
Novel Pixel-Detector Developments for Upgrades of the ATLAS Central Tracking System at the LHC

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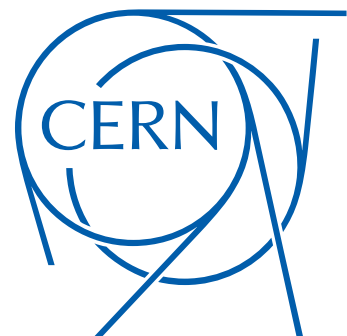
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To my dad († 2014) and my grandmother († 2017).

To Hannah (2014) and Paulina (* 2017).*

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Abstract

High-energy physics is confronted with a number of questions that could change our understanding of nature fundamentally. The discovery of the Higgs boson has shown that the LHC at CERN is currently the most important tool for answering these questions. In order to sustain this position, the full potential of the LHC is exploited by regular upgrades. They pose challenges on the detectors and push technologies to their limits. Our research was conducted to tackle the problems that arise for ATLAS, the largest experiment at the LHC.

As part of the Phase-0 Upgrade (2013–2015) the Insertable B-Layer (IBL) was installed in ATLAS. This additional silicon pixel detector layer was placed closer to the LHC beam pipe than the existing layers, which required complete reconstruction of the beam pipe. The thermal behavior of the new detector and the beam pipe had to be understood before installation. Therefore we constructed a 1:1 mock-up and conducted thermal tests. Based on these tests, the insulation and therefore material budget of the new beam pipe were reduced. We verified the heating system for the beam pipe bake-out, improved the operation of the new CO₂ cooling system of the IBL and used the tests to tune computer simulations of the detector. This work contributed significantly to the safe installation and operation of the IBL.

The Phase-II Upgrade of the LHC (2024–2026) will result in the High-Luminosity LHC (HL-LHC). It will increase the particle collision rate in the experiments by a factor of almost four. The current silicon detector system in ATLAS is not able to cope with this and new, extremely radiation-hard silicon sensors are needed. We try to meet the demands with a concept new to high-energy physics: high-voltage complementary metal-oxide-semiconductor (HV-CMOS) sensors used as semi-hybrid pixel detectors. This unique approach allows for electronics in the sensor chip and at the same time high voltage to increase the depletion zone and hence the signal. The capacitive coupling to the readout chip can be achieved by a thin glue layer, which spares complicated connection techniques like bump-bonding. We discuss the prospects and drawbacks of HV-CMOS sensors in high-energy physics and investigate the prototype family CCPD (Capacitively Coupled Pixel Detector) in detail. The gluing, the capacitive coupling and operation of the sensors after irradiation to more than 8.5 MGy (850 Mrad) and $1 \times 10^{16} \text{ n}_{\text{eq}} \text{ cm}^{-2}$ are shown. Efficiencies of 99.7 and 98 % are demonstrated for sensors irradiated to 1×10^{15} and $5 \times 10^{15} \text{ n}_{\text{eq}} \text{ cm}^{-2}$, respectively. These results are important steps toward qualification of HV-CMOS sensors for HL-LHC detectors and may inspire other experiments to consider the new approach.

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Chapter 1

Introduction

With physics we describe and try to understand nature; the word itself originates from the ancient Greek $\tauὰ φυσικά$, literally meaning “natural things”.^[1, 2] The Encyclopædia Britannica is more specific and writes “[Physics] ultimate objective is the formulation of a few comprehensive principles that bring together and explain...disparate phenomena.”^[3] Particle or High-Energy Physics (HEP) is pursuing this on the most fundamental level. Its most elaborate theory, the Standard Model (SM) of particle physics, has been very successful since its emergence in the middle of the 20th century. Many elementary particles and their properties were predicted and later confirmed by experiments, e.g., the W and Z bosons and the ratio of their masses. Concepts like the electroweak theory and quantum chromodynamics have been developed within the SM. The most recent milestone is the discovery of a Higgs boson-like particle at the Large Hadron Collider (LHC) at the European Organization for Nuclear Research (CERN); yet another strong confirmation of the Standard Model. In addition, the unprecedented center-of-mass collision energy of 13 TeV at the LHC has lead to experimental findings confirming the SM beyond the previously explored energy scale.

Nevertheless, the current scope of the SM leaves some fundamental questions open. Where does the matter-antimatter asymmetry of the universe come from? What is dark matter and dark energy? In which direction does the SM have to be extended or is there “new physics” that demands a new theory? Why does the discovered Higgs boson have such a low mass? These few examples show that there is still very much to discover. Being at the energy forefront, the experiments at the LHC will either answer some questions or give directions where to find them. The European Strategy for Particle Physics^[4] states:

“The discovery of the Higgs boson is the start of a major program of work to measure this particle’s properties with the highest possible precision for testing the validity of the Standard Model and to search for further new physics at the energy frontier. The LHC is in a unique position to pursue

this program. Europe’s top priority should be the exploitation of the full potential of the LHC, including the high-luminosity upgrade of the machine and detectors with a view to collecting ten times more data than in the initial design, by around 2030.”

The mentioned upgrade of the LHC is planned to be implemented from around 2024 onwards, resulting in the HL-LHC (High-Luminosity LHC). The central improvement will be the increase of the nominal luminosity from 1×10^{34} to around $7.5 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$.^[5, 6] This is the principal step in delivering significantly more data to the experiments and thus improving the statistical uncertainties of measurements. It will lead to a more precise knowledge of, e.g., the properties of particles like the Higgs boson and possibly open the door to new discoveries around the TeV scale.

Once the framework of the enhanced collider is given, the experiments and their detectors have to cope with the new settings. Technologies that are currently installed and successfully used in the experiments are often at their limits. Only innovative instrumentation and dedicated detector R&D (research and development) ensure that the full potential of the LHC and HL-LHC can be exploited. This thesis deals with two upgrade activities of ATLAS (A Toroidal LHC Apparatus), the largest detector at the LHC.

Silicon sensor development for the HL-LHC upgrade of ATLAS

The increased luminosity in the HL-LHC means a larger rate of particle collisions and hence a higher rate of secondary particles in the detectors. This results in increased radiation damage and higher occupancy especially in the tracker systems, which are closest to the interaction point. The currently installed system in ATLAS, the ID (Inner Detector), is not designed for the additional load and will be replaced by the ITk (Inner Tracker) as part of the so-called Phase-II Upgrade. It will be installed in the years 2024 – 2026 during the LHC’s third long shutdown.^[6] The innermost layers of both the ID and the ITk are silicon pixel detectors. The original pixel layers of the ID must withstand an integrated 1 MeV-neutron equivalent fluence of around $1 \times 10^{15} \text{ n}_{\text{eq}} \text{ cm}^{-2}$ during the lifetime of the LHC.^[7] For the ITk this value rises to around $2 \times 10^{16} \text{ n}_{\text{eq}} \text{ cm}^{-2}$.^[6] This poses a challenge for the whole detector design and the technologies used. In Chapter 4 we are presenting our R&D-effort to tackle this challenge for the crucial detector part of silicon sensors. The idea of using high-voltage complementary metal-oxide-semiconductor (HV-CMOS) processes for sensor production leads to new sensor concepts beyond the classic monolithic or hybrid ones. We are presenting the sensor-family CCPD (Capacitively Coupled Pixel Detector), which pursues a semi-hybrid approach. It is based on active pixels that have a limited amount of electronics implemented, e.g. the first signal amplification stage. The sensor is still coupled to a readout chip, implemented either as a strip or pixel chip. Using the latter, the sensor can be capacitively coupled

to the readout chip by a simple glue layer, which has not been done before in HEP. We examine the introduction of the high-voltage CMOS technology to particle physics, prove several new concepts to work and show irradiation results up to $1 \times 10^{16} \text{ n}_{\text{eq}} \text{ cm}^{-2}$. A discussion of large detector aspects in view of the HL-LHC completes the chapter.

Thermal performance of the IBL package as part of the ATLAS Phase-0 Upgrade

ATLAS' Pixel Detector was designed for the LHC's nominal luminosity of $1 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$. The extraordinary performance of the LHC in its first years of operation and upgrades in the injector chain enable the LHC to run for a significant part of its lifetime at higher values up to an ultimate luminosity of around $2 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$.^[8] This causes the Pixel Detector to age faster than foreseen and might provoke problems in the readout due to the higher occupancy of the sensors. Altogether it could reduce the physics performance of ATLAS.^[9] To eliminate this risk it was decided to add an additional pixel layer as part of the Phase-0 Upgrade during the first long shutdown of the LHC (Feb. 2013 – Mar. 2015).^[10, 11] This pixel layer is referred to as a separate detector called IBL (Insertable B-Layer). It was installed between the original pixel layers and the LHC beam pipe. The very short distance of $\approx 3 \text{ cm}$ to the interaction point and the limited space put stringent demands on the detector design. A new, smaller beam pipe was necessary, forming a very dense package together with the IBL. The beam pipe reaches a temperature of more than 220°C during the necessary bake-out. At the same time, the new pixel sensors that are located only several mm away must never reach more than $+40^\circ \text{C}$ and nominally operate at temperatures down to -40°C . To guarantee safe operation with respect to temperature throughout the lifetime of the IBL, we investigated the thermal performance of the package with a 1:1 mock-up before installation in ATLAS. The mock-up was also used to test integration and assembly procedures and different materials.

In Chapter 3 we present the detailed thermal tests that we performed with the mock-up. The focus lies on the extreme scenario of the bake-out and simulated accidents. We show successful tuning of the parameters of the computational fluid dynamics simulation that was used to predict the behavior of the real IBL. In addition, the experience gained with the carbon dioxide (CO_2) cooling system is discussed. With the IBL, such a system was installed for the first time in a general purpose detector for HEP. We conclude the chapter with data from the real LHC bake-out from Run 2, where the IBL had already been successfully integrated into ATLAS.

In Chapter 2 we give the context and theory that are necessary for this work. Sections 3.3 and 4.7 form the summaries of the results from the IBL and HV-CMOS chapter, respectively. In Chapter 5 we discuss the impact of our work within the large picture of

ATLAS and the LHC. Additional material and our main publications can be found in the Appendices A to D.

Chapter 2

Context & Theory

In this chapter we explain selected concepts that are important for particle detection. The focus lies on silicon-based tracking systems. Section 2.1 outlines the evolution of the LHC and how this lead to our research topics. Section 2.2 explains ATLAS and with it the principle of general-purpose, large-scale particle detectors. The tracking system and upgrades are emphasized. Section 2.3 gives details on the first upgrade of the ATLAS Pixel Detector, the IBL. It is the basis for Chapter 3. Section 2.4 finally deals with the theory of particle detection with silicon sensors, forming the basis for Chapter 4.

2.1 The LHC and its upgrades

In Chapter 1 we mention some important questions in HEP that are currently unanswered. Many experiments around the world try to shed light on them. The current center and focus of experimental HEP is CERN with the most powerful man-made particle accelerator to date, the LHC. The LHC produces for the most part p^+p^+ (proton-proton) particle collisions with a center-of-mass collision energy ($\sqrt{s}$) of up to 14 TeV. This is more than seven times the energy of the previous record-holder, the Tevatron at Fermilab.^[12–14] There are well-founded hopes that the LHC will discover processes or particles that have not been accessible at the previously reached energies. Amongst the immense number of collisions that the LHC delivers, the ones involving potentially interesting processes are rare. This is caused by the low cross-sections of these processes. For example, at $\sqrt{s} = 14$ TeV the SM production cross section of a Higgs boson with a mass of $125 \text{ GeV } c^{-2}$ is around 57 pb.^[15] The total cross-section for p^+p^+ collisions at that energy is around 100 mb.^[16] The event rate dN/dt for a process is calculated with

$$\frac{dN}{dt} = \sigma \mathcal{L} \tag{2.1}$$

where $\mathcal{L}$ is the instantaneous luminosity^[17] and σ the cross-section. Integrating over time yields the total number of events,

$$N = \sigma \int \mathcal{L}(t) dt = \sigma \mathcal{L}_{\text{int}}. \quad (2.2)$$

$\mathcal{L}_{\text{int}}$ is the integrated luminosity. It is commonly expressed in fb^{-1} (inverse femtobarn) which can be regarded as the number of events per femtobarn of cross-section for the process. The projected integrated luminosity for the LHC is 300 fb^{-1} . The number of events involving SM Higgs physics is therefore $\approx 1.7 \times 10^7$ out of $\approx 3 \times 10^{16}$ p^+p^+ events, yielding a ratio of less than one in a billion.

2.1.1 Phase-II Upgrade

The number of events determines the statistical precision of the experimental results. It can be increased by a longer running time of the collider or by an increase of the luminosity. However, it scales only with $\sqrt{N}$.^[18] This is the reason why the statistical gain of running the LHC longer without a significant luminosity upgrade is marginal after the 300 fb^{-1} are reached around the year 2023.^[8] Therefore the upgrade to the HL-LHC is planned from 2024 onwards. It is called Phase-II Upgrade and will take place during the LS3 (Long Shutdown 3) of the LHC. The main change will be the increase of the instantaneous luminosity to around $7.5 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$.^[6] The HL-LHC is planned to deliver 3000 fb^{-1} (3 ab^{-1}) to the experiments.

2.1.2 Phase-I Upgrade

The Phase-I Upgrade will take place during the LS2 (Long Shutdown 2) of the LHC in 2019 and 2020.^[19] The main activity will be the LIU (LHC Injectors Upgrade). It concerns the whole LHC injector chain from the hydrogen injection to the last pre-accelerator: the LINACs (Linear Accelerators, especially LINAC4),^[20] the PSB (Proton Synchrotron Booster),^[21] the PS (Proton Synchrotron)^[22] and the SPS (Super Proton Synchrotron).^[23] It aims to prepare the injectors to match already the requirements for the HL-LHC. A complete overview of the LIU can be found in [24]. During the LS2 it is also planned to perform a major maintenance of the LHC and consolidate part of the machine. Where possible, preparations for the HL-LHC will be implemented.^[25]

2.1.3 Phase-0 Upgrade

The Phase-0 Upgrade took place during the LS1 (Long Shutdown 1) of the LHC between Feb. 2013 and Mar. 2015. The most important work was the consolidation of

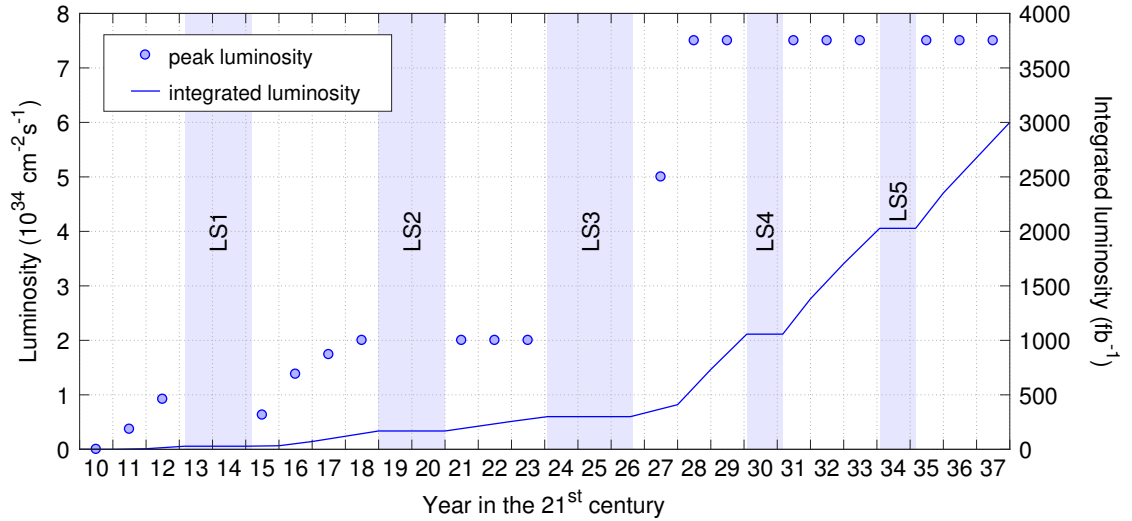


FIGURE 2.1: Long-term evolution of the LHC’s instantaneous luminosity (dots) and integrated luminosity (line). The Long Shutdowns (LS1–LS5) are also shown. During LS3 the upgrade to the HL-LHC will take place, resulting in a significant step in the instantaneous luminosity. The values for the instantaneous luminosity are the maxima from each year. The integrated luminosity is interpolated between the end-of-year values. Measured data is available for 2010–2016.^[26] Values from 2017 onwards are estimations taken from [8, 27, 28].

the high-current splices between the superconducting magnets. This prepared the LHC for operation at the design collision energy of 14 TeV.⁽¹⁾ The LS1 was also used to perform maintenance and renovation work on other parts of the LHC, the injectors and connected infrastructure.

Figure 2.1 shows the long-term schedule for the LHC and HL-LHC including the foreseen Long Shutdowns.

2.1.4 Consequences for the detectors

Technology advances also for the detectors of the experiments at the LHC. In addition to upgrades and consolidation works which have been planned from the beginning, they are constantly adapted to be able to exploit any increase of luminosity that the LHC delivers.^[29] The extraordinary performance of the LHC results in a faster increase of the luminosity than initially foreseen. The instantaneous luminosity surpassed its nominal value of $1 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ in 2016, reaching around $1.5 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ in that year.^[26] Until 2023 a regular increase is projected up to the ultimate value of more than $2 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$. This has two main effects on the experiments.

First, the aging of the detectors is accelerated by the increased levels of radiation. The

¹ Before the LS1 the LHC operated at a maximum collision energy of 8 TeV because of issues with the splices.

high luminosity means more particle collisions per bunch crossing.⁽²⁾ Hence, more secondary particles are created resulting in increased radiation levels and radiation damage. In general, the radiation damage reduces the performance of detectors. This loss has to be compensated for by consolidation works or the detector's initial design ensures performance above a certain limit until the end of the foreseen lifetime where it is replaced. Radiation damage is an issue especially relevant for items that are located close to the interaction points.

Second, the higher event rate results in a higher occupancy of the detectors. This means that their readout systems have to deal with more secondary particles per bunch crossing and the reconstruction of tracks and clusters has to be done in a more complicated environment. This is reflected in the so-called pile-up. A pile-up of one means that there is on average one p^+p^+ collision per bunch crossing. The expected pile-up at the LHC's nominal luminosity is 23.^[30] At the LHC's ultimate luminosity this value rises to around 51.^[9] At the HL-LHC it will reach values of up to 200.^[6] Like above, each detector is designed to perform well enough up to a certain level of pile-up. Above that, the detector has to be improved or replaced.

2.2 The ATLAS detector and its Inner Detector upgrades

ATLAS is one of the two large general-purpose detectors at the LHC. The other is CMS (Compact Muon Solenoid). They both have the same purpose: to cover the largest possible range of known and unknown physics that is accessible with the LHC. As such they are designed to capture any product of the p^+p^+ collisions.⁽³⁾ In this chapter we describe ATLAS, but the concepts are valid for CMS and smaller general-purpose detectors as well.

2.2.1 Particle detection with ATLAS

The ATLAS detector is a combination of several sub-detectors and other sub-systems built around one of the four LHC's interaction points. The main parts and the scale is shown in Figure 2.2. The sub-detectors serve to measure the trajectory, momentum and energy of each traversing particle. Additional properties like charge, mass and hence the type of particle can be deduced from these data. Figure 2.3 shows the principle of particle detection in a cross-section of ATLAS perpendicular to the LHC beam axis. We describe the principle from the outside to the inside.

² The protons in the LHC are concentrated in so-called bunches that circulate in opposite directions in the accelerator. At four interaction points these bunches are steered to collide. The collisions of the bunches are called bunch-crossings and happen every 25 ns at nominal running conditions, both for the LHC and the HL-LHC.

³ This hermetic design is valid except for two small areas where the proton beams enter and leave the detector.

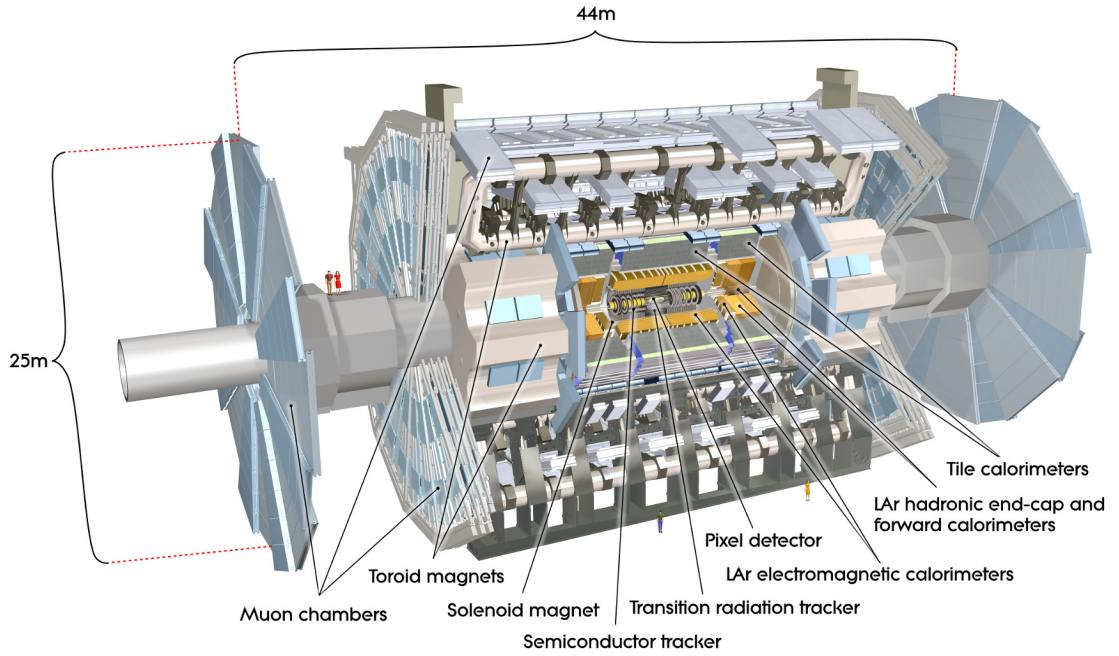


FIGURE 2.2: Model of the ATLAS detector from [31]. The dimensions and major sub-systems are shown. It is practical to use cylindrical coordinates in ATLAS. The origin is in the center at the nominal interaction point of the proton bunches. The z -axis is parallel to the beam pipe, the angle φ covers 2π around the axis and r is the distance to the axis. LAr stands for liquid argon.

Neutrinos are the only known particles that leave the detector without being directly detected. Due to their leptonic and charge-neutral nature they hardly interact with known matter. Their presence, direction and momentum, respectively energy are determined only by conservation laws. The other known type of particles that usually leaves the detector are muons. They are also leptons but are charged and therefore interact via electromagnetic processes with matter. The outermost sub-detector, the muon spectrometer, is designed for muon identification and muon tracking.

All other particles are usually stopped further inside the detector by the calorimeters. Calorimeters measure the energy of a particle and thus they ideally absorb all the particle's energy. The hadronic calorimeter is designed to effectively stop hadrons such as neutrons and protons. The electromagnetic calorimeter is designed to effectively stop photons and e^- (electrons). In both cases, the stopping process is a statistical one and there are two appropriate parameters that describe the interaction of the impinging particle with matter. For hadronic interactions it is the nuclear interaction length λ_I . It is the mean distance traveled by a particle before participating in an inelastic nuclear interaction. For electromagnetic interactions it is the radiation length X_0 . It is the mean distance over which a high-energy electron loses all but $1/e$ of its energy by bremsstrahlung and it is $7/9$ of the mean free path for pair production by a high-energy photon.^[33] The amount of material in a detector is commonly expressed in percent of

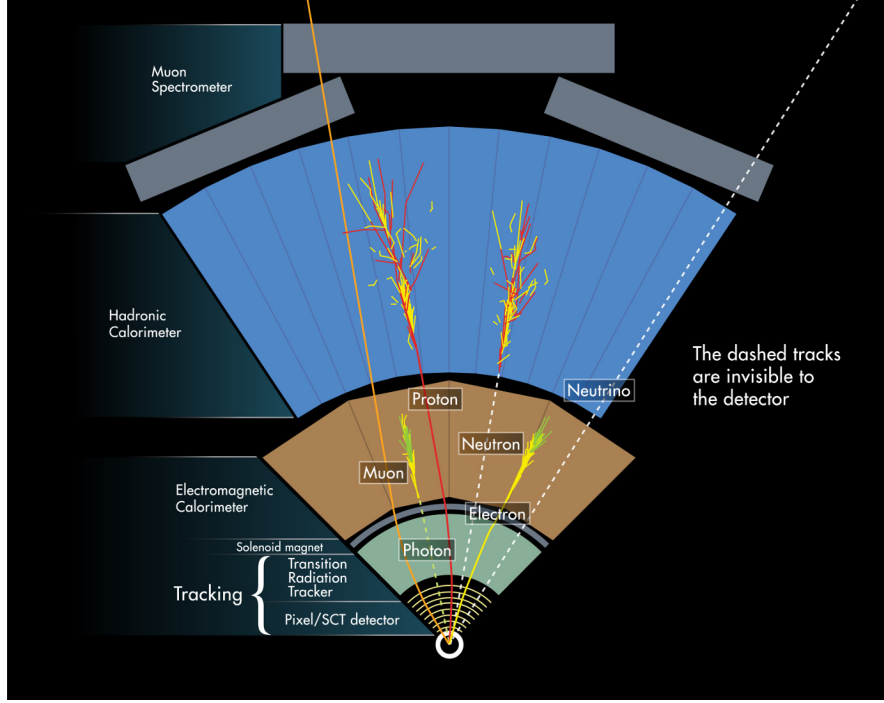


FIGURE 2.3: Schematic of particle detection with ATLAS from [32]. Details are given in the text.

X_0 . This measure is also called material budget. λ_I and X_0 are usually measured in g cm^{-2} . To get the actual length for a certain material, they have to be divided by the material's density.

The innermost part of ATLAS is the ID. Its main purpose is to measure the tracks of electrically charged particles as precise as possible. This is essential to determine the position of the primary vertices of the p^+p^+ collisions and identify secondary vertices of decay processes. The latter is especially important for b-tagging, which plays an important role in many physics analyses for, e.g., Higgs-physics and searches for CP-violation.^[34] The track information is also used to identify the momentum and charge of the particles. In order to keep the influence on the traversing particles as low as possible, the material budget of the ID is kept to a minimum. A large material budget would alter the tracks by multiple scattering and also bias the energy measurement of the calorimeters. The ID consists of the TRT (Transition Radiation Tracker) and two silicon detectors: the SCT (Semiconductor Tracker) and the Pixel Detector.

ATLAS' magnet system creates a strong magnetic field throughout the detector, reaching 2 T in the Inner Detector and up to 4 T on the other sub-detectors. It is necessary for the momentum measurement and particle containment.

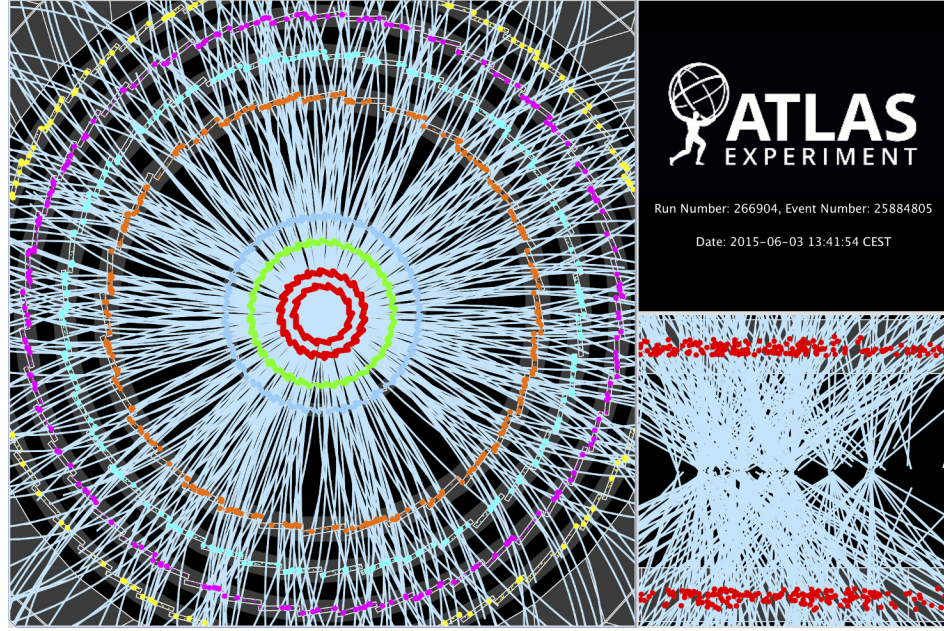


FIGURE 2.4: Display of a $p+p$ collision event at 13 TeV recorded by ATLAS. Particle tracks reconstructed by the tracking detector are shown as light blue lines, and hits in the layers of the SCT and the Pixel Detector are shown as colored dots. The four outer layers belong to the SCT and three inner layers to the Pixel Detector. The innermost layer is the IBL. The view on the bottom right shows that the tracks originate from multiple $p+p$ collisions around the interaction point. A total of 17 collision vertices has been reconstructed. It is the main task of the tracking detector to identify the tracks and their corresponding vertices. Figure from [37].

2.2.2 The silicon detectors

Silicon detectors are used for tracking devices (often just called “trackers”) due to their excellent spatial resolution. The geometric resolution of position sensitive devices with binary readout is

$$\sigma_{\text{pos}} = \frac{p}{\sqrt{12}} \quad (2.3)$$

where p is the pitch of the sensing elements, i.e. pixels or strips.^[35] The nominal pixel size of ATLAS’ Pixel Detector is $50 \times 400 \mu\text{m}^2$, yielding $\sigma_{\text{pos}} \approx 14 \mu\text{m}$ in the small dimension. Silicon detectors rely on collection of free charge carriers created by traversing ionizing particles (see Section 2.4.2). Exploiting information about the collected charge in a pixel, a spatial resolution down to $7 \mu\text{m}$ is achieved.^[36] This resolution is necessary to effectively identify the primary collision vertices and secondary vertices of events, as is illustrated in Figure 2.4.

Both the SCT and the Pixel Detector show a barrel-like design. Coaxial cylindrical layers are closed by so-called end-caps. The SCT has four barrel layers with nominal radii between 299 and 514 mm. They extend 749 mm in each z -direction. The Pixel Detector has three barrel layers with nominal radii between 50.5 and 122.5 mm. They extend 400.5 mm in each z -direction. All barrel layers are visible in the event display in

Figure 2.4. One additional layer is visible at $r = 33$ mm. It is the IBL which is discussed in detail in Section 2.3. The IBL and the pixel layers are also visualized in Figure 2.6. The SCT is laterally closed by nine end-caps on each side and the Pixel Detector by three. This design ensures a coverage of pseudorapidity up to $|\eta| = 2.5$. The pseudorapidity describes the scattering angle Θ of a particle relative to the z -axis and is defined as^[38]

$$\eta \equiv -\ln \left(\tan \frac{\Theta}{2} \right). \quad (2.4)$$

The SCT consists of 15 912 microstrip sensors with ≈ 6.3 million readout channels. The strip pitch is between 57 and 94 μm and the total active area around 60 m^2 . More details can be found in [7, Section 4.2.1]. The Pixel Detector consists of 1744 pixel sensors, covering an active area of approximately 1.7 m^2 . The 80.4 million pixels are read out by the ATLAS FE-I3 readout-chip.^[39]

The ID suffers severe radiation damage due to the position close to the interaction point. This is a challenge especially for the silicon sensors. They have been designed to maintain an acceptable performance up to certain levels of irradiation. The most affected part is Layer 0 of the Pixel Detector, the innermost layer. It is also called B-Layer because of its importance for the above mentioned b-tagging. Simulations yield an particle fluence of $1.4 \times 10^{15} \text{ n}_{\text{eq}} \text{ cm}^{-2}$ and an ionizing dose of 790 kGy (79 Mrad) for the B-Layer after 500 fb^{-1} of integrated luminosity.⁽⁴⁾ The innermost SCT-layer will receive $8 \times 10^{13} \text{ n}_{\text{eq}} \text{ cm}^{-2}$ and 38 kGy (3.8 Mrad). The whole ID is designed for operation up to 700 fb^{-1} , covering the whole LHC lifetime with a safety margin of around 2.^[7] The only exception is the B-Layer, which was designed to be replaced after around three years of operation.⁽⁵⁾ After that time the radiation damage was expected to cause such a performance drop of the B-Layer so that it would impact ATLAS' physics performance (see Figure 2.5). However, it was decided to not replace the B-Layer but to compensate for the performance loss by the introduction of the new pixel layer IBL during the LS1.

2.2.3 The upgrades

Phase-0 Upgrade

The major upgrade for the ID during LS1 was the installation of the IBL. Section 2.3 is dedicated to the IBL. In addition, the on-detector services for the Pixel Detector were replaced by the nSQP project,^[40] including installation of the DBM (Diamond Beam Monitor).^[41]

⁴ Details on radiation damage in silicon and explanation of the units are given in Section 2.4.5.

⁵ At the time of the design of the B-Layer, technology was not advanced enough to construct a detector that ensured good performance for a longer period in such a radiation-harsh environment.

Phase-I Upgrade

There are no Phase-I upgrades foreseen concerning the ID directly. However, the installation of the FTK (Fast Tracker), a hardware track finder for the ATLAS trigger system, is foreseen.^[42] It relies on the hit information provided by the ID.

Phase-II Upgrade

Due to the upgrade to the HL-LHC also ATLAS will undergo major upgrades during LS3. A comprehensive overview can be found in [6]. One of the upgrades is the complete replacement of the ID by a new tracking system, the ITk.

2.2.3.1 The ITk

The ITk will be an all-silicon detector comprising a pixel system for the inner layers and a strip system for the outer layers. The projected active sensor areas are 15 m^2 for the pixel system and 165 m^2 for the strip system.^[43] In addition to this large silicon surface, several other requirements make the ITk a challenging enterprise:

- The projected lifetime is 10 years, covering the 3000 fb^{-1} delivered by the HL-LHC.
- Even in the presence of a pile-up of 200, the performance of the b-tagging should match the performance of the current detector in the presence of a pile-up of 50, including the IBL.
- The occupancy of the strip system has to be less than 1 % and for the pixel system less than 0.1 %.
- A high spatial accuracy is required for the physics program.
- The readout has to be fast enough to cover the requirements for the trigger system set by the 25 ns bunch-crossing interval of the HL-LHC.
- The innermost pixel barrel layer has to withstand a particle fluence of up to $2.1 \times 10^{16}\text{ n}_{\text{eq}}\text{ cm}^{-2}$ and an ionizing dose of 12 MGy (1.2 Grad). These values include uncertainties in the simulations but no safety factors.
- The maximum fluence and dose for the strip system are $1.2 \times 10^{15}\text{ n}_{\text{eq}}\text{ cm}^{-2}$ and 432 kGy (43.2 Mrad).

These points are discussed in detail in [44] and a more comprehensive list can be found in [45]. They make clear why intense research and development is required for the construction and installation of the ITk. The R&D is especially extensive in the field

of silicon sensors: in addition to technological challenges like small pixel size/small strip pitch and affordable large-area production, there are intrinsic, physical ones. For example, the currently installed sensors would not cope with the high radiation levels. Their hit efficiencies would drop below useful values and the increase of their leakage current would exceed the capacities of the power supplies and of the cooling systems.^[45] In Section 2.4 we give the theoretical background for these effects. Chapter 4 covers our R&D-work in the field of silicon sensors for the ITk and for other detectors in highly irradiated environments.

2.2.4 System aspects for large detectors

The size and complexity of ATLAS necessitates the consideration of large-system aspects already in the R&D-phase of the underlying detector technologies. For example, the optimization of the power consumption of a single silicon pixel sensor might not play an important role during development of the first prototypes. Any standard laboratory power supply is able to deliver the demanded power and cable losses are negligible. However, scaling to large systems changes the picture. The nominal power supply of the ATLAS Pixel Detector is 24 kW and only 6 kW of this are consumed by the sensors and the front-end electronics.^[7] The rest is dissipated by cables and power regulators. This example also highlights the importance of mechanical and thermal management. ATLAS is a very densely packed structure in an underground cavern and space is limited. Services like cables, cooling pipes and mechanical support structures have to fit and be installed in the available volume. Additionally, their influence on the probed particles and on the sensing elements has to be optimized or at least known. For the former, the above-mentioned material budget and simulation tools like FLUKA or GEANT4 are important.^[46–48] For the latter, mechanical properties and thermal behavior are crucial. The silicon sensors of the ID have to be operated between -5 and -10°C to mitigate irradiation effects and prevent dangerous scenarios like thermal runaway (see Section 2.4.5.2). Given the power dissipation mentioned above, this requires an effective cooling system. The consequence is a complex system of heat sources, heat sinks and heat transfer. Temperature gradients in space and time provoke mechanical stress, e.g., due to CTE mismatch.⁽⁶⁾ Cold surfaces have to be protected from condensation which is achieved by flushing the affected volume with a dry gas like nitrogen.

Due to the complexity, the sub-systems of large detectors are designed separately. It is absolutely necessary that precise agreements for the common interfaces are established and that they are strictly followed.

⁶ CTE is the coefficient of thermal expansion. Many different materials with different CTEs are present in the detector. Changing temperatures can then cause problems in the mechanical structure.

On the whole, the behavior of every bit of the detector has to be understood thoroughly already in the design phase. This eliminates possible problems already before construction. CAE (Computer Aided Engineering) including powerful simulation methods are essential tools. For example, CFD simulations (Computational Fluid Dynamics) are used to predict the thermal behavior when gases or liquids are present.

Accidental scenarios must not be ignored even if the risk is small. The detector relies on predefined performance of all sub-systems and failure of one part might affect the overall performance. Additionally, the time scale to access and replace hardware in the center of a detector like ATLAS is - if possible at all - in the order of months. Therefore, security measures are in place to prevent high-impact accidents. Common measures are interlocks and redundancy. For example, certain power supplies are switched off if the cooling is malfunctioning. The IBL is running with two cooling plants: one in nominal operation and the other in standby and ready to switch in case of problems.

2.3 The IBL

The IBL is the additional pixel layer that was added to the ID in the Phase-0 Upgrade. It assures ATLAS' vertexing and b-tagging performance at increased pile-up and compensates for the expected degradation of the B-Layer. Even a complete failure of the B-Layer can be tolerated. Figure 2.5 shows this in terms of light jet rejection as a function of pile-up.

The sensors of the IBL were placed in a volume between the LHC beam pipe and the B-Layer from the ID, extending from $r=31$ to 40 mm. This was only possible by removing the original beam pipe and replacing it by a new, slimmer one. Due to space constraints the new beam pipe had to be part of the IBL for the installation. Together with the services this formed a more than 7 m long package of slightly more than 85 mm in diameter which had to be inserted into the very center of ATLAS.

2.3.1 Sensors and readout chips

The inner part of the IBL that houses the active silicon area extends 374 mm in each z -direction. The center of the sensors is located at $r=33$ mm. They cover a pseudorapidity of $|\eta| < 3$. Figure 2.6 illustrates the arrangement of the sensor modules within the ID. The IBL was designed for an integrated luminosity of 850 fb^{-1} . For the sensors this means a particle fluence of up to $5 \times 10^{15} \text{ n}_{\text{eq}} \text{ cm}^{-2}$ and a total ionizing dose of up to 1.6 MGy (160 Mrad), including safety factors. The active silicon area is less than 0.2 m^2 . All sensors are thin edge n-in-n sensors. 75 % are planar sensors which are located around the center and 25 % are double-sided 3D sensors which are located at the extremities in z .^[10, 50] The different sensor technologies are explained in Section 2.4.

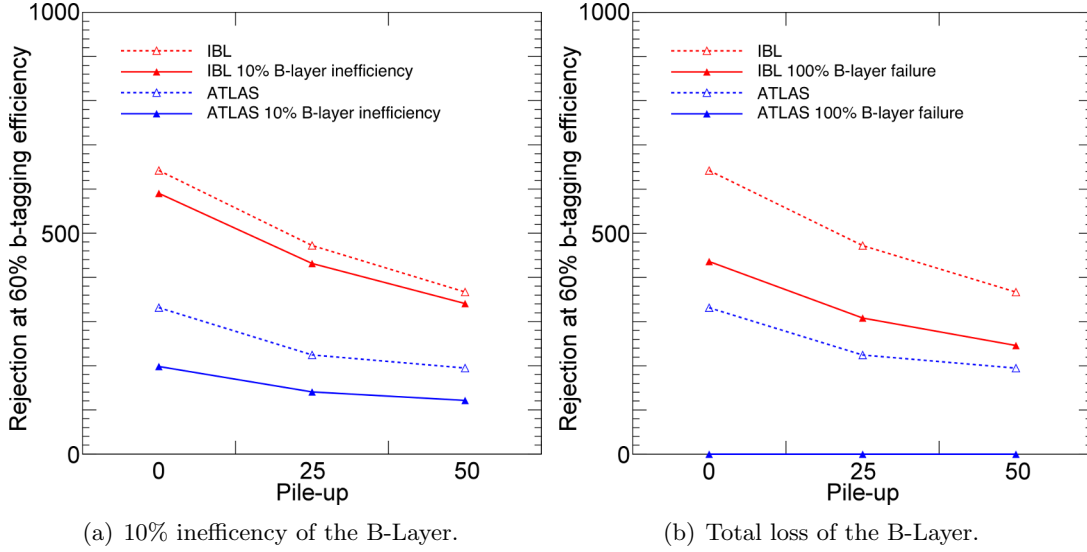


FIGURE 2.5: Example of ATLAS’ performance loss due to degradation of the B-Layer and performance gain due to the IBL. Shown is the light jet rejection at 60 % b-jet efficiency for the combined IP3D+SV1 tagger^[49] as a function of the average pile-up. The values for ATLAS without the IBL are shown in blue and the values including the IBL are shown in red. The dotted lines correspond to a fully functioning B-Layer and the solid lines to a 10 % inefficient B-Layer (left plot), respectively a total loss of the B-Layer (right plot). The light jet rejection is the number of true light jets per falsely tagged light jet. A higher value is beneficial for ATLAS’ physics performance. It can be seen that the IBL can compensate for the potential complete loss of the B-Layer. With a functioning B-Layer, it increases the performance at a pile-up of 50 to a level which is not even reached at a pile-up of 0 without the IBL. Figure adapted from [9].

The sensors are read out by the ATLAS FE-I4 chip.^[51–53] Compared to its predecessor, the FE-I3, it has a smaller pixel size ($250 \times 50 \mu\text{m}^2$) and a higher rate capability. This is necessary due to the close position to the interaction point and the high pile-up at the ultimate LHC luminosity. Each sensor is connected to the FE-I4 pixels via 26 880 bump-bonds, adding more than 12 million pixels to the ID. The sensors and the 448 FE-I4s are arranged in modules on 14 identical staves. One stave flex (flexible printed circuit board) per stave connects the modules via adapters to the so-called type 1 services. These are the cables that take care of the data and power transmission between the active, inner part of the detector and more accessible regions outside the 7 m long IBL package.

Being the innermost detector layer in ATLAS, the IBL has to be as lightweight as possible in terms of material budget. At z_0 ,⁽⁷⁾ its radiation length at perpendicular incidence is 1.54 % of X_0 , which is approximately 60 % of the Pixel B-Layer. This low value was achieved by using more aggressive technological solutions such as a new module design, thinning of the front-end chips, thin flex circuits, staves made of low density

⁷ The axial center of ATLAS is called z_0 . It is also the nominal z-coordinate of the interaction point.

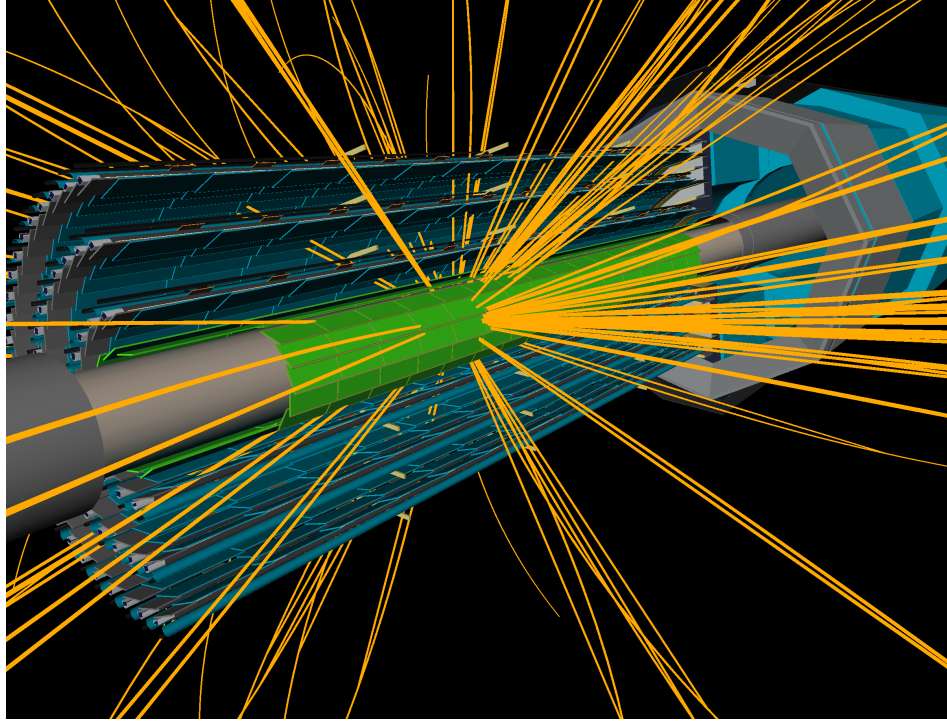


FIGURE 2.6: Visualization of a simulated event in ATLAS. Shown are the beam pipe (gray cylinder), the IBL layer (green), the three pixel layers including parts of their mechanical support (dark cyan, partly opened) as well as the pixel barrel supports and endcap structures in the background. The particle tracks are depicted as orange lines. Figure from [9].

carbon foam and a cooling system based on CO_2 .^[9, 54] Especially the latter is of importance for our work due to the thermal conditions in the IBL-package that are discussed in the next section.

2.3.2 The LHC beam pipe bake-out

The static pressure in the LHC beam pipe is typically in the order of 10^{-11} mbar. This ultra-high vacuum can only be achieved by complex pumping techniques. Sputtered NEG (non-evaporable getter) films on the inside walls of the vacuum systems are part of these. They have been developed at CERN during the 1990s and have simplified many vacuum systems. A NEG film coating transforms the walls from being gas sources to being pumping surfaces.^[55, 56] NEG films work by chemisorption and have to be activated. This is done by heating the coated items to $+180^\circ\text{C}$ for approximately one day. The beryllium (Be) beam pipe in ATLAS is one of these items. It is part of the central beam vacuum chamber in ATLAS, called VI-section (Vacuum Inner Detector). Due to the difficult access, this section has to be heated in-situ. The system requires a specific temperature profile with higher temperatures, reaching more than $+220^\circ\text{C}$.^[57] The heating cycle is called bake-out and it is a critical step for ATLAS. The introduction of the IBL, which placed temperature-sensitive modules and cooling pipes of an evaporative cooling

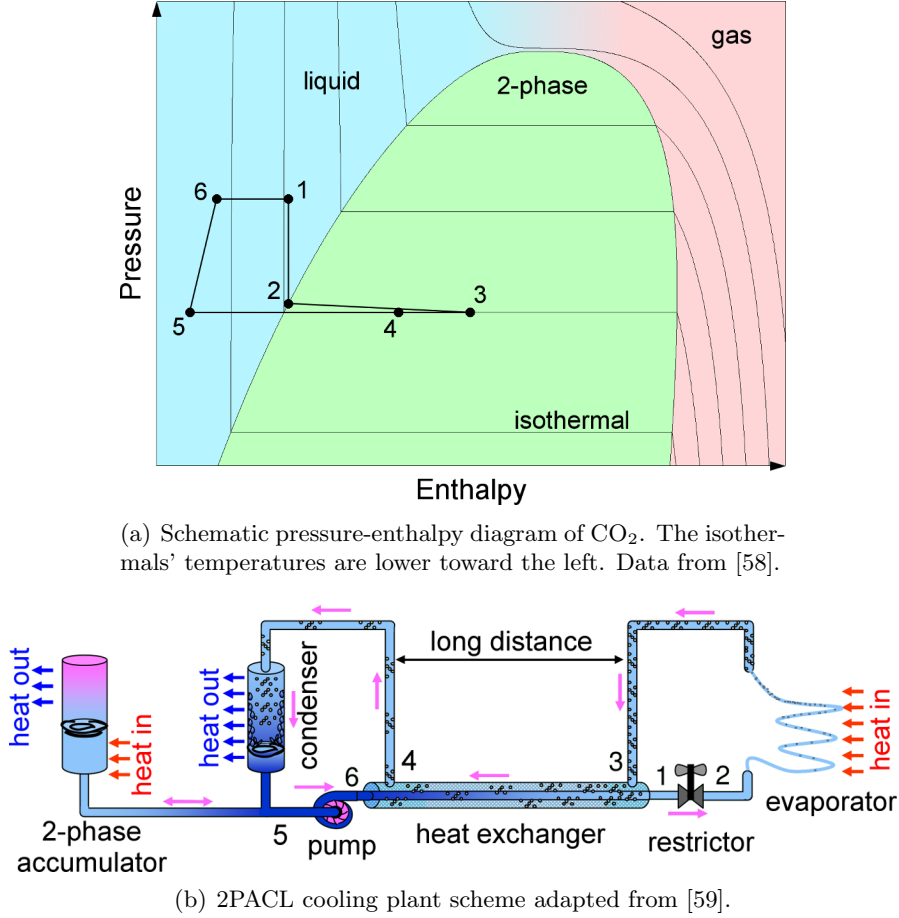


FIGURE 2.7: The 2PACL cooling cycle in the pressure-enthalpy diagram and the scheme of a 2PACL cooling plant. The numbers in the cycle correspond to the positions mentioned in the text.

system very close to the beam pipe, aggravated the procedure. The heating system as well as the insulation had to be revisited and tested before installation. These tests are covered by Chapter 3 of this work. They were also used to investigate the thermal behavior of the IBL during bake-out and the effectiveness of the CO₂ cooling system.

2.3.3 CO₂ evaporative cooling

Existing evaporative cooling systems based on C₃F₈ (octafluoropropane) are common in HEP. Currently designed systems are increasingly based on CO₂. The reasons are that CO₂ as refrigerant offers a lower evaporation temperature and it is more efficient in terms of mass flow and pipe size, which lowers the material budget. After the VELO^[60] and AMS-02^[61] detector systems, the IBL is the third HEP experiment with CO₂-cooling. The cooling method is called 2PACL (2-Phase Accumulator Controlled Loop), which delivers a very stable temperature without any active components inside the detector. The plant scheme is shown in Figure 2.7(b) and the corresponding cooling cycle in the pressure-enthalpy diagram in Figure 2.7(a). The main features are:

- The restrictor, realized as a capillary, which causes the abrupt pressure drop into the two-phase region (Region 1–2).
- The boiling tubes inside the detector where the cooling performance is realized by partial evaporation of the CO₂ (Region 2–3).
- The condenser which liquefies the CO₂ again (Region 4–5).
- The accumulator. Its temperature sets the evaporation pressure and consequently the evaporation temperature in the boiling tubes inside the detector.
- An external chiller which provides the cooling power for the condenser and accumulator.
- A pump for achieving the CO₂-flow (Region 5–6).

More details on the principle of CO₂ cooling systems and 2PACL can be found in [59]. Specific information on the IBL cooling plant is given in [9, Section 6.6],[62] and [63]. The design cooling power of the plant is 2 kW and the minimum evaporation temperature -40°C .

Within the scope of this thesis we do not cover more background information about the IBL. The IBL technical design report and its addendum^[9, 10] offer comprehensive information and references for further reading.

2.4 Particle detection with silicon sensors

In this section we cover the theory of particle detection with silicon sensors and practical aspects for detector construction. We outline the processes around the interaction of particles with matter, both the ones that are exploited for particle detection (creation of free electric charge and signal formation) and the ones that complicate it (irradiation effects). Signal processing and technological matters relevant for silicon detector design are discussed. This section forms the basis for Chapter 4: “HV-CMOS sensors for the ATLAS Phase-II Upgrade”.

