu m)</td>
<td>Y coordinate of the cluster pixels’ center</td>
</tr>
<tr>
<td>is\text{PixelCalibrated}[4][10]/O</td>
<td></td>
<td></td>
<td>True if calibration curve fit was successful</td>
</tr>
</tbody>
</table>
Bibliography


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