2.4.1 Particle interaction with matter

We limit the theoretical discussion to the interaction of heavy, electrically charged particles with matter. This covers, e.g., protons, muons and charged pions. For silicon detectors, the electronic interactions with the target material are of interest. These happen in single collisions where the impinging particle transfers the energy W to an electron, leading to ionization and atomic or collective excitation in the target material.^[33] W is a stochastic variable and so is the total energy loss of the particle when traveling a distance x in the target. It is the sum of the energy transfers of all individual collisions during the passage. The mean rate of energy loss is described by the energy-loss formula

$$\left\langle -\frac{dE}{dx} \right\rangle = 2\pi m_e n_e r_e^2 c^2 \frac{z_c^2}{\beta^2} \left[\ln \frac{2m_e c^2 \beta^2 \gamma^2 W_{\max}}{I_e^2} - 2\beta^2 - \delta - 2\frac{C}{Z} \right] \quad (2.5)$$

where the symbols have the following meaning (units and references are given on the right-hand side):

E	energy of the impinging particle	MeV	
m_e	electron mass	MeV c^{-2}	Appendix D
n_e	electron density	g^{-1}	Equation 2.6
r_e	classical electron radius	cm	Equation 2.7
c	speed of light in vacuum	cm s^{-1}	Appendix D
z_c	charge number of the particle	dimensionless	
β	ratio of the particle's speed v to c	dimensionless	Appendix D
γ	Lorentz factor	dimensionless	Appendix D
$W_{\max}$	maximum energy transfer in a single collision	MeV	Equation 2.8
I_e	mean excitation energy	eV	
δ	density-effect correction	dimensionless	
C	shell correction	dimensionless	
Z	atomic number of the target material	dimensionless	

$\langle -dE/dx \rangle$ is also called stopping power or, with the units in $\text{MeV cm}^2 \text{g}^{-1}$, mass stopping power. The proportionality to the electron density n_e signifies that electrons are the

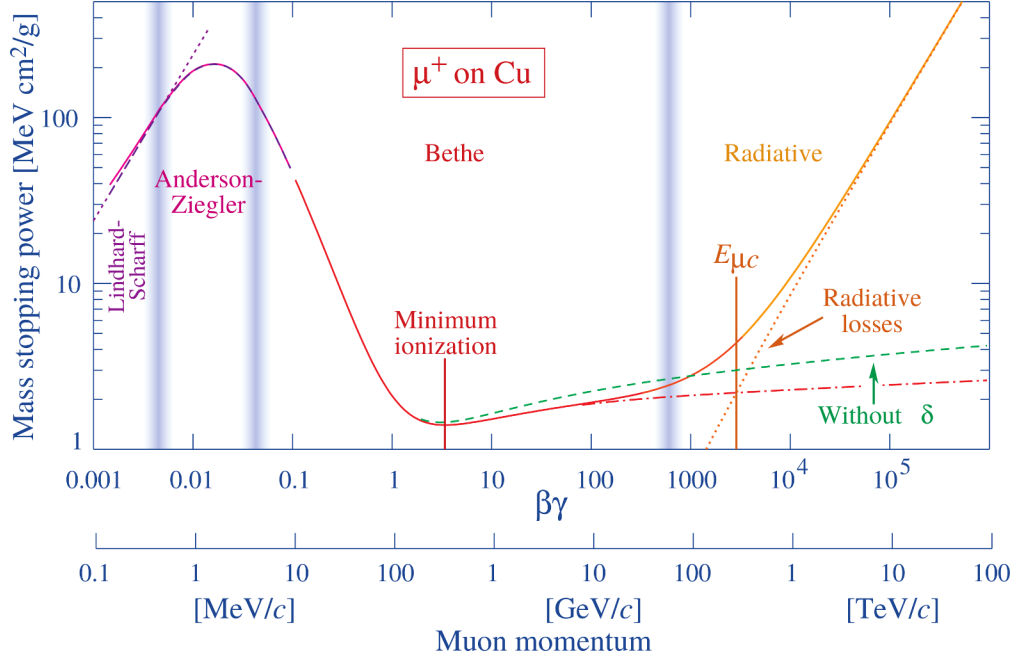


FIGURE 2.8: Mass stopping power $\langle -dE/dx \rangle$ for antimuons (μ^+) in copper (Cu) as a function of $\beta\gamma$ and momentum. The solid curve indicates the total stopping power. The dash-dotted, red curve indicates the stopping power without radiative losses and the dashed, green line without radiative losses and without the density-effect correction δ . The dotted, orange line indicates the contribution from radiative losses. $E_{\mu c}$ is the critical energy for muons. It is the limit above which radiative losses are larger than all other losses combined. Minimum ionization occurs at $\beta\gamma \approx 3$, as is discussed in Section 2.4.1.2. The vertical bands indicate the boundaries between different theoretical approximations, the Bethe-region being in the middle. For particles that are more massive than muons, the momentum scale shifts to the left with respect to the $\beta\gamma$ -scale. Figure adapted from [33].

interaction partners. The electron density is given by

$$n_e = \frac{Z N_A}{A_m} \quad (2.6)$$

where N_A is Avogadro's number in mol^{-1} (see Appendix D) and A_m is the molar mass of the target material in g mol^{-1} . The energy-loss formula was first derived by Bethe,^[64, 65] starting from the Rutherford differential cross-section that describes scattering of heavy particles from free electrons.^[33] This is reflected in the appearance of the classical electron radius r_e in the formula. It is calculated with

$$r_e = \frac{e^2}{m_e c} \frac{1}{4\pi \varepsilon_0} \quad (2.7)$$

where ε_0 is the vacuum permittivity (see Appendix D). The maximum energy transfer in a single collision, $W_{\max}$, is derived from relativistic two-body scattering as

$$W_{\max} = 2 m_e c^2 \beta^2 \gamma^2 \left[1 + \left(\frac{m_e}{M} \right)^2 + 2 \gamma \frac{m_e}{M} \right]^{-1} \quad (2.8)$$

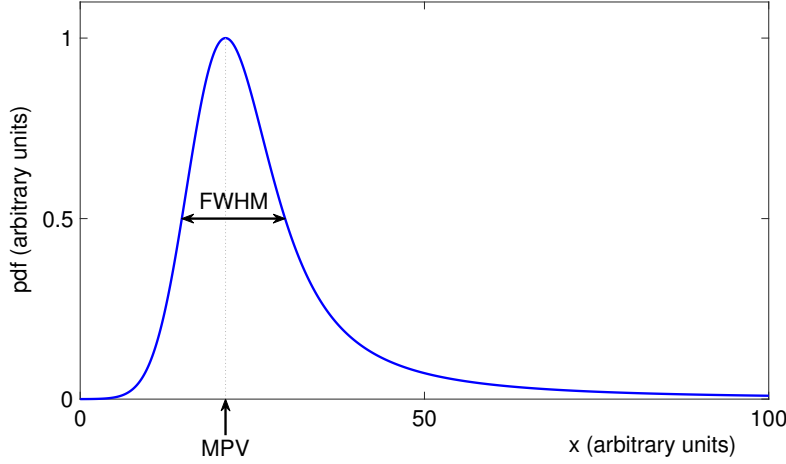


FIGURE 2.9: The pdf (probability density function) of a Landau distribution with its MPV and FWHM. Due to the long tail of the distribution the mean is undefined.

where M is the rest mass of the impinging particle in $\text{MeV } c^{-2}$. Bloch derived an approximation for the mean excitation energy I_e as a function of the atomic number of the material, Z .^[66] This approximation is nowadays replaced by tables of I_e , which are available for many different materials.^[67] Nevertheless, the energy-loss formula is often referred to as the Bethe or Bethe-Bloch formula. The form in equation 2.5, which includes the density-effect and shell correction terms, is valid within a few percent for intermediate- Z target materials and particles with $\beta\gamma$ between approximately 0.1 and 1000. At the lower limit the particle velocity becomes comparable to “atomic electron velocities” and at the upper limit radiative effects begin to be important.^[33] As an example, $\langle -dE/dx \rangle$ for antimuons in copper is given in Figure 2.8 for a wide range of $\beta\gamma$.

2.4.1.1 Straggling functions

The energy-loss formula describes well the mean of the underlying distribution of the energy loss dE/dx . This distribution is called straggling function. The theoretical formulation of this distribution is an extensive task especially for cases where the particle traverses a small amount of matter compared to its range, i.e. for thin absorbers. A theoretical calculation based on the Rutherford differential cross-section was done by Landau in 1944^[68] which was later extended by Vavilov.^[69] The derived straggling functions are called Landau or Landau-Vavilov distributions and depend on the absorber thickness. They can be described by their MPV (most probable value) and the FWHM (full width at half maximum). An example distribution is shown in Figure 2.9. The characteristic property is the large skewness, i.e. a long tail toward large energy losses. This tail is due to the rare but possible single collisions that transfer a large amount of energy.

For thicknesses below a few hundred μm , which is the case for state-of-the-art silicon

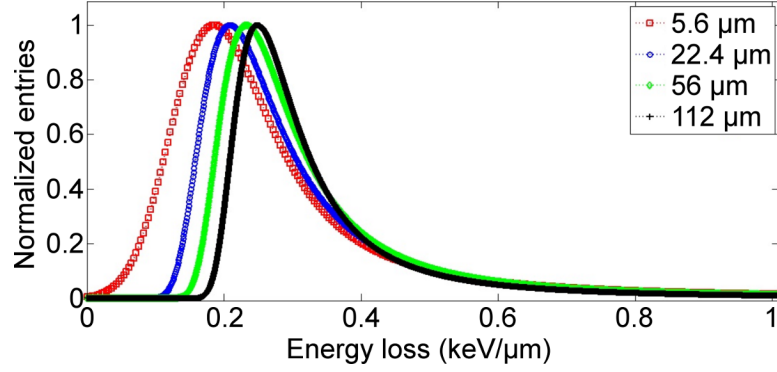


FIGURE 2.10: Fitted Langau distributions from measurements with thin silicon sensors. The sensor thicknesses are color-coded. The shift of the MPVs toward lower energies with decreasing thickness is visible (see Relation 2.9). Figure from [71].

detectors, Bichsel provides an adequate theoretical description.^[70] The resulting straggling functions are called Bichsel functions. Mathematically they are the convolution of a Landau-Vavilov and a Gaussian distribution, which is also referred to as improved energy-loss distribution or Langau distribution. The relation of the MPV of the Langau distribution to the absorber thickness x is

$$\text{MPV} = x(a + b \ln x) \quad (2.9)$$

where a and b are constants. Bichsel derives theoretical values of $a = 100.6 \text{ eV } \mu\text{m}^{-1}$ and $b = 35.35 \text{ eV } \mu\text{m}^{-1}$ when the MPV is expressed in eV and x in μm .⁽⁸⁾ Measurements by [71] yield very similar values. The fitted Langau distributions for these measurements are shown in Figure 2.10, illustrating the dependency of the MPV on the detector thickness.

The Bethe-Bloch formula describes the mean of the energy loss distribution. For the Landau distribution the mean is theoretically undefined due to the tail toward large energies. In experimental data, however, the tail of the Landau distribution is truncated at the largest observed value of dE/dx . Therefore the mean of the data set can be calculated in practice, but it strongly depends on the value of the largest observed value. The MPV is more robust, easier to measure and hence the adequate quantity to describe the energy loss in thin detectors. Figure 2.11 shows the differences between the mean derived by the Bethe-Bloch formula and the MPV derived by the Bichsel functions for different absorber thicknesses. A more detailed comparison can be found in [72].

2.4.1.2 MIPs

Figures 2.8 and 2.11 show that both the Bethe-Bloch mean and the Bichsel MPV have a minimum when plotted against the incident particle energy. When radiative losses

⁸ Relation 2.9 with these values for the parameters approximate the theoretically derived values of the MPV within 1.2% for particles with an electric charge of $\pm 1 e$, $\beta\gamma > 100$ and a silicon absorber thickness between 13 and 110 μm .

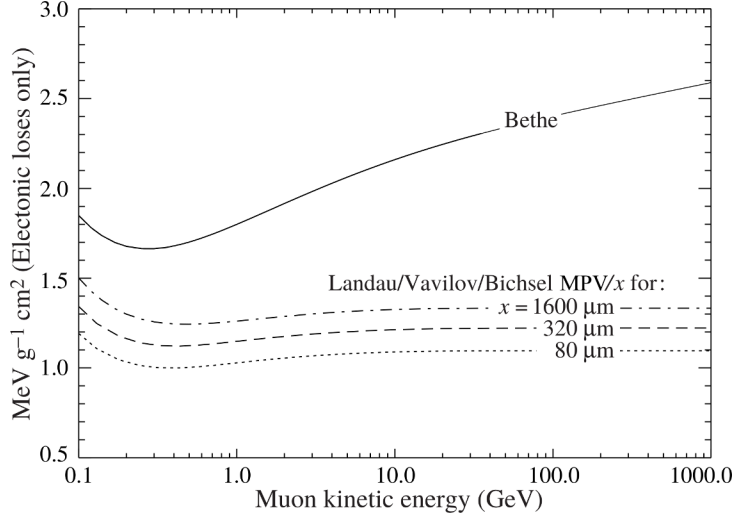


FIGURE 2.11: The mass stopping power of muons in silicon. The solid curve shows the mean value calculated with the Bethe-Bloch formula. The other curves are the MPV per unit thickness derived from the Bichsel functions based on the Landau theory. The change of MPV/x with the thickness illustrates the $\ln x$ dependency given in Relation 2.9. Radiative losses are excluded. Figure adapted from [33].

are disregarded, the MPV rises only slightly with higher particle energies, merging to a plateau. This is used in the concept of MIPs (minimum ionizing particles): above a certain energy, particles with the same electric charge behave very similar concerning energy loss. The lower limit is usually defined as the point where the kinetic energy of the particle is twice its rest energy. This is true when $\beta\gamma = 2\sqrt{2} \approx 2.8$. Protons reach this value at a momentum of approximately $2.7 \text{ GeV } c^{-1}$ and muons at approximately $0.3 \text{ GeV } c^{-1}$. The Bethe-Bloch mean and the Bichsel MPV rise drastically below this limit. This is relevant for particle sources with a large energy spectrum, notably beta-sources. Strontium-90 (^{90}Sr) is a beta-source which is commonly used for characterization of silicon sensors. Its daughter nucleus yttrium-90 emits electrons with energies up to 2.28 MeV .^[73] Only about $1/4$ of these electrons are MIPs, the rest is below the MIP limit. Measuring the energy loss of all emitted electrons therefore results in a shift of the Landau distribution and its MPV to higher values. Selecting MIPs, i.e. high-energy electrons, can be achieved by shielding the sensor or by shielding a scintillator trigger behind the sensor which then selects only the electrons that are energetic enough to pass. A monoenergetic particle source like a high-energy testbeam is more appropriate for Landau measurements.

The content of this Section is a summary of excerpts from the following literature: [70], [71], Section 2.1 of [38], Sections 2.2 and 2.6 of [67], Sections 33.1 and 33.2 of [33]. Complementary and more detailed information can be found in these references.

2.4.2 Signal creation

The energy deposited by ionizing particles in a semiconductor like silicon causes creation of free charge carriers in the form of e-h pairs (electron-hole pairs). The band gap of silicon is 1.12 eV ⁽⁹⁾ but a higher energy of 3.65 eV ⁽¹⁰⁾ is needed on average for creation of one e-h pair. The reason is phonon excitation caused by the indirect band gap of silicon. Relation 2.9 can be translated to be valid for the MPV in units of e^- by

$$\text{MPV} = \frac{x}{3.65 \text{ eV}/e^-} (a + b \ln x) . \quad (2.10)$$

By putting an electrode in the semiconductor the free charge carriers induce an electric signal and the passage of the ionizing particle can be detected. Motion of the free charge carriers is a condition for signal induction. The two important mechanisms leading to motion are diffusion and drift.

2.4.2.1 Diffusion

Diffusion is a result of the random thermal motion of charge carriers combined with a concentration gradient. In presence of a concentration gradient, the random motion has a net direction toward lower concentration areas. Given a point-like charge carrier profile at the time t_0 , this profile will spread out over time to form a Gaussian distribution. After the time t , the distribution's standard deviation σ_{Diff} will be^[35]

$$\sigma_{\text{Diff}} = \sqrt{D t} \quad (2.11)$$

where D is the material and carrier dependent diffusion constant. It is linked to the carrier mobility μ by the Einstein relation for electric mobility^[38]

$$D = \frac{\mu k_B T}{q} \quad (2.12)$$

where k_B is the Boltzmann constant, T the absolute temperature and q the electric charge of the carrier. In silicon at 300 K and low electric field strength the electron mobility (μ_e) and hole mobility (μ_h) are 1350 and $450 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$, respectively. Using the elementary charge e , this yields diffusion constants of $D_e = 34.9 \text{ cm}^2 \text{ s}^{-1}$ and $D_h = 12.4 \text{ cm}^2 \text{ s}^{-1}$ for electron and holes, respectively. Table 2.1 summarizes the values. Electrons will therefore take about 29 ns and holes 81 ns to reach a standard deviation in the order of $10 \text{ }\mu\text{m}$. This leads to two important points why diffusion is not the preferred charge collection mechanism for LHC and HL-LHC experiments. First, the time scale

⁹ This value is valid at room temperature under the pressure of one atmosphere.^[74]

¹⁰ The ionization energy depends on various environmental parameters. The value stated here is adequate for the calibration measurements of this thesis and is in accordance with several publications, e.g. [75–79].

TABLE 2.1: Charge carrier mobilities (from [80]) and diffusion constants (calculated with equation 2.12) for electron and holes in silicon at 300 K.

charge carrier	mobility μ ($\text{cm}^2 \text{V}^{-1} \text{s}^{-1}$)	diffusion constant D ($\text{cm}^2 \text{s}^{-1}$)
electron	1350	34.9
hole	450	12.4

is too slow. Charge collection by diffusion takes longer than the nominal bunch crossing time of 25 ns even for very short collection paths. Second, radiation damage causes charge trapping, which reduces the charge signal available for detection. After a particle fluence of $1 \times 10^{15} \text{ n}_{\text{eq}} \text{ cm}^{-2}$ the trapping time scale is in the order of nanoseconds (see Table 4.1). Hence, the charge will mainly get trapped instead of collected. Additionally, recombination of e-h pairs is not actively counteracted. Charge collection by drift is favorable concerning these points.

2.4.2.2 Drift

Drift is a forced motion due to an external influence. If charge carriers are subject to an electric field, they feel a force in direction of the field lines. Inside a semiconductor, interactions of charge carriers with the lattice result in the drift velocity $\vec{v}_d$ being proportional to the applied electric field $\vec{E}$ with the carrier mobility as proportional factor:

$$\vec{v}_d = \mu \vec{E} . \quad (2.13)$$

At high electric field strengths above $\approx 5 \times 10^4 \text{ V cm}^{-1}$, μ becomes inversely proportional to the field strength, leading to a constant drift velocity irrespective of the field strength.^[35] In silicon at 300 K this saturation velocity is around $1 \times 10^7 \text{ cm s}^{-1}$, both for electrons and holes. At high enough fields, 10 μm of silicon are therefore traversed in around 100 ps.⁽¹¹⁾ This short time reduces charge trapping significantly and it is way below the bunch crossing time. Additionally, $\vec{v}_d$ is opposite for electrons and holes which separates them and inhibits recombination.

In a semiconductor, the electric field can be introduced by a p-n junction, i.e. a simple diode structure. For particle detectors, the diode is normally realized by a p or n-type silicon substrate and a thinner electrode of the other type, which is more heavily doped than the substrate. Therefore, the reverse bias voltage (V_b) extends the depletion volume mainly into the substrate.⁽¹²⁾ The depletion volume, where a strong electric field is present, is the effective zone of charge collection by drift. The depletion depth d_{dep} is

¹¹ The field strength in most of the depletion volume of the sensors that are investigated in this thesis is above the mentioned limit, see Figure 2.15. Therefore the saturation velocity is used for the estimation.

¹² For the use in Equations 2.14 and 2.16, the reverse bias voltage is defined to be positive.

calculated with ^[38]

$$d_{\text{dep}} = \sqrt{\frac{2\varepsilon}{e|N_{\text{eff}}|} (V_0 + V_b)} \quad (2.14)$$

where ε is the absolute permittivity of silicon, N_{eff} the effective doping concentration of the substrate in charge carriers per unit volume and V_0 the built-in potential of the junction. ε is obtained by multiplying the vacuum permittivity ε_0 with the relative permittivity of silicon ε_{Si} which has a value of 11.9.^[81] With the relation to the substrate resistivity ρ ,

$$\rho = \frac{1}{\mu e |N_{\text{eff}}|} , \quad (2.15)$$

d_{dep} can be calculated with

$$d_{\text{dep}} = \sqrt{2\varepsilon\rho\mu(V_0 + V_b)} \quad (2.16)$$

where μ for the majority charge carriers in the substrate has to be taken. Equation 2.10 shows that the MPV of free charge created by an ionizing particle increases with the silicon thickness that is traversed. Taking only drift into account, this means that a larger bias voltage or a larger substrate resistivity result in an increased charge signal.

2.4.2.3 The Shockley-Ramo theorem

The electric signal in an electrode on the semiconductor surface is due to induction of current in the electrode and not due to the charge collected by the electrode. Still, the process is commonly called “charge collection” in the field of silicon detectors. The Shockley-Ramo theorem is the adequate theory for this process.^[82, 83] It is described in detail in many textbooks, e.g. [35]. The essentials for the case of segmented electrodes on a depleted bulk (i.e. pixel or strip-detector) are:

- The trajectory and velocity $\vec{v}_p$ of a point charge q_p in the bulk are determined by the electric field $\vec{E}$.
- The so-called weighting field $\vec{E}_w$ is calculated by setting all conductors to ground potential and not considering q_p . Only the electrode for which the current signal is calculated is set to unit potential.
- The instantaneous current on this measurement electrode is then given by

$$I_i = -q_p \vec{v}_p \cdot \vec{E}_w . \quad (2.17)$$

Figure 2.12 illustrates this case and an important consequence for e-h pairs created in the bulk. Integrating I_i over the whole signal time gives the net charge signal of the e-h pair. Because of the shape of the weighting field, a net charge signal is induced only in

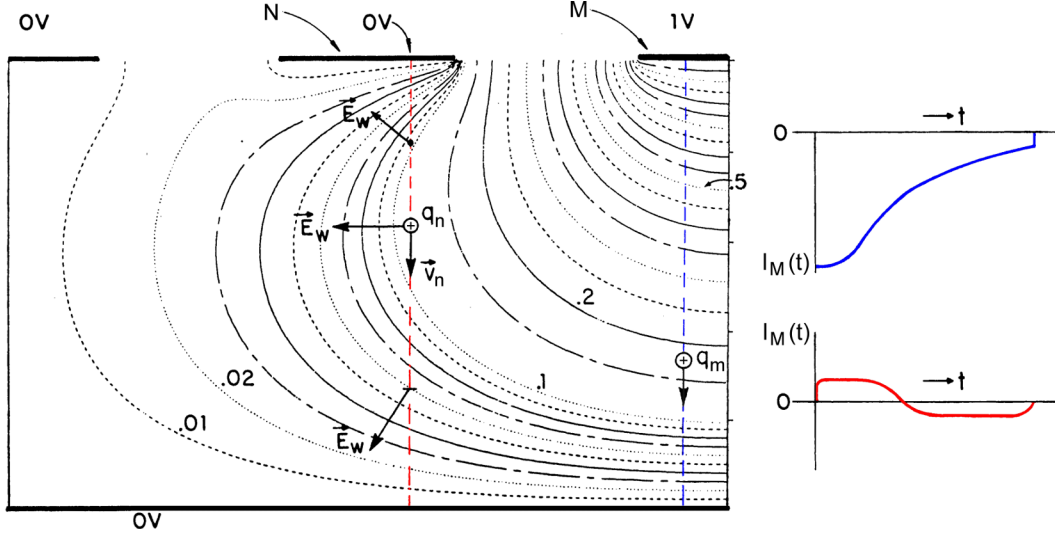


FIGURE 2.12: Cross-section of a segmented silicon detector with illustration of the Shockley-Ramo theorem. The electrodes on the top and the bias contact on the bottom are on ground potential. Only the main electrode (M) lies on unit potential. The resulting weighting potential is depicted (black lines). Its magnitude rises toward the main electrode. The path of the two positive charges q_m and q_n is shown as colored dashed lines. The path of q_m starts at the main electrode and the path of q_n on the neighboring electrode (N). The resulting currents I_M that are induced on the main electrode when the charges are moving from the electrodes to the bias contact are depicted on the right. The current induced by q_n (red solid line) changes sign over time and the integral, which corresponds to the net charge signal, sums up to zero. The integral of the current induced by q_m (blue solid line) yields the total charge collected, which is equal to q_m . Graphic adapted from [84].

the electrode that collects the free charge. It is important to note that the electron and the hole move in opposite directions, so one of them is collected by the electrode and the other is collected by the contact for the bias voltage. Together, they form one single trajectory from the electrode to the contact, which is equal to the electron moving along the whole trajectory or the hole doing the same in the opposite direction. Most of the signal is induced in the final part of the trajectory at the side of the electrode because the weighting potential rises steeply toward the electrode. This results in a difference between electron and hole collection if charge carriers cannot reach the electrode due to recombination or trapping (see Sections 2.4.5.2 and 4.1.2.1).

2.4.2.4 The CCPD as an example

Figure 2.13 illustrates the presented concepts by the example of a pixel of a CCPD-sensor. Chapter 4 deals with this sensor family in detail. The sensor substrate or bulk is p-type silicon and the collecting electrode is realized as a deep n-well. The bias contact is realized as a grid between the pixels on the top of the substrate but due to the low substrate resistivity of about $10\,\Omega\text{cm}$ the applied bias potential extends far into the substrate (this is explained in more detail in see Section 2.4.4). The depletion

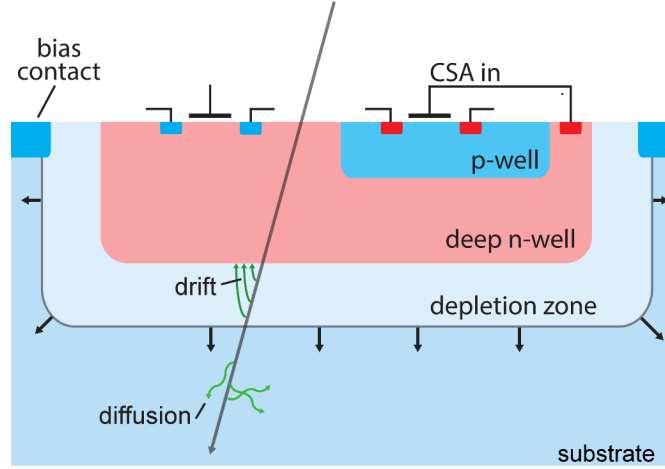


FIGURE 2.13: Schematic cross section of a CCPD pixel. The depletion zone forms around the p-n junction between the p-substrate and the deep n-well (red) that houses the in-pixel electronics. A traversing MIP (long black arrow) creates free charge carriers that move by drift and diffusion. The motion of electrons is indicated by the green arrows. The deep n-well acts as collecting electrode and is connected to the input of a charge sensitive amplifier (CSA), the first part of the signal readout chain. Dimensions are not to scale. Figure adapted from [85].

zone forms around the deep n-well. A MIP passing the sensor results in a signal in the electrode that consists of two superimposed parts. The drift part results from the free charge carriers that are created inside the depletion zone. They are collected fast, as we explained above. The diffusion part comes from the free charge carriers created in the undepleted volume of the substrate, creating a longer-lasting and low-amplitude signal when compared to the drift part. Both parts are important to understand and interpret the total signal in the electrode.

The electrode is a triple-well structure so that it can house the sensor electronics that is realized in CMOS-technology. The sensor electronics are the first part of the detector's readout-chain, which is explained in the next Section. Details on the sensor electronics are given in Section 4.2.2.

2.4.3 Signal processing - The electronics

The current signal in a detector electrode forms the raw data of a particle hit. Usually one electrode is equal to one readout channel of a silicon detector. For a low number of electrodes and moderate particle rates the signal can be directly recorded for later offline analysis. However, at particle rates in LHC-experiments involving detectors with millions of channels, a direct online analysis and hence signal processing by front-end electronics is necessary. Here we describe the signal processing of a typical pixel detector readout scheme.

2.4.3.1 Basic signal processing

Due to the small total free charge created by a passing MIP (around $1000e^-$ for the CCPD-case), the first stage of signal processing is a CSA. The minimum useful information of one pixel is if there is a particle hit in a certain period of time and the starting time of that period. The decision if there is a particle hit is done by a comparator that fires above a certain threshold. The precision of the time information is theoretically limited by the underlying electronics' clock but is usually limited by analog factors like jitter or timewalk (see [86] for a detailed discussion on this). For the LHC, the precision has to be below 25 ns.

In many cases, the total charge is also an essential information. The comparator in the FE-I4 of the IBL, e.g., is designed to provide this information in the so-called ToT (time-over-threshold).^[52]

Between preamplifier and comparator there are electronic elements summarized by the term “shaper”. They are designed to optimize the noise characteristics of the CSA by altering the signal transfer function (see next section). The minimum implementation are simple RC-circuits that realize high-pass and/or low-pass filters.

The front-end electronics are implemented as custom ASICs (application-specific integrated circuits). Therefore any analysis could be performed on the initial signal by arbitrarily complicated electronics. However, practical requirements limit the possibilities. For LHC experiments, the limitations are mainly set by the time scale of 25 ns as well as by power and data rate restrictions.

The schematic of the pixel electronics for the CCPD-case is shown in Figure 4.5.

2.4.3.2 Noise

The SNR (signal-to-noise ratio) is an important measure of a signal. It is defined as the ratio of the signal amplitude to the noise amplitude. The noise in the readout chain up to the shaper is conveniently expressed as the ENC (equivalent noise charge). It is equal to the detector charge signal that yields a SNR of one. The definition and calculation of different noise sources that contribute to the ENC in an electronic circuit are found, e.g., in [35, Section 1.10]. Important sources are shot noise due to electron emission statistics, thermal noise due to thermal velocity fluctuations of charge carriers and $1/f$ -noise due to trapping and de-trapping of charge carriers. For electrical considerations, a pixel detector can be modeled as the capacitance C_D between the ground and the input of the preamplifier. Calculations yield

$$\text{ENC} \propto C_D . \quad (2.18)$$

Reducing the detector capacitance by, e.g., reducing the pixel size is an efficient measure to raise the SNR. C_D is made up of several contributions: the capacitance between the

pixel electrode and the bias contact, between the pixel electrode and neighboring pixels (which also determines the cross-talk between pixels) and smaller parasitic contributions. Another important contribution to the ENC comes from the leakage current I_L of the reversely biased diode. It is proportional to $\sqrt{I_L}$ and depends strongly on the absolute temperature T :^[87]

$$I_L \propto T^2 e^{-\frac{E_g}{2k_B T}} \quad (2.19)$$

where E_g is the band gap energy of the semiconductor.

2.4.3.3 Higher level functions

The information from single pixels is further processed on the level that comprises all pixels from a sensor or readout chip. This includes addressing, merging of information and transmission. In addition there is input to the pixels to control and power the electronic elements. This is done by analog power supply lines and digital input parameters that control built-in digital-to-analog converters (DACs).

2.4.3.4 Monolithic versus hybrid

Sensors where the higher level functions and front-end electronics for the pixels are implemented on the sensor chip itself are called monolithic. Alternatively, the electronic functionality can be put on a dedicated readout chip forming a hybrid detector. Hybrid detectors need an interconnection for each pixel between the sensor electrode and the corresponding pixel cell on the readout chip. The principal advantages and disadvantages of the two solutions are discussed in Section 4.1.1.

2.4.3.5 Calibration

For absolute charge measurements, a calibration of the sensor and readout system is necessary. The radioactive isotope iron-55 (^{55}Fe) is commonly used for charge calibration of silicon sensors. Its daughter nucleus manganese-55 emits soft X-rays with three main peaks at 5.899 keV (K_{α_1}), 5.888 keV (K_{α_2}) and 6.490 keV (K_{β_3}).^[88] In silicon, the two K_{α} peaks correspond to 1615 and 1787 e-h pairs per photon, respectively. A comprehensive discussion about calibration with ^{55}Fe can be found in [75, Chapter 2.3.2].

Another important tool is charge injection which makes it possible to inject a specified amount of charge to the preamplifier input (see Section 4.2.4). This allows for testing of the electronics and the whole readout chain with reproducible input signals.

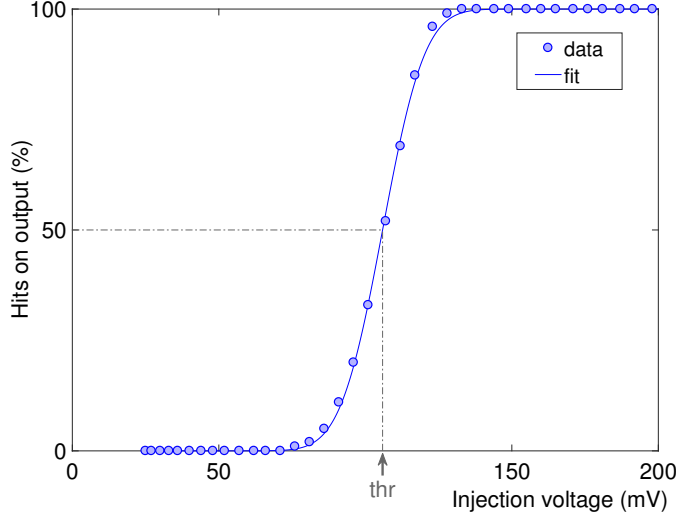


FIGURE 2.14: S-Curve of a sensor pixel of a CCPD from the measurements described in Section 4.4.5. The relation given in Equation 2.20 is fitted to the data. This fit yields the threshold (thr) and the noise, which is explained in the text.

2.4.3.6 The pixel threshold

The threshold of the comparator in every pixel is an important value and can be determined by the following procedure. While scanning the injection amplitude, a fixed number of injections is sent to the preamplifier for each amplitude step. The response of the comparator is recorded. Injections resulting in a preamplifier output lower than the threshold should ideally result in no response (i.e. the comparator does not fire). Injections above the threshold should always trigger the comparator. The graph showing the relative number of measured output signals per injection vs. applied injection amplitude should theoretically be a shifted Heaviside step function. In reality the function is smeared out by noise contributions which results in a S-curve (a sigmoid function or scaled error function). Assuming Gaussian noise, the function can be expressed by

$$S(x) = \frac{1}{2} \cdot \left[1 + \operatorname{erf} \left(\frac{x - \text{thr}}{\sqrt{2} \cdot \sigma_{\text{ENC}}} \right) \right] \quad (2.20)$$

where x is in this case the injection amplitude and erf is the error function defined by

$$\operatorname{erf}(x) = \frac{2}{\sqrt{\pi}} \cdot \int_0^x e^{-t^2} dt . \quad (2.21)$$

σ_{ENC} is the standard deviation of the Gaussian noise expressed in units of the injection amplitude. The ENC in units of charge can be calculated by the charge calibration as is mentioned above. The threshold (thr) is the abscissa value where $S(x)$ crosses 50 % of its maximum. Figure 2.14 shows a measured S-curve with the fit of $S(x)$ to the data and the method for extraction of the threshold value. The S-curve is obtained by varying the injection amplitude on the input side of the pixel. Threshold and noise obtained this way are therefore called “input referred”.

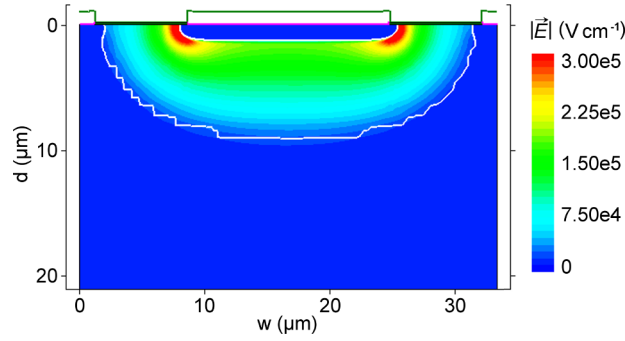


FIGURE 2.15: Simulation of the electric field in an SAMP-pixel of an unirradiated CCPDv4 (see Section 4.2 for sensor details). The cross-section is along the short pixel dimension. Only the top 20 μm of the 250 μm thick sensor and one single pixel are shown. The simulation included the whole thickness and neighboring pixels. The resistivity of the bulk was set to 10 Ωcm and the bias voltage to 80 V. The sensor electrode is the centered blue bar on the top edge. The bias contacts are the short pink bars in the top corners. The edge of the depletion zone is depicted as a white line.

The threshold value of a pixel can be adjusted in order to equalize fluctuations from fabrication and to set application-specific values. Usually, a global parameter affects the coarse value for all pixels of a sensor chip and a local parameter is available for fine-tuning of each pixel. Section 4.4.6 deals with this tuning in more detail.

2.4.4 Simulation of the sensor

Semiconductor devices are commonly simulated with TCAD tools (Technology Computer Aided Design). The results of such a simulation for the CCPD, as it is described in Section 2.4.2.4, are shown in Figures 2.15 and 2.16.⁽¹³⁾ The first figure shows the top 20 μm of one pixel and the electric field strength around the pixel electrode. The thickness of the sensor is 250 μm . The field strength has approximately the same value of 0 in most of the substrate, including the implants for the bias contacts. This means that these zones are practically on the same electric potential, which is the bias voltage V_b . When moving the bias contact to the back side of the substrate, i.e. the opposite side of the electrodes, the electric potential does not change significantly. This is due to the low substrate resistivity. The round shape of the depletion zone is an effect of the spread of the bias potential.

Figure 2.16 shows the current and charge signal of a traversing MIP. The MIP path is perpendicular to the sensor (i.e. vertical in Figure 2.15) and centered with respect to the pixel sides. The signals induced on the electrode of the pixel where the MIP passes (main pixel) and of the neighboring pixel are shown. The effects of the Shockley-Ramo theorem as they are discussed in Section 2.4.2.3 are visible. The current in the main pixel is always positive whereas the current in the neighboring pixel changes sign over time.

¹³ The software used was Synopsis Sentaurus TCAD. The simulations are from [89].

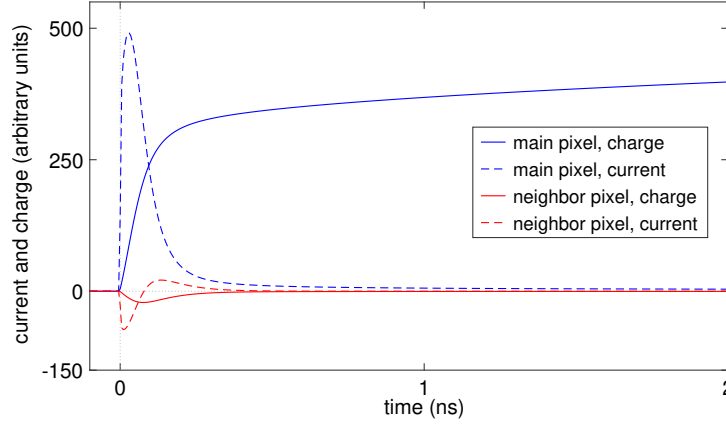


FIGURE 2.16: Simulated current and charge signals of a MIP that traverses the pixel centered and perpendicular to the sensor surface. The charge signal is the running integral of the current signal. In blue, the signal induced in the electrode of the pixel that is traversed by the MIP. In red, the signal of the neighboring pixel. The time range is limited to 2 ns in order to show the details at the beginning of the signals. The colors qualitatively correspond to the ones used in Figure 2.12.

Given a large enough integration time, a net charge signal is therefore detected only in the main pixel. The fast rise of the “collected” charge in the main pixel within the first hundreds of picoseconds corresponds to charge drift. The order of magnitude of the time scale agrees with the estimation done in Section 2.4.2.2. The slower, persisting rise corresponds to charge diffusion. This part disappears to a certain extent in irradiated sensors, which is explained in the next section.

2.4.5 Radiation damage in silicon sensors

The underlying, microscopic processes leading to radiation damage in silicon sensors are manifold. Comprehensive discussions can be found in many textbooks, e.g. [35, Chapter 7]. Here we give an overview of the different damage mechanisms and the effects on detector functions. There are two different types of radiation damage in a semiconductor: ionization damage and displacement damage.

2.4.5.1 Ionization damage

The creation of free charge carriers by ionization has negative effects in insulators. There the carriers drift or diffuse until they are trapped either in the insulator or on interfaces. Accumulation can lead to unwanted charge concentrations which create parasitic electric fields and possibly conducting channels. Semiconductor devices that depend on insulators like silicon dioxide (SiO_2) might degrade or fail. For example, MOSFETs (metal–oxide–semiconductor field-effect transistors) rely on insulated gates and are therefore prone to ionization damage. The amount of damage depends mainly on the total ionizing dose (TID) but also on the dose rate, the absorbing material, the

mobility of the trapped charge and time and voltage dependancy of the charge states. The TID is measured in gray (Gy) which is defined as one joule of radiation energy per kilogram of matter. A unit still used in HEP is the rad, which is equal to 0.01 Gy. Strongly ionizing particles can deposit a large amount of charge in a semiconductor. If this happens in a sensitive node of a microelectronic device, a so-called single event upset (SEU) can occur.^[90] A SEU can result in, e.g., switching of a memory bit and incorrect behavior of an electronic device.

2.4.5.2 Displacement damage

Displacement damage refers to atoms in the semiconductor crystal which are dislocated from their lattice sites by interaction of the impinging particles with the nuclei. The displaced nucleus can displace further atoms, leading to defect clusters. The NIEL scaling hypothesis states that displacement damage is proportional to the non-ionizing energy loss (NIEL), which in turn depends on the particle type and energy. The NIEL for 1 MeV-neutrons is set as a normalizing value. When the fluence Φ of a certain particle type and energy is given, the equivalent monoenergetic fluence Φ_{eq} of 1 MeV-neutrons that causes the same damage is calculated with ^[91]

$$\Phi_{eq} = k \Phi \quad (2.22)$$

where k is called hardness factor, which is obtained by measurements. Φ_{eq} is given in units of $n_{eq} \text{ cm}^{-2}$.⁽¹⁴⁾ The hardness factor of the 24 GeV-protons from the CERN PS is 0.51 ± 0.01 .^[92] A comprehensive compilation of data and discussion on the validity of the NIEL scaling hypothesis can be found in [93]. Displacement damage changes the electrical characteristics of the crystal and can be classified as follows:

Introduction of mid-gap states

This refers to the introduction of electron states located near the middle of the band gap of the semiconductor. In non-depleted regions they facilitate recombination of free charge carriers. In the depletion region they lead to a current proportional to Φ that adds to the leakage current. This increases the shot noise and might lead to destructive thermal runaway. The latter can happen because of ohmic heating caused by the increased leakage current, which in turn amplifies the leakage current due to the strong temperature dependancy shown in Equation 2.19.

Introduction of states close to the band edge

These states facilitate trapping, i.e. free charge is captured and released after a while.

¹⁴ Φ_{eq} is only used here to distinguish it from Φ in Equation 2.22. Elsewhere, it is also denoted by Φ . The difference is obvious in the units.

This results in loss of charge and therefore loss of signal. A given charge carrier concentration decays to equilibrium with the lifetime τ . This leads to the net charge signal of a point charge being proportional to $e^{-t_c/\tau}$ where t_c is the charge collection time. The lifetime is proportional to $1/\phi$.

Change in doping characteristics

The doping characteristics are changed by removal of donor states in n-type semiconductors or acceptor states in p-type semiconductors and by creation of acceptor states in each type. This change can be described by the change of the effective doping concentration (N_{eff}). An important effect in n-type silicon is the type inversion, i.e. after a certain progress of donor removal and acceptor creation by irradiation, the initially n-type silicon changes its behavior and acts like p-type silicon. Type inversion does not occur in p-type silicon.

The evolution of N_{eff} with fluence can be parameterized by

$$N_{\text{eff}} = N_{\text{eff},0} - N_C (1 - e^{-c_r \Phi}) + g_i \Phi \quad (2.23)$$

where $N_{\text{eff},0}$ is the initial effective doping concentration, N_C is the concentration of removable donors (n-type), respectively acceptors (p-type), c_r the removal constant and g_i the acceptor introduction rate. Relation 2.23 describes the stable damage, which depends only on Φ . Additional terms have to be included for time dependent terms, which cover annealing and anti-annealing. They are parameterized by exponentials with time constants. The time constants depend strongly on temperature so that these terms can be effectively suppressed by cooling of the sensor. The comprehensive model that describes the change of N_{eff} is called the Hamburg model. It is covered by, e.g., [91].

2.4.5.3 Damage mitigation

There are effective ways of mitigating the effects of radiation damage, e.g.:

- By choosing adequate doping characteristics for the sensor production, charge collection can actually benefit from the change of N_{eff} (see Section 4.1.2.3).
- The effects of trapping can be reduced by relying on fast charge collection by drift of electrons (see Section 4.1.2.1). The drift signal scales with the depletion thickness, so maximizing the depletion thickness is also beneficial.
- The increase in leakage current can be counteracted by decreasing the temperature of the sensor, reducing noise and preventing thermal runaway.
- There are many design measures that improve the radiation hardness of electronic devices, e.g. using enclosed circular transistors instead of linear transistors.

These examples are just a few and intense research is conducted in the field of improving the radiation hardness of silicon detectors. The dedicated collaboration RD50 deals with radiation hard semiconductor devices for very high luminosity colliders. Past and current developments of the collaboration are collected in [94].

2.4.6 Sensor technologies & large scale detectors

For use in the ITk, a silicon pixel detector has to fulfill the requirements mentioned in Section 2.2.3. It is not enough to develop the sensor performance alone, but detector and large-system aspects have to be taken into account. Some important stages, respectively items for this are:

- Development of a full-size sensor chip that is suitable for module construction.
- Efficiency demonstration of the full-size sensor chip. The efficiency is defined as the ratio of detected particle hits to real particle hits (in percent). Values well above 99% are considered suitable for HEP experiments. The efficiency is measured in testbeam campaigns.
- A low number of hot and dead pixels. Hot pixels constantly detect particle hits and dead pixels never detect particle hits. Both are malfunctions and signals from affected pixels have to be ignored (masked) for detector operation.
- A low noise occupancy at a threshold that is low enough for efficient particle detection. The noise occupancy is the probability that a pixel sees a noise hit when the readout is triggered at a random time.
- The power consumption and cooling is feasible not only for single sensor chips but for the whole detector area (see the example given in Section 2.2.4).
- The production of the whole detector area is feasible in terms of cost.
- Reliability of all parts of the detector is given during the projected lifetime of the detector. High quality control and testing possibilities at early production stages are necessary for this.

This list is non-exhaustive. Detailed requirements on the pixel system of the ITk can be found in [45, Chapter 9].

The consideration of detector requirements has to steer the sensor development from the very beginning, including the choice of the underlying technology. Currently there are many options available for pixel sensors: planar, 3D, high-voltage like HV-CMOS, high-resistivity (HR), silicon-on-insulator (SOI), depleted p-channel FET (DEPFET), Monolithic Active Pixel Sensors (MAPS), etc. Some bring along further options like

- n and p-type substrate,
- monolithic or hybrid approach or a mix of both,
- DC or AC coupling in case of the hybrid approach

and many more. There are also alternatives to silicon when it comes to sensor material, e.g., diamond. Dealing with all options in detail is beyond the scope of this thesis. We compare relevant options to our HV-CMOS sensors in Section 4.1.1. Detailed overviews of sensor and detector technologies can be found in, e.g., [90, Chapter 6], [95] and [96].

The next two chapters form the main part of this thesis:

“The IBL mock-up for the ATLAS Phase-0 Upgrade” (Chapter 3) and
“HV-CMOS sensors for the ATLAS Phase-II upgrade” (Chapter 4).

Chapter 3

The IBL mock-up for the ATLAS Phase-0 Upgrade

As outlined in Chapter 2, the integration of the IBL into ATLAS meant complete reconstruction of the LHC beam pipe in ATLAS and its proximity up to the innermost barrel of the existing Pixel Detector. This included the exchange of the beam pipe, thermal insulation and heating as well as installation of the cooling system, sensors, front-end electronics, cabling and mechanical support structures. In order to understand the IBL's thermal and mechanical behavior, a real-size mock-up of the IBL was built and operated. The focus lied on the beam pipe bake-out. In addition, the results were used to tune the parameters of the CFD-simulation of the detector. Before installation of the IBL, the mock-up was modified to serve for testing and development of integration procedures. Section 3.1 describes the scope and details of the mock-up and the setup. In Section 3.2 we present the results of the various thermal tests that we conducted, including the comparisons with simulations. A summary and data from the real LHC beam pipe bake-out after successful installation of the IBL are given in Section 3.3.

3.1 IBL and mock-up design

Figure 3.1 shows a part of the IBL cross-section with nominal radial dimensions. This schematic alone makes clear why a thorough understanding of the mechanical and thermal behavior of the IBL was essential before installation. The new pixel layer is only 31 mm away from the radial center of the detector with a distance of only 2.7 mm to the beam pipe envelope. The clearance toward Layer 0⁽¹⁾ of the Pixel Detector is 5.5 mm.^[9, Table 1] The Inner Support Tube (IST)⁽²⁾ was already mounted inside the

¹ Layer 0 of the Pixel Detector is also called B-Layer which is not to be confused with the *Insertable* B-Layer (IBL).

² In some publications the IST is also called IBL Support Tube.

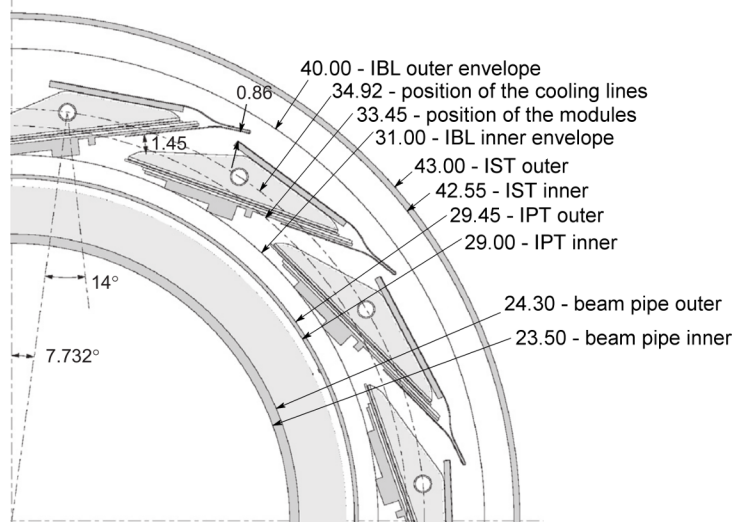


FIGURE 3.1: Cross-section of the IBL. The labeled values are radii from the center in mm. Adapted from [97].

Pixel Detector when the IBL was installed. It left a clearance of only 2.5 mm for the insertion of the more than 7 m-long IBL package. The package included the new beam pipe and the IBL with services like cabling and cooling lines. In addition to these mechanical constraints there were stringent thermal ones: During the beam pipe bake-out the heaters attained a temperature of more than $+220^\circ\text{C}$. At the same time, the IBL modules that are only 6.5 mm away from the heaters inside the dense package must not reach temperatures above $+40^\circ\text{C}$. [9, Section 10.1]

As a consequence, the thermo-mechanical properties of the IBL were investigated with a 1:1 mock-up that was built with material and geometry very similar to the IBL. The first version of the mock-up, called thermal mock-up, was used for thermal tests under various conditions and focused on the central region of the IBL where the staves and sensors sit. In the next sections we give details about the thermal mock-up and the tests performed with it. The second version, called type 1 services mock-up, focused on the service region of the detector where the cables and cooling system are routed to and from the IBL. It served mainly for testing of integration and assembly procedures and for investigation of material issues. The type 1 services mock-up can not be discussed in detail within the scope of this thesis.

3.1.1 The thermal mock-up

The thermal mock-up was built to replicate the central part of the IBL, covering the staves and additional 849 mm on each side along the z -dimension. A schematic is shown in Figure 3.3(a). The total length was 2445 mm with z_0 defined at the center. The mock-up was axially symmetric but had two features that distinguished it along z . First, the CO_2 -flow in the cooling system and the controlled gas flow of the environment was

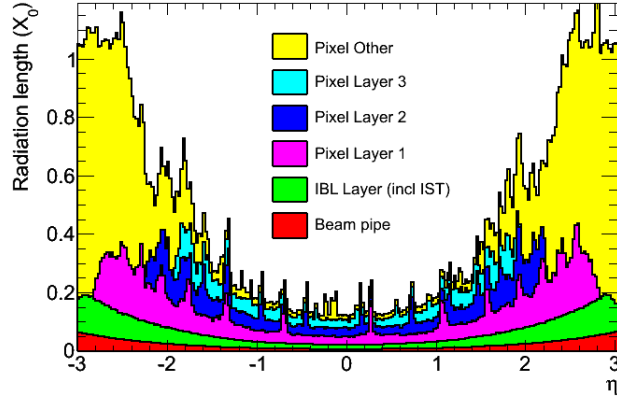


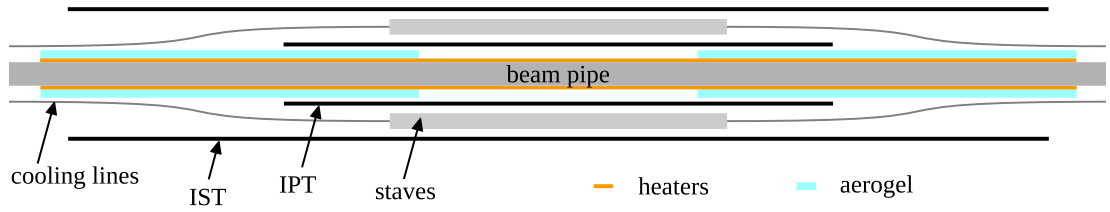
FIGURE 3.2: Radiation length as a function of the pseudorapidity η for different components of the ATLAS Inner Detector and the beam pipe. The installation of the IBL altered the contribution from the beam pipe (red) and added the contribution from the IBL (green). Plot from [9].

in direction $+z$. We refer to this direction as downstream. Second, the leads for the many temperature sensors that were installed in the mock-up were all routed toward the downstream end of the mock-up (see Figure 3.3(c)). This introduced significant material to the $+z$ -part of the mock-up. The center z_0 , the convention of the direction of $+z$ and $-z$ as well as the direction of the CO_2 -flow are depicted in Figure 3.3(b). In the IBL, the anisotropy along z is not present because adjacent staves have opposing CO_2 -flow, the services with leads are mounted on either side of z_0 and the gas flow is not directional. Given the orientation of the staves in the mock-up, downstream in the mock-up corresponds to side C of the IBL and ATLAS. Note that the z -axis of the mock-up is reversed with respect to the z -axis of the IBL and ATLAS.

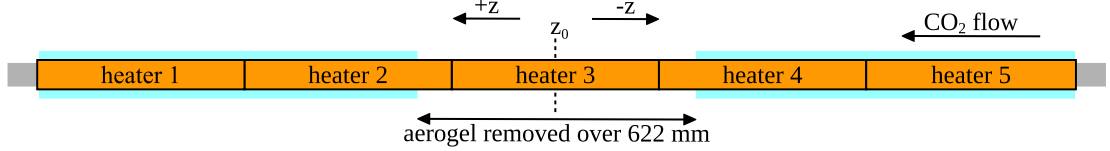
The central part of the mock-up was the aluminum beam pipe (BP) and its heating system composed of a layer of heaters, aerogel insulation and thin layers of aluminum foil and Kapton. On this thermally active beam pipe was fixed a carbon fiber tube, the Inner Positioning Tube (IPT). Around the IPT, 14 aluminum staves were mounted on two rings. Stainless steel cooling lines were present on every second staff. Finally, the IST acted as the outer envelope and was again made of carbon fiber. These items are marked in the axial cross-section shown in Figure 3.3(a) as well as in the radial cross-section shown in Figure 3.4. The dimensions and materials of all items are listed in Table 3.1 together with the corresponding IBL items for comparison.

Two different configurations were consecutively built. The first configuration lacked the IPT and had aerogel as insulation over the whole length. The IBL introduced additional material to the Inner Detector very close to the interaction point (see Figure 3.2). Therefore it was designed to be as lightweight as possible in terms of radiation length. This included optimization of the beam pipe package. Suggestions to remove the aerogel insulation around the interaction point to reduce material lead to the second configuration of the mock-up. It had the IPT installed and the aerogel was removed along 622 mm around the interaction point at z_0 . This reduced the radiation length

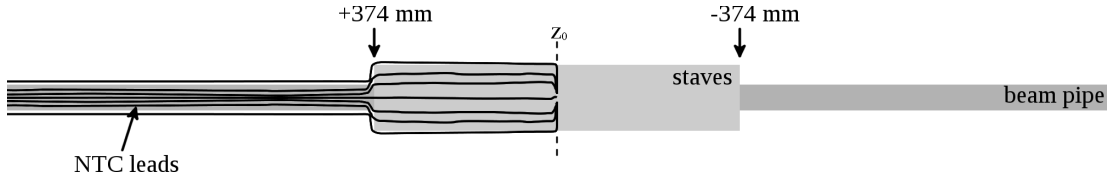
of the IBL package up to a pseudorapidity of approximately ± 3.1 . Reassured by the results presented here, this design was chosen for the IBL package.



(a) Axial cross-section of the configuration where the aerogel was removed around z_0 and with the IPT installed. Only the long dimension is to scale. The exact dimensions are listed in Table 3.1. The very thin Kapton and aluminum sheet layers are not shown for clarity.



(b) Schematic with the heaters' positions and the convention of the z -coordinate in the mock-up. The area where the aerogel is removed is shown. "Downstream" in the text refers to the direction of the CO_2 -flow which is depicted here. Downstream and $+z$ in the mockup point toward side C of ATLAS. The z -axis is reversed with respect to the IBL and ATLAS.



(c) Schematic to clarify the position of the NTC leads and the staves. The staves were positioned centered around z_0 , extending 374 mm in each direction.

FIGURE 3.3: Axial cross-section (a) and schematics (b,c) of the thermal mock-up.

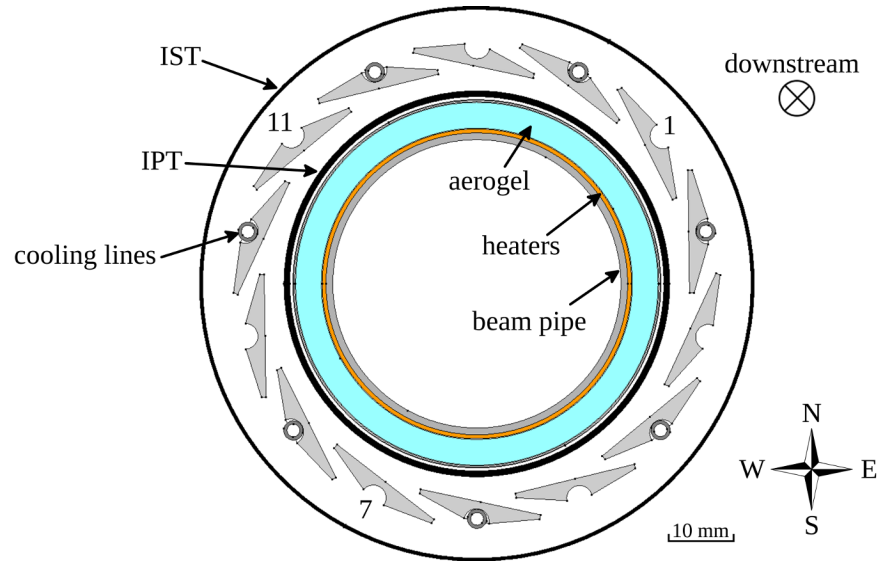


FIGURE 3.4: Radial cross-section of the mock-up looking downstream toward side C of ATLAS. The directions north, east, south and west that are used in the text are shown. The staves are numbered from 1 to 14, counting clockwise. Staves 1, 7 and 11 are labeled. All even staves are equipped with a cooling line. Adapted from [98].

TABLE 3.1: Material and dimensions used for the thermal mock-up and for the IBL. All values are in mm and nominal values. Therefore, no errors are given. CF stands for carbon fiber, ABS for acrylonitrile butadiene styrene and N/A for entries where no data is available.

item	mockup				IBL			
	material/ type	inner radius	thickness	length	material/ type	inner radius	thickness	length
beam pipe								
tube	aluminum	22.34	1.05	2445	beryllium	23.50	0.80	7300
heaters	silicone rubber	23.39	0.60	2200	RICA Kapton	24.30	0.20	7200
Kapton	Kaneka	23.99	0.12	2445	Kaneka	24.50	0.12	7200
aerogel	Aspen Pyrogel	24.11	3.50	2300	Aspen Pyrogel	24.62	4.00	7200
Kapton	Kaneka	27.61	0.12	2445	Kaneka	28.62	0.12	7200
outer layer	aluminum	27.73	0.10	2445	aluminum	28.74	0.025	7200
new IBL items								
IPT	CF (T300)	29.00	0.90	1225	CF (K13C)	29.00	0.45	6572
stave mounting	ABS plus	single stave dimensions when			CF	single stave dimensions when		
stave body	aluminum	unmounted: 18.8 wide, 3.5 high, 748 long			CF & carbon foam	unmounted: 18.8 wide, 3.5 high, 748 long		
IST	CF (T300)	42.50	0.50	2244	CF (K13C)	42.50	0.45	6600
cooling lines		cooling lines' centers sit at $r = 34.92$				cooling lines' centers sit at $r = 34.92$		
inlet capillary		0.8	N/A	5289		1.0 and 1.5	0.2	1200 and 2632
boiling tube	stainless steel	2.0	0.5	1308	titanium	1.5	0.1	1350
outlet tube		2.0	0.5	5289		2.0 and 3.0	0.3	2632 and 1200

3.1.1.1 Temperature measurement

The thermal behavior of the mock-up during the tests was recorded with almost 50 negative temperature coefficient thermistors (NTCs). They were mounted at special points of interest distributed in the mock-up. Two radial cross-sections of the mock-up were densely populated with NTCs so that the temperature of every stave was measured. These cross-sections were positioned at the z -coordinates -225 mm (z_{-225}) and $+225$ mm (z_{+225}). The sensors were glued onto the face plate of each stave and on selected positions on the outside of the aerogel, respectively the IPT and the IST. Several sensors were attached to the cooling lines both upstream and downstream of the staves. The error of the temperature taken with the NTC sensors was dominated by the quality of contact between the sensor and the item of interest. Thermal grease was applied underneath each sensor to ensure good thermal contact. Additionally, the upper surface of the sensors was covered with tapes with similar surface properties to the item of interest. This mimicked similar behavior concerning radiative and convective heat transfer to the environment. Despite these measures we assume an error of 2°C for the temperatures taken with the NTCs.

The mock-up was mounted in the ATLAS Inner Detector Integration Facility at CERN known as SR1. The ambient temperature there was constantly regulated by an air conditioning system to 19°C .

3.1.1.2 Bake-out equipment

The heating and insulation system of the beam pipe was very similar to the LHC system. The heaters were wrapped around the beam pipe followed by the aerogel insulation and a very thin layer of aluminum foil acting as reflector for thermal radiation and as a faraday cage. In between, thin layers of Kapton were used for insulation and assembly purposes. The IPT was the outer shell. We used five heaters for the mock-up, regulated by a temperature control rack that is also used for the real LHC beam pipe bake-out. In addition, several wattmeters of the type Power Analyser Triphase 106A-3 from Infratek were installed. With these we could measure the power consumption for each heater individually.

The temperature measurement of the temperature control rack was realized by several thermocouples which were attached to the heaters. Due to the thermal inertia of the beam pipe package and the binary regulation of the heaters we estimate the error of this temperature to be 5°C . During the tests where the setpoint was 180°C we observed with NTCs that the actual temperature of the beam pipe was almost 4°C lower than the setpoint value. Unfortunately these NTC-data were not available in other tests. As a result we assume an error of 5°C .

3.1.1.3 Cooling system

The IBL uses an evaporative CO₂ cooling system. As is explained in Section 2.3.3, such systems have only recently been introduced to HEP experiments. Therefore the mock-up was also used to gather experience with the CO₂ system in operation. SR1, the cleanroom where the mock-up was mounted, houses its own CO₂ cooling plant. It provided a cooling power of up to 1.4 kW, which is the nominal power for the real IBL plant. The minimum temperature setpoint was -40°C . A description of the SR1 cooling plant can be found in [99]. Details on the principle of operation of a CO₂ cooling system and specific information of the IBL cooling plant are given in Section 2.3.3.

For each thermal test we state the temperature setpoint of the cooling system. The actual temperature of the coolant was different. This temperature was not directly accessible. Instead, we measured the outside temperature of several cooling lines for each test.

When the mock-up was built, it had not been decided if the CO₂ in the IBL flows in the same direction for all cooling lines or if the direction is opposite in neighboring cooling lines. In order to not delay the mock-up construction, only seven cooling lines were implemented in the mock-up.

3.1.1.4 Controlled environment

To assure defined environmental conditions for the tests, the mock-up was placed in a sealed volume. Three transparent PMMA⁽³⁾ tubes, each 2 m long and 270 mm in inner diameter, formed a 6 m long system (see Figures 3.5 and 3.6). With a rotary vane and membrane vacuum pump we achieved a minimum pressure of 30 mbar for the mock-up configuration where the aerogel was present. Removing the aerogel obliged a complete re-mounting of the setup and allowed for improved sealing. Thereafter we achieved 1 mbar. The Pirani gauge that we used to measure the pressures was accurate within $\pm 30\%$. Many tests were conducted under ambient pressure, which for the geographic position and the period of tests we estimate to be 962 ± 27 mbar.^[100, 101] For these tests we flushed the volume with dry air or nitrogen to prevent condensation and to establish conditions similar to those in the Inner Detector. The impact of the convective heat transport by the gas flow from and to the mock-up was kept low by limiting the gas flow rate. With a nominal value of 220 l h^{-1} it took about 1.5 h to completely change the setup volume.

The humidity was monitored during all tests at ambient pressure. It was constantly below the limit of the humidity sensor, which was 9 % relative humidity.

³ PMMA (polymethyl methacrylate) is commonly known as acrylic glass.

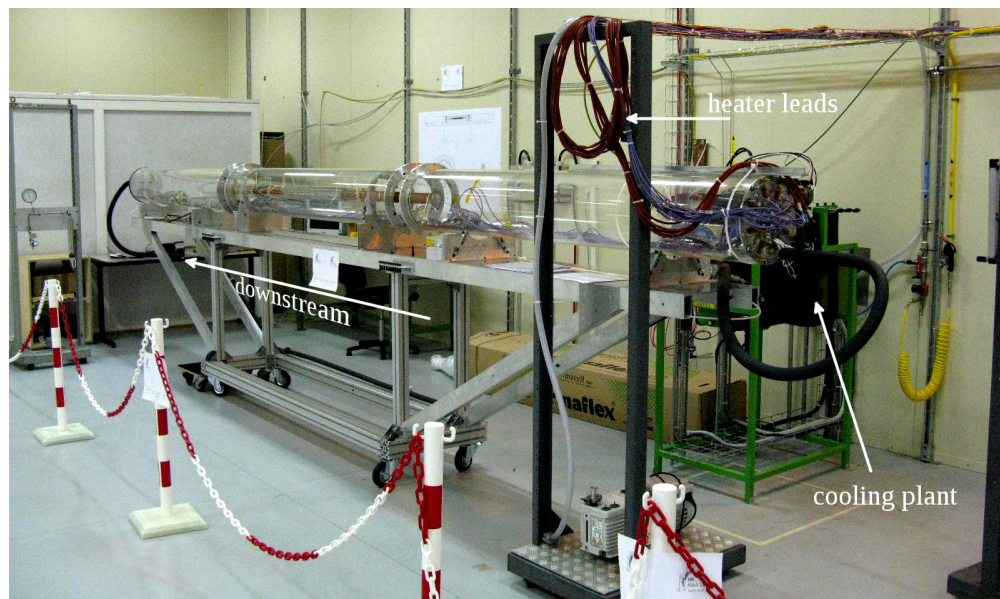


FIGURE 3.5: Setup in SR1 where the tests were conducted. The mock-up is hardly visible inside the central of the three PMMA tubes. A small part of the CO_2 cooling plant is visible on the green rack at the right. The main part of it was installed in an adjacent room. Also, the heating rack is not shown but the leads that connected to it are visible.

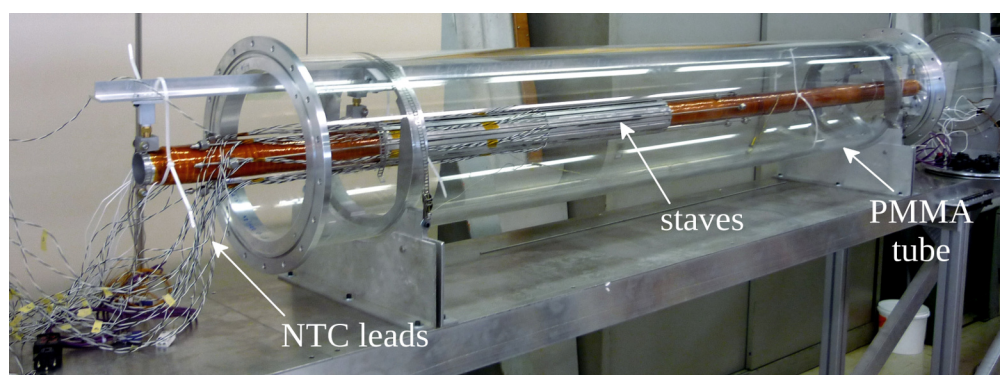


FIGURE 3.6: The thermal mock-up before final assembly in its first configuration without the IPT, mounted in the central of the three PMMA tubes. The IST was not yet installed. The orange tube is the beam pipe wrapped with the heaters, aerogel and Kapton. The aluminum staves are visible in the center with the NTC leads routed to the left.

3.2 Thermal tests

The tests performed with the thermal mock-up are listed in Table 3.2. We use the numbers in that list as references. The initial focus of the thermal mock-up was on the effects of the aerogel removal around z_0 . Three specific questions were to be answered:

- Do the sensor modules stay in the safe temperature region below $+40^\circ\text{C}$ during the bake-out if the aerogel is removed?
- Are at the same time the heaters powerful enough to heat up the beam pipe to the necessary temperature for the bake-out?
- Are the materials introduced by the IBL safe during the bake-out?

The main test (number 3 in Table 3.2) and CFD simulations were performed to answer these questions. Beforehand, two tests at lower beam pipe temperatures were conducted. Together with the other tests listed in Table 3.2 we could investigate further important points:

- Tests 1 and 2 also served for direct comparison of the two configurations aerogel versus no aerogel.
- Test 1 was used for tuning of the parameters of the simulation.
- Test 6 was used to cross-check the simulation results.
- Tests 4–7 were used to gain experience with the CO_2 -system at different temperature setpoints.
- Before we disassembled the thermal mock-up and transformed it to the type 1 services mock-up, several accident scenarios were run in tests 8–10.

The thermal boundary conditions of the main test were -40°C for the cooling setpoint and $+220^\circ\text{C}$ for the beam pipe temperature. The former was the minimum setpoint of the cooling plant and was the baseline for IBL operation.^[9] The latter was the temperature that is necessary for activation of the NEG-coating of the ATLAS beam pipe. Figure 3.7 shows the temperature evolution of different parts of the LHC beam pipe in ATLAS during the real bake-out.

3.2.1 Aerogel removal

Test number 1 was the only test conducted with the thermal mock-up in its first configuration: the aerogel was mounted all along the beam pipe and no IPT was installed. At

TABLE 3.2: Bake-out tests realized with the thermal mock-up. All temperatures are setpoint values and therefore no errors are given. The pressures of the first two tests bear an error of 30 %. The value “amb.” corresponds to ambient pressure as is explained in Section 3.1.1.4. The column captions have the following meanings:

nr.	sequential number to identify the tests
T_{bp}	temperature setpoint of the beam pipe
T_{CO_2}	temperature setpoint of the cooling system
p	absolute pressure in the setup
CO_2 -rate	flow rate of the coolant
T_{amb}	setpoint of the AC-system in SR1

nr.	comment	T_{bp} (°C)	T_{CO_2} (°C)	p (mbar)	CO_2 rate (g s ⁻¹)	T_{amb} (°C)
1	comparison: aerogel present, no IPT also used for CFD simulation tuning	180	-35	30	7.1	18.5
2	comparison: aerogel removed, IPT present	180	-35	1	7.7	19.0
3	main bake-out test	220	-40	amb.	7.7	19.0
4	investigation of different CO_2 -setpoints	220	-35	amb.	7.7	19.0
5	investigation of different CO_2 -setpoints	220	-30	amb.	10.2	19.0
6	investigation of different CO_2 -setpoints	220	-25	amb.	8.8	19.0
7	investigation of different CO_2 -setpoints	220	-20	amb.	8.1	19.0
8	accident scenario 1: CO_2 cooling failure, heaters not interlocked	230	-40	amb.	8.7	19.0
9	accident scenario 2: CO_2 cooling failure, heaters interlocked	230	-40	amb.	9.8	19.0
10	accident scenario 3: CO_2 cooling failure, heaters interlocked	220	-25	amb.	8.8	19.0

the time of the test there were only heaters available whose insulation was not rated for the planned 220 °C. We therefore heated the beam pipe only to the setpoint of 180 °C. The measured temperature was 176 ± 3 °C. The cooling system was set to -35 °C. We measured -30 ± 2 °C on the cooling lines.

This test was also used to tune the parameters of the CFD simulation. The simulation was done only in 2D in order to keep the complexity at a reasonable level. Details like cable leads for heaters or temperature sensors were not taken into account. For these reasons we deemed it useful to limit convection in the mock-up as the simulation would otherwise not reflect reality well. This was done by evacuating the sealed volume and performing the thermal test in a partial vacuum.

The second test was run with very similar settings and boundary conditions in order to be able to compare the results. A summary of the conditions is given in Table 3.2.

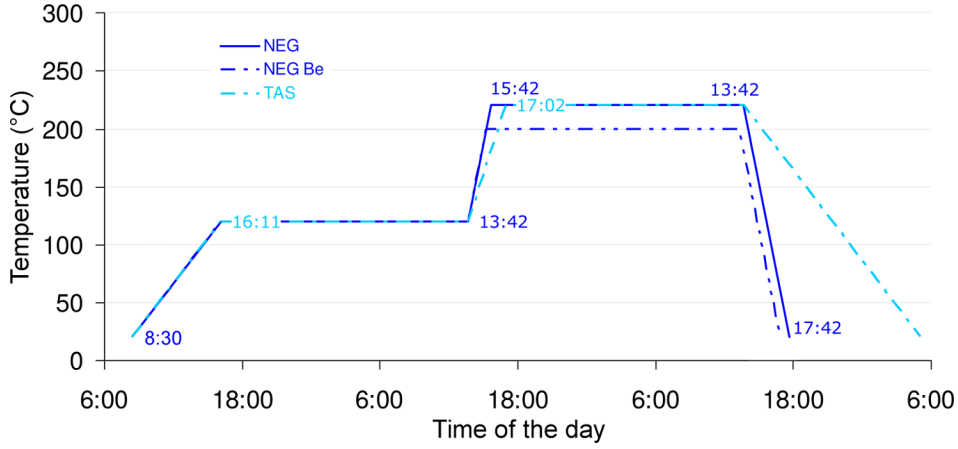


FIGURE 3.7: Bake-out and NEG activation cycle for the LHC beam pipe in ATLAS. The dashed dark blue line corresponds to the beryllium beam pipe around the interaction point in ATLAS. The solid blue line corresponds to non-beryllium sections of the beam pipe. The light blue line corresponds to the parts near the edges of the ATLAS cavern where the TAS (Target Absorber Secondaries) are located. The maximum plateau is at 220 °C. Figure adapted from [57].

Figure 3.8 shows the measured temperatures of the staves for the two first tests and the calculated differences. On average, the uncooled staves are 15 ± 3 °C warmer when the aerogel is removed. The cooled staves do not change within the error of the measurement. They are on average 1 ± 3 °C warmer.

We deduce the following situation: Due to the lack of insulation, more power was dissipated by the heaters to keep the beam pipe at the same temperature.⁽⁴⁾ However, the

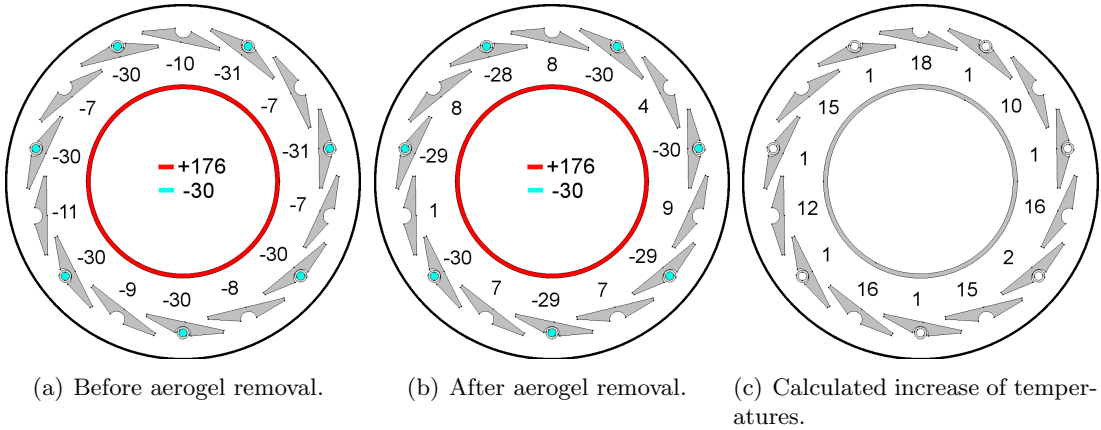


FIGURE 3.8: Temperatures of the staves at the cross-section at z_{-225} before and after removal of the aerogel. On the right, the calculated changes of the temperatures are given. The changes have been calculated with the original, non-rounded readings from the sensors. Therefore the differences of the rounded values differ for some staves. The heated beam pipe is depicted in red, the cooling lines in cyan. All temperatures are in °C. The temperatures are exact to the following values: ± 2 °C for the staves and the cooling lines and ± 3 °C for the beam pipe and the calculated differences.

⁴ The increase of heating power could not be measured because the first configuration did not have wattmeters installed. We discuss the heating power in detail in Section 3.2.2.2.

cooling capacity, respectively the coolant flow-rate of the CO₂-system, was large enough to still ensure evaporative cooling. Therefore both configurations had the same temperature in the boiling channels. Due to the good thermal conductivity of the aluminum staves and the good thermal contact to the cooling lines the temperatures on the face plates of the cooled staves increased only slightly. The uncooled staves however could give off heat only by radiation to their environment and by conduction via the NTC leads and the mounting structure. The latter was made of ABS, a polymer with a very low thermal conductivity compared to metals. Convection was reduced by the low pressure of below 40 mbar, the upper uncertainty limit of the recorded pressure. Thus, the uncooled staves were significantly warmer when the aerogel insulation was removed.

The thermal impact of the IPT can only be estimated as it was not present during the first test. Its thermal conductivity is more than 30 times larger than the aerogel's and it was about four times thinner ([102, 103] and Table 3.1). In addition, the black color of the IPT works in favor of radiative heat transfer. Therefore we do not consider it a strong heat barrier. We measured the temperature on its outside on the north⁽⁵⁾ to be $58 \pm 2^\circ\text{C}$ at z_0 where the staves were present but not the aerogel and $30 \pm 2^\circ\text{C}$ at z_{+390} where no staves were present but the aerogel was.

During the first two tests very valuable experience with the CO₂-plant was gained. Very early in the operation of the mock-up we discovered temperature oscillations of the cooling lines with an amplitude of several degrees. We discussed this observation with the Detector Infrastructure and Detector Cooling sections of CERN, who built and maintained the plant.⁽⁶⁾ It turned out that under certain running conditions of the plant some automatically controlled valves caused these oscillations. After having adapted the settings in the plant control system the oscillations disappeared. Another important point was the operation of the plant at a temperature setpoint lower than -35°C . We ran the first tests only at -35°C because at lower temperatures there were concerns about the consistency of glycol, which acts as the heat exchanging medium between the CO₂ and the primary chiller. After having completed the thermal tests we tested lower setpoints. Together with the CERN sections mentioned above we verified the reliability of the plant operation down to a temperature setpoint of -40°C . These were very interesting findings relevant for the IBL operation.

The main result of the first two tests was that removing the aerogel insulation around z_0 does not increase the temperature of the cooled staves significantly, given a large enough cooling capacity of the cooling system. To answer the next questions stated in the previous section, the main test with the boundary conditions from the IBL was conducted next.

⁵ See Figure 3.4 for the directions north, east, south and west.

⁶ PH-DT-DI: Physics Department - Detector Technology Group - Detector Infrastructure Section
EN-CV-DC: Engineering Department - Cooling and Ventilation Group - Detector Cooling Section

3.2.2 Bake-out tests

In this section the results from the main bake-out test (number 3) are presented. The power consumption of the heaters is discussed and with further tests (numbers 4–7) we investigated the influence of different CO₂-setpoints.

3.2.2.1 Main bake-out test

After the experience with the first tests described above, the main bake-out test was conducted. The conditions were set to resemble the real bake-out of the LHC beam pipe:

- The beam pipe temperature setpoint was 220 °C.
- The CO₂-setpoint was –40 °C.
- The mock-up was under ambient pressure.
- The mock-up was surrounded by dry air.

We did not follow the thermal evolution of the full two-and-a-half day bake-out cycle from Figure 3.7. Instead, we waited until thermal equilibrium was reached and all temperatures were stable. This took about four and a half hours after the ramping to 220 °C was completed. All temperatures were then monitored during approximately one hour and analyzed for the results presented here.

The temperatures of the beam pipe and CO₂ were 220 ± 5 °C and -32 ± 2 °C. The temperatures of the staves measured at the two cross-sections at z_{-225} and z_{+225} are given in Figure 3.9. The cooled staves were on average -32 ± 2 °C cold with no detectable difference in z . There was a slight tendency that staves on the north (upper) half were warmer than on the south, but the difference was smaller than its error: 1 ± 3 °C.

The uncooled staves were on average 12 ± 7 °C warm and showed a large variation in temperature. The results therefore bear large errors. A difference of 4 ± 5 °C revealed a tendency that the downstream staves were warmer. Uncooled staves on the north were on average 9 ± 8 °C warmer.

The temperatures on several other positions on the outer surfaces of the aerogel insulation, the IPT and the IST were recorded. The positions and values are shown in Figure 3.10 and Table 3.3. A vertical temperature gradient was present like for the uncooled staves: the aerogel and the IPT were warmer on their north sides. In addition, the aerogel outer surface was significantly warmer downstream at z_{+350} than upstream at z_{-350} : 92 ± 2 °C compared to 65 ± 2 °C.

The maximum temperature measured on the IPT was 89 ± 2 °C. The IPT in the IBL is a composite of carbon fibres and a resin. It is rated to keep its structural properties up

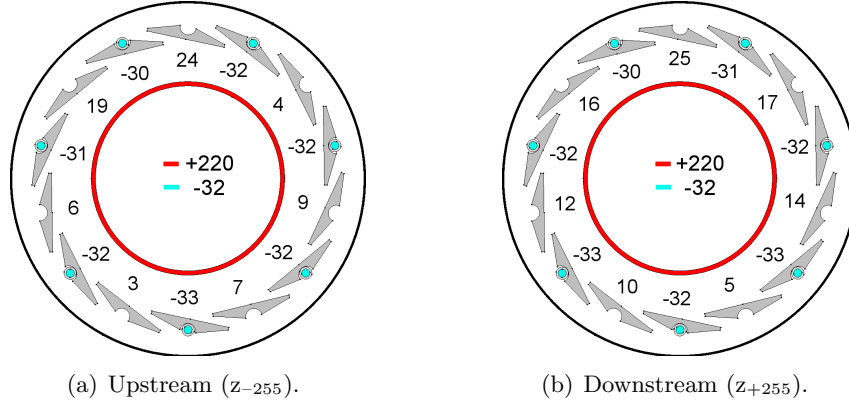
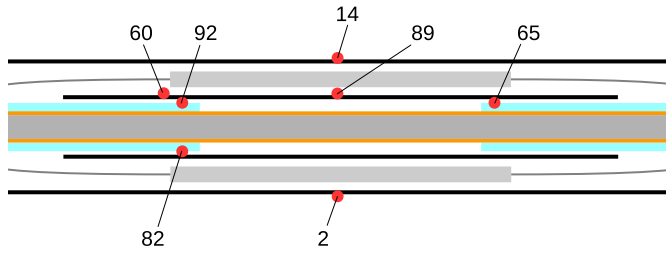


FIGURE 3.9: Temperatures of the staves during the main bake-out test at the cross-sections at z_{-225} and z_{+225} . All temperatures are in $^{\circ}\text{C}$ and bear an error of $\pm 2^{\circ}\text{C}$ except for the beam pipe temperature, which is exact to $\pm 5^{\circ}\text{C}$.



item	position		T
	z (mm)	azimuthal	($^{\circ}\text{C}$)
aerogel	-350	north	65
	+350	north	92
	+350	south	82
IPT	0	north	89
	+390	north	60
IST	0	north	14
	0	south	2

FIGURE 3.10 & TABLE 3.3: Temperatures at different points of the mock-up during the main bake-out test. All temperatures are in $^{\circ}\text{C}$ and bear an error of $\pm 2^{\circ}\text{C}$.

to around 170°C . This gives an acceptable safety margin, although locally we expect higher temperatures than what we measured. These extreme points are expected at the positions of the IPT's mounting points where an elevated heat conduction path toward the beam pipe is present.

We deduce the following points from the results:

- The cooling system was performing well, showing a cooling capacity that ensured a very homogeneous temperature of the cooled staves. The cooling lines were in very good contact with the staves. We measured the same temperature of $-32 \pm 2^{\circ}\text{C}$ on the cooling lines before and after the detector as well as on the face plates of the staves.
- There are three reasons explaining the large temperature variations of the uncooled staves. First, most of the NTC leads were present on the downstream side of the

mock-up (see Figure 3.3(c)). This caused an augmented heat conduction in that region and hence the tendency of higher temperatures of the uncooled staves on the downstream side. Second, convection of the ambient dry air transported heat from the south (bottom) to the north (top) of the setup. This caused the higher temperatures of uncooled staves on the north side. Third, mechanical inaccuracies like different distances between staves or a tilt of the setup influenced convective heat transport, leading to local variations. Also, the aerogel was manually cut and thinned to its nominal thickness. Variations in the thickness of this important insulation layer lead to local variations in the heat transfer from the heaters.

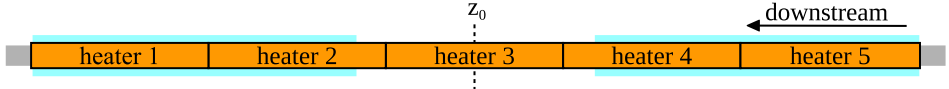
- The temperatures of the IPT, IST and aerogel support the arguments of the last point.
- Convection is an important factor under ambient pressure. The temperature differences between north and south did not develop in the tests where the setup was evacuated.

3.2.2.2 Heating power

The five heaters were arranged on the beam pipe like is depicted in Figures 3.3(b) and 3.11. Heater number 3 was centered around z_0 and was not covered with any aerogel insulation. The neighboring heaters number 2 and 4 had around 80 % of their surface covered with aerogel. Heaters number 1 and 5 were located on the extremities of the mock-up. They were fully covered with aerogel. During the time of the main test where thermal equilibrium was achieved, we recorded the power consumption of each of the heaters separately. The results are listed in Table 3.4.

The central heater needed the largest amount of power to maintain the beam pipe temperature at 220°C . This was expected because this heater was not covered with any aerogel as insulation. The neighboring heaters 2 and 4 used the least amount of power, whereas heaters 1 and 5 on the extremities used an increased amount again. This is explained by their position on the edge of the mock-up where heat is emitted to the environment. Due to the symmetry of the mock-up design, heaters 1 and 2 should have had the same power consumption like heaters 5 and 4. However, this simple approximation was not valid in practice. The leads of the NTC, which were installed on the downstream side, formed a thermal bridge between the heaters and their environment - especially the cooling lines - which resulted in an elevated demand of heating power to stay at the same temperature.

It is very important to note that in the mock-up only 7 staves were equipped with cooling lines. In the IBL 14 cooling lines are installed and therefore the power consumption of the heaters was higher. The CFD simulations of the mock-up and the IBL, which we present in Section 3.2.4, calculated an increase of 6.2 % when all 14 cooling lines are



heater nr.	1	2	3	4	5
P (W)	90.2 ± 0.4	72.1 ± 0.4	94.7 ± 0.4	58.5 ± 0.3	72.6 ± 0.4
P (W m^{-1})	205 ± 0.9	163.9 ± 0.8	215.2 ± 0.9	133.0 ± 0.7	165.0 ± 0.8

FIGURE 3.11 & TABLE 3.4: Power consumption (P) of the heaters during the main bake-out test. On the top, the positions of the heaters is shown as a reminder.

installed. Taking the values from Table 3.4, this yields a maximum power consumption of approximately 230 W m^{-1} . For the LHC beam pipe in the IBL-package two different heaters were available: the first type, which was installed before the Phase-0 Upgrade, could deliver up to 290 W m^{-1} . The second type was more powerful with a maximum of 430 W m^{-1} .^[104] Even with the less powerful heater type there was a margin of about 60 W m^{-1} for the central region. The heaters which were positioned further away from z_0 had even larger margins.

3.2.2.3 Comparison of different CO_2 -setpoints

In addition to the main bake-out test with the nominal CO_2 -setpoint of -40°C , a series of tests with higher setpoints up to -20°C was conducted. The results are summarized in Figure 3.12. As expected, all temperatures rose with higher setpoint values. The cooled staves followed the temperature of the cooling lines strictly but were slightly warmer. The IPT reached a maximum of $94 \pm 2^\circ\text{C}$ at the highest setpoint of -20°C . This was still safely below the limit of 170°C .

The power consumption of the central heater decreased only by about 3% when the setpoint was changed from -40°C to -20°C . This small value is explained by the small change of temperature difference between the heaters and the cooling lines of approximately 7%.

3.2.3 Accident scenarios

The IBL cooling system has several security measures installed to maintain acceptable temperatures of the staves in case of failure. This is important especially during the bake-out. First, the heaters are interlocked with the cooling system, i.e. when the cooling system fails, the heaters are switched off automatically. Second, two cooling plants are running in parallel. During normal conditions, one plant is cooling the detector and the other is running on standby, allowing an automatic swap in case of failure of the active plant.^[63] If this is the case during the bake-out, the heaters are again switched

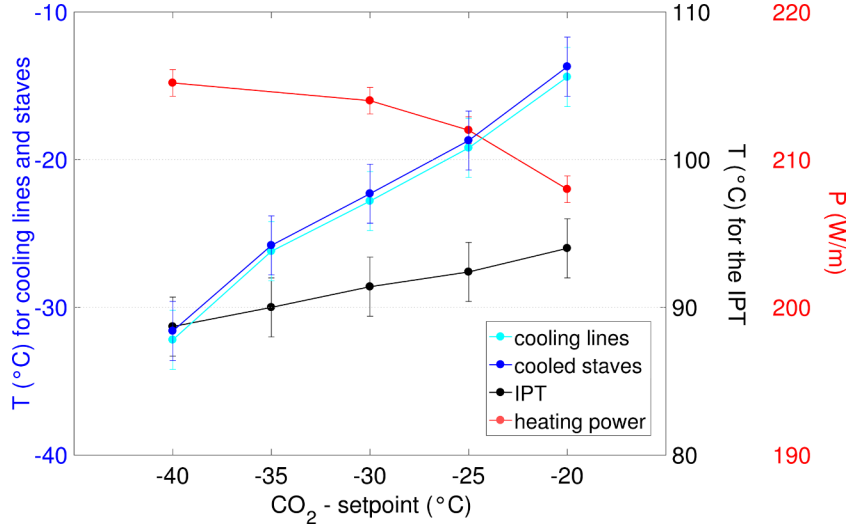


FIGURE 3.12: Overview of several temperatures and the heating power at different CO₂-setpoints. The temperatures for the cooling lines and staves (T , in blue) are the average over all sensors available. The IPT temperature (T , in black) was measured on the outside of the IPT, on the north at z_0 . The heating power per meter (P , in red) is valid for the central heater, which consumed the most power.

off automatically. As last safety measure in case of total cooling power loss, a “blow-system” is activated. When it is active, the CO₂-flow through the detector is maintained by CO₂ from bottles. Tests with the IBL have shown that this system can maintain a cooling power of 3 kW for at least 25 minutes.^[62]

Although neither scenario is supposed to ever happen in the IBL, three tests with provoked accidents were conducted. The accuracy of the temperatures of the following results is $\pm 2^\circ\text{C}$. The times bear a large error of $\pm 40\text{s}$ due to the many NTCs installed. They were split into groups which were consecutively read out. This is also the reason for the steplike shape of the temperature evolutions shown in Figures 3.13 to 3.15 where the temperature evolution of three cooled staves is shown. Staves number 12 and 14 were the uppermost cooled staves and had approximately the same position with respect to north. Stave number 2 was positioned on the east of the mock-up just north of the vertical center. The positions can be found in Figure 3.4. The temperature of stave number 14 was analyzed in more detail. The time when it reached $+30^\circ\text{C}$ after the start of each accident was extracted as well as the value and time of the maximum temperature.

The three accident tests are described and discussed in the following sections. They were conducted at ambient pressure. Table 3.5 gives an overview of the results and Figures 3.13 to 3.15 show the temperatures of the staves during the tests. Additionally, the temperatures of the IPT and IST on their outside surfaces on the north at z_0 are shown.

TABLE 3.5: Summary of the accident scenarios. The times and maximum temperature were measured with stave number 14. The time measurement bears an error of ± 40 s. The column captions have the following meanings:

test nr.	test number according to Table 3.2
T_{bp}	temperature setpoint of the beam pipe
T_{CO_2}	temperature setpoint of the cooling system
T_{max}	maximum temperature during the accident

accident	test	T_{bp}	T_{CO_2}	time to reach		T_{max}
	nr.	(°C)	(°C)	+30 °C	T_{max}	(°C)
1: no heaters' interlock	8	230	-40	6 min 50 s	N/A	+33±2
2: CO ₂ -failure	9	230	-40	6 min 30 s	20 min 15 s	+49±2
3: CO ₂ -failure	10	220	-25	5 min 30 s	15 min 15 s	+50±2

3.2.3.1 CO₂-failure and heaters' interlock failure

This accident simulated a failure of the cooling system combined with a failure of the interlock to the heating system, i.e. the cooling system was stopped and the heating continued. The CO₂ blow-system was not implemented. The temperature setpoint of the beam pipe was 230 °C and the cooling system was set to -40 °C. After thermal equilibrium had been achieved, the CO₂-flow was stopped and the heaters kept on maintaining their setpoint temperature. It took 410 s (6 min 50 s) until stave number 14 reached +30 °C. At this point the heating system was switched off and the CO₂-flow was restarted. Due to thermal inertia stave number 14 reached +33 °C. However, it then took less than one minute for the stave to reach less than -20 °C again. This means that the cooling capacity of the CO₂-system is very quickly restored if the glycol in the accumulator is already cold.

The IPT reached 104 °C during this scenario. Figure 3.13 shows the evolution of the temperatures. The results are compared to the other tests in Table 3.5.

3.2.3.2 CO₂-failure during nominal bake-out conditions

This accident simulated a failure of the cooling system, taking into account the heaters' interlock: the CO₂-flow and the heating system were stopped at the same time. The CO₂ blow-system was not implemented. The boundary conditions were the same as in the previous test. It took 390 s (6 min 30 s) until stave number 14 reached +30 °C. It continued warming up until the maximum of 49 °C was reached after 1215 s (20 min 15 s). Unlike in the previous test, the IPT started immediately to cool down monotonously, i.e. its initial temperature was the maximum. The temperature evolution is shown in Figure 3.14. The results are listed in Table 3.5 for comparison.

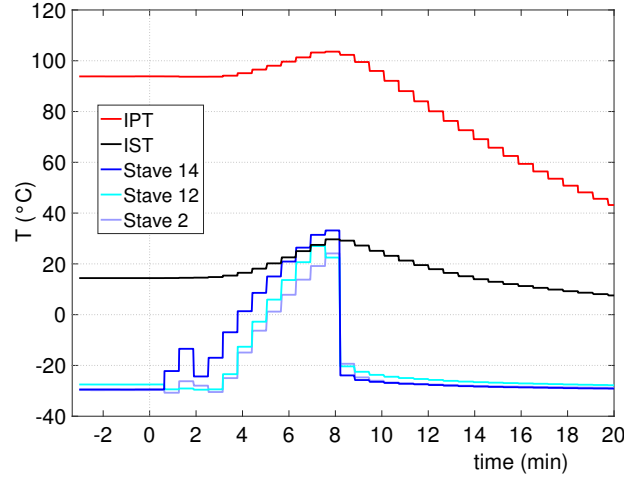


FIGURE 3.13: Temperatures during the first accident test. The accident was provoked at the time $t=0$. All temperatures rised thereafter. After stopping the heaters and re-starting the CO_2 -flow at around 7 min, the staves' temperatures dropped rapidly back to the proximity of their initial values.

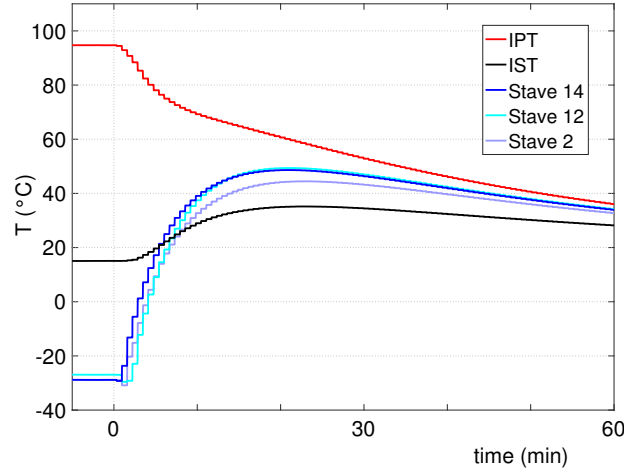


FIGURE 3.14: Temperatures during the second accident test. The accident was provoked at the time $t=0$. All temperatures outside the IPT rised thereafter, reached a maximum and converged to the ambient temperature. The IPT and hence all items inside it (aerogel, heaters, beam pipe) started to cool down instantly and approached the ambient temperature as well.

3.2.3.3 CO_2 -failure during changed bake-out conditions

This accident had the same settings as the previous one except for the setpoints of the cooling and heating system. The temperature setpoint of the beam pipe was 220°C and the cooling system was set to -25°C . It took 330 s (5 min 30 s) until stave number 14 reached $+30^\circ\text{C}$. Its maximum of $+50^\circ\text{C}$ was reached after 915 s (15 min 15 s). The IPT cooled down monotonously. The measurements showed that a higher (warmer) CO_2 -setpoint results in approximately the same maximum stave temperatures but less time is needed to reach this maximum and the limit of $+30^\circ\text{C}$.

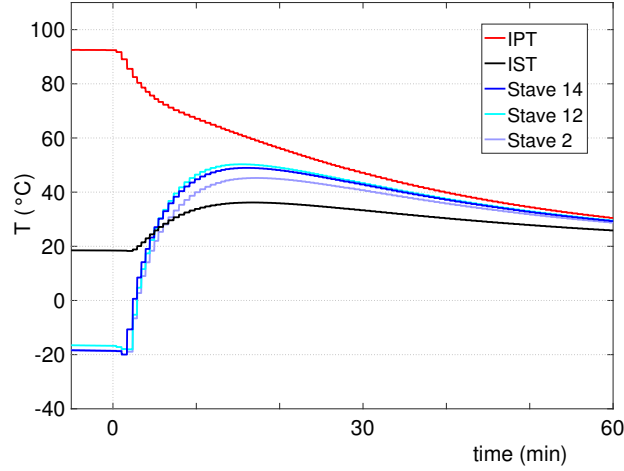


FIGURE 3.15: Temperatures during the third accident test. The crucial difference to the previous test was the higher CO_2 -setpoint of -25°C . The temperatures behaved qualitatively the same, but evolved faster.

The temperature evolution is shown in Figure 3.14. The results are listed in Table 3.5 for comparison.

3.2.3.4 Application to the IBL

The results from the accident scenarios can not be applied to the IBL in a straightforward way because of important differences between the IBL and the mock-up. The real staves are made of a carbon fiber composite and carbon foam instead of aluminum. Including the sensor modules, they weigh approximately only $2/3$ of the mock-up staves. The real IPT is about twice as thin as the IPT of the mock-up. In the IBL all 14 staves are equipped with cooling lines instead of only 7 in the mock-up.

However, the results give an idea of the temperatures reached in an accident and of their time evolution.

3.2.4 CFD simulations

Our results from the mock-up were used to tune CFD-simulations performed by the CERN section EN-CV-PJ.⁽⁷⁾ Such simulations are an important tool to predict the thermal behavior of a detector already in the design phase. This can eliminate possible problems before construction.

The first simulations were done for tests at ambient pressure with a beam pipe setpoint of 180°C and a CO_2 -setpoint of -40°C . This simulation did not correspond well

⁷ EN-CV-PJ: Engineering Department - Cooling and Ventilation Group - Projects and CFD Section. Its CFD-experts ran all the simulations that we discuss. They kindly provided the content for Figures 3.16 and 3.17.

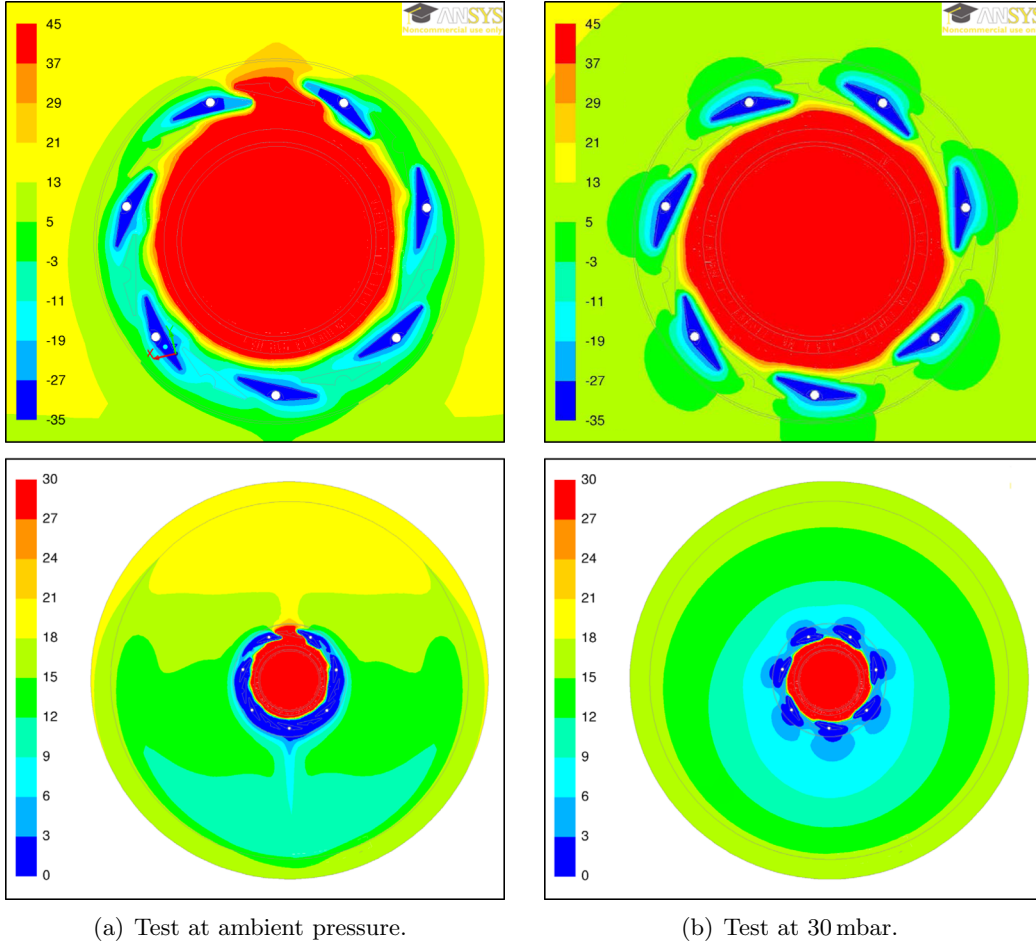


FIGURE 3.16: Results of the simulation of the thermal mock-up. The cross-section is positioned at z_0 . On the top, a zoom covering the central part of the setup is shown. On the bottom, the whole simulated area is shown. It extends to the PMMA tubes in which the mock-up is mounted. On the left, a thermal test at ambient pressure was simulated. Convection is visible by the cold areas sinking to the bottom and the warm areas rising to the top. On the right, a thermal test at 30 mbar was simulated. Convection is significantly reduced, resulting in a more symmetric distribution of temperatures. The temperature scale is in $^{\circ}\text{C}$.

to the thermal tests. The resulting temperatures for the cooled staves were on average $5 \pm 2^{\circ}\text{C}$ colder than what we measured. For the uncooled staves temperature differences between -11 and $+27^{\circ}\text{C}$ were observed. We assumed that the simplification to run the simulation in 2D was the main cause for the differences. In 2D, important mechanical details can not be incorporated and convection is badly reproduced. In order to eliminate as many differences between the simulation and the mock-up as possible, we conducted thermal tests under low environmental pressure to diminish the influence of convection. For the conditions of test 1 in Table 3.2 the simulation was run again. The main feature was the pressure of 30 mbar. Figure 3.16 shows the results of the simulations, both for ambient and reduced pressure. Convection was indeed significantly reduced at 30 mbar. This improved the results of the simulation notably: the cooled staves were on average only $1 \pm 2^{\circ}\text{C}$ warmer than what we measured, which is a difference below the

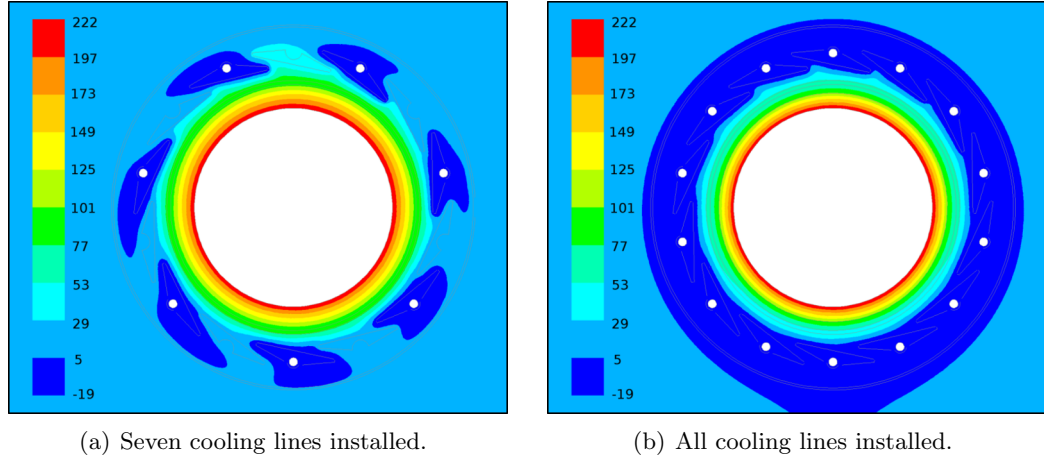


FIGURE 3.17: Results of the simulation of the thermal mock-up. The cross-section is positioned at z_0 . On the left, test number 6 was simulated with the actual design of the mock-up: 7 cooling lines were installed. On the right, the simulation was run with all cooling lines installed, like in the IBL. The temperature scale is in $^{\circ}\text{C}$.

measurement error. For the uncooled staves, however, an average difference of $14 \pm 2^{\circ}\text{C}$ was observed. The main reason for this was the mechanism which dominates the heat transfer to and from the uncooled staves. Unlike the cooled staves, whose temperature was dictated by the direct contact with the cooling lines, their temperature was very sensitive to the individual environment. The presence of services like NTC leads and mechanical inaccuracies like different distances between staves or a tilt of the setup can not be incorporated well in the 2D-simulation. In the IBL, all staves are equipped with cooling lines and therefore the problem of bad simulation of the uncooled staves in the mock-up was not regarded as a major problem.

After the tuning, the simulation was run with the conditions of test number 6: ambient pressure, beam pipe setpoint of 220°C and CO_2 -setpoint of -25°C . The differences between the simulation and the thermal tests were further reduced. The simulation yielded a temperature of the cooled staves that is $1 \pm 2^{\circ}\text{C}$ warmer than the test and for the uncooled staves it was $4 \pm 2^{\circ}\text{C}$ colder. Additional temperatures from the IPT and IST were extracted and agreed well with the measurement. The results are given in Table 3.6 and are visualized in Figure 3.17(a). The power consumption of the central heater in the simulation was 27% lower than the measurement. This was again attributed to the simplification of using a 2D-simulation. Nevertheless, the results were promising and a simulation was run that incorporated all 14 IBL cooling lines instead of only the 7 from the mock-up. The results are listed in Table 3.6 and visualized in Figure 3.17(b). The main findings when using 14 instead of 7 cooling lines were:

- The cold staves were only $0.6 \pm 0.1^{\circ}\text{C}$ colder.
- The staves were $1.5 \pm 0.3^{\circ}\text{C}$ warmer than the (fixed) temperature of the cooling lines.

TABLE 3.6: Results of the thermal test number 6, the simulation of the test and the simulation with all cooling lines installed. T stands for the temperature and P for the power consumption per unit length.

item	measure	measurement	simulation	simulation
		7 cooling lines	7 cooling lines	14 cooling lines
cooling lines	T ($^{\circ}\text{C}$)	-19 ± 2	-19.2	-19.2
cooled staves	T ($^{\circ}\text{C}$)	-19 ± 2	-17.7	-18.3
IPT (z_0 , north)	T ($^{\circ}\text{C}$)	93 ± 2	92.7	81.9
IST (z_0 , north)	T ($^{\circ}\text{C}$)	19 ± 2	13.4	2.5
IST (z_0 , south)	T ($^{\circ}\text{C}$)	9 ± 2	5.3	0.7
power consumption at z_0 (central heater)	P (W m^{-1})	212.0 ± 0.9	153.8	163.4

- The IPT and IST were around 10°C colder on their north and the IST was 4°C colder on its south.
- The power consumption of the central heater increased only by 6.2%. This means that adding 7 cooling lines does not increase the required heating power significantly.

The simulation was further cross-checked and refined with the type 1 services mock-up. Finally, the geometry of the real IBL was implemented and the simulation was run to predict the thermal behavior of the IBL. This study performed by the CERN EN-CV-group is not covered in this thesis. A report and results can be found in [105] and [106].

3.3 Summary and data from the real LHC bake-out

The thermal mock-up was successfully built and operated. Thermal tests were conducted to predict the IBL's thermal behavior and to gain experience with the CO₂ cooling system. The tests were crucial for decisions about:

- The aerogel removal.
- The choice of heaters for the LHC beam pipe bake-out.
- The choice of temperature setpoints for the cooling system during nominal IBL operation.

The mock-up showed differences to the IBL in material and geometry. However, the results of the tests provided a large margin to any limits that were set so that the conclusions for the IBL remain valid even in a conservative approach.

3.3.1 Mock-up results

The specific questions stated in Section 3.2 were answered:

- The sensor modules stay in the safe temperature region below +40 °C during the bake-out even when the aerogel is removed along 622 mm around the interaction point. Cooled staves in the mock-up were -32 ± 2 °C cold during bake-out conditions.
- The heater type that was installed before the Phase-0 Upgrade which can deliver 290 W m^{-1} of heating power can be used for the new beam pipe package installed with the IBL. In the mock-up, the central heater dissipated the largest amount of power. During bake-out conditions it was $215.2 \pm 0.9 \text{ W m}^{-1}$. The CFD-simulation showed that for a mock-up design with all 14 cooling lines this amount rises by 6.2 % to approximately 230 W m^{-1} .
- All temperatures recorded in the mock-up during bake-out conditions were within the working range of the materials used. The IPT reached a maximum temperature of 89 ± 2 °C. During a worst-case accident scenario it reached 104 ± 2 °C, which is still safely below its rated temperature limit of 170 °C.

The results lead to the decision to remove the aerogel around the interaction point in the IBL package. The radiation length of the IBL package was thus reduced.

The CFD simulation was significantly improved by comparing its outcome to the results of the mock-up tests. The simulated temperatures of the cooled staves were in the end

within the measurement error of the real temperatures. Based on this, the simulation was used during the design and construction phase of the IBL to predict the detector temperatures during operation.

The mock-up tests delivered useful experience with the CO₂-system and its complex interaction with the detector and the beam pipe environment. The control software was optimized to prevent the temperature oscillations that occurred during mock-up operation. Safe and reliable operation of the cooling system down to a temperature setpoint of -40°C was verified. Accident scenarios revealed that under certain circumstances the staves are cooled down very fast (more than 50°C in less than 60 s) when the coolant flow is started.

Different temperature setpoints and the resulting temperatures of the detector were investigated. This led to a change of the setpoint used for the real LHC beam pipe bake-out. A CO₂-setpoint of -25°C was chosen instead of the initially foreseen -40°C . The accident scenarios gave an idea on the time evolution of the detector temperatures when no heating nor cooling is present. They also showed that without the CO₂ blow-system for emergency cooling, the staves and therefore modules would most certainly surpass the upper temperature limit of $+40^{\circ}\text{C}$ if both cooling plants failed during the bake-out. In that accident scenario we measured a maximum temperature of $+50 \pm 2^{\circ}\text{C}$ on the staves of the mock-up.

After having finished the tests with the thermal mock-up, we reconstructed it to the type 1 services mock-up. It focused on the region between the interaction point (z_0) and the first patch panel (PP1). The thermo-mechanical behavior of this region was investigated and many other integration aspects were examined: validation of interfaces, functionality of different mechanical and electrical parts (clips, sealing rings, IPT, stave flex, intermediate flex, type 1 cables, etc.), verification of prototypes before production and integration procedures before installation. The type 1 services mock-up is not discussed in detail in this thesis. Details on it can be found in [107] and [108].

3.3.2 Real LHC bake-out

The IBL was successfully inserted into ATLAS on 7 May 2014. A picture taken during the procedure is shown in Figure 3.18. The LHC beam pipe bake-out was done later that year with the maximum temperatures in ATLAS on 27 and 28 October. The heaters in the VI-section reached a temperature of $226.7 \pm 0.8^{\circ}\text{C}$.⁽⁸⁾ The CO₂-system of the IBL was set to -25°C , resulting in a mean temperature of the modules on the staves of $-14.5 \pm 1.3^{\circ}\text{C}$ shortly before the end of the bake-out. The temperature evolution of the modules of two staves is shown in Figure 3.19.

Detailed analysis of the temperature distribution revealed a temperature gradient along

⁸ The measurement errors of the sensors is not known. The error of this temperature and of the staves' temperatures is the standard deviation of the mean calculated from several sensors.

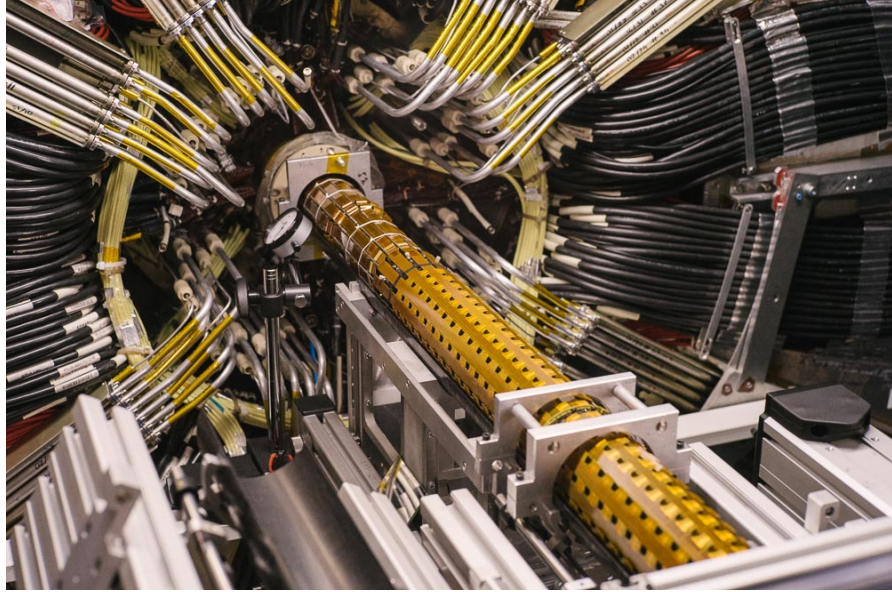
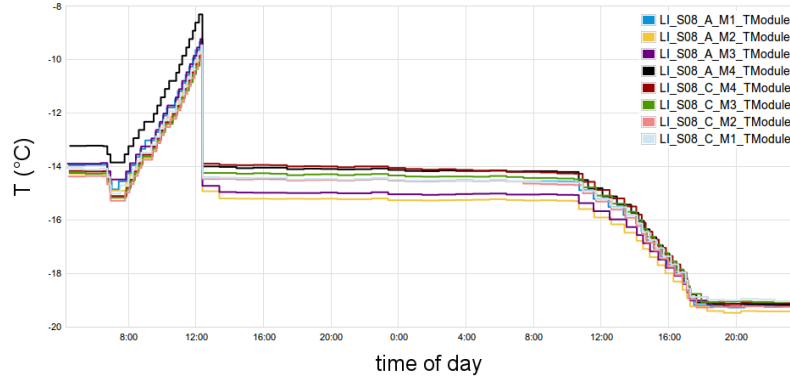
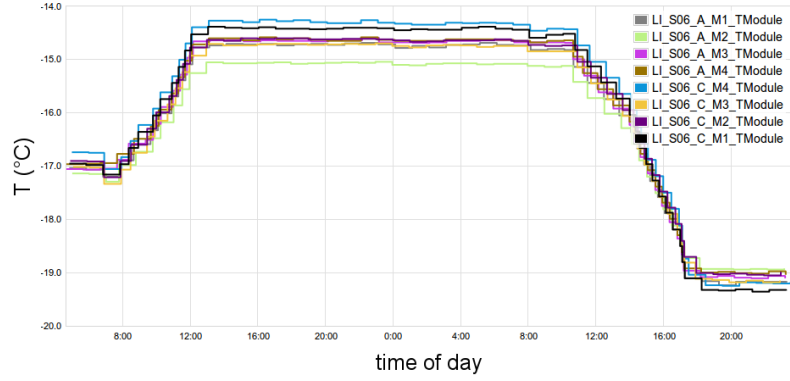


FIGURE 3.18: The IBL during insertion into ATLAS. The gold-hued outside of the IBL are the back sides of the stave flexes. The IST had already been installed in ATLAS and the long IBL-package was inserted along the beam/detector axis. The hole in the aluminum jigs through which the package was slid gives an idea of the small clearances. Picture from [110, 111].

the IBL. The cooling lines' temperature at the inlet side (upstream) was $-11.3 \pm 1.3^\circ\text{C}$ and at the outlet side (downstream) $-15.6 \pm 0.8^\circ\text{C}$. The gradient was also observed along the staves, with a difference between the two sides of approximately 1°C . The cause is the pressure drop along the cooling lines, resulting in a different boiling point of the CO_2 .^[63] Additionally, a non-optimal state of the CO_2 -coolant was observed. In some cooling lines the CO_2 stayed liquid along the IBL.^[109] Enough cooling performance was given nevertheless, but optimal performance and stable temperatures are only reached when the CO_2 is in the intended two-phase state, i.e. boiling. The consequences of liquid CO_2 during the bake-out were temperatures of the cooling lines and hence modules that were a few degrees above the intended boiling temperature. In addition, sudden temperature drops of several degrees were observed as is shown in Figure 3.19(a). They testify the transition from the liquid (single-phase) state to the boiling (two-phase) state of the CO_2 . An optimization/reduction of the flow rate in the cooling system can prevent the single-phase CO_2 . Based on this experience there are ongoing studies on this subject which are of great interest for future CO_2 cooling systems inside and outside HEP.^[62, 63]



(a) IBL stave 8 (corresponding position in the mock-up: stave 10).



(b) IBL stave 6 (corresponding position in the mock-up: stave 8).

FIGURE 3.19: Temperatures of the modules on two staves during the most critical phase of the LHC beam pipe bake-out. On the bottom, the CO₂ in the cooling line was in its intended boiling state during the whole time. On the top, the transition from fluid to boiling occurred during the ramp-up of the temperatures, when the heat load on the cooling line increased. The result was a sudden drop of the temperatures.

This chapter covered our work for the Phase-0 Upgrade of the ATLAS Pixel Detector. There will be no Phase-I Upgrade for the Pixel Detector but the Phase-II Upgrade foresees the complete replacement of the Inner Detector with the ITk. Several ongoing R&D-programs investigate the optimum technology for the sensors of this new detector. The following chapter covers our work on HV-CMOS sensors, one of the technologies considered for the Phase-II Upgrade.

Chapter 4

HV-CMOS sensors for the ATLAS Phase-II Upgrade

The previous chapter dealt with the IBL as a new detector system of the ATLAS Phase-0 upgrade. There are no further modifications of the pixel detector foreseen until it will be completely replaced by a new detector during the Phase-II upgrade. This chapter deals with a topic essential for ATLAS' reliable performance with this new detector: silicon sensor development. We present a novelty in particle detection with silicon: active pixel sensors implemented in a high-voltage CMOS process that are used together with existing readout chips as hybrid detectors. We describe the prototype chip CCPD (also known as HV2FEI4), show first results and give an outlook on future developments. In addition, we discuss characteristics important for particle detection: irradiation effects, charge collection properties and detector efficiency. The contextual and theoretical background is given in Chapter 2.

4.1 HV-CMOS in particle physics

In this section we introduce the new sensor's underlying technology and show the differences to existing solutions. We discuss assets and drawbacks to provide a basis for assessment of the technology with respect to its value for HEP.

4.1.1 Introduction

Current silicon pixel detectors in HEP experiments are mainly implemented as hybrid detectors where the sensor and readout chips are two different electronic chips. Thus they combine the advantages of the respective chip being optimized for its intended

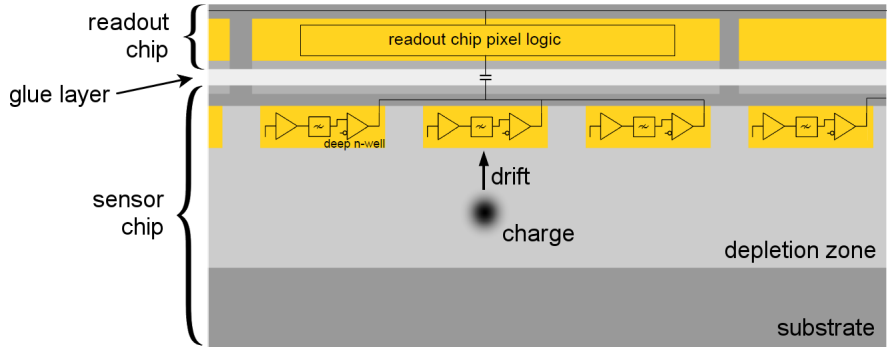


FIGURE 4.1: Schematic cross-section of a capacitively coupled pixel detector. The readout chip is glued onto the sensor. The charge generated in the depletion zone by a passing ionizing particle drifts to the pixel electrode, which creates a signal in the electrode. This signal is treated by the in-pixel electronics and transferred capacitively to the readout chip.

use without interfering with one another.⁽¹⁾ Hybrid detectors are the baseline of many tracker upgrade plans although they have an important drawback: The necessary interconnection technique (bump-bonding) is very complex and one of the cost drivers for detector construction. It requires a lot of attention to assure high production yield and the high level of quality needed for HEP detectors.^[112] In addition, it increases the material budget of the detector and puts a lower limit on the pixel size.

An alternative to hybrid detectors are monolithic detectors/sensors. They integrate the sensor and readout functionality on one chip. Therefore they do not rely on any chip-to-chip interconnection and do not show the problems mentioned above. However, drawbacks arise from the different needs of the sensor and readout part. For example, the readout electronics normally comprises sophisticated digital functionality which might corrupt the SNR of the sensor part. Conversely, the sensor part needs special material properties which might be in conflict with the electronics needed in the readout part. These problems lead to the monolithic sensors having difficulty meeting the demands of HL-LHC experiments, especially concerning radiation hardness and timing performance.

In this thesis we pursue a semi-monolithic/semi-hybrid approach. This means that the sensor chip is not used as a classic passive nor monolithic one. It has some logic implemented in each pixel but this does not comprise the whole front-end readout architecture necessary for a detector module. It still relies on a readout chip. The major difference to a classic hybrid detector is the novel interconnection technique: in-pixel amplification of the initial charge signal enables implementation of capacitive coupling to the readout chip. In other words: the sensor is simply glued onto the readout chip instead of bump-bonded. Figure 4.1 shows a schematic of the detector concept and Figure 4.2 a working prototype.

¹ The chips are physically connected so they are not completely independent. However, the restrictions due to the connection are primarily geometric ones.

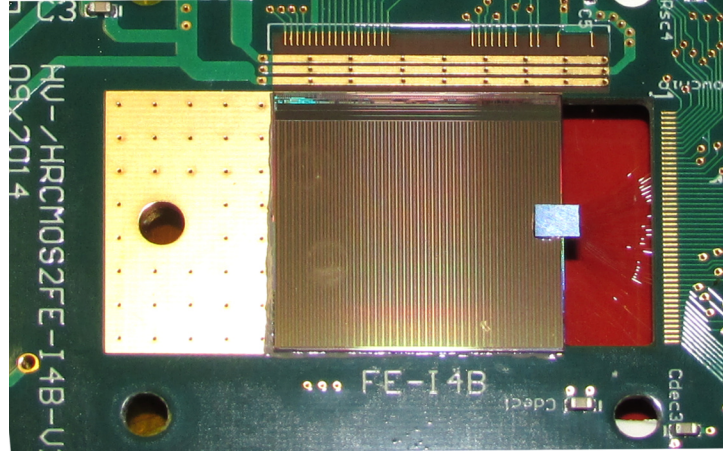


FIGURE 4.2: Working prototype sample of a HV-CMOS sensor (a CCPDv4, small gray chip) glued onto an ATLAS FE-I4B pixel readout chip (larger, bronze-hued chip).

The idea is based on the high-voltage CMOS technology. It combines standard (low-voltage) CMOS technology with on-chip high-voltage applications.⁽²⁾ The major advantage of this mix is that the full range of CMOS logic is available for sensor electronics while at the same time the high voltage can be used to create a depletion zone in the substrate which is needed for efficient charge collection. This opens the door to interesting possibilities but requires much research and development until the novel sensor is qualified for HL-LHC experiments.

4.1.2 Prospects compared to other technologies

The work presented in this chapter was conducted with sensors from the prototype family CCPD produced in the 180 nm HV-CMOS process H18 by ams AG.^[113] The following discussion focuses on these prototypes but many points are generally valid for sensors produced in an HV-CMOS process.

Key features of the H18 process with respect to HEP are:

- Its high-voltage capability.
- NMOS and PMOS logic is available in the triple-well CMOS process. The corresponding quadruple-well process is in development.
- It is an industrialized process.
- It is an n-in-p process.

Together with the design of the CCPD this leads to the following prospects.

² High voltage refers to voltages higher than the CMOS supply voltage of typically a few volts.

4.1.2.1 Efficient charge collection

In HV-CMOS sensors the important charge collection mechanism is drift in the depletion zone. Given a substrate resistivity of $10\ \Omega\text{cm}$ and a typical bias voltage of 90 V , the depletion zone extends around $10\ \mu\text{m}$ into the substrate. A MIP passing the sensor therefore creates a drift charge signal below 1000 e^- .^[71] Compared to values for the planar sensors in the IBL (depletion depth $\approx 200\ \mu\text{m}$, MIP charge signal $\approx 16\text{ ke}^-$)^[114] these values are very low. However, the thin depletion zone allows for a very fast charge collection well below 1 ns (see Section 2.4.2.2) that in turn leads to low sensitivity to charge trapping due to lattice defects. Since charge trapping is the main reason for signal degradation by non-ionizing radiation damage, the bulk exhibits high radiation hardness.

The low amount of charge signal generated by a MIP is not problematic as long as the SNR stays large enough and low thresholds are achieved. It is amplified directly in each pixel by the CSA that is implemented in the pixel electronics. The signal is then treated by the subsequent readout architecture (see Section 4.2). The initial MIP charge signal can be increased by using a substrate with higher resistivity (e.g. $100\text{--}1000\ \Omega\text{cm}$) which results in a larger depletion depth. The transistors from the in-pixel electronics are not affected since they are placed in n-wells and not in the substrate itself. However, high-resistivity wafers are often a non-standard process feature, make production more expensive and not all foundries allow them in their respective processes.

The improvement compared to low-voltage CMOS devices is the step from charge collection in an undepleted epitaxial layer relying mainly on diffusion to charge collection by drift in a larger depletion zone. This leads to a larger and faster collected MIP signal.^[115, 116]

The CCPD is implemented as an n-in-p sensor, i.e. electrons are collected at the segmented side of the sensor. At high fluences this is beneficial for charge collection compared to p-in-n solutions:

In pixel detectors most of the signal is induced in the last part of the charge drift path toward the segmented electrode. This is due to the shape of the weighting field (see Section 2.4.2.3). Therefore it is important that as many charge carriers as possible reach the electrode. Charge trapping reduces the number of charge carriers along their path and the net charge signal increases with the product $t_c \tau$ where τ is the fluence-dependent carrier lifetime (see Section 2.4.5.2). t_c is the charge collection time which is proportional to the carrier mobility μ up to moderate field strengths (Equation 2.13). The product $\mu \tau$ is larger for electrons than for holes (see Table 4.1), so collection of electrons at the segmented side of the sensor is beneficial for a large signal. This is especially important after particle irradiation, where trapping is increased.

In addition, charge multiplication occurs in n-in-p sensors under certain circumstances (e.g. after long term annealing, see [117, 118]). It can increase the charge signal further.

TABLE 4.1: Comparison of charge carrier mobility, lifetime and the product of the latter two for electrons and holes. The values for the lifetime are taken from [119], where it is called trapping time constant, and are valid for oxygen enriched silicon after irradiation to $9 \times 10^{14} \text{ n}_{\text{eq}} \text{ cm}^{-2}$.

charge carrier	mobility μ ($\text{cm}^2 \text{ V}^{-1} \text{ s}^{-1}$)	lifetime τ (ns)	product $\mu \tau$ ($10^{-6} \text{ cm}^2 \text{ V}^{-1}$)
electron	1350	3.67	5.0
hole	450	4.65	2.1

4.1.2.2 Pixel miniaturization

Very small active pixels measuring only $2.5 \times 2.5 \mu\text{m}^2$ have been achieved in a 65 nm low-voltage CMOS process and could be realized also in an HV-CMOS process.^[120] These pixels have only very basic logic implemented and are not suitable for HL-LHC purposes. Pixels in HV-CMOS technology and with logic more suitable for HEP experiments have been fabricated down to $21 \times 21 \mu\text{m}^2$.^[121] Smaller pixel size leads to smaller pixel capacitance and noise, better particle position detection and lower occupancy at high pile-up. The latter is especially important for HL-LHC detectors where the pile-up reaches values up to 200.^[44] The currently installed silicon sensors would not perform well in such an environment. Smaller pixel size is the key factor to cope with increased pile-up.

4.1.2.3 Radiation hardness

The RD50-collaboration has shown good performance of planar sensors irradiated up to a particle fluence of $2 \times 10^{16} \text{ n}_{\text{eq}} \text{ cm}^{-2}$.⁽³⁾ [94, 122, 123] We expect high bulk irradiation hardness also for the CCPD, due to the above mentioned thin depletion zone, fast charge collection by drift and favorable n-in-p configuration. The latter is also the reason why type inversion is not an issue. It does not occur in a p-type substrate. Instead, starting from the high initial doping concentration of approximately $1 \times 10^{15} \text{ cm}^{-3}$, a pronounced initial acceptor removal occurs with irradiation. This results in an augmented depletion region and a significant increase of collected charge up to around $2 \times 10^{15} \text{ n}_{\text{eq}} \text{ cm}^{-2}$. At higher fluences, a relatively slow acceptor creation dominates which reverses the behavior and decreases the collected charge. However, even after $1 \times 10^{16} \text{ n}_{\text{eq}} \text{ cm}^{-2}$ the collected charge is larger than before irradiation.^[124]

Sensors will also have to withstand a high TID in the HL-LHC environment. Total dose effects appear mainly in the sensor electronics caused by charging of the CMOS oxides. The effect is less severe the thinner the oxide is. Compared to larger feature sizes the deep sub-micron 180 nm process is less prone to ionizing dose effects.^[125] Moreover, radiation hard design elements like enclosed transistors are used to make the electronics

³ See Section 2.4.5.2 for details on this unit.

radiation hard. Promising results after more than 8.6 MGy (860 Mrad) are presented in Section 4.4.3.1.

4.1.2.4 System aspects: versatility, material budget, power supply and operating temperature

The diode structure of each pixel is enhanced by putting more or less sophisticated electronics inside it. Each CCPD pixel includes a preamplifier, a comparator and logic for addressing. The on-sensor signal amplification makes it possible to use AC-coupling to the readout chip. Instead of the complex and mechanically sensitive bump bonding the sensor chip can be simply glued onto the readout chip. This eliminates the size restriction set by the bonding bumps, pixels can be made smaller and the material budget is reduced. A special addressing scheme (see Section 4.2) makes this concept even more powerful: the sensor with a certain granularity and pixel size can be read out by a chip with lower granularity (i.e. larger pixels). In this way the pixel size of the sensor can be made smaller without the need of developing a new readout chip. The CCPD electronics is designed to be even more versatile: multiple pixels can be interconnected to form “virtual strips”. So if needed, the sensor can even be operated as a strip detector.⁽⁴⁾ This makes the CCPD very interesting also for future strip detectors and therefore for any all-silicon tracker system such as the ATLAS ITk.

As mentioned above, present-day planar silicon sensors can be operated after having been exposed to very high particle fluences. However, operation of such sensors becomes difficult because it demands large bias voltages for full depletion and extensive cooling. In the case of the CCPD, typical bias voltages around 100 V after irradiation are one order of magnitude lower than for planar sensors and the sensor works even at room temperature after irradiation to $1 \times 10^{16} \text{ n}_{\text{eq}} \text{ cm}^{-2}$. Having the big picture of large detector systems in mind these are crucial advantages.

The thin depletion zone in the CCPD makes it possible to further reduce the material budget. The sensor can theoretically be thinned down to the thickness of the depletion zone because the undepleted volume of the sensor does not contribute significantly to the collected charge.

4.1.2.5 Cost discussion

The sizes of silicon-based detectors in HEP experiments become increasingly large. The current plans for the ATLAS Phase-II upgrade comprise more than 15 m^2 of active sensor area for the pixel detector and 165 m^2 for the strip detector.^[43] CMS has even bigger

⁴ An overview of the dedicated strip-R&D is given in [126].

plans: the outer tracker installed in the Phase-II upgrade is planned to have 218 m^2 active silicon area and the HGCal (High Granularity CALorimeter) 589 m^2 .^[127] As a consequence, low cost per area is necessary for these silicon detector ventures.

The currently installed silicon sensors in the ATLAS ID (planar and 3D) were produced in customized processes. This implies higher costs than production in common industrialized processes. In addition, using a specialized process that is available only at a few or even one vendor creates high-impact risks in sensor production. The same holds true for the assembly procedure, the bump-bonding.⁽⁵⁾ Much progress has to be achieved in these production and assembly steps to make the currently used silicon detector technologies more attractive for future large-area systems. Increase in yield and a larger number of vendors on the market would be advantageous.

The HV-CMOS technology is in a good position with regard to sensor production costs. It is highly industrialized due to the demand from the automotive and smart devices sectors. This has positive effects on progress reliability (yield), production times and availability. Many foundries offer HV-CMOS processes and they are commonly implemented on 200 mm (8-inch) wafers. The result is low production cost per area and low contingency risk.

The comparison between planar and HV-CMOS sensors is more complicated for the assembly of hybrid detector modules. On the one hand, the costly and delicate bump-bonding is not necessary for HV-CMOS sensors because the sensors can be glued onto the readout chip. On the other hand the gluing has not yet been applied on an industrial scale and might involve extra costs for incorporation into the commercial assembly. In addition, the gluing requires through-silicon vias (TSVs) for electrical connection of the sensor.⁽⁶⁾ Currently, TSVs can only be produced by a post-processing of the sensor that comprises more process steps than the actual sensor production. Considering these points, the module assembly might in the end be as costly as with planar sensors although the gluing is an easy-to-handle and robust process (see Section 4.4.7.1).

We have tried to merge the experience with the construction of current pixel detectors in HEP, the findings of the prototype work with the HV-CMOS sensors and the outcome of many discussions within the HV-CMOS collaboration. The conclusion is that a *general* cost comparison between planar silicon sensors and HV-CMOS sensors is not feasible because the actual prices strongly depend on details of the detector concept, special requests from the customer, vendor, batch size, current market situation and versatility of the foundry/process. We carefully estimate that currently the production and assembly of hybrid detector modules with HV-CMOS sensors is in the same price range as when using planar sensors. If the connection of the sensor to the readout chip can be excluded - like it is the case for monolithic detector modules - then a significant cost reduction could be possible.

⁵ The IBL production experienced major problems with bump bonding.^[112]

⁶ TSVs are not needed for the prototypes presented here.

4.1.3 Drawbacks and risks

The main drawback of the HV-CMOS technology is its novelty in high-energy physics. HL-LHC experiments involve large detector areas and require long-term reliability of sensors. Neither aspect has been tested so far with HV-CMOS sensors. The first experiment that will deliver useful information about long-term, large-area operation of HV-CMOS sensors will be the Mu3e experiment at the PSI (Paul Scherrer Institute).^[128] It is planned to start high-rate data taking in 2019. Additionally and ideally sooner, it is necessary to operate a small detector in LHC or HL-LHC-like conditions to gain experience and reveal possible problems in quality and reliability of the sensors.⁽⁷⁾ This has to be done in a system whose possible failure has low impact on the experiment in which it is embedded. Building a HL-LHC detector based on HV-CMOS sensors without such a pre-run would introduce high-impact risks as no access and repair will be possible in case of failure.

The characteristic assembly step of gluing the sensor to the readout chip is also new in high-energy physics and only limited experience and expertise is available. Industrialization and high yield of this step have yet to be shown.

⁷ A similar strategy is pursued for 3D sensors, which make up 25 % of the sensors in the IBL.^[129]

4.2 The CCPD prototype sensor

In this section we describe in detail the sensor prototype family CCPD produced in 180 nm technology. The actual name of the sensor used to be HV2FEI4 or HVC MOS2FEI4 which indicates the intended main use as a pixel detector in conjunction with the ATLAS pixel readout chip FE-I4. The term CCPD was originally meant to denote more generally the *concept* of capacitive coupling. During development of the first generations it became prevalent as the *name* of the sensor. For this reason we use CCPD as the name in this work although in earlier publications it is still referred to as HV2FEI4 and HVC MOS2FEI4.

There exist five prototype generations/versions of the chip: CCPDv1 to CCPDv5. They were produced in the ams H18 proces, formerly know as IBM CMOS 7HV, a joint development of ams AG and IBM.^[113, 130, 131] The process offers a maximum reticle size of $2 \times 2 \text{ cm}^2$ on a substrate with a resistivity of $\approx 10 \Omega \text{ cm}$.⁽⁸⁾ The initial sensor design was optimized for hybrid pixel readout. Geometry and structure was chosen to match the FE-I4 readout chip. Secondary functionality like strip readout and test structures were also included. Over the generations the design has evolved, including ASIC parts optimized for other uses.

In the following Sections 4.2.1–4.2.5 we discuss in detail the first-generation sensor CCPDv1 and its main pixel type. In Section 4.2.6 below, subsequent generations and other pixel types are discussed. The discussion is complemented by the list of sensors which are related to the CCPD-family and produced in the ams 180 and 350 nm-processes. This list is given in Table C.1 in Appendix C.

4.2.1 Layout

Figure 4.3(a) shows the front side of the first sensor prototpye CCPDv1. It is $4.4 \times 2.2 \text{ mm}^2$ large with a pixel size of $33 \times 125 \mu\text{m}^2$. The 1440 pixels are arranged in 24 rows (long dimension) and 60 columns (short dimension). The convention of the row numbering is depicted in Figure 4.3(b). The sensor pixel size does not match the readout pixel size of the FE-I4 which is $250 \times 50 \mu\text{m}^2$. Compatibility with the FE-I4 is achieved by combining six pixels to form a so-called “unit cell”. This merges pairs of rows to form “unit rows” and triplets of columns to form “unit columns”. One unit cell is read out by two FE-I4 pixels meaning that three sensor pixels are connected to one readout pixel (see Figure 4.6). Each unit cell comprises 2 pixels in the long dimension and 3 pixels in the short dimension, covering an area of $250 \times 100 \mu\text{m}^2$. This is twice the size of a FE-I4 pixel. If we take into account the FE-I4 orientation with respect to the IBL this means that the sensor has a spatial resolution which is two times better in ATLAS’ z -dimension and 1.5 times better in the φ -dimension than the currently installed sensors.

⁸ The exact value of the resistivity is not disclosed by the manufacturer. A thorough discussion and measurements within the HV-CMOS collaboration suggest the stated value.

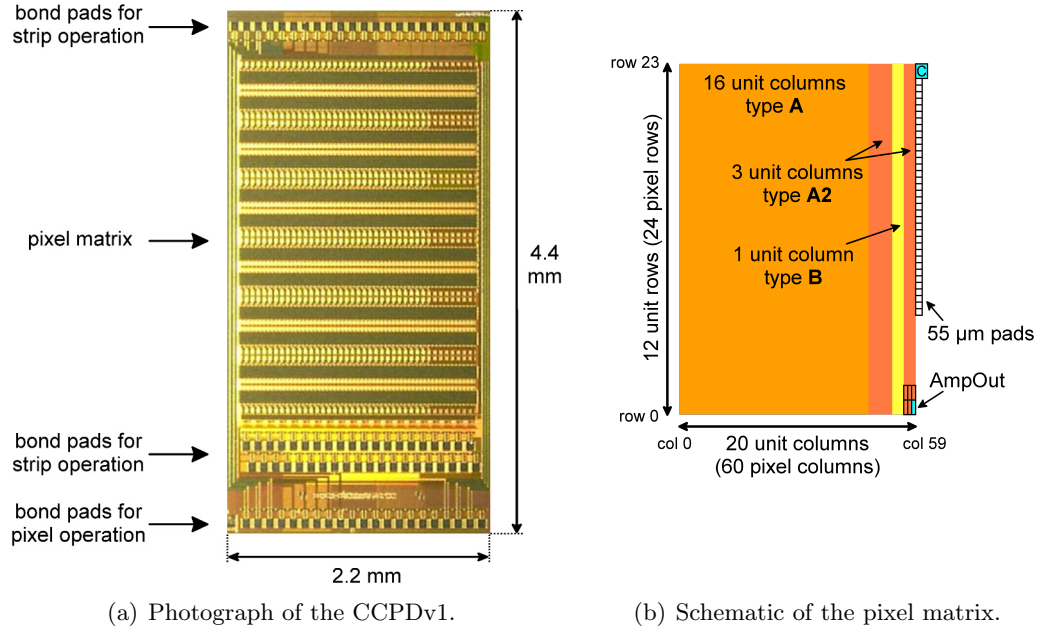


FIGURE 4.3: Front side of the CCPDv1 and schematic of its pixel matrix. The different pixel types (see Section 4.2.6.1) can be distinguished by their colors. Special pads with a $55\text{ }\mu\text{m}$ -pitch are located on the right side of the matrix. Two test functions are colored in cyan: The injection test pad sits in the top right corner (denoted by “C”) and the pixel whose preamplifier output is accessible on AmpOut is located in the bottom right corner (see Section 4.2.4).

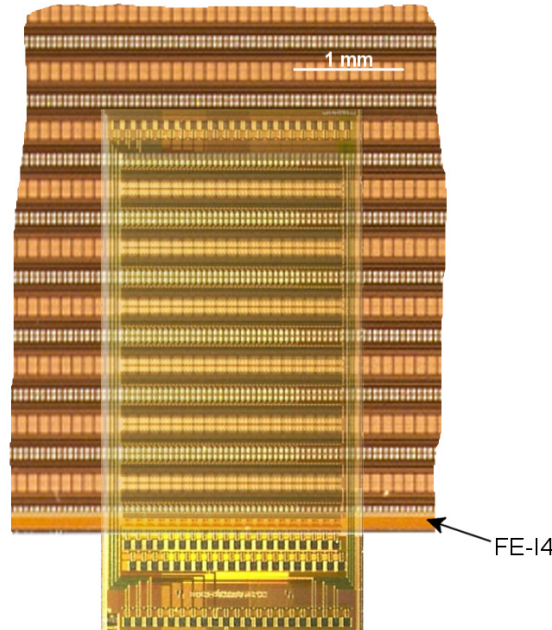


FIGURE 4.4: Visualization of the CCPDv1 on top of the FE-I4. The matching pixel pads are the small white spots arranged in horizontal lines. In the real setup, the chips’ surfaces are facing each other. Here the FE-I4 is mirrored and the CCPD is made semi-transparent.

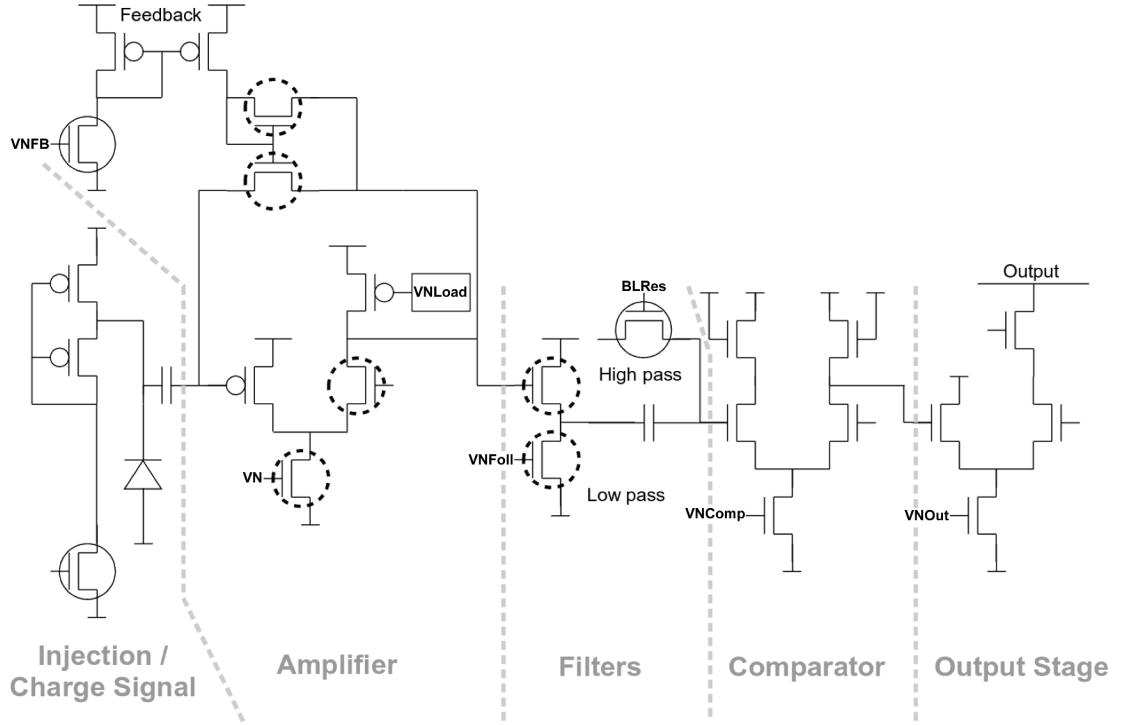


FIGURE 4.5: Schematic of the sensor pixel electronics for the first two sensor generations adapted from [132, 133]. In the CCPDv1 all transistors are standard (linear) transistors. The circles mark transistors that are replaced by transistors of a radiation hard design (enclosed transistors) in the partially and fully radiation hard pixel types of the CCPDv2. The dashed circles mark transistors that are enclosed transistors only in the fully radiation hard pixel type of the CCPDv2. Details on the marked DACs are given in Table 4.3.

4.2.2 Electronics

The CCPD's basic building block is an active pixel containing the first stages of signal processing: a preamplifier stage based on CSAs, a comparator stage with possibility of local threshold adjustment (tune-DAC) and an output stage. The signals from the output stages of three pixels are summed and transmitted to the corresponding pixel pad of one unit cell (see Figure 4.1 and Section 4.2.3).

The CCPDv1 is not designed to be radiation-hard. No enclosed transistors are used. This is done to see how suitable standard library items of the HV-process are for applications in radioactive environments. A simplified transistor-level schematic of the pixel logic is shown in Figure 4.5. This schematic is valid for the CCPDv1 and CCPDv2. The latter comprises different pixel types with different radiation-hard designs. They include enclosed transistors which are marked in the schematic. More details of the CMOS circuits of the CCPDv1 can be found in Appendix B.

The pixel area of $33 \times 125 \mu\text{m}^2$ could house more circuitry. However, more electronics means a larger area and therefore higher n-well capacitance. This increases noise. Also, digital activity in the electronics is disadvantageous for sensor noise levels. In order to obtain a good SNR, the electronics are therefore kept to a reasonable minimum.

4.2.2.1 Supply and control lines

For operation in pixel mode there are 21 wire-bond pads on the bottom of the sensor, numbered from left to right with respect to Figure 4.3(a). Their names and functions are listed in Table 4.2. Some items need special attention as they are not simple power supply lines:

- **Sin, Ld, CkConf, CkDac:** These are digital inputs for sensor configuration. The logic levels have to comply with a two-level CMOS-logic supplied with 1.8 V.
- **TH** (threshold voltage): A good starting point is about 50 mV above the base line voltage (BL). Changing the threshold voltage means changing the thresholds of the comparators for all pixels. It is therefore a *global* tune value. The *local* threshold tuning is done by dedicated tune-DACs (see 4.2.2.2).
- **SUB:** The bias voltage is an important parameter for charge collection. Most importantly: it has to be *negative* with respect to all other supply voltages. The manufacturer states a limit of -50 V .^[113] We observed electrical breakdown phenomena only at larger negative voltages and safely operated faultless samples down to approximately -60 V (CCPDv1) and -90 V (CCPDv2 and later versions).
- **monitor:** The monitor line as described in Section 4.2.4. It needs to be pulled up to a certain voltage level, e.g. by an external pull-up resistor to the pixel analog power supply (VDDA). Using a $10\text{ k}\Omega$ -resistor, the maximum possible current output from a pixel of $10\text{ }\mu\text{A}$ generates a voltage pulse of 100 mV which is easy to work with.
- **injection:** Bond pad for injections as described in Section 4.2.4. A voltage step applied to this pad injects a defined amount of charge to the preamplifier of each pixel via the in-pixel injection capacitance. Typical injection amplitudes are below 1 V.
- **AmpOut:** The AmpOut as described in Section 4.2.4. It is the output signal of the in-pixel preamplifier after being buffered by a source follower (which also acts as a low-pass filter that decreases the noise). The source resistor of the source follower is not implemented on the chip and has to be supplied externally. Ideally, a $5\text{ k}\Omega$ -resistor is connected between the AmpOut pad and a voltage supply set to -1 V .
- **Pbias:** Monitor pad to access the bias voltage for the current sources of the DACs.
- Pads **18, 19** and **20** are redundant pads to assure even voltage distribution in the sensor.

TABLE 4.2: Functions of the bond pads for pixel readout. The numbering is from left to right with respect to Figure 4.3(a). Details can be found in the text.

pad		nominal value (V)	function
nr	name		
1	VSSA	1.5	preamplifier power supply
2	VDDA	1.95	pixel analog power supply
3	GNDA	ground	analog ground
4	VCASC	1	cascode bias voltage
5	GATE	2.1 – 2.3	bias overvoltage for diodes
6	BL	0.8	base line voltage
7	TH	≈ 0.85	threshold voltage
8	GND	ground	digital ground
9	VDD	1.95	pixel digital power supply
10	SUB	–60	bias voltage
11	Sin	digital input	serial in
12	Ld	digital input	load
13	CkConf	digital input	configuration clock
14	CkDac	digital input	DAC clock
15	Pbias	DAC bias voltage	voltage monitor
16	monitor	pull up to VDDA	monitor line
17	injection	amplitude up to 1	injection line
18	GNDA	ground	analog ground
19	VDDA	1.95	pixel analog power supply
20	VSSA	1.5	preamplifier power supply
21	AmpOut	pull down to –1	output of the test pixel

4.2.2.2 Control blocks - DAC values

There are three control blocks containing the parameters for sensor operation. The global bias block is responsible for the behavior of the in-pixel electronics. The row and column blocks mainly switch between different functions (e.g. between pixel and strip-readout) and also contain the tune-DAC (TDAC) values. This section gives an overview of the parameters. More details can be found in Appendix B.

Global bias block

The global bias block generates the bias voltages for the in-pixel electronics. Fifteen 6-bit DACs supply currents which are then converted to the bias voltages. Their nominal values and functions are listed in Table 4.3.

TABLE 4.3: Overview of the DACs that set the bias voltages for the pixel electronics in the CCPDv1. They are ordered according to their position in the global configuration shift register (top=first). The range for each DAC is 0 to 63. Three positions of the register are not used. Details can be found in Appendix B.

name	nominal value	effect or controlled component
BLRes	5	an increase of BLRes results in a decrease of the time constant of the high-pass filter just before the comparator stage
ThRes	60	an increase of ThRes results in a smaller step size and a smaller range of the local threshold adjustment
VN	60	bias current of the preamplifier
VNFB	2	feedback current of the preamplifier
VNFoll	5	bias current of the source follower that buffers the output of the preamplifier
VNLoad	10	load transistor of the preamplifier
VNDAC	0	bias current of the TDAC circuit; VNDAC has an effect similar to ThRes
—	—	not used
—	—	not used
—	—	not used
VNComp	10	bias current of the comparator
VNCompL	10	load transistor of the comparator; it changes the time that the pixel output signal takes to return to the baseline
VNOut0	20	amplitude of output stage current pulse for subpixel-column 0
VNOut1	20	amplitude of output stage current pulse for subpixel-column 1
VNOut2	20	amplitude of output stage current pulse for subpixel-column 2

Column and row control blocks

The column and row control blocks contain parameters for one unit cell. The column control block comprises eleven bits and the row column block ten bits. They are listed in Table 4.4.

4.2.3 Subpixel encoding

Three sensor pixels are connected to one readout pixel which means that we have to distinguish between signals from these three pixels. This is done by the so-called “subpixel encoding”. Subpixel is the term we use for one sensor pixel when we talk of it as part of the unit cell. Thus, six subpixels make up one unit cell and three subpixels are routed to one readout pixel (see Figure 4.6). The CCPD is designed to respond to a particle hit by generating an output signal with defined amplitude. We can set this amplitude to a different value for each of the three subpixels. If we choose the

TABLE 4.4: Overview of the parameters in the column and row control blocks. Details can be found in Appendix B.

name	number of bits	function
column control block		
L0, L1, L2	1 each	flag for each of the six pixels in a unit cell to mark if the pixel output is multiplexed to the monitor line
R0, R1, R2		
Wr0, Wr1, Wr2	1 each	write signals for the TDAC values
EnStrip	1	switch that connects the pixel output to the strip pad
EnCurrent	1	switch between capacitive and DC-coupling of the pixel output to the strip pad
row control block		
EnL, EnR	1 each	switch between pixel and strip mode
InDACL, InDACR	4 each	TDAC value

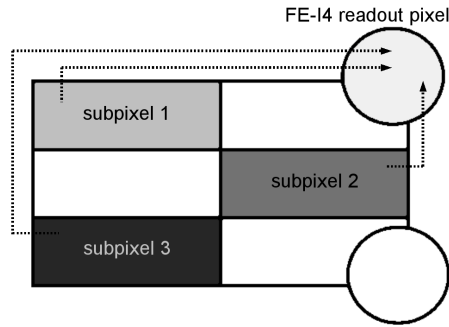


FIGURE 4.6: Schematic of a unit cell and the subpixel encoding. Three subpixels of a unit cell are routed together to one FE-I4 readout pixel. The chessboard pattern is chosen so that no direct neighbors are read out by the same FE-I4 pixel.

The white subpixels are routed to the white circle which is omitted here for clarity.

amplitudes adequately, the pixel responds to a particle hit by generating a unique signal from which we can determine the subpixel address of the hit.

The initial output signal is a current pulse of up to $10\ \mu\text{A}$, which is translated to a voltage pulse by a pull-up resistor in the pixel electronics. This voltage pulse is transferred to the pixel output pad by a $79\ \text{fF}$ capacitor where it results in a charge pulse. The output pad can be either directly connected to the FE-I4 input pad by bump-bonding or capacitively coupled by, e.g. a glue interface. The FE-I4 measures the total charge of the arriving pulse which is translated to ToT information. In the end, the ToT-value delivered by the FE-I4 corresponds a certain subpixel address of the unit cell.

We have proved this concept to work. Results and discussion of the measurements are given in Section 4.4.7.3.

4.2.4 Testing functions

The CCPD has several testing functions implemented (see also Figure 4.3(b)):

- **Injections** (see Section 2.4.3.5): A specified amount of charge can be injected to the preamplifier by externally supplied voltage signals on the dedicated injection bond pad on the sensor. The injection capacitance C_{inj} that is implemented in the sensor electronics converts voltage steps to charge signals. With the CCPDv4 we measure a value of $1.2^{+0.3}_{-0.2}$ fF for C_{inj} for both the unirradiated sensor and the sensor irradiated with 24 GeV-protons to $(1.8 \pm 0.5) \times 10^{13} \text{ n}_{\text{eq}} \text{ cm}^{-2}$.
- **Injection test pad:** In addition to the pixel output pads there is one test pad, which is directly connected to the injection line. It is located 50 μm outside the pixel matrix on the top right with respect to the schematic in Figure 4.3(b). Like the pixel pads, its geometry is FE-I4 compatible. It can be used to measure the coupling capacitance between the sensor and the readout chip.
- **AmpOut:** The preamplifier output (AmpOut) of the lowest and rightmost pixel of the matrix is accessible on a dedicated wire-bond pad. For the work presented here, AmpOut has been extensively used. The charge collection properties and single pixel efficiency results presented below have been obtained by using AmpOut.
- **Monitor:** The current output of each pixel can be multiplexed to a wire-bond pad of the chip instead of being routed to the corresponding pixel pad. This “monitor pad” can be read out with an instrument like an oscilloscope and no specific readout ASIC is needed. In combination with injections we use the monitor line to determine and tune the pixel thresholds (see Section 4.4.6).

4.2.5 Readout scenarios

The CCPD has functionality for three different readout scenarios: stand-alone, pixel and strip mode.

4.2.5.1 Stand-alone

The testing functions mentioned above allow for comprehensive probing, testing and calibration of the sensor without the need for a readout chip. Charge collection studies, behavior of the sensor electronics and threshold tuning are important examples of what can be done in stand-alone mode.

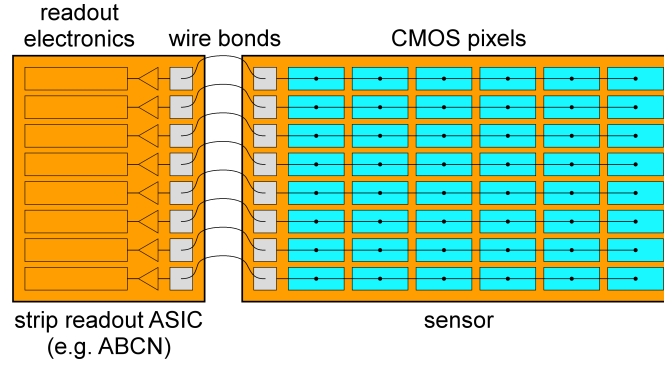


FIGURE 4.7: Schematic of the sensor operating in strip mode. The sensor pixels (cyan) are interconnected along the long dimension to form virtual strips. The readout can be realized with a suitable strip readout chip. Image adapted from [135].

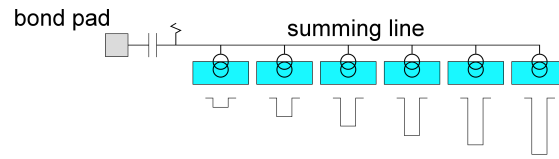


FIGURE 4.8: Schematic of the pixel address encoding in a virtual strip. Each pixel responds to a particle hit by a current pulse with well defined amplitude (depicted at the bottom of the image). Image adapted from [135].

4.2.5.2 Pixel readout

The prime use of the CCPD is a pixel detector read out by the FE-I4. The features discussed in the last sections are tailored for this use. However, compatibility with other pixel readout chips is also achieved by special structures and different pixel types. They are described in Section 4.2.6.

4.2.5.3 Strip mode

The CCPDv1 and CCPDv2 can also be operated in strip mode. When this mode is activated, the sensor electronics interconnects pixels along the large dimension to form “virtual strips” (see Figure 4.7). The readout can then be realized by an analog or digital strip readout-chip, e.g., the ATLAS ABCN or the LHCb Beetle.^[134] In addition, the position of the pixels within a strip is encoded in the signal height as depicted in Figure 4.8. Thus, 2D-information can be obtained also in strip mode. Figure 4.9 shows a 2D-image reconstructed from the pulse height information. Detailed information on the strip mode can be found in [135] and [136].

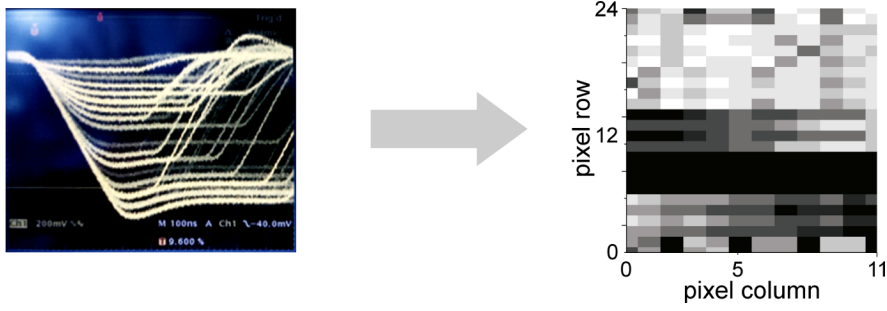


FIGURE 4.9: 2D-image reconstructed from signals obtained in strip mode. On the left, a screenshot of the oscilloscope shows the signals from a virtual strip of a CCPDv2 exposed to a ^{55}Fe -source. The different signal amplitudes corresponding to different pixels along the strip can be clearly distinguished. On the right, the reconstructed 2D-map of signal counts shows the shadow of a wire placed between the source and the sensor. A light shade of gray corresponds to many counts per pixel and a dark shade of gray to few counts. Images adapted from [136].

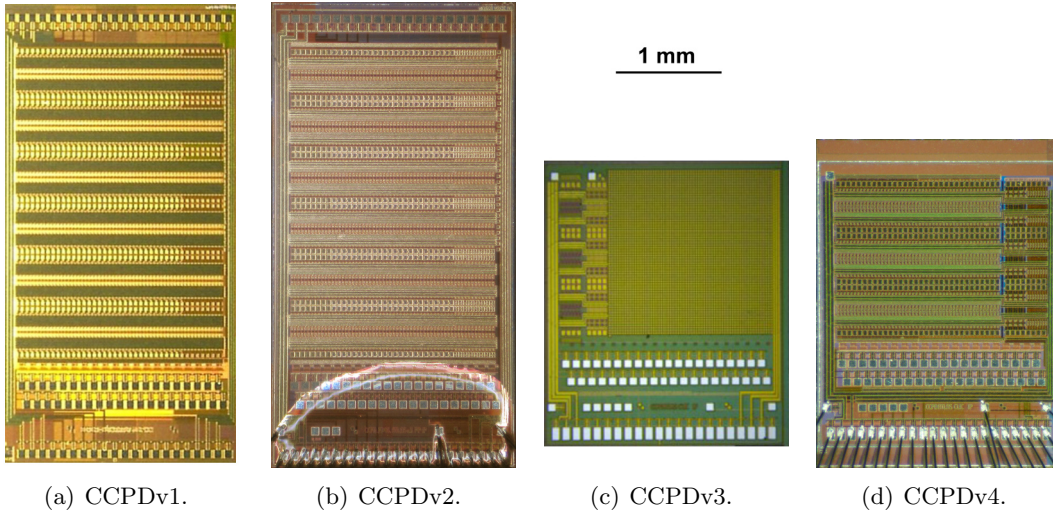


FIGURE 4.10: Photographs of the first four sensor prototypes to scale. Some of the different pixel types are distinguishable. The CCPDv2 and CCPDv4 are wire bonded for stand-alone measurements. The protective potting of the wire-bond pads (see Section 4.4.1) is visible on the bottom of the CCPDv2.

4.2.6 Versions

The last sections describe mainly the layout and functions of the prototype sensor CCPDv1 and its pixel type that is designed for FE-I4 readout. Other pixel types and subsequent sensor versions differ from this description. The main features of the various pixel types and major design differences of the different sensor versions are given in this section. Figure 4.10 shows photographs of the first four sensor versions and Figure 4.11 shows the physical position of the different pixel types on the sensors.

A complementary list of sensors related to the CCPD-family is given in Appendix C.

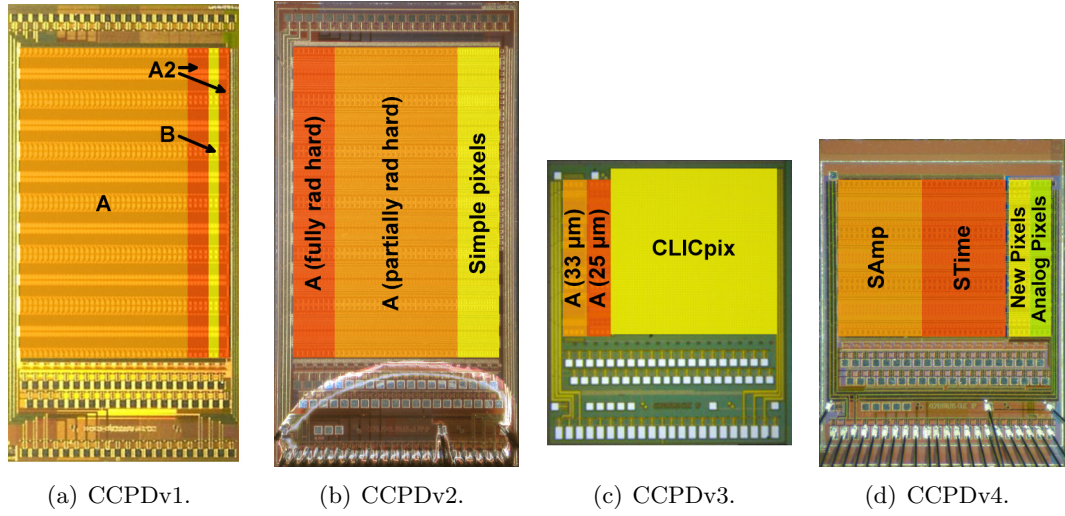


FIGURE 4.11: Position of the different pixel types on the sensors as is described in the text.

4.2.6.1 CCPDv1

The CCPDv1 comprises three pixel types (the names in capital letters correspond to those in Figure 4.11 and Appendix B):

- **A:** Unit columns 0–15. This is the main pixel type. Its layout and functionality are described in detail in the last sections. The pixel pads have passivation openings. They can be DC-coupled to the readout chip by bump-bonding or AC-coupled by a capacitive interface.
- **A2:** Unit columns 16, 17 and 19. The pixel pads do not have passivation openings and can therefore only be capacitively coupled to the readout chip.
- **B:** Unit column 18. It features simplified in-pixel electronics to obtain lower noise and higher radiation tolerance. The main simplification is that there is no TDAC implemented. The pixel pads do not have passivation openings.

In addition to the pixel pads that match the FE-I4 there are 35 pixels of the last unit column connected to 35 separate pads which have a pitch of $55\text{ }\mu\text{m}$. They are designed to fit the Timepix^[137] readout chip. The schematic of the sensor layout is shown in Figure 4.3.

4.2.6.2 CCPDv2

The CCPDv2 is geometrically equal to the CCPDv1 but the design of the electronics is improved concerning radiation hardness. There are three pixel types implemented:

- **A (partially radiation hard):** Unit columns 4–15. This pixel type is equal to the pixel type A of the CCPDv1 with one difference: some linear transistors are replaced by circular ones to improve radiation tolerance. These transistors are marked in the schematic shown in Figure 4.5.
- **A (fully radiation hard):** Unit columns 0–3. A larger number of transistors are implemented as circular transistors. These transistors are also marked in Figure 4.5. The pixel pads do not have passivation openings.
- **Simple pixels:** Unit columns 16–19. They have simpler electronics implemented than the other two pixel types.

Some electronic functions have been added, e.g., a monitor function for the shift registers and the AmpOut of more than one pixel is accessible. This results in additional parameters that have to be set. More detail can be found in [138] and [139].

Strip readout is possible; results are shown in Figure 4.9.

4.2.6.3 CCPDv3

Measuring approximately $2.8 \times 2.4 \text{ mm}^2$, the CCPDv3 is smaller than its predecessors and most of the active area is covered by pixels from the CLICpix type. These are small pixels measuring $25 \times 25 \text{ } \mu\text{m}^2$. Every pixel has its own readout cell and the pixel contains only the preamplifier. A smaller area of the sensor is covered by two ATLAS pixel types: Six pixel columns are occupied by pixels similar to type A from previous versions measuring $33 \times 125 \text{ } \mu\text{m}^2$ and eight pixel columns are occupied by pixels measuring $25 \times 125 \text{ } \mu\text{m}^2$.

In addition there are some simple diode structures implemented to allow for TCT-measurements.⁽⁹⁾ No strip readout is possible with the CCPDv3.

More detail on this version can be found in [141] and results with the CLICpix pixels are presented in [142].

4.2.6.4 CCPDv4

The CCPDv4 is again focused on the ATLAS pixel type. It is of the same size as the CCPDv3. The electronics is enhanced to reduce noise and to improve radiation tolerance and the subpixel encoding. Four pixel types are implemented:

- **SAmp:** Unit columns 0–7. This pixel type is based on the pixel type A of the previous versions. Improvements concerning noise reduction, testability, subpixel encoding and radiation tolerance are implemented.

⁹ TCT stands for transient current technique which is an important tool to investigate charge collection properties of silicon detectors, see [140].

- **STime:** Unit columns 8–15. This pixel type is equal to the SAMP-type with the exception of the subpixel encoding: it is no longer based on the amplitude of the current pulses of the output stages but on the pulse length.
- **New Pixels:** Unit columns 16 and 17. This pixel type is based on the $25 \times 125 \mu\text{m}^2$ -pixels of the CCPDv3. Improvements concerning noise reduction are implemented.
- **Analog Pixels:** Unit columns 18–25. The pixel size is $25 \times 350 \mu\text{m}^2$. The pixels contain only the preamplifier and electronics similar to the CLICpix pixels in the CCPDv3.

Some diode structures are implemented for TCT-measurements. No strip readout is possible. The summing scheme of the subpixel encoding is different to previous versions: the chessboard pattern that is depicted in Figure 4.6 is only implemented in unit columns 1 and 2. The other SAMP and STime subpixels are connected in a linear pattern. Details on this and on the many improvements of the electronics, e.g., the ability to send injections row-wise instead of flooding the whole sensor and a positive feedback in the comparator to boost weak signals, can be found in [143].

4.2.6.5 CCPDv5 and beyond

The time resolution of the CCPDv4 and earlier versions is around 100 ns due to timewalk. The CCPDv5 will have a timewalk compensation implemented to improve the resolution. Simulations suggest that a timewalk of less than 5 ns is possible.^[144] In addition, the guard ring structures will be enhanced to raise the HV-limit of the electronics. This work does not cover results obtained with the CCPDv5 and versions beyond. An outlook is given in Section 4.7.

4.2.6.6 Full-size demonstrator

Efforts to demonstrate suitability of HV-CMOS sensors for the ATLAS Phase-II upgrade have lead to the development of a full-size demonstrator chip. The ams 350 nm-process H35^[145] has been chosen because it is more mature than the H18 process and offers relevant options like HV-operation up to 120 V⁽¹⁰⁾ and the possibility to use high-resistivity wafers in the range of k Ω . This chip called H35DEMO has been submitted to the foundry in fall 2015. Results obtained with it are not covered in this work.

¹⁰ This limit is the operation limit stated by the manufacturer. Our experience is that a breakdown limit at about 150 % of this value can be expected.

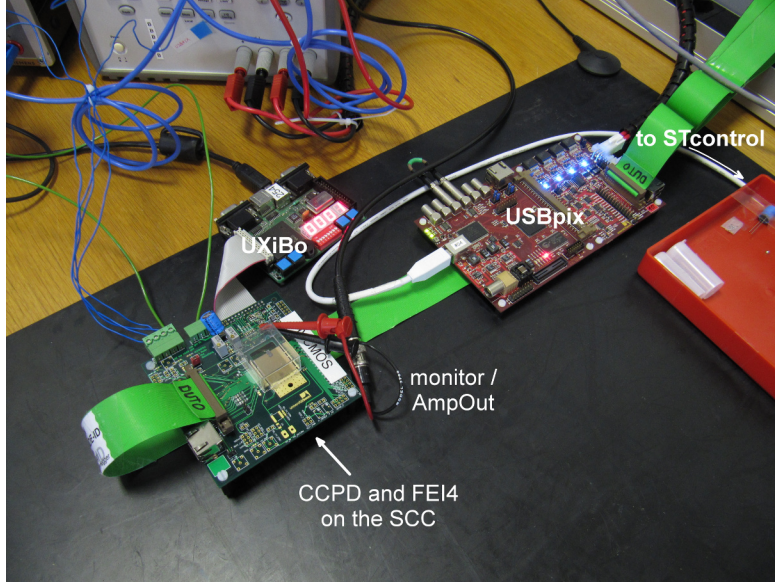


FIGURE 4.12: One of the first setups operating a CCPDv1 together with a FE-I4. Both chips are mounted on a single chip card (SCC). The CCPD is operated with the UXiBo system. The monitor, respectively AmpOut line is connected to an oscilloscope via passive probes. The FE-I4 is operated with the USBpix system, including STcontrol as user interface. Most of the later measurements were done in a shielded climate chamber.

4.3 Setup

In Section 4.2 we describe the CCPD-family in detail. In Sections 4.4 to 4.7 we present our results with the CCPD-sensors. Here we give an overview of the setups and methods we used. Our work spans over a large range of R&D for a sensor: from introduction of the first prototype to efficiency measurements for detector qualification. Consequently, many setups were used and a detailed description of each goes beyond the scope of this thesis. We list the central items in this section and give references where available.

The main operating mode for the CCPD is the pixel readout with the ATLAS FE-I4 readout chip. Therefore the existing FE-I4 readout system USBpix^[146] was used and extended for the CCPD. One of the first installations is shown in Figure 4.12.

4.3.1 Connectivity and assembly

The standard single chip card (SSC)^[147] for the FE-I4 was modified to host the I/O functions and the power supply for the CCPD. This was a time-consuming and ongoing effort of many groups in the collaboration because every sensor version is different and needs a custom printed circuit board (PCB) design. A PCB for the CCPDv1 is shown on the left hand side of Figure 4.12.

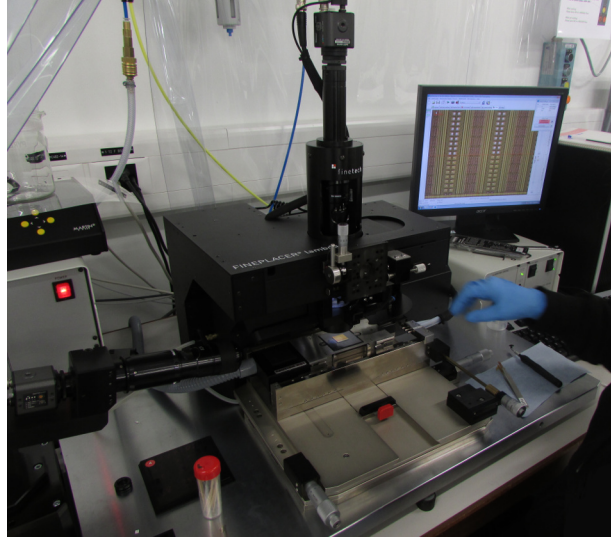


FIGURE 4.13: Gluing of samples with a die bonder. The alignment was controlled visually with the optical system of the machine as can be seen on the monitor in the background.

4.3.1.1 Wire bonding

The connection of the sensor to the PCB was done via wire bonding. This was a very critical process due to the very small bond pads on the sensor (see Section 4.4.1). First samples were connected with gold stud bonding and the majority of later samples with aluminum wedge wire bonding by the bonding laboratory at CERN.^[148]

4.3.1.2 Gluing

The glue interface between the sensor and the FE-I4 is discussed in Section 4.4.7.1. First samples were manually glued with simple setups that could perform the flip-chip procedure with a precision of several μm . Later the procedure was improved using fluid dispensers for precise glue application and die bonders with sub-micron precision like the FINEPLACER® lambda.^[149–151]

4.3.2 Control and readout

The FE-I4 was controlled and read out by STcontrol, the user interface for the USBpix system.^[152] The CCPD was connected via the UXiBo,^[153] a multi-purpose FPGA board for university courses. The sensor was controlled by the custom software HV2FEI4ctrl. It was initially written by the chip designer.^[154] We expanded and developed it further to our needs. For the R&D-phase covered by this work the UXiBo and HV2FEI4ctrl were suitable, but they are both based on hard- and software which will soon be outdated. Several groups in the collaboration started efforts to incorporate the CCPD control

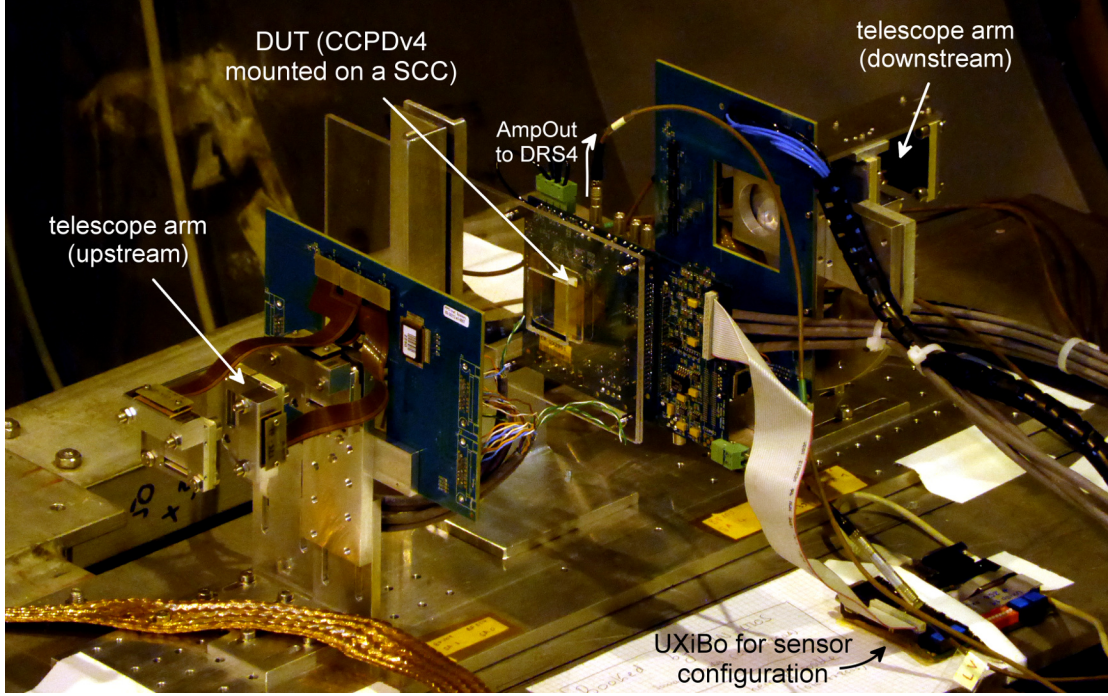


FIGURE 4.14: The setup used in the testbeam experimental zone H8A at CERN. The two compact arms of the SBM telescope can be seen as well as a CCPDv4 as DUT (device under test). Control and readout of the CCPD were done with the UXiBo and DRS4 as is described in the text.

and readout to existing sensor test systems, e.g., the USBpix. Results are presented in [155]. In addition to data recorded with the readout systems we used a lot the analog output AmpOut. We could directly access this signal and evaluate or record it with an oscilloscope. For this we mainly used the DRS4 evaluation board from PSI.^[156]

4.3.3 Testbeam

Most of the data for Sections 4.5 and 4.6 were taken in the experimental zone H8A at the testbeam facilities of the CERN North Area.^[157] The beam consisted of secondary particles after protons from the SPS hit a target. The composition was approximately 70 % protons and 30 % pions (π^+). The nominal momentum was $180 \text{ GeV } c^{-1}$. There was also a small fraction of muons present in the beam.^[158]

The data for track reconstruction was taken with the AIDA SBM telescope (see Figure 4.14). It is a compact telescope with planar silicon sensors mounted on single FE-I4Bs in six planes. Its resolution is approximately $8 \mu\text{m}$.^[159] The DUT data was taken with the DRS4 and converted for track reconstruction with the software *tbConverter*. We used *Judith*^[160] as reconstruction software and further analysis was done with *ROOT*^[161] and *MATLAB*.

4.3.4 Radioactive sources and other items

Before conducting testbeam campaigns we used radioactive sources to test and characterize the sensors in our laboratory. They were ^{90}Sr with an activity of $\approx 27\text{ MBq}$ and ^{55}Fe with an activity of $\approx 173\text{ MBq}$.⁽¹¹⁾

Further items that we used regularly for measurements were a climate chamber (CTS T -65/50/S) to control the ambient temperature and for electromagnetic shielding and several power supplies, notably the model 2410 from Keithley. The latter we controlled with LabVIEW to record the current-voltage characteristics of the sensors.

4.3.5 Irradiation campaigns

To characterize the CCPD after exposure to high doses and large particle fluences we had several sensors irradiated. We used three different types of radiation at different facilities.

4.3.5.1 Neutrons

To study bulk damage stemming from non-ionizing radiation, four CCPDv1s were irradiated with neutrons in the TRIGA reactor of the Jožef Stefan Institute in Ljubljana, Slovenia.^[162, 163] Two of them were irradiated to 1×10^{15} and two to $1 \times 10^{16} \text{ n}_{\text{eq}} \text{ cm}^{-2}$. The accuracy of the fluences is $\pm 12\%$.⁽¹²⁾ For each of these fluences one sensor was assembled with the FE-I4 and successfully operated as a pixel detector.

4.3.5.2 Protons

As discussed in Section 2.4.5, charged particle irradiation causes damage to the sensor that is different to that from neutrons. To study this damage we planned irradiation of sensors with 24 GeV-protons from the CERN PS up to $3 \times 10^{15} \text{ p}^+ \text{ cm}^{-2}$. Our irradiation campaign was part of the first run in the new irradiation facility IRRAD at CERN.^[164] No operating experience with this new facility was available at that time. This led to a wrong position of our sensors in the setup where they were not directly placed in the beam. Therefore they received only a reduced particle fluence of $3.5 \times 10^{13} \text{ p}^+ \text{ cm}^{-2} \pm 27\%$, corresponding to $(1.8 \pm 0.5) \times 10^{13} \text{ n}_{\text{eq}} \text{ cm}^{-2}$ (see Equation 2.22 for conversion).

¹¹ Because of their relatively short half-lives of 28.8 and 2.7 years, respectively, the activities diminished noticeably over time.

¹² Calculated from values given in [162].

4.3.5.3 X-rays

Several sensors of the first and second generation were irradiated at the CERN X-ray irradiation facility with 10 keV X-rays up to $8.62 \text{ MGy} \pm 20 \%$ ^[165] to understand surface effects of ionizing radiation (8.62 MGy are equal to 862 Mrad). They were used to study the performance of the sensor electronics after irradiation (see Section 4.4.3).

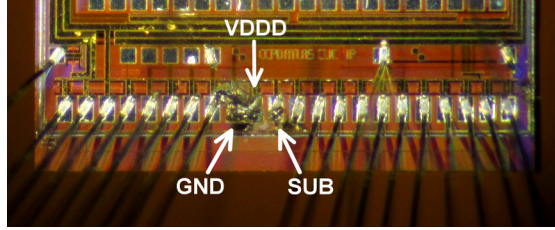


FIGURE 4.15: Picture of damaged wire bonds on a CCPDv4 glued onto a FE-I4. Several wire bonds have been ripped off by a short-circuit between SUB and adjacent pads.

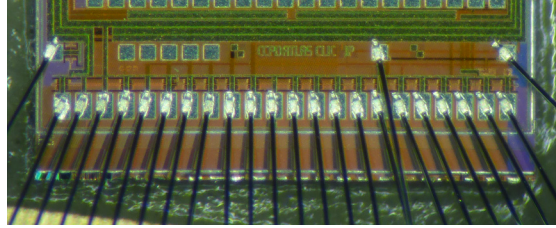
4.4 Sensor operation

4.4.1 Sample preparation

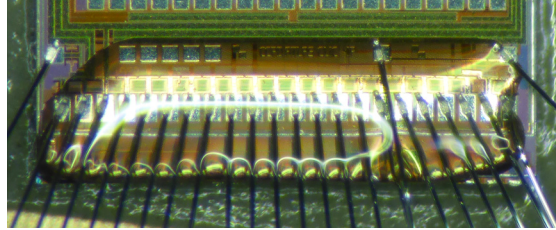
We are dealing with a new sensor chip and therefore encountered some infancy problems. The first issue came up during the aluminum wedge wire bonding. The bond pads on the sensor measure $80 \times 80 \mu\text{m}^2$ (CCPDv1 – CCPDv3) and $80 \times 130 \mu\text{m}^2$ (CCPDv4) with a gap of $20 \mu\text{m}$. This is barely enough to house one wedge which is clearly visible in Figure 4.15. In addition, the pitch of the PCB bond pads does not match the pitch of the sensor pads, so the wire bonds have to be fanned out. This results in a skew position for the wedges on the small sensor pads and metal from the bond protrudes the pad. Two problems emerge: First, there is no room for error for the wire bonding as no rework can be done in case of problems. Second, the gap does not provide enough electrical insulation of the pads. In one case we observed electric breakdown between the high-voltage supply pad (SUB) and adjacent pads which destroyed the sample. The only capacitor large enough to supply enough current for such a destructive short-circuit is connected to SUB and GND, respectively. The short-circuit therefore happened probably to GND, bridged by the VDD pad (see Figure 4.15). We assume that the combination of physical proximity of different electrical potentials, surface contamination and atmospheric humidity caused the short-circuit.⁽¹³⁾

To protect subsequent samples from the same failure we potted the area of their bond pads in PU (polyurethane). At first we tried to apply the PU by spraying with an airbrush as described in [167]. This turned out to be too complex for our use. We successfully developed a simpler procedure where droplets of PU are deposited on the wire bonds with a Nordson EFD 1500 fluid dispenser. Capillary action distributes the PU over the bonds. A CCPDv4 before and after potting is shown in Figure 4.16. Metals have a linear CTE of typically below $20 \times 10^{-6} \text{ K}^{-1}$ (e.g. for silicon it is $2.56 \times 10^{-6} \text{ K}^{-1}$).^[168] Cured PU has a significantly higher CTE (one source states $57.6 \times 10^{-6} \text{ K}^{-1}$).^[169] To check if this CTE mismatch is causing problems when the sample is cooled, we tested a potted sample by thermal cycling (31 cycles in a climate chamber between $+30$ and

¹³ A gap of $20 \mu\text{m}$ in air at atmospheric pressure protects against dielectric breakdown up to around 400 V .^[166]



(a) Before potting.



(b) After potting.

FIGURE 4.16: A CCPDv4 before and after potting of the wire bonds. The critical bond pads that are close to each other are well covered with PU. The top left wire bond which is not covered is not problematic because it is a single bond with no others close to it.

-40°C over a 47-hour period). After the cycling a visual check was performed which did not reveal any damage of the bonds nor of the sensor. I-V curves (current-voltage characteristics) were recorded via SUB before and after potting as well as before and after thermal cycling. We could not see any significant change of electrical behavior and conclude that the potting is safe for the samples.

4.4.2 Sensor configuration

The electric functions on the sensor require configuration of the sensor prior to operation. The parameters listed in Section 4.2 have to be set. Once configured, the sensor is supposed to keep its configuration as long as the power supply is not interrupted and no soft errors like SEUs occur. We observed different behavior and encountered two problems:

First, the settings for a given configuration often had to be sent multiple times to the sensor before they were adopted. Some sensors seemed to only partially accept settings, i.e. sending the same parameters resulted in different behavior of the sensor.

Second, the configuration was volatile, especially for the CCPDv1 and CCPDv2. This means the sensor lost its configuration and went to an undefined state without no apparent reason. After long investigation we found out that the sensor is very susceptible to electromagnetic disturbance. We identified ESD (electrostatic discharge) in the vicinity of the sensor as the main cause for losing configuration. Even a light switch or a person handling items that are not ESD-safe in the same room triggered loss of configuration.

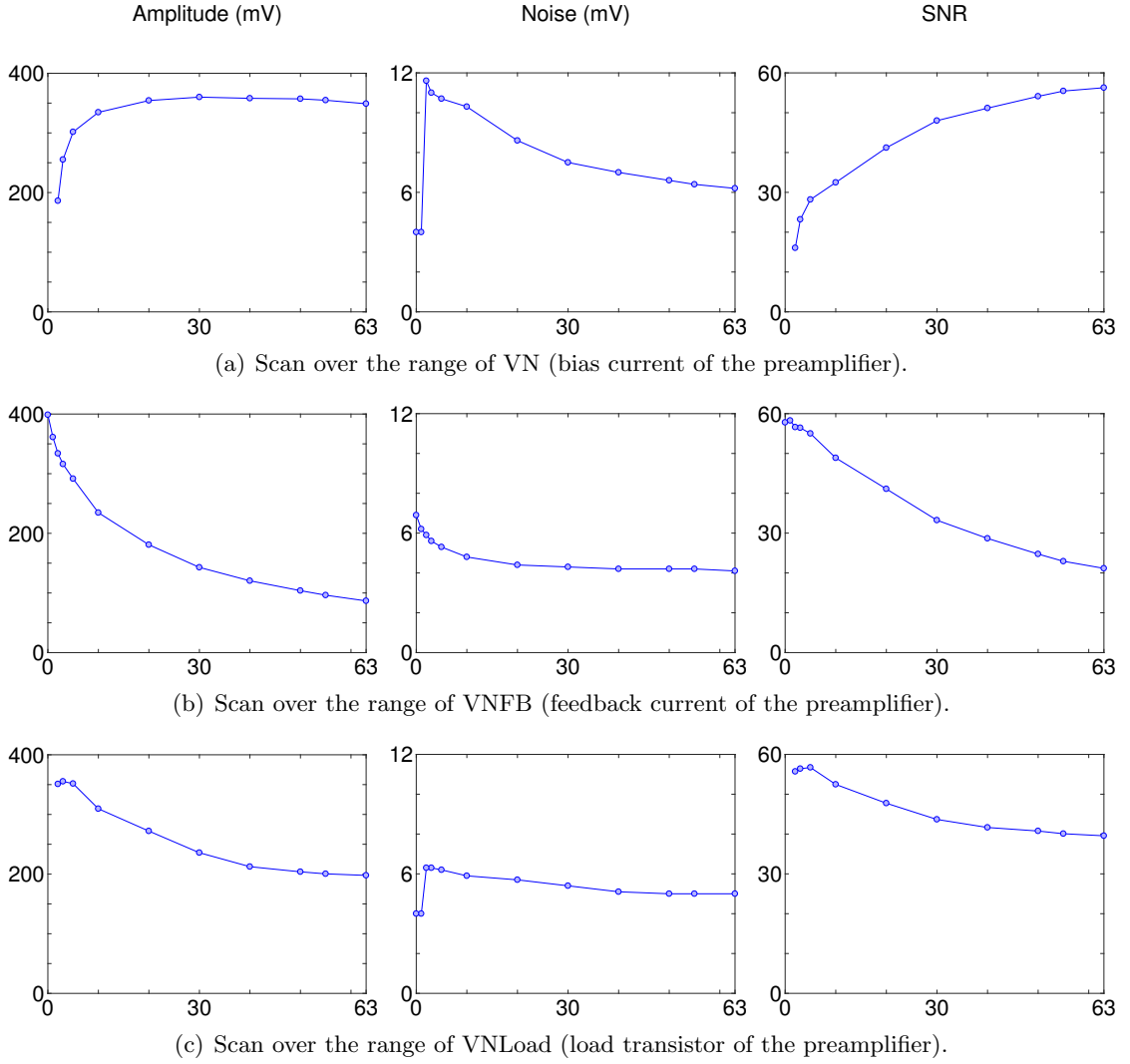


FIGURE 4.17: Parameter scans and the influence on AmpOut. The amplitude of AmpOut in response to 500 mV-injections is shown in the left and the corresponding noise in the middle column. Units of the ordinate are mV. The SNR (dimensionless) is shown in the right column. The abscissa values are the DAC values of the scanned parameter. AmpOut was taken from unit column 1 of an unirradiated CCPDv4 (SAm pixel type). Additional parameters and supply voltages that influence AmpOut were set to constant values: VNBias = 0, VNFB = 5, VDDA = 1.95 V, VCASC = 1.85 V, SUB = -75 V. The noise is the error for the amplitude and bears a measurement error of 0.005 mV itself. The error of the SNR is 1.

We could reduce the configuration problems by improving the shielding of power supply and data lines, taking great care of grounding and performing measurements in electrically shielded climate chambers where possible.

4.4.3 Influence of parameters on AmpOut

Many measurements in this work are based on AmpOut, the output of the preamplifier in a pixel. It is therefore important to know how AmpOut is influenced by the sensor

configuration. Figure 4.17 shows the behavior of amplitude and noise of AmpOut while scanning the complete range of the parameters VN, VNFB and VNLoad. The SNR is also calculated. All other parameters and supply voltages were kept constant during the scans. We were aiming for a maximum SNR which for this sample was achieved with the parameter set $VN = 63$, $VNFB = 1$, and $VNLoad = 5$. Special attention has to be given to the edges of the parameter ranges. VN below 2 or VNLoad below 5 resulted in no response of the preamplifier when sending injections (i.e. preamplifier is off).

The plots give an overview of the general behavior but each individual sample behaves differently. Therefore also the optimum parameter set is different for each sample.

4.4.3.1 Performance after X-ray irradiation

The influence of the parameters can be used effectively, e.g. when the performance of the pixel electronics decreases after irradiation. In this matter, the partially and fully radiation hard pixels of a CCPDv2 were investigated at the CERN X-ray facility. Before irradiation, an optimum set of sensor parameters was set and the preamplifier gains of different pixels were measured. The sensor was then irradiated to a total dose of $8.62 \text{ MGy} \pm 20\%$ ($= 862 \text{ Mrad}$). At each step of 1 MGy the chip was annealed for one hour at $+70^\circ\text{C}$. The preamplifier gains dropped down to below 20% of their initial values after having finished the last step of the irradiation. However, re-optimizing the chip parameters could restore the gains of the fully radiation hard pixels to about 90% of their initial value (see Figure 4.18). At the same time, the average noise increased from 75 to $150 e^-$. The gains of the partially radiation hard pixels could only be restored to about 50% of their initial value. The gain decrease is probably caused by leakage currents in the transistors used in the amplifier. The use of enclosed transistors mitigates this problem. This result is quite promising knowing that not the whole pixel electronics are implemented in a radiation hard way. Figure 4.5 shows that only some transistors are enclosed, even in the fully radiation hard pixels. The rest is implemented as standard linear transistors. This leaves possibilities for further improvement open, leading to even more radiation hard future generations of the sensor.

More details of the results can be found in [136] and [170].

4.4.4 Power consumption

Power consumption is a crucial figure of merit when designing large-area detectors. We measured the power consumption of the preamplifiers and the output stages in a CCPDv1.

The preamplifiers are powered by VSSA and regulated by VN. Figure 4.19 shows the current of VSSA and power consumption per area as a function VN. By design, the dependancy is linear which is illustrated by the linear fit that is applied. The data for

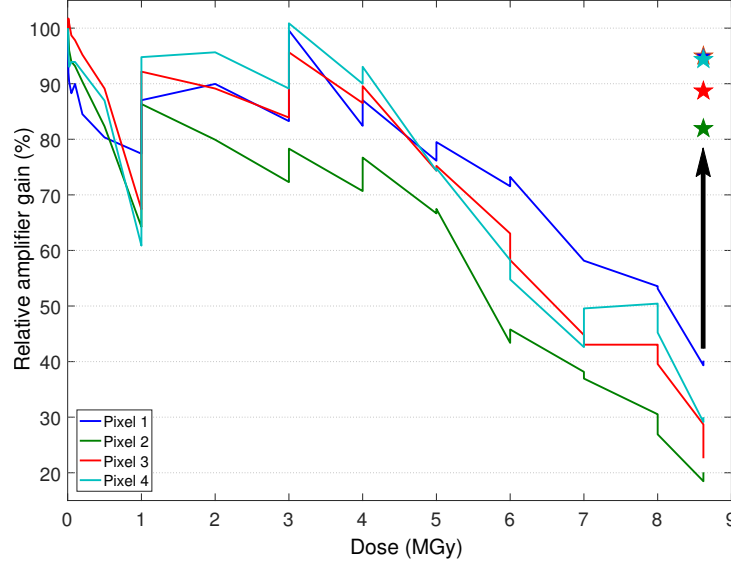


FIGURE 4.18: Preamplifier gain of four selected, fully radiation hard CCPDv2 pixels as a function of absorbed dose during X-ray irradiation. The abrupt changes at each full 1 MGy reflect the regular annealing performed at those doses. The stars represent the gain values after irradiation to the full dose of 8.62 MGy (= 862 Mrad) and subsequent re-optimization of the sensor parameters. Data from [171].

the measurement are listed in Table 4.6.

The power consumption of the output stages is estimated in Table 4.5. We consecutively switched the stages on⁽¹⁴⁾ and measured the current of VDDA. The offset of the current when the stages are switched off is due to the PCB design: VDDA and VDD are routed together and use the same power supply. In addition, VDDA is supplying other devices than the sensor on the PCB. We corrected for the offset in the calculation by defining the power consumption as zero when all stages are switched off. Therefore the values are only relative values. They bear a large error because the uncertainty for the current measurement is in the order of the differences we measure.

TABLE 4.5: Current (I) of VDDA and estimated power consumption per area (P/A) of the output stages of a CCPDv1. Details are given in the text.

VNOut			I (mA)	P/A (mW cm ⁻²)
0	1	2		
0	0	0	40 ± 4	0
60	0	0	45 ± 4	$163 \pm 116 \%$
60	60	0	50 ± 4	$325 \pm 58 \%$
60	60	60	55 ± 4	$488 \pm 39 \%$

¹⁴ A value of 0 for VNOut means that the corresponding stage is off. A value of 60 means that the stage is almost fully switched on (63 is the maximum).

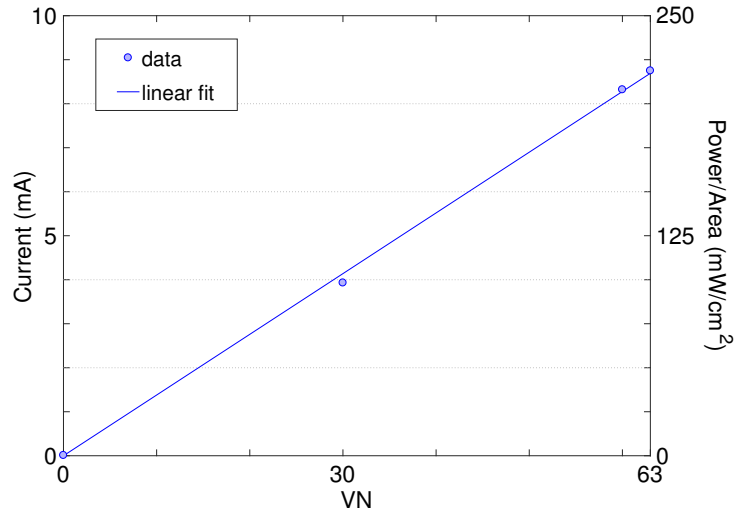


FIGURE 4.19: Current of VSSA and power consumption per area of the in-pixel preamplifiers in a CCPD1. The data and errors for the measurement are listed in Table 4.6.

TABLE 4.6: Current (I) of VSSA and power consumption per area (P/A) of the in-pixel preamplifiers in the CCPDv1 for different values of VN.

VN	I (mA)	P/A (mW cm ⁻²)
0	0.010 ± 0.005	0.2 ± 0.1
30	3.93 ± 0.01	98.1 ± 0.8
60	8.32 ± 0.02	208 ± 2
63	8.75 ± 0.02	218 ± 2

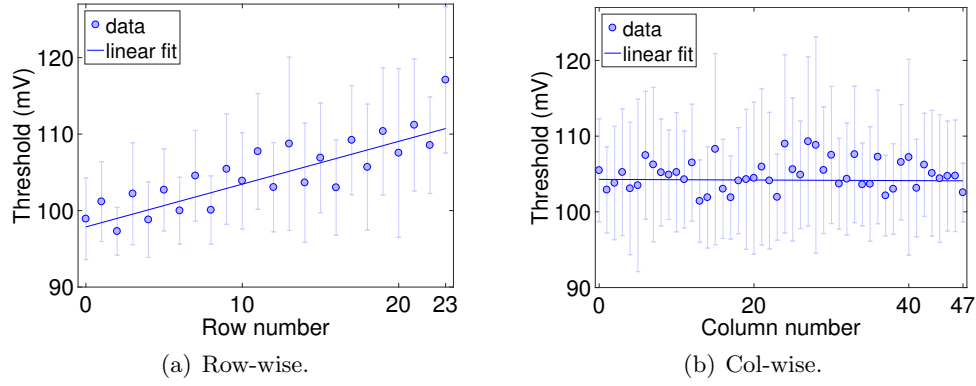


FIGURE 4.20: Threshold values averaged over columns 0 to 47 versus the row number (left) and averaged over all rows versus the column number (right) for a CCPDv1. The weighted linear fit is plotted for both data sets to visualize the dependency on the row and column numbers, respectively. The scale of the ordinate is the same for both figures. An explanation for the slope and oscillation in the left-hand plot are given in the text.

4.4.5 Input referred threshold and noise

The comparator stage in every pixel has a certain threshold value above which the comparator fires and a hit is detected. We use the injection and monitor functions of the sensor to determine the threshold of a pixel by measuring the so-called S-curve (see Sections 2.4.3.6 and 4.2.4). This is done by scanning the injection amplitude and sending 128 injections to the selected pixel for each amplitude step. The response of the pixel, which is accessible on the monitor line, is recorded. An S-curve measured with a type-A pixel of a CCPDv1 is shown in Figure 2.14.

4.4.5.1 Dependency on row and column number

We recorded S-curves for all type-A pixels of a CCPDv1. Across the sensor we observed a dependency of the threshold on the row number, but not on the column number (see Figure 4.20). We conducted many discussions with colleagues and the chip designer to explain this behavior of the CCPDv1. As explained above, the global threshold is set by the externally supplied voltage TH, which is supplied to the pixel matrix only from one side. We conclude that there is probably a voltage drop along the TH supply line inside the chip. This would explain the shift of the threshold along the long sensor dimension. However, TH is not accessible inside the sensor and can not be measured.

We also recorded the S-curves for all partially radiation hard type-A pixels of a CCPDv2. We could not record a significant dependency of the threshold on the row or column number. The changes in the electronics that are implemented in the CCPDv2 (see Section 4.2.6.2) apparently eliminate the voltage drop along the TH supply line.

Tables 4.7 and 4.8 summarize the results quantitatively. As a result of the dependency

TABLE 4.7: Values derived from the analysis of the dependancy of the threshold on row and column number for a CCPDv1. The values are the results of the fits shown in Figures 4.20(a) and 4.20(b). On the left, the threshold values on the extremities (row 23, row 0, column 47, column 0) of the pixel matrix are listed. On the right, the absolute and relative differences between the values on the extremities are given. Col stands for column.

threshold value (mV)		difference absolute relative (mV) (%)	
row 23 row 0		(row 23 – row 0)	
row-wise	110.7 ± 1.6	97.9 ± 1.6	12.8 ± 2.3 13.1 ± 2.5
col 47 col 0		(col 47 – col 0)	
col-wise	104.1 ± 0.9	104.3 ± 0.9	-0.2 ± 1.3 -0.2 ± 1.2

TABLE 4.8: Values for a CCPDv2 corresponding to the values for a CCPDv1 given in Table 4.7.

threshold value (mV)		difference absolute relative (mV) (%)	
row 23 row 0		(row 23 – row 0)	
row-wise	111.8 ± 2.4	112.1 ± 2.4	-0.3 ± 3.4 -0.3 ± 3.0
col 47 col 0		(col 47 – col 0)	
col-wise	113.6 ± 2.0	114.4 ± 2.0	-0.8 ± 2.8 -0.7 ± 2.5

on the row number we can not compare the threshold measured across the whole sensor. This is why in the next paragraph we compare values for a CCPDv1 under different conditions only for row 0.

Another phenomenon is clearly visible in Figure 4.20(a): the input referred threshold is separated in two populations. This is explained by the geometry of the pixel matrix: every second pixel row is mirrored. This introduces a systematic transistor mismatch during the lithographic steps in the production process.

4.4.5.2 Influence of the global threshold, temperature, irradiation and FE-I4 activity

We investigated the influence of different parameters and environmental conditions on the threshold and noise. Due to the wire-bonding constraints discussed in Section 4.4.1, we could not re-bond samples and therefore we had to take measurements with different samples. A comparison of the values of different samples given in volts, the unit of the injections, is not meaningful because every assembly runs with its own parameter set. Therefore a calibration with iron-55 was necessary to express the threshold and noise in units of the elementary input charge e^- .⁽¹⁵⁾ The noise then equals the ENC (see Section 2.4.3.2). The calibration was done with different samples by other institutes without taking into account the bias voltage dependancy that is discussed in Section 4.5.1. Therefore the transformation to our samples required a conservative error calculation, yielding uncertainties in the calibration factors of 40 % for the unirradiated and 50 % for the irradiated samples. As a consequence, the comparison of the samples is more of a qualitative nature than a quantitative one. Comparisons of values of the same sample is more exact, though. Table 4.9 and Figure 4.21 show the settings and results for the following measurements:

- **Global threshold**

The voltage TH sets the global threshold level. With a CCPDv1 we measure an increase of the global threshold by approximately 100–200 e^- per 10 mV of increase for TH. There is a tendency of the noise to increase as well, but the increase is small compared to the error of the measurement.

- **Irradiation and temperature**

As explained in Chapter 2, the noise of a sensor increases with the particle fluence that the sensor received. This is due to the increased leakage current. Cooling of the sensor decreases the leakage current and therefore the noise. We investigated this behavior with a CCPDv1 that had been irradiated to approximately $1 \times 10^{15} \text{ n}_{\text{eq}} \text{ cm}^{-2}$. The values we obtained bear large uncertainties but indicate a decrease of the noise by about 30 % when cooled from +22 to -10°C .

- **FE-I4 activity**

The FE-I4 houses much digital circuitry that could influence the performance of the sensor. We measured an increase of the noise by about 20 % when the FE-I4 was active with respect to the value when the FE-I4 was switched off. The threshold increases by less than 10 %. This effect is probably due to the temperature increase introduced by the power consumption of the FE-I4. Although the ambient temperature was at the same value of $+22^\circ\text{C}$ the FE-I4 heated up

¹⁵ See Section 4.5.1 for a detailed description of the calibration procedure.

to about $+37^{\circ}\text{C}$ when active.⁽¹⁶⁾ There was no direct cooling nor temperature sensors on the CCPD implemented. Future samples should include both functions to ensure exact control and measurement of the sensor temperature.

- **CCPDv1 vs. CCPDv2**

Within the uncertainty there is no difference between the noise of the CCPDv1 and CCPDv2 before irradiation.

¹⁶ This was measured with an infrared camera and has to be regarded as an approximate and local value on the FE-I4 surface.

TABLE 4.9: Settings and results for the threshold and noise measurements explained in the text. Measurements with different samples are separated by horizontal lines. The column captions have the following meaning:

v.	version of the CCPD									
Φ	fluence which the sensor has been exposed to									
T	ambient temperature									
FE-I4	status of the FE-I4 during the measurement									
TH	global threshold voltage									
threshold	measured input referred threshold									
σ_{ENC}	measured input referred noise									
ROI	region of interest (addresses of rows and columns & total number of pixels)									
bad pixels	number of pixels where the S-curve fit failed (number of hot or dead pixels)									

v.	Φ ($\text{n}_{\text{eq}} \text{cm}^{-2}$)	T ($^{\circ}\text{C}$)	FE-I4	TH (mV)	threshold (mV)	σ_{ENC} (mV)	ROI			bad pixels
							row	col	pixels	
v1	0	+22	off	846	69 ± 5	10.6 ± 1.5	0	0–47	48	6
v1	0	+22	off	856	99 ± 5	11.5 ± 1.6	0	0–47	48	2
v1	0	+22	off	867	131 ± 6	11.9 ± 1.8	0	0–47	48	0
v1	1×10^{15}	–10	off	991	166 ± 19	15 ± 3	0–23	34	24	0
v1	1×10^{15}	+22	off	991	200 ± 10	22 ± 5	0–23	34	24	0
v2	0	+22	on	855	120 ± 12	13 ± 3	0–23	29	24	4
v2	0	+22	off	855	113 ± 14	11 ± 4	0–23	29	24	5

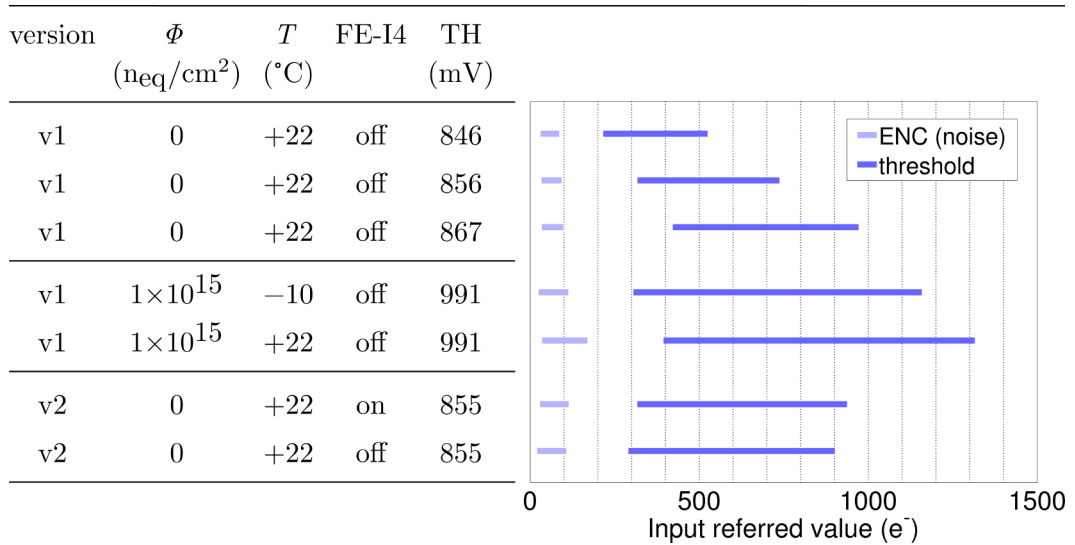


FIGURE 4.21: Settings and results for the threshold and noise measurements as is described in Table 4.9. The units of the threshold and noise are converted into e^- as is described in the text. The bars represent the range of the measured values, including uncertainty.

4.4.6 Tuning

In order to get maximum hit efficiency and lowest noise hit rate for the pixel matrix, the threshold dispersion has to be minimized. This is done by setting the threshold for each pixel adequately. First, the global threshold is set by the external voltage TH. The difference between TH and the baseline voltage BL is the threshold voltage for the discriminator. It is equal for all pixels. Second, small corrections to the global setting can be applied by choosing a value for the 4-bit TDAC for each pixel. In our configuration software HV2FEI4ctrl (see Section 4.3.2) a value of 15 does not influence the global threshold voltage. Lower values decrement the global threshold voltage by an amount that depends on ThRes and VNDAC (see Section 4.2.2.2).

4.4.6.1 Procedure and measurements with the CCPDv1

There exist different tuning procedures for the pixel thresholds. HV2FEI4ctrl has a procedure implemented that is based on the input referred threshold. The TDAC value is the independent parameter that is changed until the measured threshold is within a certain distance to a given target threshold.

Figure 4.22 shows the threshold distributions of different tunings of a CCPDv1. The ROI (region of interest) includes all rows (0–23) and columns 12–48 which amounts to 864 pixels. Comparing the distribution from the untuned sensor to the distribution with a target value of 219 mV, we notice that the tuning successfully shifts μ_{Dist} (the mean of the distribution) to the target value within 5%. However, σ_{Dist} (the threshold dispersion

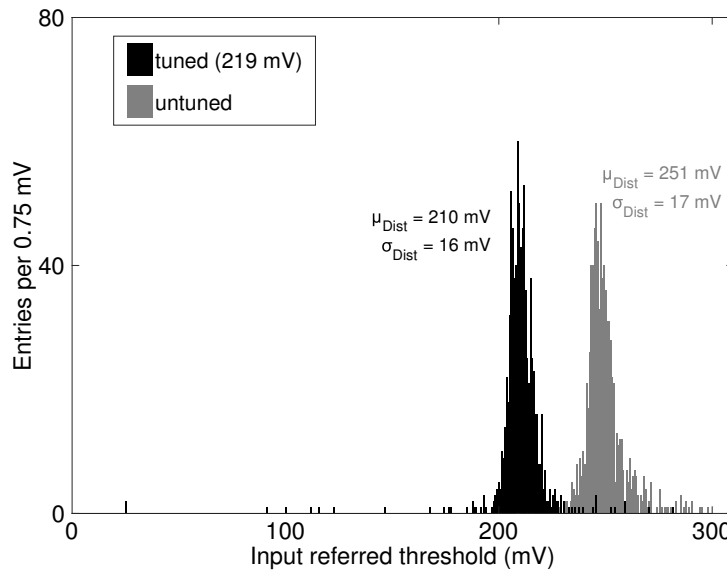


FIGURE 4.22: Threshold distributions of different tunings of a CCPDv1. The ROI comprised 864 type-A pixels. The distribution on the right represents an untuned sensor. The distribution on the left represents a tuned sensor with a target threshold of 219 mV. The mean (μ_{Dist}) and standard deviation (σ_{Dist}) are given for each distribution.

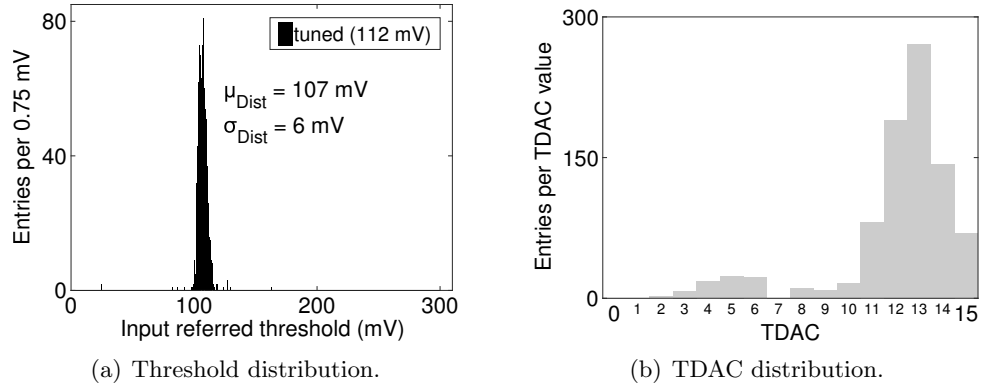


FIGURE 4.23: Threshold and TDAC distributions for a tuning of a CCPDv1 with a target threshold of 112 mV. The ROI comprised 864 type-A pixels.

expressed by the standard deviation of the distribution) does not change significantly. This has two reasons:

First, we observed that the threshold depends on the row number (see Section 4.4.5). The threshold is lowest for row 0 and increases toward row 23. Taking all pixels into account like it is done in Figure 4.22 increases the threshold dispersion. We calculated σ_{Dist} for each row separately and found that the tuning lowers the threshold dispersion on average by 34 %. Taking the whole ROI into account, this value is only 6 %.

Second, the tuning procedure is not optimized. Figure 4.23(b) shows the TDAC distribution for a tuning of the same sensor with a target threshold of 112 mV. It can be regarded as the distribution of the local threshold corrections from the pixels. The distribution shows two populations with one of them being placed near the upper limit of the TDAC range. A good tuning would show one distribution centered around the middle. This means that the tuning procedure does not find the optimum values for TH, ThRes, VNDAC and subsequently for the TDAC. Nevertheless, this was one of the lowest tunings that we achieved, yielding $\mu_{\text{Dist}} = 107 \text{ mV}$ and $\sigma_{\text{Dist}} = 6 \text{ mV}$ for the threshold distribution shown in Figure 4.23(a). With the calibration done as is described in Section 4.4.5.2, this corresponds to a mean between 361 and 759 e^- and a dispersion between 20 and 43 e^- .

4.4.6.2 Improvements

Clearly, the tuning procedure has to be improved. First, the S-curve analysis that is implemented in HV2FEI4ctrl is not as well developed as the one we presented in Section 2.4.3.6 and used in Section 4.4.5. We have started to incorporate our detailed S-curve analysis into the tuning procedure. Second, a comprehensive tuning procedure should include the global parameters TH, ThRes and VNDAC as free parameters. However, this and further development of the tuning procedure is beyond the scope of this work. Other groups in the collaboration continued building on our work. Results can be found,

e.g., in [172].

Except for test functions, the CCPD only provides binary information about a hit in a pixel (hit/no hit) and no information about the amount of charge collected. Therefore the tuning of the thresholds to a desired absolute value is not as crucial as in the case of a sensor that delivers charge information. That is why we believe that an alternative tuning procedure based on the noise edge of each pixel is more adapted for the CCPD. We observed large crosstalk and voltage drop problems when using injections, especially with the CCPDv1. A noise tuning avoids injections: the threshold is scanned for each pixel to determine the value of the noise edge. The local threshold is then set to a value just above this edge. Such a tuning was successfully applied to several CCPDv2 sensors, allowing for subsequent testbeam measurements showing homogeneous detection efficiency close to 100 % across large areas of the pixel matrix.^[173]

Furthermore, improvements of sensor test systems will be beneficial for the tuning. As mentioned in Section 4.3.2 there are ongoing efforts to incorporate the CCPD sensor-family to the USBpix system which will provide well developed tuning procedures that are already in use for the FE-I4.

4.4.7 FE-I4 readout

The focus of the CCPD design lies in compatibility with the FE-I4 readout chip and the main novelty is the capacitive coupling via a glue interface. We have successfully assembled and operated complete detector prototypes: Particles from a radioactive source and from particle accelerators were detected by the sensor and read out by the FE-I4 that was glued onto it. In this section we describe the gluing procedure and first experience with the FE-I4 readout.

4.4.7.1 The glue interface

Little experience about gluing sensors was available when we started assembling prototype detectors. We identified the following main issues when it comes to developing the gluing method:

- A distance between the sensor and the readout chip that is below 10 μm and homogeneous.
- Mechanical stability.
- Chemical stability.
- Radiation tolerance.

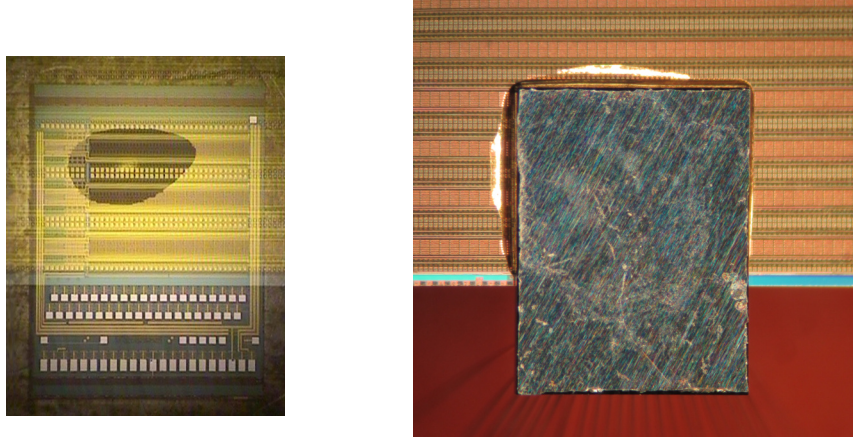


FIGURE 4.24: Gluing of a CCPDv4 onto a FE-I4. On the left the sensor and read-out chip seen through the optics from the die-bonder for alignment just before gluing (adapted from [151]). The image of the CCPD is mirrored and the structures of the FE-I4 are only slightly visible outside the area covered by the CCPD. The dark spot is the applied droplet of glue (in this case it was the glue UHU[®] Endfest 300).^[175] On the right the cured and wire-bonded sample, i.e. a fully assembled capacitively coupled particle detector, is shown. The reflection of the excess glue and the structure of the FE-I4 pixel matrix are well visible.

- Aspects for large-area production and long-term use: reproducibility, reliability and industrialization.

First tries in the collaboration included different glues, methods for dispensing and curing as well as adhesive foil. Systematic tests were conducted with sensor dummies and glass plates on different machines to identify the most suitable procedure. Layer thicknesses down to several μm and a lateral alignment accuracy of $\approx 1\mu\text{m}$ were achieved with commercial die-bonders (see Section 4.3.1.2, [151] and [150]). With the gained experience the production of many samples was possible (see Figures 4.24 and 4.25). However, to qualify the procedure for production for HL-LHC uses, the issues listed above have to be addressed in detail. This is not part of this work. First results of the research on gluing can be found in [142] and [174]. Close collaboration with industry is ongoing to explore industrialization of the process.

4.4.7.2 Source measurements

We assembled several CCPDv1s into fully capacitively coupled pixel detectors with FE-I4 readout. They were operated with UXiBo, USBPix, HV2FEI4ctrl and STcontrol as is described in Section 4.3. We could demonstrate particle detection with an unirradiated sample and a sample irradiated to $1 \times 10^{16} \text{ n}_{\text{eq}} \text{ cm}^{-2}$. For this we exposed the samples to a ^{90}Sr -source. Figure 4.26 shows the response of the FE-I4 during exposure recorded with STcontrol. It shows the occupancy plot of the FE-I4, which is a schematic of the

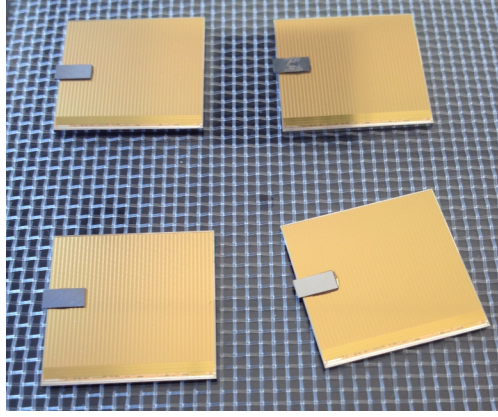


FIGURE 4.25: Several CCPDv2s glued onto FE-I4s before wire bonding.

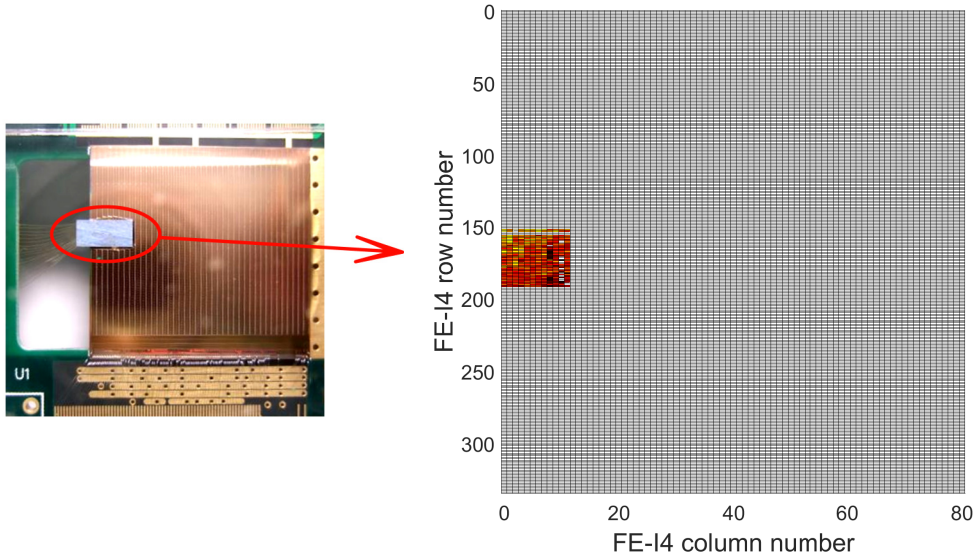


FIGURE 4.26: A prototype particle detector proving the capacitive coupling of the CCPD to the FE-I4 to work. On the left, an unirradiated CCPDv1 glued onto a FE-I4. On the right, the corresponding FE-I4 occupancy plot showing the response to exposure to a ^{90}Sr -source. Only the pixels that are coupled to the sensor recorded particle hits.

FE-I4 pixel matrix with each pixel colored according to the number of recorded hits in the pixel. The position of the CCPD in the pixel matrix can clearly be seen; no hits were recorded outside this region. Figure 4.27 shows a zoom of the same occupancy plot. The source was placed on the top left of the sensor, which resulted in an increased occupancy in this corner. The threshold settings and parameters for both the FE-I4 and the CCPD were set so that no hits were detected when the source was shielded. Pixels that constantly fired (hot pixels) and dead pixels were identified and masked by dedicated scans of STcontrol. Those pixels are black in the zoomed occupancy plot. The FE-I4 was set to self-trigger mode.

This first measurement proved the concept of the CCPD in conjunction with the FE-I4 to work. More detailed measurements were done with the highly irradiated sample in

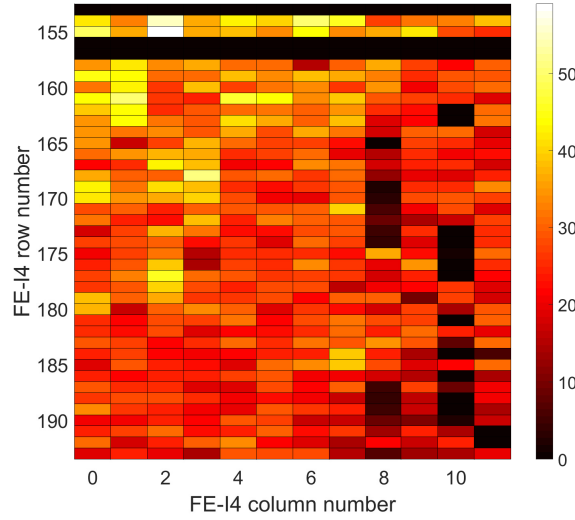


FIGURE 4.27: Detail of the occupancy plot shown in Figure 4.26. It is one of the first images of a radioactive source taken with the CCPD and FE-I4 glued together to form a capacitively coupled pixel detector. The source was placed on the top left of the sensor which is clearly visible in the plot. The colors represent the number of hits in each readout pixel as is depicted in the colorbar to the right.

an enhanced setup: Instead of the self-trigger mode a scintillator and a photomultiplier tube were used for external triggering of the readout. Figure 4.28 shows the occupancy plot of the FE-I4 region that was covered by the CCPD for this measurement. Again, the FE-I4 detected no hits outside this region. In addition the level-1 trigger distribution is shown. This histogram is filled with the measured time periods between a hit signal in the FE-I4 and its corresponding trigger. A distinct peak is visible on a flat background. This verifies that we detected particles stemming from the radioactive source. The sensor threshold was set to a global value where the noise occupancy in the FE-I4 was below 1×10^{-9} and hot and dead pixels were again masked. Later measurements with only then available improved control software for the sensor showed that the optimum threshold level lies lower than the level used for this source measurement. Also, no tuning of the sensor was performed because it was not available at that time. The non-ideal threshold setting caused the sensor to most probably only detect particles from the low-energy range of the source's spectrum. These particles deposit more energy than the rest of the spectrum, resulting in an excessive tail of the Landau distribution.⁽¹⁷⁾ This assumption is reinforced by the very low event rate of below 10 Hz for the sensor compared to several hundred Hz for the same scintillator area. Nevertheless, the result of this measurement is a very important one due to two reasons:

- Not only did we prove a clear signal from particles but it was done with a sensor that had been irradiated to $1 \times 10^{16} \text{ n}_{\text{eq}} \text{ cm}^{-2}$ prior to the measurement. This is an important step toward radiation hardness at HL-LHC fluences.

¹⁷ See Section 2.4.1.2 for the theoretical discussion.

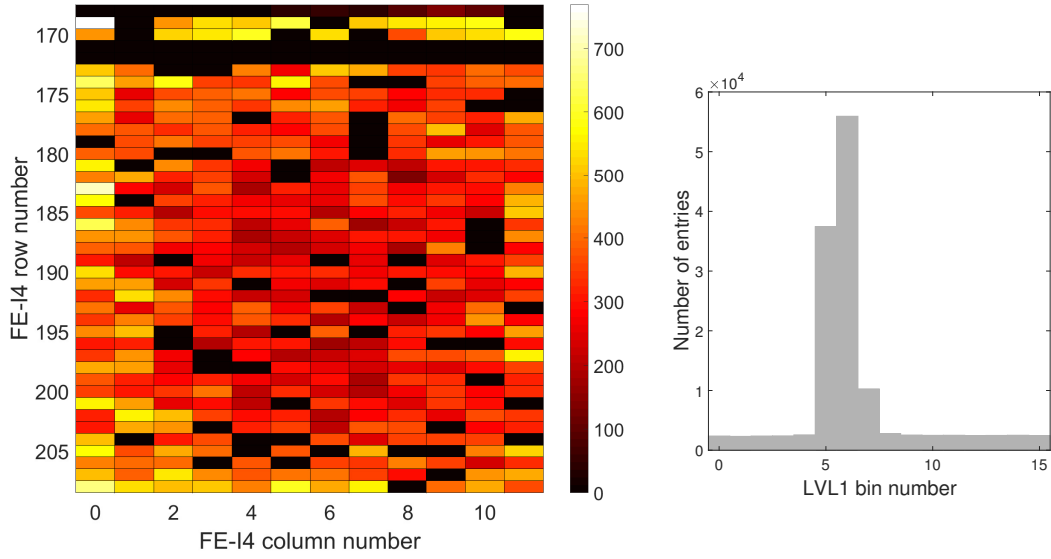


FIGURE 4.28: Occupancy plot (left) and its level-1 trigger distribution (right) of a FE-I4 that was capacitively coupled to an irradiated CCPDv1 and exposed to a ^{90}Sr -source. This CCPDv1 had been irradiated to an particle fluence of $1 \times 10^{16} \text{ n}_{\text{eq}} \text{ cm}^{-2}$ prior to the measurement. The sensor was biased with -20 V and its temperature was approximately $+37^\circ\text{C}$. The peak in the level-1 trigger distribution is the proof that particles stemming from the radioactive source were detected.

- The ambient temperature during the measurement was $+22^\circ\text{C}$. The sensor temperature was about $+37^\circ\text{C}$ due to the power dissipated by the running FE-I4, which was measured with an infrared camera. This means that the sensor is capable of particle detection at room temperature and above even after irradiation and does not require cooling per se. This could lead to significant simplifications in the cooling requirements for large-area detector systems.

4.4.7.3 Subpixel encoding

The output signals of three sensor pixels (called subpixels in the context here) are summed and coupled to one readout pixel. This encoding of the subpixel address in the signal is explained in Section 4.2.3. Figure 4.29 shows the ToT-histogram of one FE-I4 readout pixel after exposure of the unirradiated CCPDv1 to the ^{90}Sr -source. There are clearly three distinct peaks visible, each of them corresponding to one of the three subpixels routed to the readout pixel. The concept of the address encoding is thus proven to work. However, we had to tune the three sensor pixels and the FE-I4 pixel by hand to be able to show the encoding. This is due to the fact that no automatic communication between the sensor control system and the readout system was implemented. As explained above, the USBpix readout system has recently been extended to include sensor controls and automated tuning of more than one pixel can

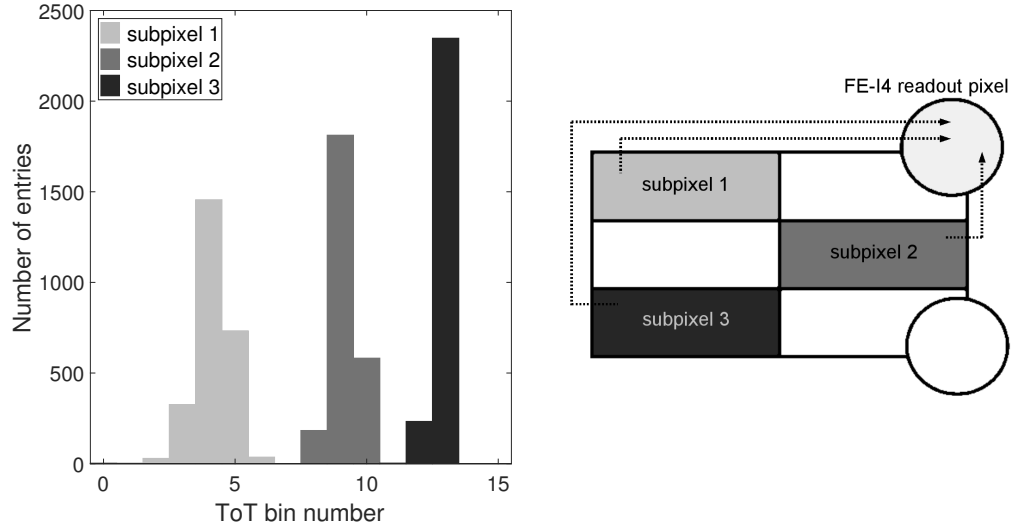


FIGURE 4.29: Measured subpixel encoding of the sensor pixel address. On the left, the ToT-spectrum of one FE-I4 pixel shows three distinct peaks corresponding to the three sensor pixels connected to the readout pixel. The FE-I4 was tuned so that a ToT-value of 6 corresponds to a charge signal of $10\,000\,e^-$ and the threshold target was $4000\,e^-$. The amplitudes of the output stages of the three subpixels were set to $VNOut0 = 2$, $VNOut1 = 4$ and $VNOut2 = 20$. On the right the schematic of the pixel routing is shown as a reminder. No neighboring sensor pixels share the same readout pixel in order to prevent corruption of the sub-pixel encoding due to charge sharing.

be achieved. This is not covered by this work.

It is important to mention that the tuning is not only essential for the optimum setting of the threshold values to achieve good efficiency and noise figures but can also compensate potential assembly errors. [176] measured the ToT-values of the whole pixel matrix of a CCPDv1 when the output stages of the sensor were all set to the same value. The ToT-distribution was not centered around a mean value, but showed a linear dependency on the column number. This was the result of an inhomogeneous glue thickness; the sensor was glued at an angle to the FE-I4. A comprehensive tuning procedure can to a certain extent compensate for such errors.

4.4.8 Leakage current

The leakage current of a sensor is an important value because it affects the noise level and it can lead to thermal runaway or amplifier saturation of the sensor. Especially after irradiation, when the leakage current is increased due to damage in the sensor, it has to be understood well (see Sections 2.4.3.2 and 2.4.5.2). We measured the leakage current driven by the bias voltage at different temperatures with CCPDv1s irradiated with thermal neutrons to different particle fluences. During the measurements neither the sensor nor the attached FE-I4 were powered. The dissipated electrical power was not enough to heat up the detector significantly. Therefore no thermal runaway occurred and the measured ambient temperatures represent the sensors' temperatures well. This

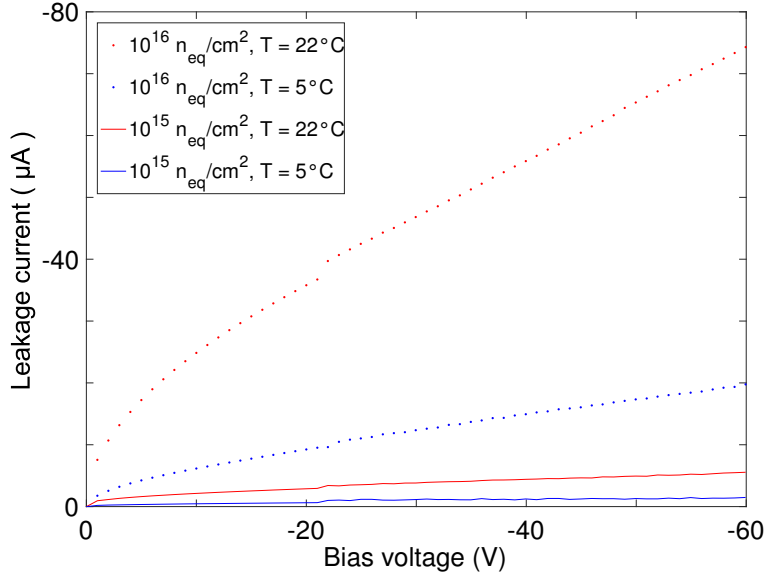


FIGURE 4.30: Leakage current of two CCPDv1s depending on temperature (T) and received particle fluence. The measurement errors add up to $1\ \mu\text{A}$ and $0.1\ \text{V}$ respectively. Temperatures are accurate to $0.2\ ^\circ\text{C}$. The kink at around $-22\ \text{V}$ is caused by the change of the measurement range of the instruments.

was confirmed with an infrared-camera.

The recorded I-V curves for two CCPDv1s are shown in Figure 4.30. The maximum leakage current was drawn at the warmer temperature of $22\ ^\circ\text{C}$ by the sensor that was irradiated to the maximum of $1 \times 10^{16}\ \text{n}_{\text{eq}}\ \text{cm}^{-2}$. At $-60.0 \pm 0.1\ \text{V}$ it reached $-74 \pm 1\ \mu\text{A}$. This corresponds to $1.25 \pm 0.02\ \text{mW}\ \text{cm}^{-2}$ for the active sensor area. The sensor irradiated to only $1/10$ of the fluence ($1 \times 10^{15}\ \text{n}_{\text{eq}}\ \text{cm}^{-2}$) shows a leakage current about 13 times smaller.

Currents drawn at $22\ ^\circ\text{C}$ were about 4 times larger than at $5\ ^\circ\text{C}$, which translates into doubling the current approximately every $8.5\ ^\circ\text{C}$. This behavior is in good agreement with the theoretical behavior of bulk leakage current (see Equation 2.19). We can therefore attribute the increase of the leakage current to the irradiation damage of the bulk. The leakage current for the unirradiated sensor was below the detection limit of the setup that we used for this measurement, which was $25\ \text{nA}$.

The measurements with the CCPDv1s were done with fully assembled detector samples up to a voltage limit of $-60\ \text{V}$. This is already in excess of the limit specified by the manufacturer, which is $-50\ \text{V}$. We did not increase the voltage further in order to not destroy the samples, which were very limited in number for the CCPDv1. After gaining experience with the later generations and enhancing the setup by a probe station, we were able to characterize the sensors up to the electric breakdown limit. Figure 4.31 shows the I-V curves of twelve bare and unirradiated CCPDv4s. All of them show the typical rapid increase of the leakage current before electric breakdown at around $-90\ \text{V}$. This is almost twice as high as the limit given by the manufacturer.

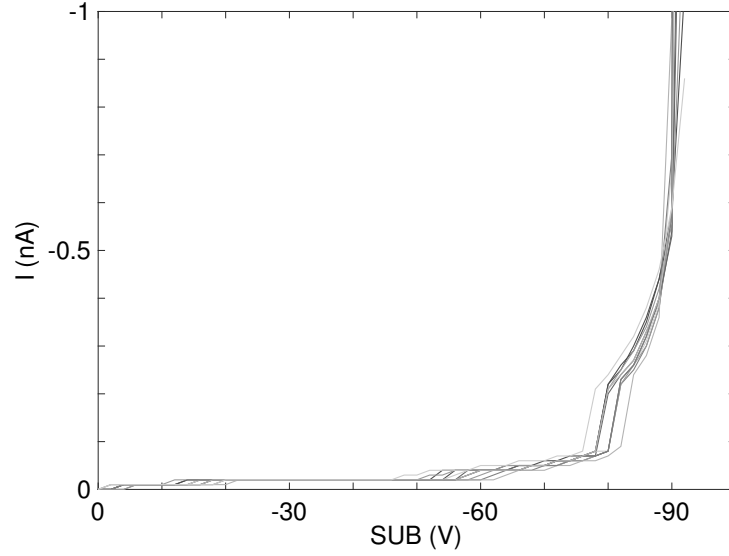


FIGURE 4.31: I-V curves of twelve bare and unirradiated CCPDv4s. The electric breakdown limit is clearly visible at around -90 V. The measurement errors add up to 0.07 nA and 0.14 V respectively. The kink at around -80 V is caused by the change of the measurement range of the instruments.

The I-V curves were obtained by connecting only the ground and bias voltage wire-bond pads via a probe station. When connecting the other supply voltages necessary for sensor operation we sometimes observed a dramatic change in the leakage current. When this happened the leakage current was out of the $1\text{ }\mu\text{A}$ -range of the ammeter. We could not identify the source of this malfunction and assume a susceptible electronic component within the sensor electronics to be responsible for it. Sensors showing this behavior were rejected for further sample assembly. This peculiarity shows that it is absolutely necessary to perform basic function tests of all bare sensors before admitting them to further characterization or assembly.

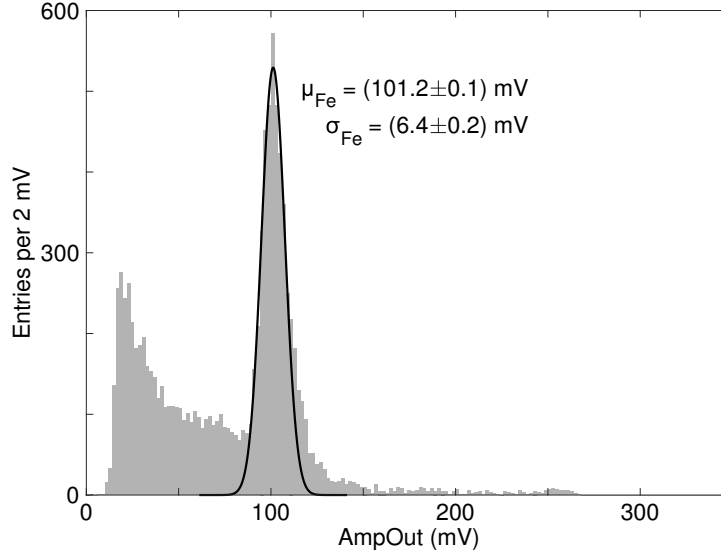


FIGURE 4.32: Spectrum of the ^{55}Fe -source obtained with the CCPDv4 irradiated to $3.5 \times 10^{13} \text{ p}^+ \text{ cm}^{-2}$. The bias voltage was set to -80 V . The K_{α} -peak is well visible and fitted with a Gaussian. The mean μ_{Fe} and standard deviation σ_{Fe} of the Gaussian are used to determine the conversion factor for transformation of the AmpOut values (in mV) to charge (in e^-). The ^{55}Fe -spectrum was measured and fitted for each sensor and each bias voltage for the testbeam measurements.

4.5 Charge collection studies

The most probable amount of charge that is collected when a MIP traverses the sensor is a very important figure. Together with the threshold value and efficiency it forms a criterion for the sensor's suitability for particle detectors in HEP.

In this section we present charge collection studies on unirradiated and irradiated CCPDs obtained with a ^{90}Sr radioactive source and with testbeam campaigns. The measurement and analysis methods are described and further sensor characteristics are deduced from the results.

4.5.1 Calibration with iron-55

In order to get absolute values for the charge, calibration measurements were done with ^{55}Fe . In silicon, the soft X-rays from this source result in a peak in the spectrum of the collected charge centered around $1615 e^-$ (see Section 2.4.3.5 for details on this). The width of the peak corresponds to the charge resolution of the sensor and its readout system. Figure 4.32 shows a calibration measurement performed with a CCPDv4. With the iron peak's mean value μ_{Fe} in mV and measured with AmpOut, the charge conversion factor

$$k_c = \frac{1615 e^-}{\mu_{\text{Fe}}} \quad (4.1)$$

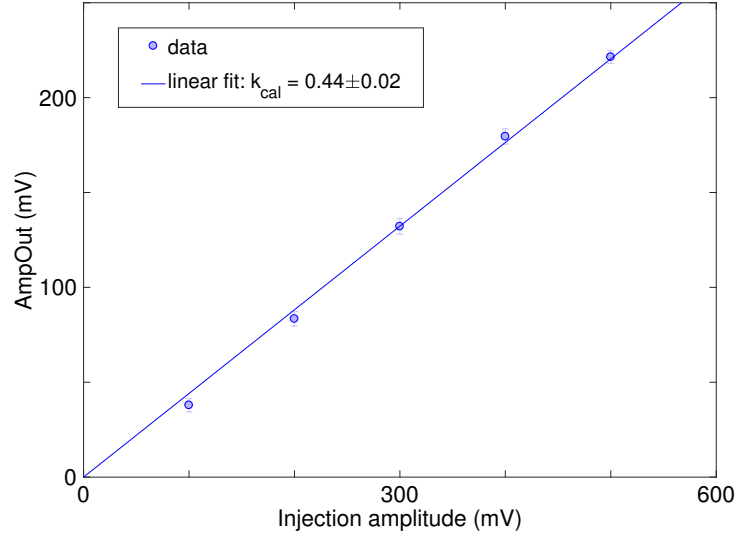


FIGURE 4.33: Response of AmpOut to injections with different amplitudes for the CCPDv4 irradiated to $3.5 \times 10^{13} \text{ p}^+ \text{ cm}^{-2}$. The bias voltage was set to -80 V . The data are fitted with a linear function through the origin. The slope of the fit, here k_{cal} , is used for the scaling of the charge conversion factor. For this, the slope is determined with the same setup and settings that are used for the ^{55}Fe -calibration measurement (k_{cal}) and for the setup used in the experiment (k_{exp}). This was done for each sample and bias voltage separately.

is calculated. If AmpOut responses linearly with the input, this factor can be used over the whole range of AmpOut. To check the linearity we used the injection function of the sensor. Figure 4.33 shows the response of AmpOut to different injection amplitudes. We observed linearity with all sensors and settings that we used and applied, respectively. The injection measurements are also used to scale k_c . This is necessary when the calibration cannot be done in the same setup than the experiment itself. Differences in the setup, in the settings of the sensor and readout or different environmental conditions like temperature require this scaling. The scaling factor between the experimental setup and the calibration setup is the ratio of the slopes k_{cal} and k_{exp} derived from the fit to the injection data like it is done in Figure 4.33. This leads to the conversion from the measured value of AmpOut in mV to the collected charge C_c in electrons:

$$C_c = \text{AmpOut} \cdot \frac{k_{\text{cal}}}{k_{\text{exp}}} \cdot k_c \quad (4.2)$$

During the calibration measurements we noticed a significant dependency of k_c on the bias voltage of the sensor as is shown in Figure 4.34. It can be explained by the change of detector capacitance with the bias voltage. The detector capacitance decreases when the depletion zone is increased by the applied bias voltage. The gain of the preamplifier is inversely proportional to the detector capacitance, resulting in a larger output signal for the same input charge when the bias voltage is increased. This change is less pronounced or even suppressed for largely or fully depleted sensors. For the CCPD however, it can not be neglected because the depletion zone is small and shows a large relative change

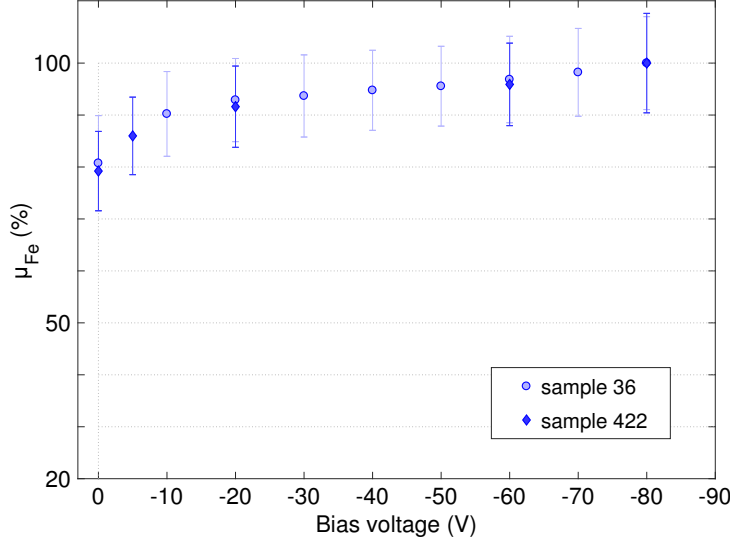


FIGURE 4.34: Relative values of the ^{55}Fe -peak measured with AmpOut versus the bias voltage obtained with the CCPDv4 irradiated to $3.5 \times 10^{13} \text{ p}^+ \text{ cm}^{-2}$ (sample 36) and an unirradiated CCPDv4 (sample 422). A significant dependency on the bias voltage is apparent for both samples. For this reason the calibration measurements have to be performed for each voltage step separately.

within the range of the bias voltage.

The testbeam measurements with the CCPDv4 presented in Section 4.5.3 were done with standalone sensors in our lab, including the conversion and scaling for each value of the bias voltage separately. For the measurements with the CCPDv1 and CCPDv2 that are presented in the next section and in Figure 4.21 we relied on calibration measurements by colleagues at other institutes. We did not have any working standalone sensors; they were all glued onto the FE-I4 which obscured the front side of the AmpOut-pixel. The pixel was therefore effectively shielded from the soft X-rays from the iron source by the silicon of the FE-I4 (front side) and of the sensor bulk (back side).

4.5.2 Source measurements with strontium-90

As we explain in Section 2.4.1, MIPs passing a silicon sensor cause charge signals following a Landau-distribution. The MPV of this distribution is a good instrument to characterize and compare different sensors.

We recorded the spectrum of a ^{90}Sr -source with a CCPDv1 that was neutron irradiated to $1 \times 10^{15} \text{ n}_{\text{eq}} \text{ cm}^{-2}$. It was obtained by measuring the maximum of the single pulses with an oscilloscope. Figure 4.35 shows the spectrum with a Landau-fit applied to the data outside the noise region. We measured a MPV between 67 and 72 mV. Using the conversion factor from a calibration measurement this corresponds to 1100 to 1190 e^- . The same measurement with an unirradiated CCPDv1 by colleagues yielded a value of about 1600 e^- . This reduction of the total signal between 26 and 31 % can be explained by reduction of the diffusion part of the signal caused by bulk defects (see Section 2.4.5).

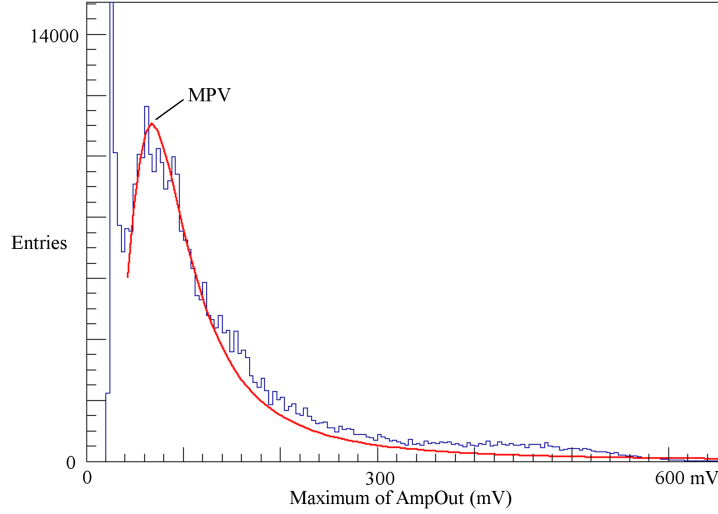


FIGURE 4.35: In blue the spectrum of a ^{90}Sr -source recorded with a CCPDv1 that was neutron irradiated to $1 \times 10^{15} \text{ n}_{\text{eq}} \text{ cm}^{-2}$. In red the fit of the Landau distribution to the data. The bias voltage was set to -55 V and the ambient temperature was $+5^\circ \text{C}$. The MPV lies between 67 and 72 mV.

Taking the noise level into account we obtain a minimum SNR of 23.

At large amplitudes the measured spectrum shows more entries than expected from the Landau distribution. This is due to the spectrum of the ^{90}Sr -source, which includes low-energy electrons (see 2.4.1.2 for the theory). More accurate measurements can be achieved by using a scintillator as trigger or using a testbeam where all source particles are MIPs. For the CCPDv4 we conducted a testbeam campaign. The results are presented in the next section.

4.5.3 Testbeam campaign

We showed that the CCPDv1 works after irradiation to $1 \times 10^{16} \text{ n}_{\text{eq}} \text{ cm}^{-2}$ (see Section 4.4.7.2). With the CCPDv4 we undertook a more comprehensive measurement campaign. One CCPDv4 sensor was irradiated with protons to $(1.8 \pm 0.5) \times 10^{13} \text{ n}_{\text{eq}} \text{ cm}^{-2}$ and then characterized using particles from a testbeam.⁽¹⁸⁾ An unirradiated CCPDv4 was also characterized for comparison. In this section we refer to these two samples as the unirradiated and irradiated one. The intention of the campaign was to determine the MPV from MIPs passing the sensor and deduce important sensor properties from the results. For this we placed the sensors as DUTs⁽¹⁹⁾ in the AIDA SBM-telescope which was mounted in line with the $180 \text{ GeV } c^{-1}$ charged hadron beam in the CERN North Area. The telescope delivered the trigger information to the DRS4 with which we recorded the corresponding DUT signals. The raw information was saved and analysis

¹⁸ We initially planned a higher irradiation, see Section 4.3.5.2.

¹⁹ In the context of testbeam measurements with a telescope it is less ambiguous to use the term DUT (Device Under Test) instead of sensor.

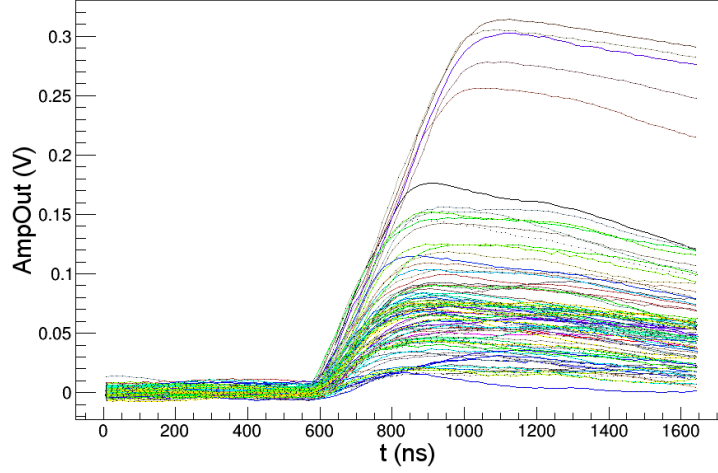


FIGURE 4.36: A set of particle signals recorded with the DRS4 after applying the first three cuts listed in the text. These signals are passed on to the track reconstruction software for further analysis.

was done offline. Details about the particle beam and the setup can be found in Section 4.3.3. The calibration measurements were done in our laboratory as is described above in Section 4.5.1.

4.5.3.1 Most probable energy deposition

AmpOut is accessible only for one single sensor pixel at a time in the CCPDv4. For this reason we had to perform “single pixel measurements”. The small pixel area of $33 \times 125 \mu\text{m}^2$ resulted in a low event rate in the DUT. Even when selecting a very small ROI in the telescope planes, only less than 1 % of the triggers resulted in a particle signal in the DUT. Therefore we had to apply effective cuts on the DUT data to determine the DUT-hits:

1. Only the signal after 500 ns is taken into account for analysis.
2. Only signals that show a slope of more than +5 mV in a running 50 ns-window are selected.
3. Only signals where the baseline corrected maximum is larger than 20 mV are selected. This limit corresponds to 270 to 480 e^- , depending on the sample and bias voltage.

Figure 4.36 shows a set of particle signals from the DUT after applying the first three cuts. These and the rest of the remaining signals are regarded as DUT-hits and the corresponding telescope events were subsequently fully analyzed. This includes calculation of track residuals in the DUT-plane. The track residual is the distance of the reconstructed particle track to a certain point in the DUT-plane, ideally the center of

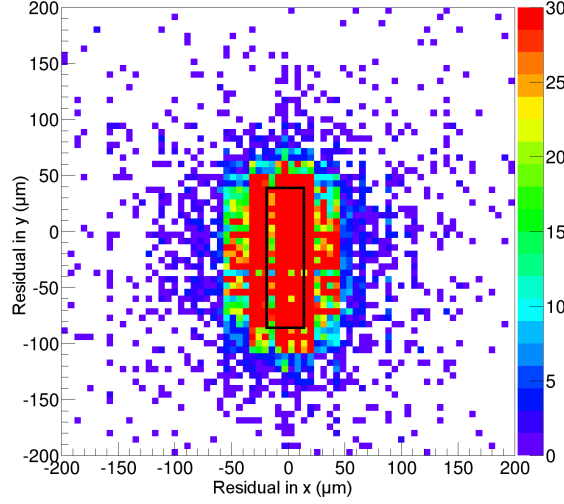


FIGURE 4.37: Visualization of the track residuals in the DUT-plane. The number of residuals at each point is color-coded. The values of the residuals can be regarded as local x and y -coordinates used by the track reconstruction software. Their respective mean values are used to calculate the position of the pixel, depicted as the black box in the center.

the pixel. Figure 4.37 shows the number of residuals versus their position in the DUT-plane for the unirradiated CCPDv4 biased with -80 V. The calculated position of the pixel is marked. No hit information of other pixels is available, because of the single pixel measurement. Therefore any hits that passed the first three cuts are contributed to this single pixel, even if their reconstructed position is outside the calculated pixel area. If the signals of neighboring pixels were available, a comparison of the signals would certainly attribute these hits to other pixels. There are several reasons why the single pixel is sensitive to particle hits outside its own pixel volume:

- Diffusion causes free charge carriers to travel in any direction. This results in the diffusion part of the signal that we discuss in Section 2.4.2. It is relatively slow and low in amplitude. It stems from outside the depletion regions in the sensor and can travel in the bulk silicon across many pixels. The time window after each trigger where the DUT is sensitive to hits is approximately $1\text{ }\mu\text{s}$ long. With relation 2.11 we therefore estimate most of the erroneous drift signals to come from less than $59\text{ }\mu\text{m}$ away from the single pixel. A smaller fraction will come from further away.
- The Shockley-Ramo theorem tells us that charge moving toward and collected by a certain electrode will induce a current signal in the neighboring electrode. This induced current signal changes sign over time and no net charge signal is detected if the integration time is large enough (see Section 2.4.2.3 and Figure 2.16). In the real readout circuit this means that the input of the preamplifier has to act as a charge drain as well as a charge source. Our amplifier is not able to do the latter therefore only one part of the signal is detected, the integral does not cancel out

and a net signal is detected. This effect is significant only from nearest-neighbor pixels.

- The telescope’s resolution is approximately $8\text{ }\mu\text{m}$.^[159] This limits the accuracy of track detection and reconstruction.

If we want a “clean” Landau distribution that is not corrupted by the influence of neighboring pixels, we have to apply another cut to select only particle tracks within the pixel area. In addition, edge effects can be suppressed by applying an even more stringent cut to select tracks only from the central region of the pixel. The main effect that is avoided then is the passage of the particles through the depletion volume where the volume deviates from the “flat” shape and the scaling of the thickness with the square root of the bias voltage is corrupted. The shape of the depletion volume is shown in Figure 2.16.

For these reasons we apply a cut on the residuals: only tracks that lie within the central 25 % of the pixel area are taken into account for the charge collection analysis. The effectiveness of this cut can be seen in Figures 4.38 to 4.41. The first two figures show the detection time versus the signal amplitude for each hit in the DUT. On the left, no cut is applied on the residuals. On the right, the cut is applied. The plots show from top to bottom the results from

- the unirradiated and unbiased CCPDv4,
- the unirradiated CCPDv4 biased with -80 V ,
- the irradiated and unbiased CCPDv4 and
- the irradiated CCPDv4 biased with -80 V .

These plots confirm the considerations discussed above and reveal interesting information:

There are two populations of hits distinguishable in the data from the unirradiated and biased sensor (Figure 4.38(c)): one thin and long “cloud” on the bottom of the plot and a large “blob” toward lower amplitudes and later times (on the left in the plot). This blob remains more or less at its position when reducing the bias voltage, whereas the thin cloud moves its maximum to lower amplitudes. The latter can therefore be attributed to the particles passing the pixel whose signals comprise a minor diffusion and a dominant drift part. The drift part causes larger amplitudes at higher bias voltages because the depletion zone grows with the bias voltage. The blob on the other hand comprises the hits at the pixel edges whose drift part is already significantly reduced by the effect of the edge on the depletion volume. These signals are dominated by their diffusion part. In addition, diffusion signals from the substrate within and outside the pixel area may result in hits populating the blob. After applying the cut on the residuals (Figures

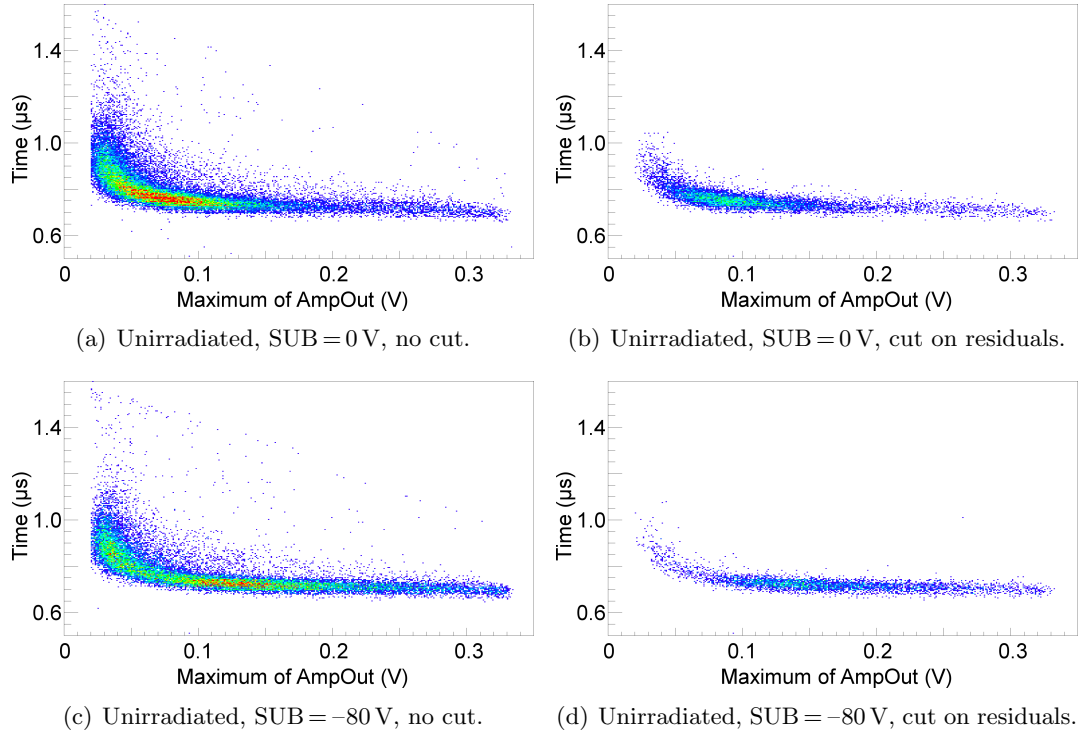


FIGURE 4.38: Detection time versus signal amplitude from the DUT-hits in the unirradiated sensor. For details see caption of Figure 4.39.

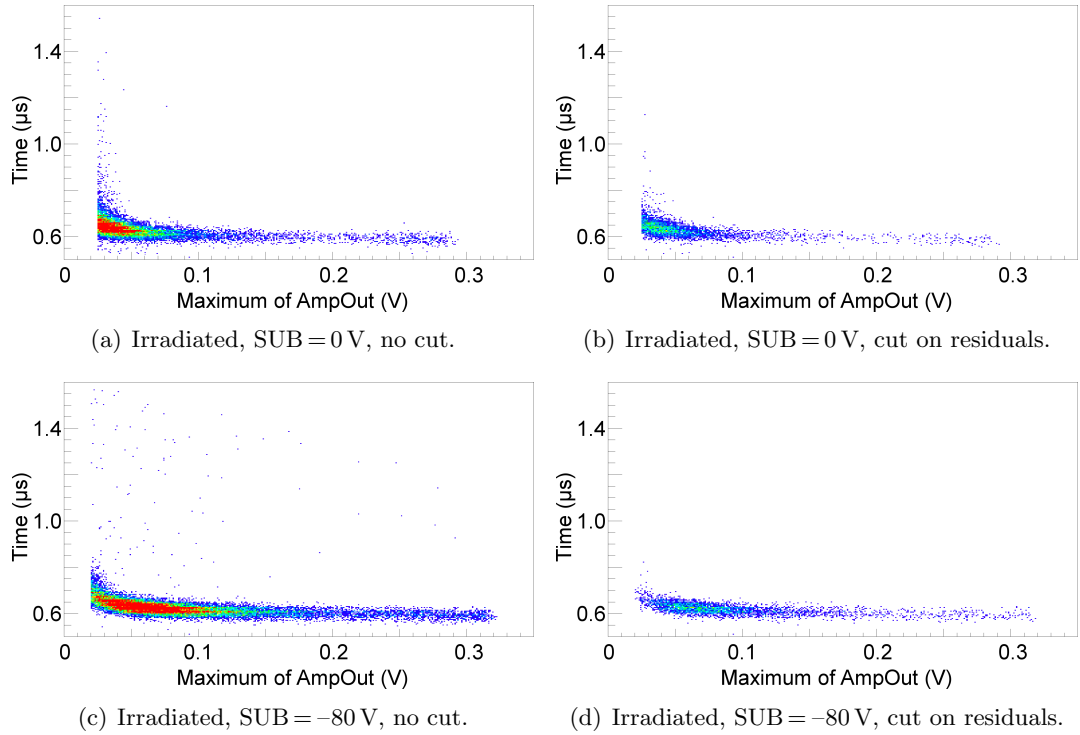


FIGURE 4.39: Detection time versus signal amplitude from the DUT-hits in the irradiated sensor. The number of entries is color-coded (blue: few entries, red: many entries). On the left, no cut is applied on the residuals. On the right, the cut on the residuals is applied. In the top row the sensor is unbiased and in the bottom row it is biased with -80 V. Details and discussion are given in the text.

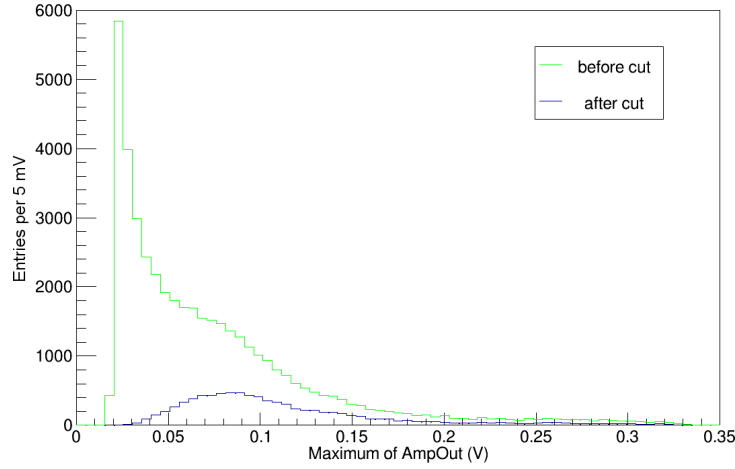


FIGURE 4.40: Distribution of the signal amplitudes for the unirradiated and unbiased sensor before and after applying the cut on the residuals. The meaningful distribution appears only after applying the cut. See Figure 4.41 for a zoom and the Landau fit.

4.38(b) and 4.38(d)) the blob mostly disappears whereas the thin cloud remains. This is necessary to even be able to fit the Landau distribution to the data, as can be seen in Figure 4.40. It shows the projection of the data of Figures 4.38(b) and 4.38(d) onto the x -axis, yielding the distribution of the signal amplitudes before and after the cut. The distribution before the cut has no clearly distinguishable peak in the region where the Landau fit makes sense. After the cut, the distribution appears sharply. Figure 4.41 shows the same distribution zoomed in and the fit of a Landau distribution convoluted with a Gaussian (Langau, see Section 2.4.1.1).

Figure 4.39 shows the plots for the irradiated sensor. Two facts are obvious: first, the thin cloud has its maximum at lower amplitudes than the unirradiated sensor. This can be attributed to the diffusion part of the signal which is diminished due to charge trapping at lattice defects (see Section 2.4.5). These defects are caused by the irradiation. The drift part is less sensitive to defects and remains largely intact. In total, the signal is smaller than before irradiation. Second, the blob is much less pronounced. Unfortunately it is hardly visible because the amplitudes where it sits are partly cut off by cut number 3 from the list given at the beginning of this section. The suppression of the blob is attributed to the missing diffusion signals. After applying the cut on the residuals, the cloud becomes clearer (Figures 4.39(b) and 4.39(d)) resulting in the distinct Landau distribution when projected onto the x -axis.

The track reconstruction of the testbeam data, calculation of residuals, applying the cuts and fitting was done for both samples at different bias voltages. Table 4.10 lists the obtained values including the results from the calibration.

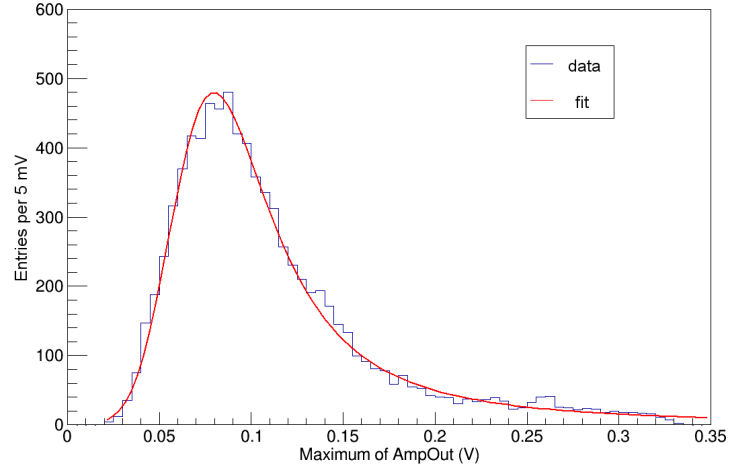


FIGURE 4.41: Distribution of the signal amplitudes for the unirradiated and unbiased sensor after applying the cut on the residuals. A Langau is fitted to the data. This fit yields the MPV corresponding to the most probable energy loss of a MIP passing the sensor.

TABLE 4.10: Results from the testbeam campaign. The calculated MPVs and data from the calibration are given. Sample 422 (the top 5 rows) is the unirradiated sensor and sample 36 (the bottom 9 rows) is the irradiated sensor. The column captions have the following meaning:

SUB	bias voltage
MPV	most probable value of the fitted Langau distribution
μ_{Fe}	mean of the iron peak of the calibration measurement
k_c	charge conversion factor (see Equation 4.1)
scaling factor	see explanation in Section 4.5.1

sample and SUB (V)	MPV (mV)	μ_{Fe} (mV)	k_c (e^-/mV)	scaling factor $k_{\text{cal}}/k_{\text{exp}}$	MPV (e^-)
422					
0	74.8 ± 6.1	83.1 ± 5.7	19.4 ± 1.3	1.04 ± 0.12	1508 ± 123
5	88.3 ± 5.4	90.2 ± 4.9	17.9 ± 1.0	1.02 ± 0.10	1616 ± 99
20	103.7 ± 5.6	96.1 ± 5.0	16.8 ± 0.9	1.02 ± 0.09	1771 ± 96
60	119.0 ± 5.6	100.6 ± 4.8	16.1 ± 0.8	1.02 ± 0.09	1939 ± 91
80	129.8 ± 8.0	104.9 ± 7.1	15.4 ± 1.0	1.03 ± 0.09	2049 ± 126
36					
0	24.2 ± 10.9	81.7 ± 7.7	19.8 ± 1.9	1.03 ± 0.05	498 ± 223
10	35.2 ± 6.4	91.3 ± 5.9	17.7 ± 1.1	1.03 ± 0.05	643 ± 117
20	37.8 ± 6.2	94.0 ± 5.5	17.2 ± 1.0	1.03 ± 0.05	672 ± 110
30	42.3 ± 5.7	94.8 ± 5.3	17.0 ± 1.0	1.03 ± 0.05	744 ± 100
40	45.9 ± 5.5	95.9 ± 4.9	16.8 ± 0.9	1.05 ± 0.06	808 ± 97
50	48.6 ± 5.3	96.7 ± 4.8	16.7 ± 0.8	1.03 ± 0.05	838 ± 91
60	51.1 ± 6.3	98.0 ± 5.7	16.5 ± 1.0	1.03 ± 0.05	869 ± 107
70	54.6 ± 6.2	99.4 ± 5.8	16.2 ± 0.9	1.03 ± 0.05	914 ± 104
80	56.5 ± 6.9	101.2 ± 6.7	16.0 ± 1.1	1.03 ± 0.05	930 ± 114

TABLE 4.11: Signal-to-noise ratio (SNR) for different bias voltages (SUB) for the unirradiated sensor (left) and the irradiated sensor (right).

SUB (V)	SNR	SUB (V)	SNR
0	69 ± 6	0	14 ± 6
5	86 ± 5	10	22 ± 4
20	111 ± 6	20	25 ± 4
60	127 ± 6	30	28 ± 6
80	138 ± 9	40	31 ± 4
		50	32 ± 4
		60	34 ± 4
		70	36 ± 6
		80	39 ± 5

4.5.3.2 Signal-to-noise ratio

We recorded the noise for each measurement and calculated the SNR defined by

$$\text{SNR} = \frac{\text{MPV}}{\text{noise}}. \quad (4.3)$$

The SNR of the irradiated sensor is reduced by 70–80 % compared to the unirradiated sensor.

4.5.3.3 Effective doping concentration and substrate resistivity

The amount of free charge carriers created by a passing MIP in silicon is proportional to the depletion thickness d which is in turn proportional to the square root of the bias voltage SUB (see Section 2.4.2). In Figure 4.42 we fitted the calculated MPVs (in e^-) versus SUB with the relation

$$\text{MPV} = e_0 + K \cdot \sqrt{\text{SUB}}. \quad (4.4)$$

e_0 is the charge collected when the sensor is unbiased and K a proportionality factor. It comprises the contribution from the thin depletion zone created by the built-in voltage of the p-n junction and the contribution from the diffusion process in the bulk. The latter is affected by lattice defects and so should diminish after irradiation of the sensor. Indeed, we observe a reduction of e_0 of 69 ± 3 % with the irradiated CCPDv4.

Knowing the factor MPV/x , which is the average number of e-h pairs created per μm of silicon by a passing MIP, we can transform the ordinate to the effective depletion thickness d . Although in literature this value is often regarded as a constant with a value of around 80, this is only valid for a certain thickness of the sensitive volume.

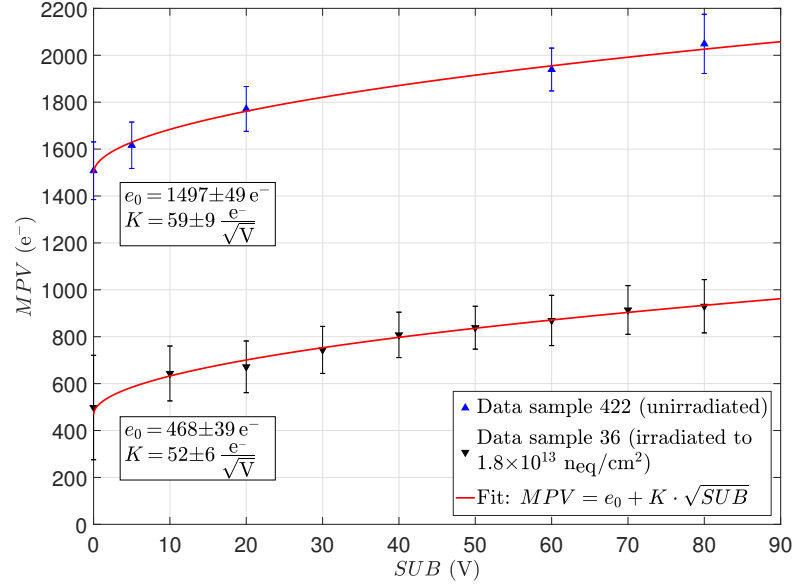


FIGURE 4.42: The most probable charge created by a MIP passing the sensor (MPV) versus the absolute value of the bias voltage (SUB) for the unirradiated and irradiated CCPDv4. The relation given in Equation 4.4 is fitted to the data from the unirradiated and irradiated CCPDv4. Discussion in the text.

In general, MPV/x depends on the volume thickness d which is especially important when dealing with thin detectors. The theoretical background for this is given in Section 2.4.1.1, where we also give a relation valid for our sensor dimensions and particle type:

$$MPV = \frac{d}{3.65 \text{ eV/e}^-} (100.6 \text{ eV}/\mu\text{m} + 35.35 \text{ eV}/\mu\text{m} \ln d) . \quad (4.5)$$

With the last equation we can translate the obtained MPVs in e^- to d in μm . The result is plotted in Figure 4.43. Using equation 2.14 we fitted the data with

$$d = d_0 + \sqrt{\frac{2 \cdot \varepsilon_{\text{Si}} \cdot \varepsilon_0 \cdot \text{SUB}}{e \cdot N_{\text{eff}}}} . \quad (4.6)$$

Now it becomes clear why here we call d the *effective* depletion thickness. The absolute value of d can not be regarded as a thickness directly: the offset d_0 includes the same contributions as e_0 above. Only the difference of d to d_0 corresponds to the actual thickness of the depletion zone. From the fit we get a thickness at -80 V of $8.2^{+2.1}_{-1.9} \mu\text{m}$ for the unirradiated and $8.2^{+1.7}_{-1.7} \mu\text{m}$ for the irradiated sensor. This equality is also reflected in the calculated effective doping concentration: we get a N_{eff} of $(1.55 \pm 0.23) \times 10^{15} \text{ cm}^{-3}$ for the unirradiated and $(1.58 \pm 0.18) \times 10^{15} \text{ cm}^{-3}$ for the irradiated sensor. Within the uncertainties we could not identify any change in the effective doping concentration due to irradiation. Equation 2.15 translates N_{eff} to the substrate resistivity ρ . We obtain values for ρ of $9.0 \pm 1.3 \Omega \text{ cm}$ for the unirradiated sensor and $8.8 \pm 1.0 \Omega \text{ cm}$ for the irradiated sensor.

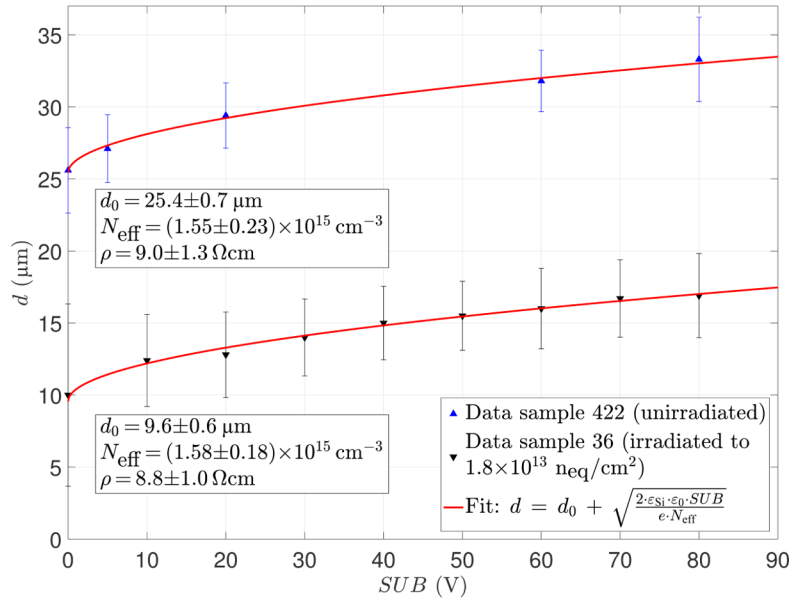


FIGURE 4.43: Effective depletion thickness (d) versus the absolute value of the bias voltage (SUB) for the unirradiated and irradiated CCPDv4. The relation given in Equation 4.6 is fitted to the data. This fit yields the effective doping concentration (N_{eff}). The substrate resistivity (ρ) is calculated with equation 2.15. Discussion in the text.

4.6 Efficiency

A high particle detection efficiency is required for HEP tracking detectors.⁽²⁰⁾ Therefore it is investigated already at the early stage of the development of a new detector. As soon as we were able to operate a CCPD together with a FE-I4 we planned testbeam campaigns to measure the efficiency. Two initial campaigns at the testbeam facilities of DESY in Hamburg were conducted with the first working samples of the CCPDv1 and CCPDv2, respectively. They did not yield reliable data for efficiency analysis but valuable experience for sensor operation. At that time no test system that could handle both the CCPD and the FE-I4 was available and no tuning procedures were implemented. Later test systems were developed based on the experience of the first campaigns. Further measurements yielded the first reliable efficiency figures. [173] shows a CCPDv2 efficiency of around 97 % before irradiation and larger than 95 % after irradiation to $1 \times 10^{15} \text{ n}_{\text{eq}} \text{ cm}^{-2}$. In addition, a spatial analysis revealed a drop in efficiency in the areas between pixels. This can be attributed to the shape of the depletion region caused by the low substrate resistivity (see Section 2.4.4).

The most recent efficiency studies were done with CCPDv4s. Testbeam measurements were performed with the FE-I4 telescope from UniGE (University of Geneva) at the CERN facilities. Two samples were investigated: one unirradiated sensor and one sensor that was neutron irradiated to $1 \times 10^{15} \text{ n}_{\text{eq}} \text{ cm}^{-2}$ before installation. Both samples were glued onto and read out with the FE-I4. Figure 4.44 and 4.45 show the particle detection efficiency measured across the sensor. One pixel in the plots corresponds to two FE-I4 readout pixels and six sensor pixels. This is due to the finer granularity of the sensor pixel matrix with respect to the readout chip as is discussed in Section 4.2.3. For this reason, sensor pixels on the edge and pixels with masked or faulty neighboring pixels show a misleading low efficiency and are not taken into account for calculation of the total efficiency.

A total efficiency of 99.5 % was obtained with the unirradiated sample despite the relatively low applied bias voltage of 12 V. It is hardly visible in Figure 4.47 and within the uncertainty,⁽²¹⁾ but the efficiency for the unirradiated sensor rises from 99.1 % at 0 V bias voltage to 99.5 % at 12 V. Therefore we assume that an even higher efficiency can be obtained when exploiting the whole bias voltage range to its upper limit of $\approx 90 \text{ V}$. Unfortunately this was not possible for these measurements, since the samples showed electric breakdown at very low voltages due to the problems discussed in Section 4.4.1. A total efficiency of 96.2 % was obtained with the irradiated sample. Again, only a moderate bias voltage of 35 V could be safely applied. In this case, Figure 4.46 strongly

²⁰ The definition of efficiency is given in Section 2.4.6.

²¹ The absolute uncertainty of the values for the efficiency is approximately 1 %. Note that the % is the unit of the efficiency.

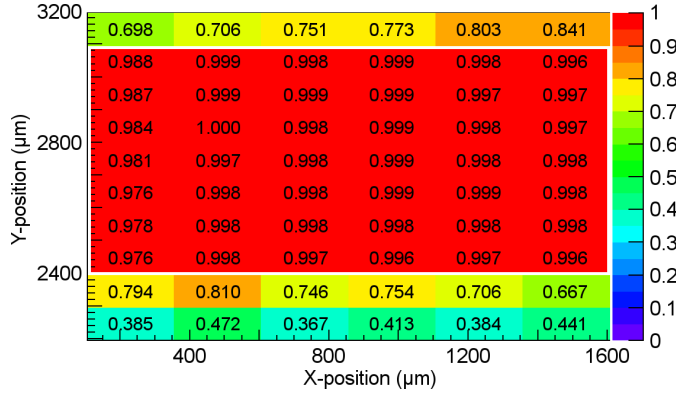


FIGURE 4.44: Efficiency plot of an unirradiated CCPDv4. The numbers of the color scale are fractions of 100 %. One pixel in this plot corresponds to six pixels in the sensor (see text for explanation). The groups of pixels at the upper and lower border have been excluded for the total efficiency calculation, since their position yields misleading values. Only the pixels within the white frame (252 sensor pixels) have been taken into account. Figure adapted from [177].

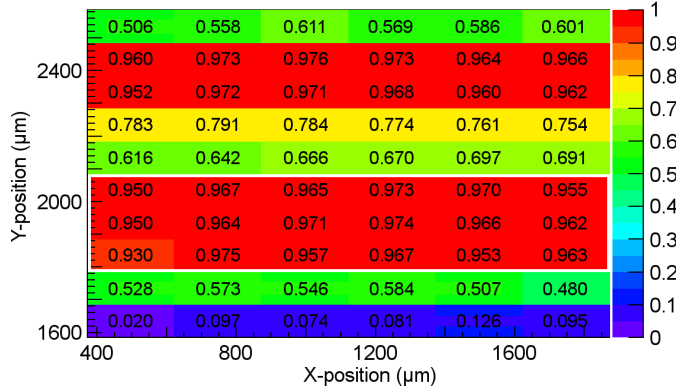


FIGURE 4.45: Efficiency plot of a CCPDv4 irradiated to $1 \times 10^{15} \text{ n}_{\text{eq}} \text{ cm}^{-2}$. The numbers of the color scale are fractions of 100 %. Pixels at the upper and lower border as well as pixels containing a defect pixel row have been excluded for the total efficiency calculation. Only the pixels within the white frame (108 sensor pixels) have been taken into account. Figure adapted from [177].

supports the assumption that higher efficiency values can be reached at higher bias voltages.

Figure 4.47 points out another way of raising the efficiency. It shows the efficiency versus the global threshold of the pixel matrix. We can see that a lower threshold results in a higher efficiency. However, the global threshold can not be set arbitrarily low, since then some pixels start to become too noisy to operate correctly. The future tuning possibilities discussed in Section 4.4.6.2 offer optimization of local threshold settings and we expect the efficiency to reach higher values when this optimization is applied.

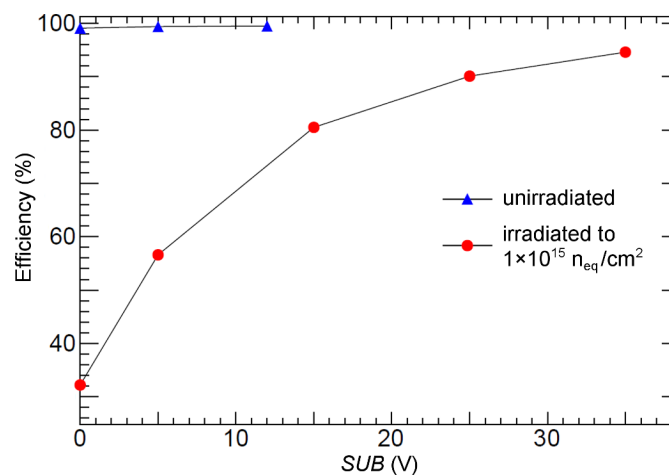


FIGURE 4.46: Efficiency versus the absolute value of the bias voltage (SUB) for an unirradiated and irradiated CCPDv4. The graph suggests strongly that higher efficiencies could be reached when the bias voltage is increased further, especially for the irradiated sensor. Figure adapted from [177].

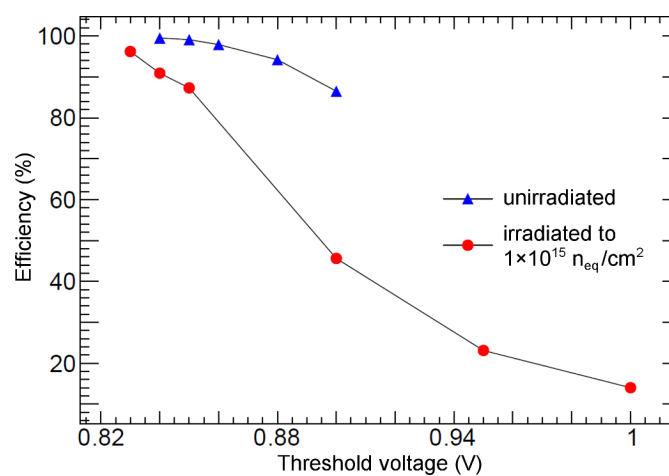


FIGURE 4.47: Efficiency versus the global threshold voltage for an unirradiated and irradiated CCPDv4. Higher efficiencies could be reached when improved tuning procedures allow for lower threshold values. Figure adapted from [177].

4.6.1 Single pixel efficiency

In principle, the data collected for the charge collection studies in Section 4.5.3 can be used to calculate a “single pixel efficiency”. During the analysis of these data, however, we discovered some circumstances that make the calculation of the single pixel efficiency disproportionately complicated and imprecise:

- The dimensions of the ROI in the DUT-plane (= size of the single pixel) are in the same order of magnitude as the telescope resolution.
- The dimensions of the telescope pixels are in the same order of magnitude as the ROI, introducing strong discretization effects.
- The small area of the ROI requires very long data taking to gather enough data required for thorough analysis.

In addition, the single pixel measurement does not represent the sensor well. Different pixels of the same sensor might show significant differences in their properties, as we discovered by the threshold measurements presented in Section 4.4.5.1.

However, the findings and examination of the problems listed above are useful for future single pixel measurements or more general: for testbeam measurements where any dimension of the ROI is in the same order of magnitude than the telescope resolution or telescope pixel size. We have not found any literature about the discretization effects that we encountered. Consequently, we have run simulations to reproduce and quantify this effect. This lead already to significant correction factors for measurements by colleagues. Details are not within the scope of this thesis and the analysis of the single pixel efficiency was not pursued further.

4.7 Summary and outlook

In this chapter we presented the extensive prototype work done with the silicon-sensor family CCPD. It ranges from basic proofs of concepts of new ideas up to testbeam characterization of the first capacitively coupled particle detectors.

4.7.1 A new technology in high-energy physics

The expected assets of HV-CMOS for particle physics and the reasons for it are discussed in Section 4.1. Efficient charge collection, small pixels, radiation hardness and system aspects like versatility, material budget and operating temperature are covered. The risks caused by the infancy of the technology in HEP are also outlined which leads to our recommendation for a test run of HV-CMOS based sensors in LHC-like conditions. Ideally, HV-CMOS sensors should be embedded in an existing or soon to be started experiment, much like it has been done with 3D-sensors in the IBL.

A cost estimation compared to planar silicon sensors yields a probable cost reduction when using the monolithic approach. For hybrid detector concepts we can not conclude a general cost benefit at the current stage. The sensor production could be done cheaper but the innovative interconnection concepts involve procedures and specialties like TSVs which are not yet standard in industry. They are therefore expensive and introduce risks which are hard to predict.

4.7.2 Sensor description & basic sensor properties

An extensive overview of the CCPD sensor family and its electronic functionality is given in Section 4.2 and is complemented by Appendices B and C. In Section 4.2.6 the different prototype versions are presented. We have developed custom PCBs and software to operate and characterize the sensors. This was the basis for further developments leading to incorporation of the CCPD family into existing control and readout systems (see Section 4.3.2). This is essential for the next steps: engineering and production runs.

Important experience was gained concerning interconnection techniques. The sensor bond pads were initially designed too small, resulting in assembly problems and destructive electric short-circuits. Future iterations of the sensor will have an optimized bond-pad design. Additionally, we successfully adapted a PU-potting procedure from the IBL, which protects wire bonds and bond pads.

Because we are dealing with an active sensor, the power consumption of the electronic components is of great interest. With the CCPDv1 we measured a maximum power consumption of the preamplifiers of $218 \pm 2 \text{ mW cm}^{-2}$ when they are fully switched on. The three pixel output stages each consume $163 \text{ mW cm}^{-2} \pm 39\%$ when fully switched

on. These values are large but represent only the maxima. Lower values are reached by choosing the sensor parameters accordingly.

The power dissipated by the leakage current is rather small. After irradiation to $1 \times 10^{16} \text{ n}_{\text{eq}} \text{ cm}^{-2}$ we measured only $1.25 \pm 0.02 \text{ mW cm}^{-2}$ at $+22^\circ\text{C}$. We identified the leakage current as a bulk leakage current. The largest value with the CCPDv1 was measured after irradiation to $1 \times 10^{16} \text{ n}_{\text{eq}} \text{ cm}^{-2}$: $74 \pm 1 \mu\text{A}$ at 60 V bias voltage. Sensors irradiated to $1/10$ of the fluence showed leakage currents around 13 times smaller. Cooling of the sensor resulted in half the leakage current every 8.5°C .

The input referred noise and pixel thresholds were investigated with the injection and monitor functions of the sensor. A detailed S-curve analysis was developed and simple tunings were applied. We discovered a dependency of the threshold on row number in the CCPDv1 but in no subsequent versions. A voltage drop along the voltage distribution lines in the sensor is likely to have caused this effect. Tunings of single rows down to thresholds values of $370 \pm 150 e^-$ were achieved. The ENC was $58 \pm 28 e^-$ for this tuning. The tuning procedure was not well developed and adapted for the CCPD. Later developments included enhanced tuning procedures, based on the noise edge instead of a target threshold.^[173] The incorporation of the sensor into USBpix made existing and well proven tuning procedures available for the sensor.^[155]

We could not find significant changes of the ENC at different conditions. The large errors on the calibration of the CCPDv1 prevented identifying a definite increase after irradiation to $1 \times 10^{15} \text{ n}_{\text{eq}} \text{ cm}^{-2}$. Cooling after irradiation from $+22^\circ\text{C}$ to -10°C indicates a decrease of the noise by about 30 % but the values are smaller than their uncertainty. The FE-I4 activity worsens the threshold and noise of the sensor slightly, but this is probably due to the heating of the FE-I4 when it is on.

Within the errors no difference in noise between the CCPDv1 and CCPDv2 could be observed.

The influence of the total dose received by the sensor on the electronics is shown in Section 4.4.3.1. The preamplifiers' gains in a CCPDv2 dropped significantly after X-ray irradiation to 8.62 MGy. Re-optimizing the chip parameters could restore the gains of the fully radiation hard pixels to about 90 % of their initial value. At the same time, the noise increased from 75 to $150 e^-$. The gains of the partially radiation hard pixels could only be restored to about 50 % of their initial value. Recent measurements with the CCPDv4 up to 10 MGy (1 Grad) can be found in [178] and [179].

4.7.3 Novel ideas

We showed the versatility of the CCPD aside its main use as a pixel sensor combined with the FE-I4. It can be used with other pixel readout sensors like the CLICpix.^[142]

Strip readout is possible with any digital or analog strip readout chips, e.g. the ABCN or LHCbeetle. An innovative approach makes it possible to get 2D hit-information even in strip-mode. Details and results are given in Section 4.2.5.3.

The connection to the FE-I4 can be done traditionally with bump-bonding, but the intention is to use capacitive coupling via a glue interface. This gluing was investigated and developed from first tries to μm -precision. Successful coupling to and readout with the FE-I4 have been shown to work (see Section 4.4.7). The gluing procedure has still to be refined and its suitability for production has yet to be shown.

Additionally, the concept of the subpixel encoding has been proven to work (see Section 4.4.7.3). This means that the pixel size of the readout chip is not the limiting factor for the sensor pixel size any more. Several sensor pixels can be read out by one single pixel of the readout chip. However, we could only show the concept with one single FE-I4 pixel as we had to tune the pixels by hand. The above mentioned incorporation of the sensor into existing readout systems will enable the subpixel encoding for larger areas. Recent results on this can be found in [180].

4.7.4 Particle detection

The next step after proof of concepts was the detection of particles. In Section 4.4.7.2 we show that particles from a radioactive source were successfully detected by the CCPDv1 glued onto the FE-I4. Even a sensor irradiated to $1 \times 10^{16} \text{ n}_{\text{eq}} \text{ cm}^{-2}$ shows clear particle signals. This is an important step toward radiation hardness at HL-LHC fluences. The measurements were done at sensor temperatures of up to $+37^\circ\text{C}$. This means that the sensor does not require cooling per se which could lead to significant simplifications in the cooling requirements for large-area detector systems.

Charge collection studies were performed with the CCPDv1 and radioactive sources. Partner institutes measured a most probable charge deposition from MIPs of approximately $1600 e^-$ in the unirradiated sensor. Our investigation of a sensor irradiated to $1 \times 10^{15} \text{ n}_{\text{eq}} \text{ cm}^{-2}$ yielded around $1145 e^-$. This reduction of 29 % is attributed to the reduction of the diffusion signal after irradiation. However, the total reduction of the drift signal could not be determined, because acceptor removal caused by the irradiation increases the resistivity and therefore the drift signal at the same time. To study this effect in more detail and to entangle the contribution from diffusion and drift, we conducted detailed testbeam studies.

The testbeam studies were done with unirradiated and proton irradiated CCPDv4s. Due to the reconstruction of the irradiation facility a fluence of only $3.5 \times 10^{13} \text{ p}^+ \text{ cm}^{-2} \pm 27\%$, corresponding to $(1.8 \pm 0.5) \times 10^{13} \text{ n}_{\text{eq}} \text{ cm}^{-2}$ was achieved. We measured a total most probable charge deposition from MIPs of $2049 \pm 126 e^-$ in the unirradiated sensor at 80 V bias voltage. In the irradiated sensor we measured $930 \pm 114 e^-$. The detailed analysis presented in Section 4.5.3.3 shows that the part of the signal that includes the

contribution from diffusion is reduced by $69 \pm 3\%$ after irradiation. The drift part does not change within the error of the measurement. The effective depletion thickness at 80 V is $8.2^{+2.1}_{-1.9} \mu\text{m}$ for the unirradiated and $8.2^{+1.7}_{-1.7} \mu\text{m}$ for the irradiated sensor. It does not change within the error of the measurement. We conclude that the effects of charge trapping are largely suppressed for the drift part. Corresponding to the equality of the effective depletion thickness, no change in effective doping concentration and therefore resistivity caused by the irradiation is observed. For the unirradiated sensor the measured values are $(1.55 \pm 0.23) \times 10^{15} \text{ cm}^{-3}$ respectively $9.0 \pm 1.3 \Omega \text{ cm}$ and for the irradiated sensor $(1.58 \pm 0.18) \times 10^{15} \text{ cm}^{-3}$ respectively $8.8 \pm 1.0 \Omega \text{ cm}$. These values are in accordance with other measurement of the CCPD which are presented in [181]. Within the scope of this thesis we could not conduct additional measurements with sensors that were irradiated to higher fluences. Such measurements are ongoing by partner institutes in the collaboration. They reveal interesting information on irradiation damage properties like rates of initial acceptor removal and generation of deep stable acceptors. First results can be found in [181] and [182].

Extensive charge calibration measurements were conducted for the testbeam campaign. We discovered that the calibration factors depend significantly on the bias voltage for active sensors where the depletion thickness is very thin. It is therefore inevitable to perform a charge calibration for every value of the bias voltage. We found this to be not very common in the field.

The SNR of the sensors increases with bias voltage and decreases with irradiation. The unirradiated CCPDv4 showed a SNR of 138 ± 9 at 80 V bias voltage and 69 ± 6 at 0 V. After proton irradiation to $(1.8 \pm 0.5) \times 10^{13} \text{ n}_{\text{eq}} \text{ cm}^{-2}$ it decreased to 39 ± 5 and 14 ± 6 , respectively. The CCPDv1 showed a SNR after neutron irradiation to $1 \times 10^{15} \text{ n}_{\text{eq}} \text{ cm}^{-2}$ of approximately 23 at 55 V bias voltage.

First efficiency measurements with the CCPDv2 showed inefficiencies between pixels. We first assumed that they are due to the front biasing, but simulations revealed that they are due to the combination of the pixel electrode structure and the low resistivity. This results in the bias potential reaching the front of the detector even when biased from the back side (see Section 2.4.4).

The unirradiated CCPDv4 shows an efficiency of 99.5 % percent. After irradiation to $1 \times 10^{15} \text{ n}_{\text{eq}} \text{ cm}^{-2}$ it decreases to 96.2 %. These values were obtained at low bias voltages of 12 and 35 V, respectively, and the thresholds were not well tuned. The measurements suggest that a higher efficiency can be reached with higher bias voltages and well tuned thresholds. This is supported by recent results shown in [183] and [184]. They report CCPDv4 efficiencies of 99.7 % for the unirradiated and $1 \times 10^{15} \text{ n}_{\text{eq}} \text{ cm}^{-2}$ -irradiated sensor and 97–98 % for the $5 \times 10^{15} \text{ n}_{\text{eq}} \text{ cm}^{-2}$ -irradiated sensor.

In principle, the data from our testbeam campaign could be used to deduce the single

pixel efficiency. However, results from colleagues showed that this method is very imprecise and would not reveal any new information for our sensors. During development of this method though, we discovered important effects concerning testbeam measurements where any dimension of the ROI is in the same order of magnitude than the telescope resolution or telescope pixel size. We ran simulations to reproduce and quantify this effect which lead to significant correction factors that have to be considered in such measurements.

The timing resolution of the CCPDs is around 100 ns. This is caused by the time-walk of the signal. Effects of this on the efficiency are described in [184]. For HL-LHC use, the timing performance has to be improved. From CCPDv5 onwards, a timewalk compensation is implemented in the pixels that could decrease the timewalk down to ≈ 5 ns (see Section 4.2.6.5).

4.7.5 Toward the HL-LHC

The results from the CCPD-family are encouraging with respect to suitability for HL-LHC experiments. However, the sensors are prototypes with relatively small pixel matrices and shortcomings have been identified. In order to overcome the shortcomings and verify feasibility on a full-reticle-size scale ($\approx 2.5 \times 2 \text{ cm}^2$), demonstrator chips have been designed. The ams process H35 offers more versatility and features than the H18, like a high-voltage rating up to 120 V and the possibility of using high-resistivity wafers. These items are beneficial for charge collection in the sensor. In order to study their effects the first demonstrator H35DEMO has been produced in the 350 nm process. A brief description can be found in [178] and promising first results in [185].

A full-size demonstrator in 180 nm (H18DEMO) is foreseen for the end of 2016. Its performance will decide whether HV-CMOS sensors produced in the ams H18 process will be considered an option for the ATLAS ITk. The ITk Technical Design Reports in 2017 will then pin down the technologies that are further pursued.

Chapter 5

Impact & Conclusion

The detailed results of our research are summarized at the end of the previous two chapters, namely in the Sections 3.3 (IBL related) and 4.7 (HV-CMOS related). The outlook on further work is also given there.

In this chapter we put our work into the larger picture of ATLAS and the LHC.

5.1 Successful integration of the IBL

The IBL was inserted into ATLAS in May 2014 and the ATLAS beam pipe bake-out was performed in October 2014. The bake-out was safely executed but showed that the CO₂ flow rate needed to be optimized to ensure stable temperatures all along the detector.^[63] The IBL started taking data with 99.5 % of the pixels being operational.^[186] One of the first events that were recorded with ATLAS including the IBL shortly after the bake-out is shown in Figure 5.1. Figure 5.2 shows the threshold and noise values achieved by the IBL pixels during the quality assurance testing.^[187] During alignment with cosmic ray data in early 2015 a mechanical distortion of the IBL caused by the CTE mismatch of the IBL stave components was discovered. This distortion could largely be corrected for by the detector alignment procedure.^[189] Full data taking of Run 2 started in May 2015 after re-commissioning of the ATLAS detector. With increasing irradiation, an unexpected increase of the low-voltage current of the FE-I4s was observed. A detailed investigation revealed that safe operation could be maintained by changing the IBL's temperature.^[190] ATLAS recorded 3.9 fb⁻¹ of data in 2015.^[191] Even with this modest amount of data, ATLAS' performance improvement due to the IBL is clearly visible. As an example, Figure 5.3 compares the transverse impact parameter resolution for low transverse momentum tracks of the 2012 and 2015 data. It improved by a factor of almost two.

Our work contributed to the safe installation of the IBL and successful integration into ATLAS. The type 1 services mock-up was essential for testing integration procedures

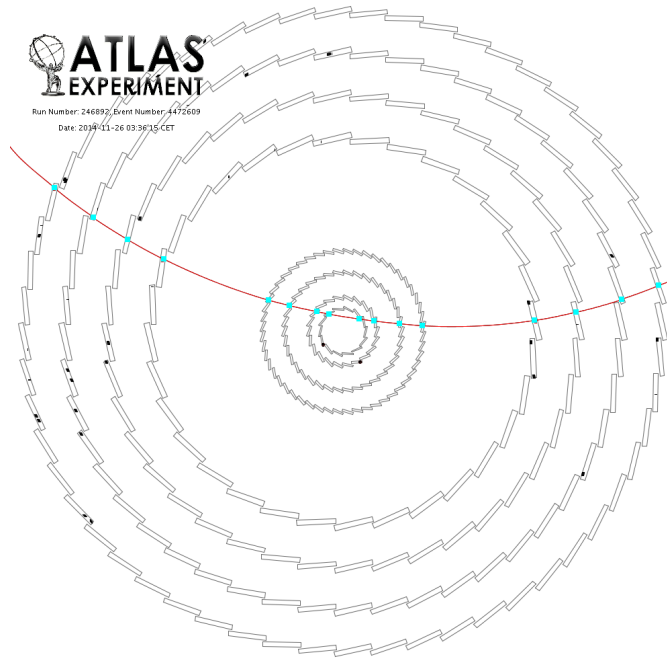


FIGURE 5.1: Display of one of the first events detected by the IBL. A charged particle from a cosmic event passes the ID. Its track is bent by the solenoidal magnetic field of ATLAS. The IBL is the innermost layer in the display, contributing two points for the track reconstruction. Figure adapted from [188].

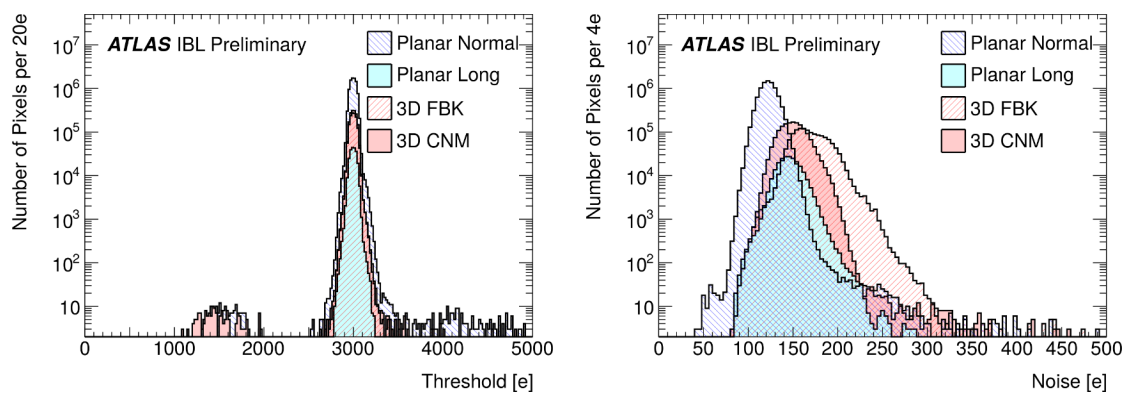


FIGURE 5.2: Threshold and noise distributions for the 14 IBL staves after tuning of all pixels to a target threshold of 3000 e^- . The modules' temperature was $+22^\circ\text{C}$. The different distributions in the plots correspond to the different pixel and sensor types in the IBL. Figure from [187].

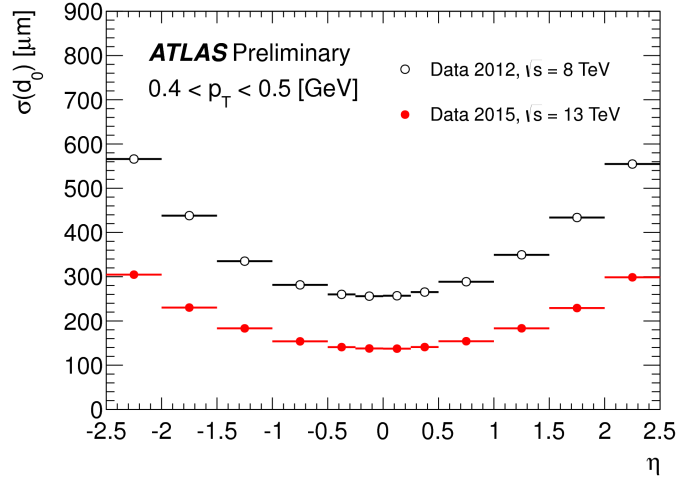


FIGURE 5.3: Unfolded transverse impact parameter resolution $\sigma(d_0)$ as a function of the pseudorapidity η for low transverse momentum tracks. The data from 2015 (in red) shows an improvement by a factor of almost two compared to the data from 2012 (in black). Figure from [192].

and for the design of the type 1 service region. Our tests with the thermal mock-up lead to the removal of the aerogel insulation around z_0 , reducing the material budget of the IBL. The choice of heaters was also evaluated. We verified reliable operation of the novel CO₂ cooling system and showed that the IBL is thermally safe during the ATLAS beam pipe bake-out and during nominal operation. Accident simulations revealed the timescale for intervention in case of cooling failures. The simulations also verify the installed security measures. The temperature setpoints for different scenarios were investigated and optimum initial values were identified.

The operating conditions of the IBL will change during the lifetime of the LHC. The optimum temperature setpoints have to be constantly redefined. Further bake-outs will be necessary and heating/cooling issues or unplanned consolidation work on the detector or on the beam pipe can occur. In these cases the results of our work will be of importance and should be consulted together with the data from the 2015 beam pipe bake-out and data from the IBL operation.

Good performance of the IBL during its full lifetime is crucial for ATLAS' physics program until further Inner Detector changes for the HL-LHC are implemented.

5.2 HV-CMOS sensors for the ITk

We try to fulfill the ITk requirements on silicon detectors with the CCPD sensor family. The underlying HV-CMOS technology is new to HEP and therefore a thorough discussion and research program is necessary. The advantages like cheap sensor production, radiation hardness, small pixel size and simple interconnection to the readout chip need to be balanced against the novelty of the technology. The new concepts have never been

applied in HEP and experience is needed to be ready for large-scale detector production. Quality has to be assured and infancy risks identified and eliminated. We have taken important steps in that direction.

The AC-coupling of the sensor to the readout chip by a simple glue-layer was proven to work. A large number of prototype-sized, capacitively coupled pixel detectors were assembled and detector operation was developed to a stage where the next step is a full reticle-size engineering run. A gluing procedure was established and has matured but further cooperation with industry is necessary to include this assembly step in production lines. The versatile sensor also provides a strip-readout mode in which it can be used with strip readout chips forming a strip-detector.

The second important concept that we showed to work is the subpixel encoding. It allows for miniaturization of the sensor pixels regardless of restrictions set by the readout chip. The sensor pixels are simpler than the readout pixels and could therefore evolve faster in terms of smaller size. The subpixel encoding realizes this possibility by entangling the sensor and readout pixel sizes.

The testing of the CCPD sensor family required considerable hardware and software development. It is an essential basis for operation of the future sensors from engineering or production runs.

We investigated the charge collection and radiation hardness of the sensors in detail. We showed particle detection after irradiation to $1 \times 10^{16} \text{ n}_{\text{eq}} \text{ cm}^{-2}$, which is an important step toward the value of $2.1 \times 10^{16} \text{ n}_{\text{eq}} \text{ cm}^{-2}$ required for the ITk. The irradiated sensors were stably operated at room temperature which could lead to significant simplifications in the detector cooling system at large scales. The sensor electronics' performance after irradiation to 8.62 MGy (862 Mrad) was restored to 90 % of the initial value, which is also an important step toward the requirement of 12 MGy for the ITk. Dedicated radiation-hard design of the electronics is necessary to reach this limit.

Our charge collection studies in the testbeam revealed that the part of the signal which includes diffusion was reduced significantly after irradiation to $1.8 \times 10^{13} \text{ n}_{\text{eq}} \text{ cm}^{-2}$. The drift signal, however, did not change. This shows that the charge collection of electrons by drift in the CCPD is largely uninfluenced by charge trapping up to this irradiation level. No change in the effective doping concentration, N_{eff} , could be measured. The resistivity of the substrate was determined to be $9.0 \pm 1.3 \Omega \text{ cm}$ for the unirradiated sensor, which confirms the assumed value of $10 \Omega \text{ cm}$. These values are in accordance with measurements by colleagues. They irradiated the sensors to higher fluences and showed a strong initial acceptor removal and a moderate introduction of acceptors with irradiation. Up to around $1 \times 10^{16} \text{ n}_{\text{eq}} \text{ cm}^{-2}$ this change in N_{eff} is actually beneficial for charge collection and can be exploited. The n-in-p technology and the low resistivity are the determining factors leading to these advantages.

Detector efficiencies were measured in testbeam campaigns. Efficiencies of 99.7 % were achieved for unirradiated sensors and also for sensors irradiated to $1 \times 10^{15} \text{ n}_{\text{eq}} \text{ cm}^{-2}$. Values of up to 98 % were shown for sensors irradiated to $5 \times 10^{15} \text{ n}_{\text{eq}} \text{ cm}^{-2}$.

These results look promising for the suitability of HV-CMOS sensors for HEP. However, the results were achieved with prototype versions of the sensors with a size in the order of mm^2 . A much larger, full reticle-size demonstrator chip with a feature size of 350 nm has been produced and a demonstrator with the feature size of the prototypes (180 nm) is also foreseen. The results of these demonstrators will decide if a HV-CMOS process will be considered an option for the ATLAS ITk. The ITk Technical Design Reports in 2017 will pin down the technologies that are further pursued. For the ITk but also for potential other large scale experiments we recommend a test-run with HV-CMOS sensors in a LHC-like environment. Ideally, the sensors should be embedded in an existing or soon to be started experiment, much like it was done with 3D-sensors in the IBL. This will ensure the experience necessary to build and run a reliable, large-scale silicon detector based on HV-CMOS sensors.

Appendix A

Main publications

Our most important publications are attached in this appendix. They are in chronological order:

- **Journal of Instrumentation (JINST) 2014:** Performance of capacitively coupled active pixel sensors in 180 nm HV-CMOS technology after irradiation to HL-LHC fluences.^[132, 133]
- **Proceedings of Science (PoS) 2014:** Radiation-hard active pixel sensors for HL-LHC detector upgrades based on HV-CMOS technology.^[193]
- **Institute of Electrical and Electronics Engineers (IEEE) 2015:** Latest results on the HV-CMOS Pixel Sensor in the ams H18 process.^[177]

Selection of further publications (not attached):

- **Nuclear Instruments and Methods in Physics Research Section A (NIMA) 2013:** High-voltage pixel detectors in commercial CMOS technologies for ATLAS, CLIC and Mu3e experiments.^[194]
- **Proceedings of the International Image Sensors Workshop 2013:** Radiation-hard active pixel detectors for tracking of charged particles based on HV-CMOS technology.^[134]
- **NIMA 2013:** High-voltage pixel sensors for ATLAS upgrade.^[136]
- **Technical Note of the CERN Experimental Physics Department (PH-EP) 2014:** IBL thermal mockup bake-out tests.^[195]



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M

R : December 11, 2013

R : January 13, 2014

A : January 15, 2014

P : March 14, 2014

TOPICAL WORKSHOP ON ELECTRONICS FOR PARTICLE PHYSICS 2013,
23–27 SEPTEMBER 2013,
PERUGIA, ITALY

Performance of capacitively coupled active pixel sensors in 180 nm HV-CMOS technology after irradiation to HL-LHC fluences

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A : In this ATLAS upgrade R&D project, we explore the concept of using a deep-submicron HV-CMOS process to produce a drop-in replacement for traditional radiation-hard silicon sensors. Such active sensors contain simple circuits, e.g. amplifiers and discriminators, but still require a traditional (pixel or strip) readout chip. This approach yields most advantages of MAPS (improved resolution, reduced cost and material budget, etc.), without the complication of full integration on a single chip. After outlining the basic design of the HV2FEI4 test ASIC, results after irradiation with X-rays to 862 Mrad and neutrons up to $10^{16} (1 \text{ MeV n}_{\text{eq}})/\text{cm}^2$ will be presented. Finally, a brief outlook on further development plans is given.

K : Radiation damage to electronic components; Radiation-hard detectors; Radiation damage to detector materials (solid state); Radiation-hard electronics

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1 Introduction

Future upgrades of the LHC (high luminosity LHC, HL-LHC) have direct impact on the requirements for future high energy physics particle detectors [1]. Especially tracker detectors used at HL-LHC experiments will suffer from significantly higher radiation doses. For this reason, currently installed silicon pixel and strip detectors in ATLAS will have to be replaced around 2018. Intense R&D effort is done to provide improved and ready-to-use sensor technologies for the replacement.

One very promising candidate is planar silicon sensors in deep sub-micron high voltage CMOS technology (AMS 180 nm high voltage CMOS process [2]). It evolved from the classic diode-based pixel sensor where an ionizing particle deposits charge in a reversely biased diode structure. Here, the diode is formed by a deep n-well in a p-substrate. The reverse bias voltage in the order of 100 V creates a strong electric field. This causes effective charge collection by drift and the n-well acts as potential minimum for the electrons. The novelty of the HV-CMOS sensor is that despite the high voltage applied, the deep n-well also serves as substrate for PMOS transistors placed directly on the sensor chip. Additional p-wells inside the n-well host NMOS transistors and so the full range of CMOS logic is available. We refer to this concept as “smart diodes” and in the arrangement of a pixel matrix as “smart diode array” (SDA) [3].

The sensors investigated in this report are prototype pixel sensors designed for a hybrid detector using existing readout chips. Each pixel contains first stages of signal processing on the sensor: charge sensitive amplifier, comparator with possibility of local threshold adjustment and an output stage. Together with specific HV-CMOS process properties, this creates several advantages for the use as a tracking detector:

- With a substrate resistivity of about $20\ \Omega\text{cm}$ and a maximum allowed bias voltage of 60 V, the depletion zone extends around $15\ \mu\text{m}$ into the substrate. The expected charge collected by drift is therefore in the order of 1000 electrons. This relatively low signal can still be easily detected and readout thanks to the direct in-pixel amplification. The thin depletion zone allows for a very fast charge collection that in turn leads to low sensitivity to charge trapping at lattice defects. Since charge trapping is the main reason for sensor degradation by non-ionizing radiation, a high bulk radiation hardness can therefore be expected.
- Deep sub-micron CMOS electronics can be designed to be relatively resistant to ionizing radiation. Therefore high radiation hardness of the electronics is also given.
- Low “high voltage” compared to most current particle silicon sensors.
- On-sensor signal amplification makes it possible to use AC-coupling to the readout chip. Instead of the highly complex, mechanically sensitive and expensive bump bonding, the sensor chip can be simply glued onto the readout chip. This is referred to as “capacitively coupled pixel detector” (CCPD) [4, 5].
- Current prototypes are designed to be used with the existing ATLAS pixel readout chip FE-I4 [6]. No development of a new readout ASIC is needed and the advantages of SDA sensors can be combined with the advantages of a highly developed and well known readout chip.
- The very thin depletion zone allows for thinning of the sensor to $50\ \mu\text{m}$ and below. Together with capacitive coupling this leads to low material budget compared to other hybrid detectors.
- The pixel size can be made smaller because there is no size restriction from metal bumps. From the electronics side, pixel sizes down to $20 \times 20\ \mu\text{m}^2$ can be easily realized [4]. Smaller pixel size leads to smaller pixel capacitance and noise, better particle position detection and lower pile-up. The latter is especially important for high luminosity detectors.
- The pixel sensor can also be operated in “virtual strip detector”-mode. The sensor electronics interconnect pixels along one dimension and encode the position along the virtual strip in the signal height. Readout can thus be realized by existing analog or digital strip readout chips. Consequently, currently developed pixel chips present an alternative for future strip detector replacements.
- The HV-CMOS process is a standard electronic production process and therefore cheap and widely available compared to customized processes. This is an attractive feature for large-area detectors like the ATLAS strip detector.

In this publication first results obtained with prototype sensors irradiated to an integrated neutron flux of $10^{16}\ (1\ \text{MeV}\ n_{\text{eq}})/\text{cm}^2$ and a total ionizing dose of 862 Mrad are presented.

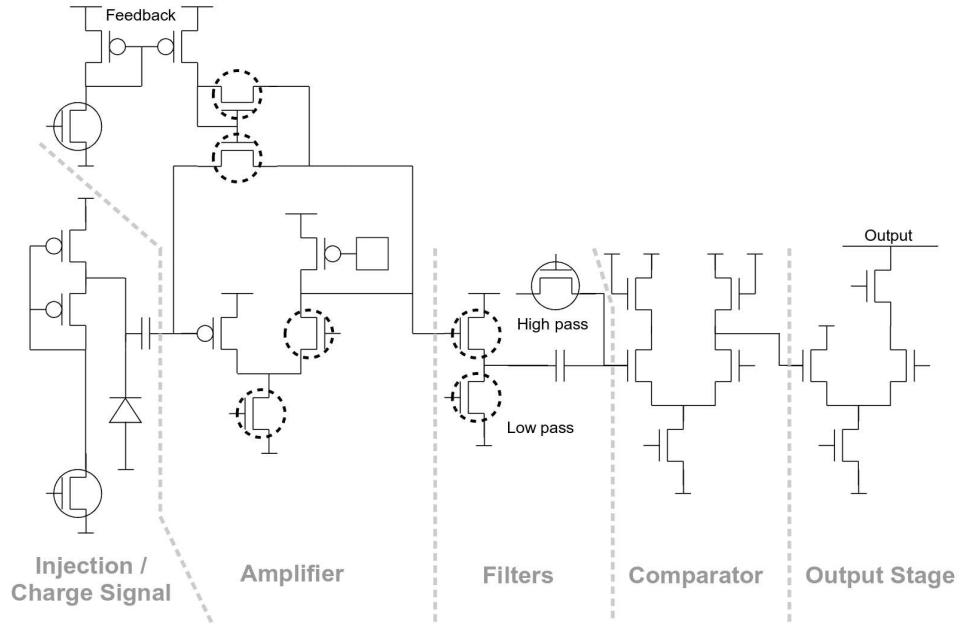


Figure 1. Schematic of the sensor pixel electronics. The circles represent transistors implemented in a radiation hard design (enclosed transistors). The dashed circles represent transistors, which are implemented as standard transistors in the first generation prototype and as enclosed transistors in the radiation hard pixel type of the second generation prototype.

2 Prototype demonstrator chips

Two small-size prototypes to test the concept in 180 nm technology are currently available: HV2FEI4v1 (first generation) and HV2FEI4v2 (second generation). Both chips are geometrically equal. The first generation uses only standard CMOS elements for the pixel logic with no optimization for radiation hardness. The second generation comprises three pixel types, two of them with radiation hard electronic elements (e.g. circular transistors) partially implemented. The schematic shown in figure 1 gives more detail on this.

Figure 2 shows the front side of the HV2FEI4v1. It is $4.4 \times 2.2 \text{ mm}^2$ large with a pixel size of $125 \times 33 \mu\text{m}^2$. The 1440 pixels are arranged in 24 rows and 60 columns. Wirebond pads for the pixel- and for the strip-readout sit on respective sides of the chip. The electronics power consumption is measured to be approximately 185 mW/cm^2 .

To study bulk damage stemming from non-ionizing radiation, four chips of the first generation were neutron irradiated in the TRIGA reactor of the Jožef Stefan Institute in Ljubljana, Slovenia [7, 8]. Two of them were irradiated to 10^{15} and two to $10^{16} (1 \text{ MeV } n_{\text{eq}}) / \text{cm}^2 (\pm 10 \%)$. For each of these fluxes one chip was finally assembled into a CCPD and successfully operated. A representative test setup is shown in figure 3. Results of operation after irradiation are given below.

One second generation chip was irradiated at the CERN X-ray irradiation facility to 862 Mrad to understand surface effects of ionizing radiation. It was used to extensively study the performance of the sensor electronics after irradiation. The main results are presented below.

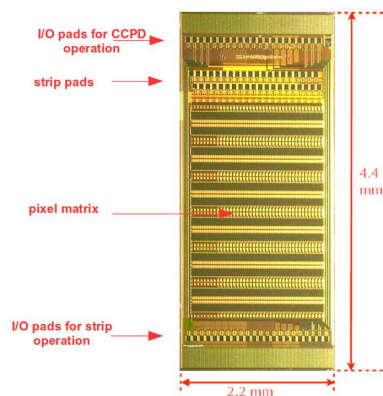


Figure 2. Front side of the prototype demonstrator chip HV2FEI4v1.

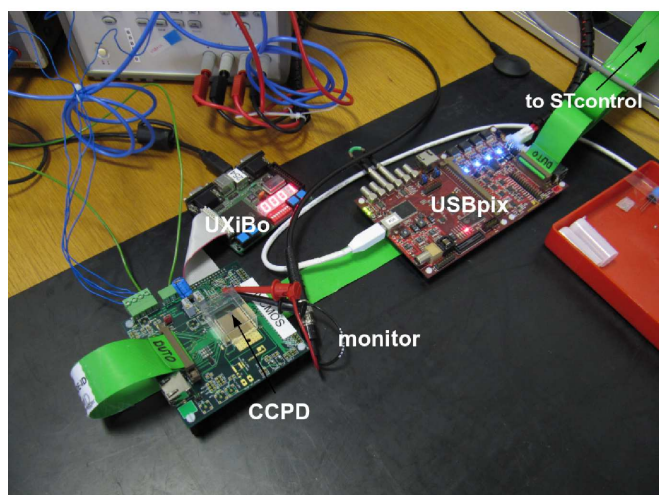


Figure 3. A CCPD installed on a modified FE-I4 single chip card for testing. A UXiBo board is used for communication with the sensor chip. The FE-I4 is operated with a USBpix system. Most of the testing has been done in a climate chamber, including a ^{90}Sr radioactive source.

3 Sub-pixel encoding

The ratio of the areas of a FE-I4 readout pixel ($250 \times 100 \mu\text{m}^2$) and of a HV2FEI4 sensor pixel is 3:1. To realize compatibility, the output signals of three sensor pixels are summed and connected to one readout pixel (see figure 4). Each of the three sensor pixels sends a current pulse with defined and constant amplitude when being hit by a particle. These three amplitudes are chosen in a way that the pixel position can be reconstructed from the summed amplitude. The FE-I4 readout pixel is able to measure the summed amplitude and converts it into time-over-threshold (ToT) information. In the end, the address of the firing sensor pixel can be reconstructed from the address and ToT information of the corresponding readout pixel.

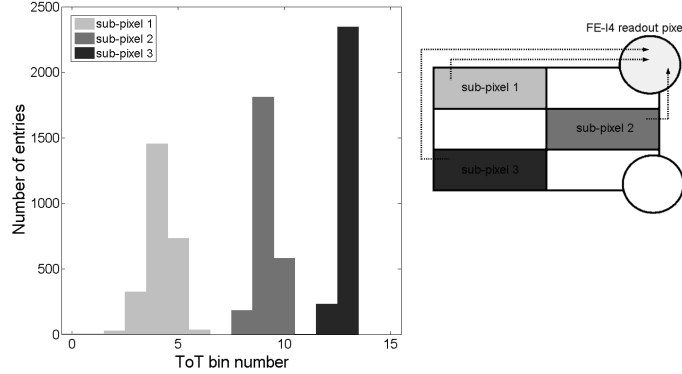


Figure 4. Sub-pixel encoding of sensor pixel address. On the left, the ToT spectrum of one FE-I4 pixel shows three distinct peaks corresponding to the three sensor pixels connected to the readout pixel. On the right the schematic of the pixel routing is shown. No neighboring sensor pixels share the same readout pixel in order to prevent corruption of the sub-pixel encoding in case of charge sharing.

Figure 4 shows the ToT histogram of one FE-I4 readout pixel after CCPD exposure to a ^{90}Sr radioactive source. This CCPD comprised an unirradiated HV2FEI4v1 chip. There are clearly three distinct peaks visible, each of them corresponding to one of the three sensor pixels routed to the readout pixel. The concept of this so-called “sub-pixel encoding” is thus proven to work. However, we had to tune the three HV2FEI4 pixels and the FE-I4 pixel by hand to be able to show the encoding. This is due to the fact that no communication between the sensor control system and the readout system was implemented. There is ongoing effort to incorporate the custom sensor control (hard- and software) into the readout control. This will then provide automated tuning for the whole sensor area.

4 Particle detection after $10^{16} (1 \text{ MeV } n_{\text{eq}}) / \text{cm}^2$ neutron irradiation

Neutron irradiation causes mainly bulk damage in the silicon substrate. This is due to interaction of the neutrons with the lattice nuclei. In the early HV-CMOS R&D-phase radiation tolerance of up to $10^{15} (1 \text{ MeV } n_{\text{eq}}) / \text{cm}^2$ was shown. Sensors worked after irradiation even at room temperature, but with a somewhat increased noise level [3, 9]. HL-LHC silicon strip sensors will see an integrated particle flux of around $10^{15} (1 \text{ MeV } n_{\text{eq}}) / \text{cm}^2$. Fluxes at the level of the silicon pixel sensors will reach even higher values. Therefore we had HV2FEI4v1 sensors irradiated up to $10^{16} (1 \text{ MeV } n_{\text{eq}}) / \text{cm}^2$.

Test results show that the sensors are still operating after irradiation and particles from a ^{90}Sr source have been detected. The CCPD was placed between the source and a scintillation counter. The latter was used for triggering. Figure 5 shows the occupancy plot of the FE-I4 region where the small demonstrator chip is glued onto. The FE-I4 detected no hits outside this region. In addition, the level-1 trigger distribution is shown. This histogram is filled with the measured time periods between a hit signal and its corresponding trigger. One distinct peak is visible on a flat background. This verifies that we really see mostly only particles stemming from the radioactive source. The

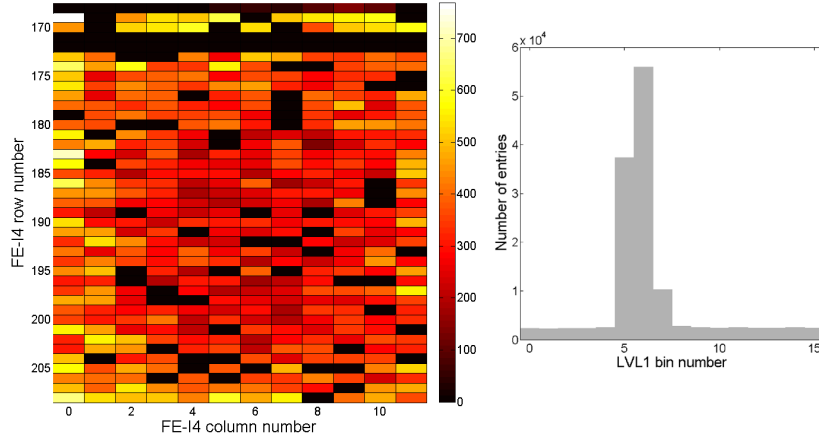


Figure 5. FE-I4 occupancy plot and its level-1 trigger distribution of a CCPD placed under a ^{90}Sr radioactive source (see section 4 for detailed explanation and discussion).

sensor threshold was set to a global value where the noise occupancy was below 10^{-9} and some exceedingly noisy pixels were masked. Later measurements with only then available improved control software for the sensor showed that the optimum threshold level lies lower than the level used for the presented measurements. New measurements with the optimum threshold setting could not be conducted, since unfortunately the CCPD got damaged during manipulation for a planned test beam measurement. Further CCPDs with samples irradiated up to $10^{16} (1 \text{ MeV } n_{\text{eq}}) / \text{cm}^2$ will only be available later this year.

The non-ideal threshold setting caused the sensor to most probably only detect the high energy tail of the Landau distribution. This assumption is reinforced by the very low event rate of the sensor (below 10 Hz for the whole sensor area compared to several hundred Hz for the same scintillator area). Future measurements will include a threshold tuning of the sensor chip as well as further investigation of threshold settings.

The occupancy plot shown was recorded at an ambient temperature of 22°C in a light-tight climate chamber (error for temperature measurements 0.2°C). The applied bias voltage was set to -20 V . Note that the sensor temperature was about 15°C higher due to the power dissipated by the running readout chip (measured with an infra-red camera). This holds true also for section 4.1.

4.1 Temperature and bias voltage dependence

Further measurements have been conducted to investigate the behavior of particle detection depending on temperature and bias voltage. Figure 6 shows the absolute event rate of all active sensor pixels combined for the setup described above. The bias voltage was varied between 0 V and the limit defined by the foundry (-60 V). The measurements were done at two different ambient temperatures: 22 and 5°C . We can not see saturation of the rate at high bias voltages at room temperature. This suggests that we have not yet reached the maximum charge collection efficiency. Also at 5°C saturation is not seen albeit a tripled event rate. Further measurements at lower temperatures and higher bias voltages will be conducted to investigate a wider parameter range.

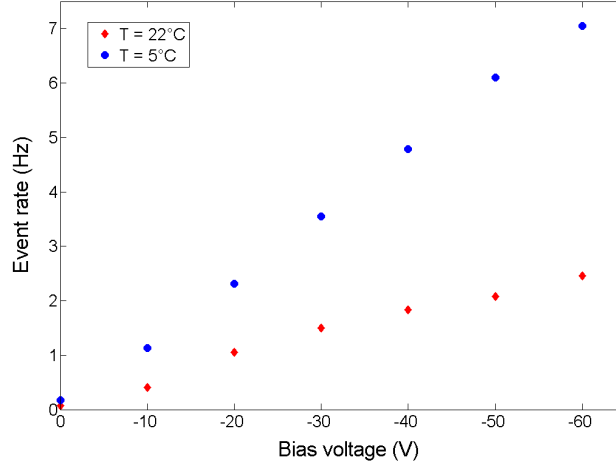


Figure 6. Event rate (detected particles per time unit) at different temperatures as a function of bias voltage for the HV2FEI4v1 after irradiation to $10^{16} (1 \text{ MeV } n_{\text{eq}})/\text{cm}^2$. The absolute values of this measurement bear large errors (not shown) due to a lack of automated measuring method. The graph is only intended to give a first idea of the sensor's behavior.

4.2 Leakage current

The leakage current driven by the bias voltage has been measured at different temperatures and with chips that received different integrated particle fluxes. Results are shown in figure 7. During these measurements neither the HV2FEI4 nor the FE-I4 were powered, hence no significant amount of electrical power was dissipated. Consequently, the measured ambient temperature represents the sensor's temperature well. This was also confirmed by an infra-red camera measurement.

The maximum leakage current is drawn at a temperature of 22°C by the chip irradiated to $10^{16} (1 \text{ MeV } n_{\text{eq}})/\text{cm}^2$. At $-60.0 \pm 0.1 \text{ V}$ the current reaches $-74 \pm 1 \mu\text{A}$. This corresponds to $1.25 \pm 0.02 \text{ mW}/\text{cm}^2$ for the active sensor area of 5.94 mm^2 . The chip irradiated to only 1/10 the flux ($10^{15} (1 \text{ MeV } n_{\text{eq}})/\text{cm}^2$) shows a leakage current about 13 times smaller. Currents drawn at 22°C are about 4 times larger than at 5°C , which translates into doubling the current approximately every 8.5°C . This behavior is in very good accordance with the theoretical behavior of a volume current (see [10]).

The leakage current for the unirradiated sensor is below 25 nA , which was the detection limit of the measurement setup used.

5 Performance of electronics after 862 Mrad

Performance of HV-CMOS sensor pixels is discussed in [3, 9, 12]: good signal-to-noise ratio and nearly 100% detection efficiency was shown. The most recent measurements on radiation hard pixel types were done on the HV2FEI4v2 chip during irradiation at the CERN X-ray facility. The most important results are briefly mentioned. A more complete discussion will be published elsewhere.

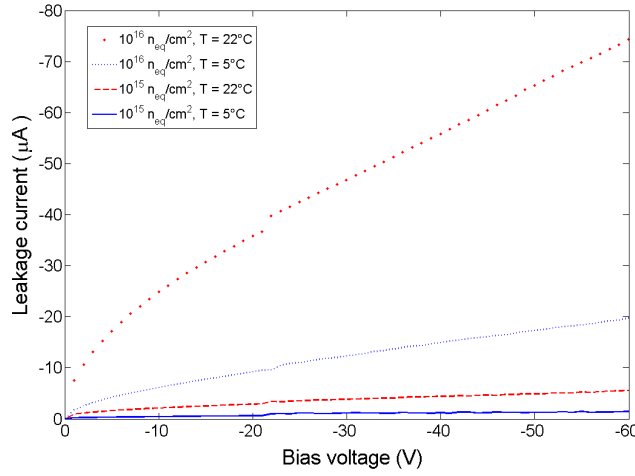


Figure 7. Leakage current of the HV2FEI4v1 depending on temperature and received particle flux. Measurement errors add up to 1 μA and 0.1 V respectively. Temperatures are accurate to 0.2 $^\circ C$. The kink at around -22 V is caused by change of measurement range of the used instruments.

Before irradiation an optimum set of chip parameters was set and the preamplifier gains of different pixels were measured. The sensor was then irradiated to a total dose of just over 860 Mrad. At each step of 100 Mrad the chip was annealed for one hour at 70 $^\circ C$. The preamplifier gains dropped below 20 % of their initial values after having finished the last step of irradiation. However, by re-optimizing the chip parameters we could restore the gains to about 90 % of their initial value (see figure 8). At the same time, the average noise only doubled from 75 to 150 electrons [11].

This result is quite promising and even more so knowing that not the whole pixel electronics are implemented in a radiation hard way. Figure 1 shows that only some transistors are enclosed and therefore can be expected to be radiation hard. The rest is implemented as standard transistors. This leaves possibilities for further improvement open, leading to even more radiation hard future generations of this chip.

6 Summary and outlook

Performance of capacitively coupled active pixel sensors in 180 nm HV-CMOS technology has been investigated. Focus lied in characterizing prototype sensors that were irradiated to HL-LHC fluences. The first two prototype generation chips have been measured separately after irradiation to $10^{16} (1 \text{ MeV } n_{eq}) / cm^2$ and 862 Mrad respectively. Non-ionizing irradiation was used to study bulk damage effects. Successful operation as capacitively coupled pixel detector after irradiation has been shown, even at room temperature. Saturation of the event rate at high bias voltages has not been observed which suggests that charge collection efficiency has not yet reached its highest possible value. Leakage current studies have been performed to confirm that the radiation damage from neutron irradiation really mainly affects the sensor substrate.

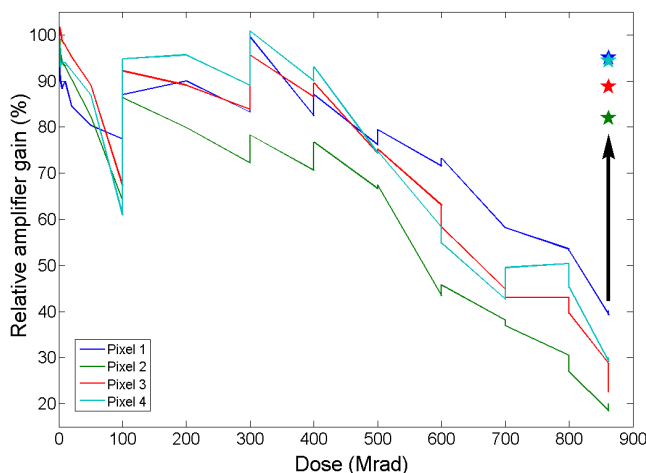


Figure 8. Preamplifier gain of four selected radiation hard HV2FEI2v2 pixels as a function of absorbed dose during X-ray irradiation. The abrupt changes at each full 100 Mrad reflect the regular annealing performed at those doses. The stars represent the gain values after irradiation to the full dose of 862 Mrad and subsequent re-optimization of the sensor chip parameters.

Irradiation with ionizing radiation (X-rays) was performed to study surface effects on the sensor electronics. Severe degradation of the preamplifier gains after irradiation has been measured. However, regular annealing during the irradiation process improved performance. Together with optimization of sensor chip parameters we were finally able to almost reach the initial gain values again. An increased noise level has been observed after irradiation. Under real conditions for large HEP experiments, sensors might run at low temperatures and therefore less annealing occurs. More detailed studies on the influence of annealing on pixel electronics will therefore be conducted.

Further measurements will include combined non-ionizing/ionizing radiation with protons to simulate conditions of HL-LHC operation as well as possible. Operational parameters of the sensor will be further optimized and the sensor performance studied in greater detail. Radiation hardness will be improved by optimizing the design of the next prototype generation. After the small-size prototypes an engineering run is planned to produce a cheap and radiation hard full reticle size chip. The ultimate goal is to provide a pixel detector that is suitable for HL-LHC detectors. Due to the flexibility of the sensor it also offers an alternative for the necessary replacement of the ATLAS silicon strip detector.

Acknowledgments

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Erratum: Performance of capacitively coupled active pixel sensors in 180 nm HV-CMOS technology after irradiation to HL-LHC fluences

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ERRATUM TO: [2014 JINST 9 C03020](#)

The caption of figure 1 in the original publication should be replaced by: “Schematic of the sensor pixel electronics. In the first generation prototype, all transistors are standard (linear) transistors. The circles represent transistors that are replaced by transistors of a radiation hard design (enclosed transistors) in the partially and fully radiation hard pixel types of the second generation prototype. The dashed circles mark transistors that are enclosed transistors only in the fully radiation hard pixel type.”

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Radiation-Hard Active Pixel Sensors for HL-LHC Detector Upgrades Based on HV-CMOS Technology

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Currently deployed silicon sensors in particle tracking detectors of the Large Hadron Collider (LHC) experiments will not withstand the augmented radiation levels in the foreseen High-Luminosity upgrade of the LHC (HL-LHC). Therefore, improved radiation hard sensors are necessary for HL-LHC experiments. We have developed several prototypes of High-Voltage CMOS (HV-CMOS) sensors compatible with the current read-out chip of the ATLAS pixel detector, FE-I4, and compatible with various analog and digital strip read-out systems.

This paper shows results of spectrum measurements with a Strontium-90 radioactive source of a sensor irradiated to 10^{15} (1 MeV n_{eq})/cm². Preliminary data analysis yields a charge signal decrease as much as 31% due to irradiation. An outlook on measurements with an enhanced setup to confirm the number stated above is given.

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Amsterdam, the Netherlands*

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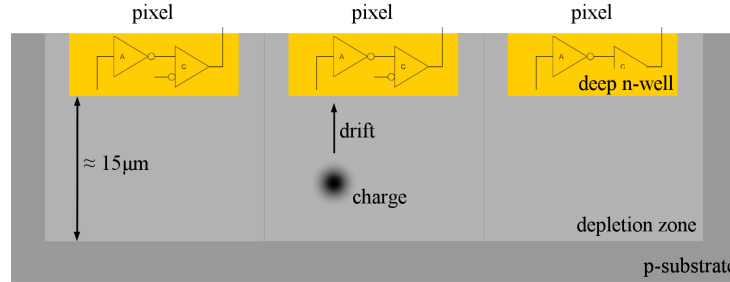


Figure 1: Schematic cross-section of the pixel sensor. The charge generated in the depletion zone by a passing ionizing particle is brought to the pixel electrode by drift. There it is amplified (and treated further) by the in-pixel electronics. The required CMOS-logic is embedded in a deep n-well and a subsequent additional p-well (not shown in the figure).

1. Sensor Prototypes

Tracker detectors are the parts of high-energy-physics collider experiments which are the closest to the particle collisions. Therefore they receive large amounts of particle flux and radiation dose. The innermost part of the tracking detector in the ATLAS experiment at CERN's LHC is composed of silicon semiconductor detectors. Currently the two technologies used (pixel and strip detectors) are designed to withstand a particle flux up to 10^{15} and 10^{14} ($1\text{ MeV } n_{eq}$)/ cm^2 respectively. These figures are significantly lower than the radiation levels that will be reached in the HL-LHC [1]. This is why new radiation hard technologies are required for HL-LHC tracking detectors. One promising candidate for HL-LHC silicon detectors is the HV-CMOS technology. First, it is expected to withstand high non-ionizing particle fluxes due to a very short charge collection time as well as high ionizing radiation doses thanks to the deep sub-micron process [2]. Second, it features a list of properties advantageous for its use as a silicon particle tracking detector, like high spatial resolution, low operation voltage, easier thermal management, and cheap production costs (a more exhaustive list is discussed in [3]).

In this paper we discuss results obtained with prototype sensors manufactured in a commercial 180 nm HV-CMOS process by AMS [4]. Key feature of these sensors is simple in-pixel electronics together with high-voltage capability on a bulk with moderate resistivity ($\approx 20\ \Omega\text{cm}$). The depletion depth is estimated at only $15\ \mu\text{m}$. With a high electric field applied, the charge collection by drift is very fast ($\approx 1\text{ ns}$) and therefore nearly insensitive to trapping by irradiation-induced bulk defects. The diffusion part of the charge signal is affected by bulk defects and will decrease the total signal after irradiation. The relatively low drift charge signal of about 1000 electrons generated by a minimum ionizing particle (MIP) is still reliably detected thanks to the in-pixel electronics, which includes pre-amplification of the signal (figure 1).

The sensor is designed to match the existing and well-known FE-I4 pixel readout chip [5]. In addition, the on-sensor electronics makes it possible to also use it as a strip-like detector and connect it to strip read-out systems of both the analog and digital kind. More information on the sensor can be found in [6], [7], [8], [9].

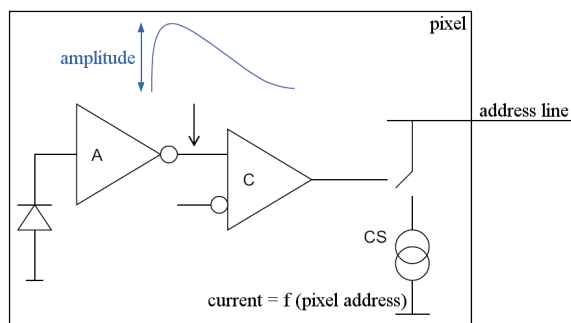


Figure 2: Schematic of the in-pixel electronics. The charge signal created in the depletion zone (depicted as a diode) is amplified by a charge sensitive pre-amplifier (A). The resulting signal is then treated by a comparator (C) and sent to the address line. The current source (CS) level is set in a manner so that different pixels can be identified by the signal height in the address line. The arrow indicates where we measure the amplitude for the spectrum measurements.

2. Spectrum Measurements

Although we expect the sensor to show high radiation hardness due to its design and process properties, it still suffers from signal degradation caused by irradiation effects. The first effect is the reduction of the initial charge signal. We measure this effect by recording the spectrum of a strontium-90 radioactive source with the sensor under test. Having the source emitting MIP-like electrons, the spectrum follows a Landau-distribution with the Most Probable Value (MPV) as characteristic value. Comparing the calibrated MPVs of different spectra puts in relation the charge created by a passing MIP. We obtain the spectrum by measuring the amplitudes of the particle signals directly after the pre-amplifier in one pixel (figure 2). These values (in mV) are then translated into charge units by performing a calibration measurement with an iron-55 source. Figure 3 shows the spectrum measured with a first generation prototype that was neutron irradiated to 10^{15} (1 MeV n_{eq})/cm² at the JSI TRIGA Mark II research reactor in Ljubljana, Slovenia. The fit of the Landau-distribution to the data outside the noise region gives an MPV of 67 to 72 mV. Using the conversion factor from a calibration measurement this corresponds to 1100 to 1190 electrons. The same measurement with an unirradiated sensor yields a value of about 1600 electrons. We deduct a value for the charge signal degradation due to irradiation between 26 and 31 %.

3. Perspectives

The method of taking all signals of the pre-amplifier above a certain threshold into account is actually biasing the Landau-distribution of the spectrum. All electrons from the source that reach the sensitive volume are taken into account. However, only the electrons near the upper limit of the source spectrum (2.28 MeV for strontium-90) act as MIP-like particles. A more exact measurement would include a scintillator trigger "behind" the sensor in order to measure only signals from particles with a high enough energy to traverse the sensor and arrive at the scintillator. Such a setup has been built and we are currently taking data in order to give a more exact result.

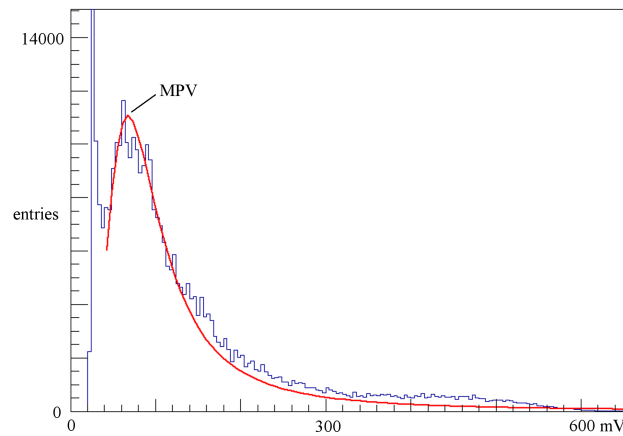


Figure 3: In blue, the spectrum of a strontium-90 radioactive source recorded with the neutron irradiated sensor. On the abscissa the amplitude heights measured after the pre-amplifier are plotted. In red the fit of a Landau distribution to the data is shown. The MPV serves as characteristic value for the spectrum. At larger amplitudes the measured spectrum shows more entries than expected from the Landau distribution. This is due to low-energy non-MIP-like electrons from the source. Future measurements will include an enhanced setup, which is only selecting high-energy particles in order to get more accurate results.

In addition, the described measurement has only been done with the first generation sensor prototype. The second and third generation have been produced and will also be measured within this year. These results will be published elsewhere.

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The publication

Latest results on the HV-CMOS Pixel Sensor in the ams H18 process ^[177]

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Latest results on the HV-CMOS Pixel Sensor in the ams H18 process ^[177]

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Latest results on the HV-CMOS Pixel Sensor in the ams H18 process ^[177]

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Appendix B

Description of the CCPDv1 chip design

The following document was kindly provided by Ivan Perić.^[154] It dates from 2012 and describes the CCPDv1 from the chip designers' view. Back then the CCPDv1 was still called HVC MOS2FEI4, which is reflected in the title of the document.

HVCMOS2FEI4 Detector Description

Prof. Dr. Ivan Perić

Overall structure of the chip

HVCMOS2FEI4 (shorter HV2FEI4) is an active pixel detector for ionizing particles; its pixel matrix is based on so-called “smart diodes”. Pixel electronics contains a CMOS charge sensitive amplifier, a comparator with the possibility of local threshold adjustment and an output stage.

A pixel responds to a particle hit by generating an output signal (a current pulse) with defined and constant amplitude.

HV2FEI4 can be readout in three ways:

1. Stand-alone readout: Pixel signals can be multiplexed to an output pad (monitor pad), in this way the chip can be tested alone, without an additional readout ASIC.
2. Hybrid-pixel readout: HV2FEI4 can be mounted on the FEI4 pixel-readout chip and readout as a smart pixel sensor.
3. Strip-like readout: HV2FEI4 can be connected to a strip-readout chip.

The hybrid-pixel readout is the main operation mode of the chip. The geometry and structure of the ASIC have been chosen to optimize such a readout.

The pixel matrix on HV2FEI4 is based on the unit cells that contain six pixels each $125\text{ }\mu\text{m} \times 33\text{ }\mu\text{m}$ large. The unit cell has an area that corresponds to two FEI4 pixels - $250\text{ }\mu\text{m} \times 100\text{ }\mu\text{m}$. The structure of one unit cell is shown in figure 1.

The entire pixel matrix is made by copying twelve such unit cells in y-direction (left-right direction in the figure 1 – the figure is rotated by 90°) and copying 20 unit-cell columns in x-direction (top-bottom direction in the figure).

In the case of the hybrid-pixel readout, signals EnR and EnL are zero. (These signals are generated by the row-control block that will be introduced later.) The output signals (currents) of the three yellow and the three grey pixels are summed and connected to the corresponding yellow- (“so”) or grey (“st”) pixel-pads via two pixel lines. (Every pixel line has its pull-up “resistor” that converts the summed current into a voltage pulse. The pull-up resistors are implemented as diode-connected NMOS transistors.) The pixel-pads are used to establish contact with two FEI4 channels placed above the unit cell. The signal can be transmitted either via a bump-bond (DC transmission) or

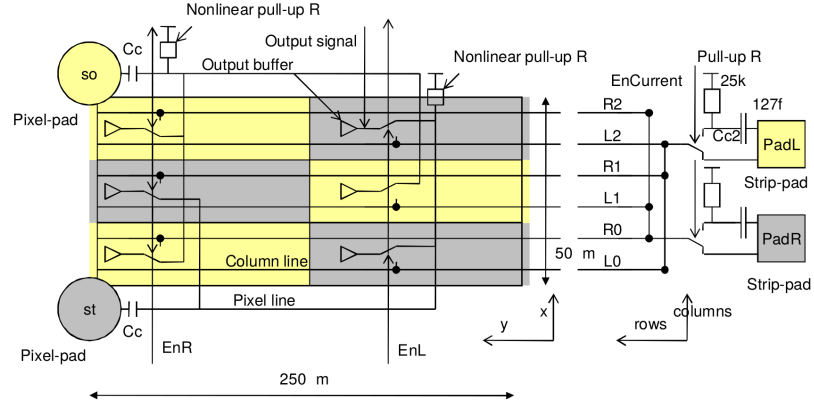


FIGURE 1: Structure of the unit cell

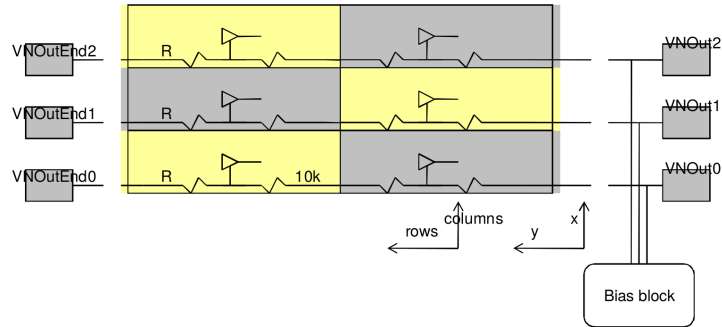


FIGURE 2: Biasing of output stages in the unit cell

capacitively (bumpless AC transmission). The yellow/grey pattern is chosen so to avoid that two neighbour pixels share the same pad.

The output buffers of the pixels placed in the different three columns of a unit cell are biased with different voltages and thus generate currents with different amplitudes. The biasing scheme is shown in figure 2.

The scheme assures that every pixel in a group (grey or yellow) has its unique signal amplitude.

(The current-amplitude can be set up to 10 μA , the value of the pull-up resistor is signal-dependent (nonlinear circuits) and need to be simulated.)

Since FEI4 can measure signal amplitudes, it will be possible to reconstruct the hit-position by examining the amplitude information.

Notice that the spatial resolution of HV2FEI4 is two times better in x-direction (z in ATLAS detector) and by factor 2/3 better in x direction (φ in ATLAS detector) than the resolution of the standard ATLAS sensor. Another advantage of the concept would be the possibility to build a hybrid detector without bumps.

In the case of the strip-like readout, signals EnR and EnL are set to one. The output signals of the pixels are connected to column-lines $L0/1/2$ and $R0/1/2$. There are six such lines per a $100\text{ }\mu\text{m}$ -wide unit-cell column (consist of 12 unit-cells in y -direction). There are therefore two column lines for every pixel column. The lines are shorted at the bottom of the column in the way that the “grey” pixels sent their signals to the “grey” strip-pad ($PadR$) and the “yellow” pixels to the “yellow” strip-pad ($PadL$). The bias scheme (figure 2) should, as first, assure that the hits occurring in the different $33\text{ }\mu\text{m}$ -wide pixel columns can be distinguished. We would also like to distinguish the hits according to their y (row) position. For this, we have the resistors R along the bias lines. By connecting the pads $VNOut0/1/2$ and $VNOutEnd0/1/2$ to suitable voltages, we can generate voltage drops along the bias lines. The pixel signals will be, in this case, both y - and x -dependent. The strip-like readout can be done using a charge sensitive or a current-sensitive readout chip. If we use a charge-sensitive readout chip (like a strip-detector readout ASIC), we will set $EnCurrent$ to zero. The current-signals flowing thorough the column lines are then converted to a voltage using $25\text{ k}\Omega$ linear pull-up resistors. The voltage pulses are then AC-coupled to the output pads using 127 fF capacitors $Cc2$. In the case of current-mode readout, $EnCurrent$ is one. A current-sensitive readout chip (like DCD) can so directly receive the current-mode signals. It is very important to keep in mind that every second cell is mirrored as shown in figure 3.

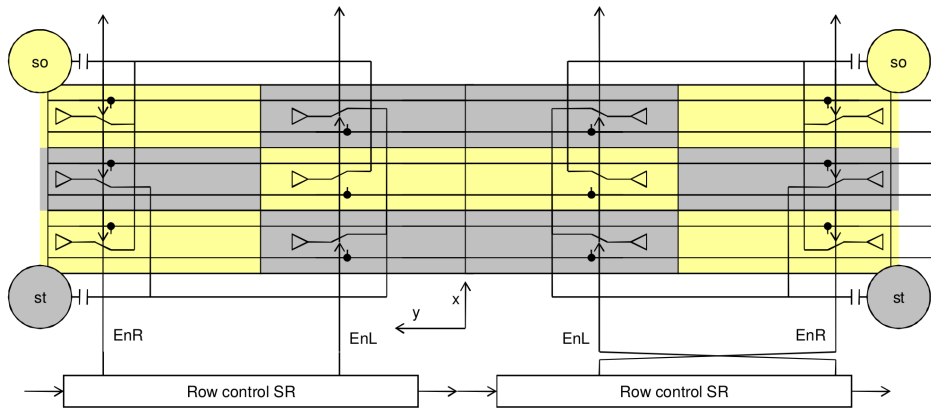


FIGURE 3: Mirroring

The pads of the outermost unit cells are oriented to outside. Such a mirroring was the easiest way to match the pixel-pads to the FEI4 geometry. Unfortunately it was done in a hurry and it imposes a few complications that, actually, were avoidable. The mirroring should not affect the hybrid-detector readout in any negative way (except for the unequal relation between the output signal amplitudes and the y hit-positions that will measure the pixels in the opposite parts of an FEI4 column pair).

Unfortunately, there is an unwanted effect to the strip-like readout. Grey and yellow

[illegible]

The block scheme of the chip is shown in figure 4. As already mentioned, the detector matrix contains 20 columns and 12 rows of unit cells, or 60x24 pixels. The row-control block is basically a shift register with the possibility to load the shift register bits into D-latches. The outputs of the D-latches are controlling the row-signals for the pixels such as EnR, EnL and several others that will be explained later.

The bias block contains fifteen 6-bit DACs that generate bias-voltages for the pixels.

Writing into the DACs is based on a shift register with attached D-latches as well. The serial input and the load (latch) are connected to the same pads as in the case of the row/column control. The clock for the DAC shift-register is connected to pad CkDAC. Outputs of the config- and DAC shift-registers are not accessible.

The pads for the strip-like readout (two per unit-cell column, strip-pads PadL/R in figure 1) are staggered (upper row PadL0-20, lower row PadR0-20) with a $100\mu\text{m}$ pitch in x-direction.

IO pads (listed later) are duplicated and placed at the bottom and at the top of the chip. In the case of the hybrid-detector readout, only the lower pad row is accessible, as shown in the right part of figure 4. In the case of strip-like readout, the readout chip is placed below the HVCMOS detector and the IO signals are connected to the upper IO pad row (see figure 4).

The pixel matrix contains three variants of pixels. The main pixel type – type A is designed to be compatible to DC- and AC readout (with- and without bumps). Sixteen (out of 20) unit-cell columns (columns 0-15) are made of such pixels. (Figure 1 shows a type A unit-cell.) Type A2 is a sub-variant of type A, the difference is that these pixels, when used in a hybrid-detector, can only be readout capacitively. (The strip-like readout is still possible in the same way as for the other pixel types.) The pixel-pads of these pixels (“st” and “so” in figure 1) are made without passivation openings. Also, capacitors C_c in figure 1 are replaced by short connections. Unit-cell columns 16, 17 and the last column (19) use such pixels. Type B pixels are used in the unit-cell column 18. These pixels have simplified electronics; I expect them to have a lower noise and a higher radiation tolerance. These pixels have the pixel-pads without passivation and capacitors C_c shorted as in the case of pixel variant A2.

The shaper output (will be explained later) of the pixel in the lower right corner of the pixel matrix is buffered using a source-follower and connected to the test pad - AmpOut. This signal can be measured. Notice that the source resistor for the NMOS-based source-follower is not implemented on the chip. A source resistor of about $5\text{ k}\Omega$ from the pad to ground (or better from the pad to a negative voltage of -1V) should be implemented on the PCB.

The shaper outputs of 35 pixels that belong to six uppermost unit-cells in the last unit-cell column are connected to the $55\mu\text{m}$ -pitch pixel pads (“ $55\mu\text{m}$ pads”). These pads can be used to readout the pixels using a TimePix ASIC. The connection assignment for the $55\mu\text{m}$ pads is shown in the figure as well. There is also a test pad – C - that has the FEI4-compatible geometry and is placed $50\mu\text{m}$ away from the “so” pad of the unit cell in the upper-right matrix corner. This test pad is connected to signal Injection that will

The diagram illustrates the internal structure of the Row control SR and Column control SR. The Row control SR (left) is a 12x4 grid of memory cells. It features word lines (Wr0, Wr1, Wr2) and bit lines (L0, L1, L2). The Column control SR (right) is a 20x6 grid of memory cells. It features word lines (Wr0, Wr1, Wr2) and bit lines (L0, L1, L2). The schematic also shows the internal structure of the Row control SR, including the EnR, InDACR(3:0), EnL, and InDACL(3:0) signals, and the internal structure of the Column control SR, including the EnStrip, EnCurrent, Pullup R, Cc2, PadL, and PadR signals.

Figure 5 shows one unit-cell with the segments of the row- and column-control blocks that provide the signals for this certain cell. Let us as first discuss the row-control signals.

There are eleven column-control bits for every unit-cell column. Notice that every column line can be separately connected to the monitor line by setting of bits L0-R3. The monitor line is a test feature that allows stand alone measurements with HV2FEI4 chip. The signal currents are in this way accessible through the monitor pad. The simplest way to use the monitor bus is to connect an external $\approx 10\text{ k}\Omega$ pull-up resistor to the monitor pad. In this way, a particle hit in one of the pixels that is connected to the monitor line generates a pulse of up to 100mV. (The maximal current amplitude generated by a single pixel is 10 μ A.)

In the case of the strip-like operation we would disconnect the column-lines from the monitor structure and connect them to strip-pads PadL and PadR by setting signal EnStrip to 1. As already explained, we can send the pixel currents directly to the strip-pads by setting EnCurrent to one, or (for EnCurrent=0) convert the current-pulse to a voltage-signal (using the 25 k Ω resistors) and couple the voltage pulse capacitively to the strip-pads (using 127 fF capacitors Cc2). Signals Wr0-Wr2 are write-signals for the tune-RAM.

The position of the control bits in the 11-bit segment of the column-control register is shown in the lower part of the figure.

Global bias block

The global bias block generates the bias voltages for the circuits in the pixels. The block contains fifteen 6-bit DACs. The DACs generate currents that are converted to bias voltages using diode-like circuits – the “bias diodes”. The bias voltages are then distributed in the pixel-matrix. Digital DAC values are written using a shift register – we refer to it as the DAC register. The structure of the DAC register-cell is equal to the one of the row/column configuration register-cell. The digital signals for the global shift-register are provided by the IO pads CkDAC, as well as Sin and Ld. The block diagram of the global bias block is shown in figure 6.

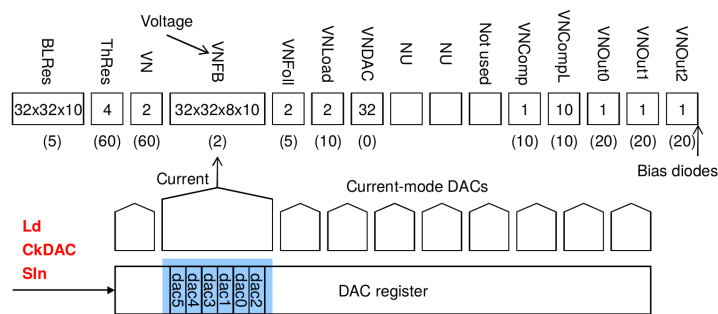


FIGURE 6: Global bias block

The figure also shows the position of DAC bits (dac5 is the MSB) as well as the position of the bias-diodes. The 6-bit DACs are based on current sources – one DAC consists of 63 identical PMOS current-sources that can be switched on and off according to the binary-weighted scheme. The bias voltage for the current-sources is generated by a diode-connected transistor with an attached pull-down resistor. The bias voltage is accessible via pad PBias. The full-scale DAC current is nearly 10 μ A. The numbers in the bias diodes denote the current reduction factors from the DAC to the element that uses the bias voltage. The nominal DAC values are written in brackets below the diodes. For example, in the case of diode VN, factor “two” means that the amplifier bias current

is two times smaller than the current that DAC generates. For the nominal DAC setting 60, the amplifier current is $\approx 5 \mu\text{A}$.

Pixel

A pixel is implemented as a “smart diode” – the pixel electronics is entirely placed inside a high voltage n-well. The n-well to p-substrate diode is used as a depleted sensor – n-well is the collecting electrode of the pixel. The pixel electronics uses n- and p-channel transistors. N-channel transistors are placed in a p-well that is surrounded by the n-well. The schematic of a pixel of type A/A2 is shown in figure 7.

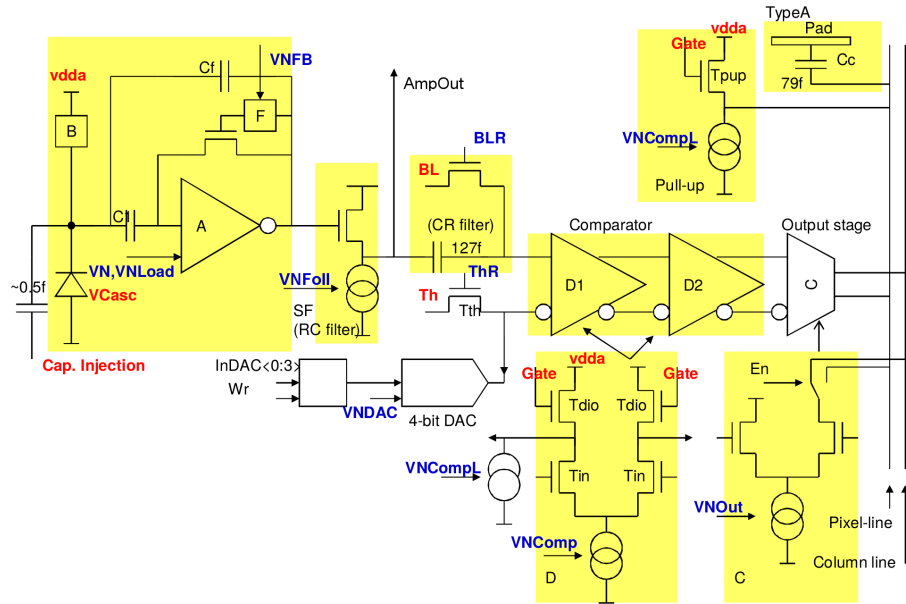


FIGURE 7: Schematic of the type A pixel

The p-substrate is connected to a high negative voltage – typically -60V . The N-well is biased using a highly-resistive element based on a PMOS (block B in figure 7) which assures that the signal charge, collected by n-well, can be amplified before it slowly flows into vdda.

Bias voltages (blue), are generated in the bias block placed on the chip periphery. Other voltages (red) are generated outside the chip and connected through IO pads. The connection between the n-well and the input of the charge sensitive amplifier A is established by capacitor C1 (implemented as a PMOS). The feedback capacitor Cf connects the output of the amplifier and the n-well.

The amplifier output is connected to a source follower (SF) that is used here as a nonlinear low-pass filter to decrease noise. The source follower output AmpOut is then

AC coupled to the non-inverting input of the two-stage comparator (D1 and D2) using a CR filter.

The use of AC coupling assures a well defined base line – the potential BL. This potential is generated outside the chip. The capacitance of the CR filter is implemented as MiM capacitor and the resistance as an NMOS transistor. By increasing of bias voltage BLRes, the time constant of the filter can be shortened.

The purpose of the comparator is, of course, to compare the signal with a threshold and in this way detect a particle hit. The inverting input of the comparator is connected to threshold voltage Th. An NMOS acting as resistance Tth is introduced to allow a fine adjustment of the threshold voltage. (Resistance of Tth can be decreased by increasing bias voltage ThRes.) Four-bit DAC (tune DAC) generates a current that flows through Tth and introduces a voltage across the device that adds to threshold Th. In this way, threshold can be adjusted in every pixel individually. The threshold dispersion caused by transistor mismatch can be so reduced. The four-bit tune DAC value is stored in four RAM cells. The RAM cells can be written using row-wise InDAC and column-wise Wr signals coming from the configuration registers. The DAC is based on NMOS current sources and it lowers the threshold when set to a higher value.

The comparator is made out of two fully-differential stages D. These amplifiers are implemented only with NMOS transistors, in order to avoid the capacitive crosstalk to the large HV n-well. (Notice that the n-well is shielded from the NMOS transistors by the p-well.) The load elements of amplifier D are two diode-connected NMOS transistors Tdio. The gain of the stage is equal to the ratio between W/L of Tin and Tdio. In order to maximize gain, transistors Tdio are about 17 μ m long and only 400nm wide. Bias currents connected to VNLoad are used to assure that outputs are not slowly pulled towards vdda by Tdio operating in subthreshold region when the respecting Tin is turned off. This would slow down the response of the amplifier.

One disadvantage of the diode-connected transistors versus the linear resistors is a large voltage drop from vdda to the output node due to the threshold voltage of the transistor. This limits the signal swing. In order to mitigate this, we have connected the gates of all diode-connected transistors to a separate pad (Gate) that can be put at a typically 300-400mV higher potential than vdda. We use VGate $\approx$ 2.1V and vdda = 1.95V.

The purpose of the output stage (C) is to generate the output current pulse with the amplitude derived from the bias voltage VNOut. The current of the output stage can be either directed into the pixel line (En=1) or into the column line (En=0).

In the case of the hybrid-detector readout, the output currents of three pixels are summed. The pixel-line is connected to the pull-up element that is implemented in only one pixel. The pullup element consists of a diode-connected transistor Tpup and a VNLoad-source.

The voltage signal on the pixel-line is either, in the case of pixel type A, coupled capacitively to the pixel-pad using MiM capacitor C_c (79fF), or in the case of pixel type A2 it is directly connected to the pad. Recall that type A2 pixel can not be bump-bonded since their pixel-pads do not have passivation openings.

The transistor-level schematic of the charge sensitive amplifier (type A pixel) is shown in figure 8.

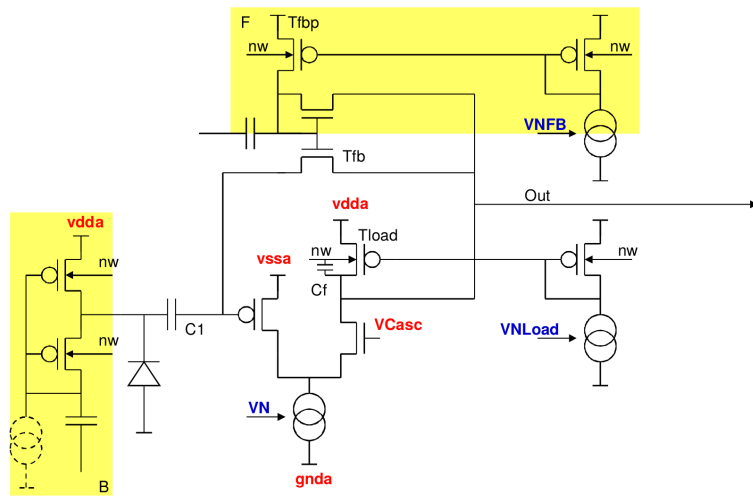


FIGURE 8: Transistor level schematic of the type A charge sensitive amplifier

Notice that feedback capacitor C_f is implemented using the drain diffusion capacitance of transistor T_{load} . The DC feedback is implemented with T_{fb} , such feedback has a nonlinear characteristics and it discharges C_f with nearly constant current. Transistor level schematics of bias blocks B and F are also shown.

Figures 9 and 10 show the schematics of the type B pixel. This pixel has simplified electronics with less NMOS transistors. In this way, I would like to achieve a lower noise and a better radiation tolerance. Note that a complex electronics introduces additional capacitive load for the high voltage n-well. Simpler electronics mean also a lower n-well capacitance and thus a lower noise. The main simplification is omitting of the tune DAC. Instead, I have added an additional second amplifier to the output of the preamplifier. If the main source of the threshold mismatch is the comparator, the additional amplification will reduce the threshold mismatch and hopefully make a tune DAC unnecessary. The discriminator of type B pixel consists of only one stage.

The second difference compared to type A is the absence of the source follower.

The schematic of the preamplifier is also simplified as can be seen in figure 10. Biasing of transistors T_{fbp} and T_{load} is now direct and not through additional NMOS transistors (compare with figure 8). Notice that this might impose a slight mismatch between the currents in the bias diodes (placed in the bias block) and the currents in transistors T_{fbp} and T_{load} , since the bulk of the diodes is connected to v_{dda} and the bulk of T_{fbp} and

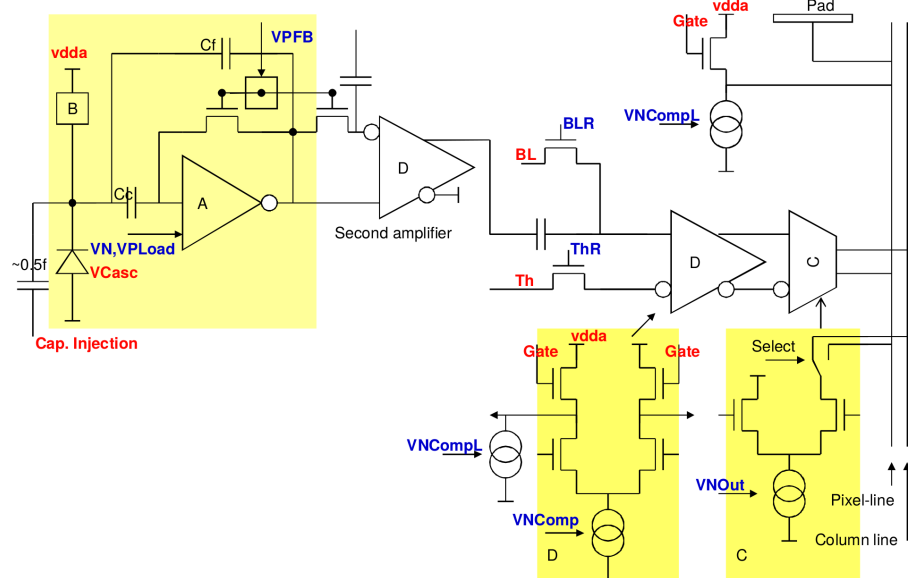


FIGURE 9: Schematic of the type B pixel

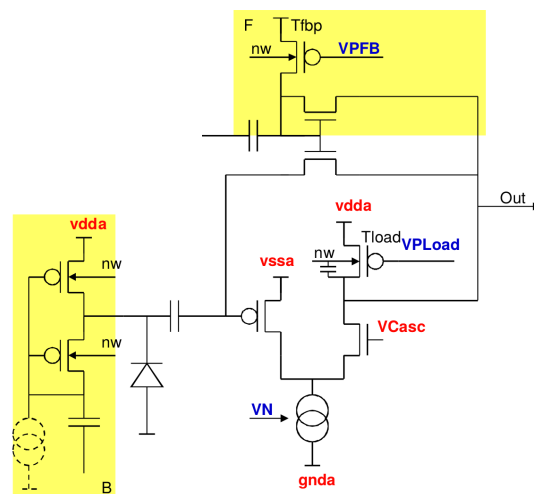


FIGURE 10: Transistor level schematic of the type B charge sensitive amplifier

Tload to the high-voltage n-well. This was the reason for choosing the more complicated scheme as the base line.

IO pads

The following table gives the pad list for the bottom pad row. The pads are numbered from left to right. These pads are used in the case of the hybrid-detector readout.

Number	Pad Name	Description	Value	Type
1	Vssa	Supply for the pixel amplifier input transistor	1.5V	Analog
2	Vdda	Pixel analog supply	1.95V	Power P (connected to protection diodes)
3	Gnda	Analog ground	0	Power N (connected to protection diodes)
4	VCasc	Cascode bias voltage	1.0	Analog
5	Gate	Bias overvoltage for diodes	2.1-2.3V	Analog, protection diodes with R
6	BL	Base line voltage	0.8V	Analog
7	Th	Threshold voltage	~0.85V	Analog
8	Gnd	Digital ground	0	Analog
9	Vdd	Digital supply	1.95V	Analog
10	Sub	P-substrate bias voltage	-60V	Analog
11	SIn	Digital input		1.8V CMOS
12	Ld	Digital input		1.8V CMOS
13	CkConf	Digital input		1.8V CMOS
14	CkDAC	Digital input		1.8V CMOS
15	PBias	DAC bias voltage - monitor	Connect decoupling cap	Analog
16	Monitor	Monitor line	Pull up to Vdda	Analog
17	Injection	Test pulse		Analog
18	Gnda	Analog ground (2)	0	Power N (connected to protection diodes)
19	Vdda	Analog supply (2)	1.95V	Power P (connected to protection diodes)
20	Vssa	Supply for the pixel amplifier input transistor (2)	1.5V	Analog
21	AmpOut	Output of the test pixel	Pull down to -1V necessary	Analog

The following table gives the pad list for the top pad row. The pads are numbered from left to right. These pads are used in the case of the strip-like readout.

Number	Pad Name	Description	Value	Type
1	Vssa	Supply for the pixel amplifier input transistor	1.5V	Analog
2	Vdda	Pixel analog supply	1.8V	Power P (connected to protection diodes)
3	Gnda	Analog ground	0	Power N (connected to protection diodes)
4	VCasc	Cascode bias voltage	1.0	Analog
5	Gate	Bias overvoltage for diodes	2.1-2.3V	Analog, protection diodes with R
6	BL	Base line voltage	0.8V	Analog
7	Th	Threshold voltage	~0.85V	Analog
8	Vdd	Digital supply	1.8	Analog
9	Gnd	Digital ground	0	Analog
10	Sub	P-substrate bias voltage	-60V	Analog
11	CkConf	Digital input		1.8V CMOS
12	SIn	Digital input		1.8V CMOS
13	Ld	Digital input		1.8V CMOS
14	CkDAC	Digital input		1.8V CMOS
15	Monitor	Monitor line	Pull up to Vdda	Analog
16	VNOut0	Output stage bias		Analog
17	VNOut1	Output stage bias		Analog
18	VNOut2	Output stage bias		Analog
29	Injection	Test pulse		Analog
20	VNOutEnd2	Output stage bias		Analog
21	VNOutEnd1	Output stage bias		Analog
22	VNOutEnd0	Output stage bias		Analog

Appendix C

Inventory of HV-CMOS sensors for high-energy physics

Brief history

Pixelated sensor chips for particle physics fabricated in a HV-CMOS process were first proposed in 2005 and a research project was funded in 2006.^[154] Subsequent measurement results with the first HV-CMOS MAPS were published in 2007.^[196] In 2009, the concept of the “Capacitively Coupled Pixel Detector” was introduced by suggesting a bumpless hybrid pixel detector.^[197] The underlying principle of having an n-in-p diode with the pixel electronics lying inside the deep n-well of this diode led to the term “smart diode” and “smart diode array” (SDA) for multiple diodes forming a pixel sensor.^[198] Finally, in 2012, HV-CMOS sensors were for the first time mentioned in conjunction with the HL-LHC⁽¹⁾ and ATLAS upgrades.^[120] In this year also the first prototype sensor of the CCPD-family was introduced, intended to serve as a proof of concept for ATLAS upgrades.

Overview of the H18 and H35 sensors

The following list comprises the sensors that were produced or are foreseen in the H18 and H35 processes from ams AG. It is supposed to complement the information given in this work and represents the status as at the end of 2015.

¹ At that point the HL-LHC project was still called sLHC (super LHC).

TABLE C.1: Overview of the sensors produced in the processes H18 and H35 from ams AG. The list represents the status as at the end of 2015. The sensors that are treated in this work are highlighted in gray.

process	name	also known as	readout scheme	date of submission
H18	CCPDv1	HV2FEI4v1	hybrid	Nov. 2011
	CCPDv2	HV2FEI4v2	hybrid	Nov. 2012
	CCPDv3	HV2FEI4v3	hybrid	Nov. 2013
	CCPDv4	—	hybrid	May 2014
	CCPDv5	—	hybrid	Feb. 2015
	H18DEMO	—	N/A	N/A
	HPixel	—	monolithic	Aug. 2011
	MuPix1	—	monolithic	Feb. 2011
	MuPix2	—	monolithic	Nov. 2011
	MuPix4	—	monolithic	Aug. 2012
	MuPix6	—	monolithic	Apr. 2013
	MuPix7	—	monolithic	Nov. 2013
H35	HVPixel1	—	monolithic	2006
	HVPixel2	—	monolithic & hybrid	2007
	HVPixelM1	PM1	monolithic	Feb. 2008
	HVPixelM2	PM2	monolithic	Feb. 2010
	CCPD1	—	hybrid	2007
	CCPD2	—	hybrid	July 2009
	H35CCPDv1	—	hybrid	Aug. 2014
	H35CCPDv2	—	hybrid	Feb. 2015
	H35DEMO	H35 Demonstrator	monolithic & hybrid	Sep. 2015
	HVStripV1	ATLAS Strip H35 v1	monolithic	Apr. 2014

Appendix D

Glossary

Abbreviations

^{55}Fe	iron-55
^{90}Sr	strontium-90
ABS	acrylonitrile butadiene styrene
AmpOut	buffered output signal of the in-pixel preamplifier of the CCPD
ATLAS	A Toroidal LHC Apparatus
2PACL	2-Phase Accumulator Controlled Loop
AMS-02	Alpha Magnetic Spectrometer
ASIC	application-specific integrated circuit
Be	beryllium
BL	base line voltage of the CCPD
BP	beam pipe
C3F8	octafluoropropane
CAE	computer aided engineering
CCPD	capacitively coupled pixel detector
CCPDv1 – CCPDv5	capacitively coupled pixel detector versions 1 – 5
CERN	Conseil Européen pour la Recherche Nucléaire (European Organization for Nuclear Research)
CF	carbon fiber
CFD	computational fluid dynamics
CMOS	complementary metal-oxide-semiconductor
CMS	Compact Muon Solenoid
CO ₂	carbon dioxide

CSA	charge sensitive amplifier
CTE	coefficient of thermal expansion
Cu	copper
DAC	digital-to-analog converter
DEPFET	depleted p-channel FET
DBM	Diamond Beam Monitor
e^-	electron or charge in quantities of the elementary charge e
e-h pair	electron-hole pair
ENC	equivalent noise charge
FET	field-effect transistor
FE-I3	ATLAS pixel readout chip (1 st generation)
FE-I4	ATLAS pixel readout chip (2 nd generation)
FE-I4B	ATLAS pixel readout chip refined for the IBL
flex	flexible printed circuit board
FTK	Fast Tracker
FWHM	full width at half maximum
GND	digital ground of the CCPD
H18	180 nm HV-CMOS process by ams AG
H35	350 nm HV-CMOS process by ams AG
HEP	high-energy physics
HGCAL	High Granularity Calorimeter
HL-LHC	High-Luminosity LHC
HR	high-resistivity
HV2FEI4	deprecated name of the CCPD sensor family
HVCMOS2FEI4	deprecated name of the CCPD sensor family
HV-CMOS	high-voltage CMOS
IBL	Insertable B-Layer
ID	Inner Detector
IP3D	tagger based on the impact parameter significance
IPT	Inner Positioning Tube
IST	Inner Support Tube
ITk	Inner Tracker
LAr	liquid argon
LHC	Large Hadron Collider
LINAC	linear accelerator
LINAC4	Linear Accelerator 4
LIU	LHC Injectors Upgrade

LS1 – LS5	Long Shutdown 1 – Long Shutdown 5
μ^+	antimuon
MAPS	Monolithic Active Pixel Sensors
MIP	minimum ionizing particle
MOSFET	metal–oxide–semiconductor field-effect transistor
MPV	most probable value
N/A	not applicable or data not available
NEG	non-evaporable getter
NIEL	non-ionizing energy loss
NMOS	n-type metal-oxide-semiconductor logic
NTC	negative temperature coefficient thermistor
p^+	proton
PMMA	polymethyl methacrylate (acrylic glass)
PMOS	p-type metal-oxide-semiconductor logic
PP1	patch panel 1
PS	Proton Synchrotron
PSB	Proton Synchrotron Booster
PSI	Paul Scherrer Institute
R&D	research and development
RD50	CERN research collaboration “Radiation Hard Semiconductor Devices for Very High Luminosity Colliders”
SEU	single event upset
SiO_2	silicon dioxide
SCT	Semiconductor Tracker
SM	Standard Model
SNR	signal-to-noise ratio
SOI	silicon-on-insulator
SPS	Super Proton Synchrotron
SR1	ATLAS Inner Detector Integration Facility
SUB	bias voltage of the CCPD
SV1	secondary-vertex tagger
TAS	Target Absorber Secondaries
TCAD	technology computer aided design
thr	threshold
TH	global threshold voltage of the CCPD
TID	total ionizing dose
ToT	time-over-threshold

TRT	Transition Radiation Tracker
TSV	through-silicon via
VELO	Vertex Locator
VI	Vacuum Inner Detector
VCASC	cascode bias voltage of the CCPD
VDD	pixel digital power supply of the CCPD
VDDA	pixel analog power supply of the CCPD
VSSA	preamplifier power supply of the CCPD
z_0	origin of the z-coordinate, nominal interaction point in ATLAS
z_z	position at the z-coordinate z (in mm)

Units

Numerical values are from [199]. Uncertainties are given in the concise notation where the number in the bracket applies to the preceding least significant digits.

Quantity	Unit	Symbol	Conversion
length	meter	m	m
mass	kilogram	kg	kg
time	second	s	s
electric current	ampere	A	A
temperature	kelvin	K	K
amount of substance	mole	mol	mol
mass	gram	g	10^{-3} kg
mass		$\text{eV } c^{-2}$	$1.782\,661\,906(11) \times 10^{-36}$ kg
momentum		$\text{eV } c^{-1}$	$5.344\,285\,948(33) \times 10^{-28}$ kg m s $^{-1}$
time	minute	min	60 s
time	hour	h	60 min
temperature	degree celsius	°C	K − 273.15
force	newton	N	kg m s $^{-2}$
energy	joule	J	N m
energy	electron volt	eV	$1.602\,176\,6208(98) \times 10^{-19}$ J
power	watt	W	J s $^{-1}$
pressure	pascal	Pa	N m $^{-2}$
pressure	bar	bar	10^5 Pa
electric charge	coulomb	C	A s
electric potential	volt	V	J C $^{-1}$
electrical resistance	ohm	Ω	V A $^{-1}$
electrical capacitance	farad	F	C V $^{-1}$
magnetic flux	weber	Wb	V s
magnetic flux density	tesla	T	Wb m $^{-2}$
absorbed ionizing radiation dose	gray	Gy	J kg $^{-1}$
absorbed ionizing radiation dose	rad	rad	10^{-2} Gy
radioactivity	becquerel	Bq	s $^{-1}$
frequency	hertz	Hz	s $^{-1}$
volume	litre	l	10^{-3} m 3
cross section	barn	b	10^{-28} m 2

Unit prefixes

Multiple	Prefix	Symbol
10^{12}	tera	T
10^9	giga	G
10^6	mega	M
10^3	kilo	k
10^{-2}	centi	c
10^{-3}	milli	m
10^{-6}	micro	μ
10^{-9}	nano	n
10^{-12}	pico	p
10^{-15}	femto	f
10^{-18}	atto	a

Constants

Numerical values are from [199]. Uncertainties are given in the concise notation where the number in the bracket applies to the preceding least significant digits.

Quantity	Symbol	Value
speed of light in vacuum	c	$2.997\,924\,58\,\text{m s}^{-1}$ (exact)
Euler's number	e	$\sum_{n=0}^{\infty} \frac{1}{n!} = 2.718\,281\,828\,459\,045\dots$ (exact)
elementary charge	e	$1.602\,176\,6208(98) \times 10^{-19}\,\text{C}$
vacuum permittivity (electric constant)	ε_0	$\frac{1}{\mu_0 c^2} = 8.854\,187\,817\dots\,\text{F m}^{-1}$ (exact)
Boltzmann constant	k_{B}	$1.380\,648\,52(79) \times 10^{-23}\,\text{J K}^{-1}$ $= 8.617\,3303(50) \times 10^{-5}\,\text{eV K}^{-1}$
electron mass	m_{e}	$9.109\,383\,56(11) \times 10^{-31}\,\text{kg}$ $= 0.510\,998\,9461(31)\,\text{MeV } c^{-2}$
vacuum permeability (magnetic constant)	μ_0	$4\pi \times 10^{-7}\,\text{N A}^{-2}$ (exact)
Avogadro constant	N_{A}	$6.022\,140\,857(74) \times 10^{23}\,\text{mol}^{-1}$
pi	π	$3.141\,592\,653\,589\,793\dots$
classical electron radius	r_{e}	$2.817\,940\,3227(19) \times 10^{-15}\,\text{m}$

Roman symbols

The values and units are those used in this thesis.

Symbol	Description	Value/Unit
%	percent	dimensionless
a	constant in Relation 2.9	$\text{eV } \mu\text{m}^{-1}$
b	constant in Relation 2.9	$\text{eV } \mu\text{m}^{-1}$
A	area	cm^2
A_{m}	molar mass	g mol^{-1}
c_{r}	removal constant	cm^2
C	shell correction	dimensionless
C_{D}	detector capacitance	F
d, d_{dep}	depletion thickness	length
d_0	offset to the depletion thickness	length
D	diffusion constant	$\text{cm}^2 \text{s}^{-1}$
D_{e}	diffusion constant for e^-	$\text{cm}^2 \text{s}^{-1}$
D_{h}	diffusion constant for holes	$\text{cm}^2 \text{s}^{-1}$
erf	error function	dimensionless
E	particle energy	MeV
E_{g}	band gap energy	eV
$E_{\mu\text{c}}$	critical energy for muons	
$\vec{E}$	electric field	V cm^{-1}
$\vec{E}_{\text{w}}$	weighting field	V cm^{-1}
f	frequency	Hz
g_{i}	acceptor introduction rate	cm^{-1}
I	electric current	A
I_{i}	instantaneous current	A
I_{L}	leakage current	A
I_{e}	mean excitation energy	eV
k	hardness factor	dimensionless
ln	natural logarithm	dimensionless
$\mathcal{L}$	instantaneous luminosity	$\text{cm}^{-2} \text{s}^{-1}$
$\mathcal{L}_{\text{int}}$	integrated luminosity	b^{-1}
M	rest mass	$\text{MeV } c^{-2}$
n_{e}	electron density	number of e^- per g

Symbol	Description	Value/Unit
$n_{\text{eq}} \text{ cm}^{-2}$	unit of the 1 MeV-neutron equivalent flux	
N	number of events	dimensionless
N_{C}	concentration of removable dopant atoms	cm^{-1}
N_{eff}	effective doping concentration	cm^{-1}
$N_{\text{eff},0}$	initial effective doping concentration	cm^{-1}
p	pixel or strip pitch	length
p	pressure	mbar
pdf	probability density function	dimensionless
P	power	W
q	electric charge	C
q_{p}	point charge	C
r	radial coordinate in ATLAS	length
$\sqrt{s}$	center-of-mass collision energy	TeV
S	S-curve function	dimensionless
t	time	time
t_0	starting time of a time period	time
t_{c}	charge collection time	s
tan	tangent	dimensionless
T	temperature	$^{\circ}\text{C}$ or K
T_{amb}	setpoint of the AC-system in SR1	$^{\circ}\text{C}$
T_{bp}	temperature setpoint of the beam pipe	$^{\circ}\text{C}$
T_{CO_2}	temperature setpoint of the cooling system	$^{\circ}\text{C}$
T_{max}	maximum temperature	$^{\circ}\text{C}$
v	speed	m s^{-1}
$\vec{v}$	velocity	m s^{-1}
$\vec{v}_{\text{d}}$	drift velocity	cm s^{-1}
$\vec{v}_{\text{p}}$	velocity of a point charge	cm s^{-1}
V_0	built-in potential	V
V_{b}	reverse bias voltage	V
W	energy transfer in a single collision	eV
W_{max}	maximum energy transfer in a single collision	MeV
x	generic abscissa coordinate or length	arbitrary or length
X_0	radiation length	g cm^{-2}
z	axial coordinate of ATLAS and the IBL mock-up	length
z_{c}	charge number	dimensionless
Z	atomic number	dimensionless

Greek symbols

Symbol	Description	Value/Unit
β	$\frac{v}{c}$	dimensionless
γ	$\frac{1}{\sqrt{1-\beta^2}}$ (Lorentz factor)	dimensionless
δ	density correction	dimensionless
ε	absolute permittivity	F m ⁻¹
ε_{Si}	relative permittivity of silicon	11.9 ^[81]
η	pseudorapidity	dimensionless
θ	scattering angle	angle
λ_{I}	nuclear interaction length	g cm ⁻²
μ	charge carrier mobility	cm ² V ⁻¹ s ⁻¹
μ_{e}	electron mobility	cm ² V ⁻¹ s ⁻¹
μ_{h}	hole mobility	cm ² V ⁻¹ s ⁻¹
ρ	electrical resistivity	Ω cm
σ	cross-section	b
σ_{Diff}	standard deviation of a charge distribution spread out by diffusion	length
σ_{ENC}	standard deviation of the Gaussian noise	mV
σ_{pos}	geometric resolution	length
τ	charge carrier lifetime	s
φ	azimuthal coordinate in ATLAS	angle
Φ	particle flux	particles per cm ²

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The following abbreviations of journal names are used in the bibliography:

- Chin. Phys.: Chinese Physics;
- JINST: Journal of Instrumentation;
- NIMA: Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment;
- PoS: Proceedings of Science.

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