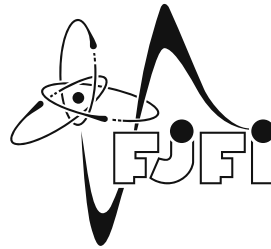


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Faculty of Nuclear Physics and Physical Engineering

Department of Physics
Nuclear and Particle Physics



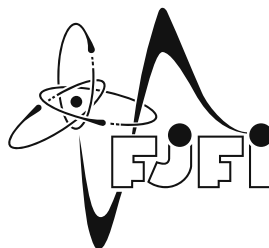
Evaluation of SiPMs for current and future High Energy Physics detectors

BACHELOR'S THESIS

Author: Timea Szöllösová
Supervisor: Solangel Rojas Torres Ph.D.
Year: 2024

České vysoké učení technické v Praze
Fakulta jaderná a fyzikálně inženýrská

Katedra fyziky
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Evaluace křemíkových fotonásobičů pro současné a budoucí detektory fyziky vysokých energií

BAKALÁŘSKÁ PRÁCE

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Jazyk práce: Angličtina

Pokyny pro vypracování:

- 1) Revize literatury
 - a) Současné HEP detektory využívající SiPM
 - b) Budoucí HEP detektory využívající SiPM
- 2) Evaluace SiPM
 - a) Vytvoření zkušebního držáku pro studium SiPM v laboratoři s (a) laserem a (b) kosmickým zářením
 - b) Charakterizace různých SiPM a jejich porovnání

Doporučená literatura:

- [1] Frank Simon, Silicon photomultipliers in particle and nuclear physics, Nuclear Instruments and Methods in Physics Research Section A, Volume 926, 2019, doi.org/10.1016/j.nima.2018.11.042.
- [2] Robert Klanner, Characterisation of SiPMs, Nuclear Instruments and Methods in Physics Research Section A, 2019, doi.org/10.1016/j.nima.2018.11.083.
- [3] ALICE Collaboration, Letter of intent for ALICE 3: A next generation heavy-ion experiment at the LHC, CERN-LHCC-2022-009, LHCC-I-038, 2022, <https://cds.cern.ch/record/2803563>.
- [4] W. Baldini et al, Measurement of parameters of scintillating bars with wavelength-shifting fibres and silicon photomultiplier readout for the SHiP Muon Detector, Journal of Instrumentation, 2017, 12 P03005, doi.org/10.1088/1748-0221/12/03/P03005.
- [5] Maciej Slupecki, The Fast Interaction Trigger for the ALICE Upgrade, 2020, <https://cds.cern.ch/record/2741462>.

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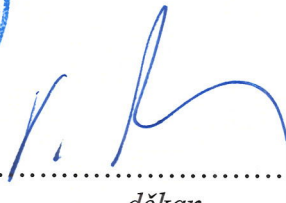
Termín odevzdání bakalářské práce: 02.08.2023

Doba platnosti zadání je dva roky od data zadání.


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Academic year: 2022/2023



Student: Timea Szöllösová

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Instructions:

- 1) Literature revision
 - a) Current HEP detectors using SiPMs
 - b) Future HEP detectors using SiPMs
- 2) Evaluation of SiPMs
 - a) Set up a test bench to study SiPMs in the laboratory with (a) laser and (b) cosmic ray radiation
 - b) Characterise different SiPMs and compare their performance

Recommended literature:

- [1] Frank Simon, Silicon photomultipliers in particle and nuclear physics, Nuclear Instruments and Methods in Physics Research Section A, Volume 926, 2019, doi.org/10.1016/j.nima.2018.11.042.
- [2] Robert Klanner, Characterisation of SiPMs, Nuclear Instruments and Methods in Physics Research Section A, 2019, doi.org/10.1016/j.nima.2018.11.083.
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- [5] Maciej Slupecki, The Fast Interaction Trigger for the ALICE Upgrade, 2020, <https://cds.cern.ch/record/2741462>.

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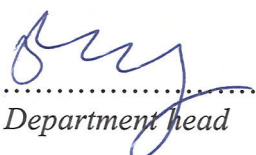
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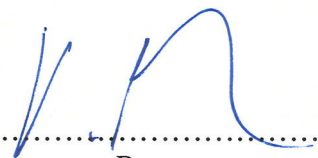
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In Prague on 20.10.2022



PROHLÁŠENÍ

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podpis

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Timea Szöllősová

Title:

Evaluation of SiPMs for current and future High Energy Physics detectors

Author: Timea Szöllösová

Study program: Nuclear and Particle Physics

Supervisor: Solangel Rojas Torres Ph.D.

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Abstract: This work explores the role of the silicon photomultipliers (SiPMs) in use for high-energy physics (HEP) detectors. As the semiconductor industry is rapidly evolving, SiPMs emerged as a promising solution for current and future HEP experiments. Thanks to their high efficiency and precision in photodetection, remaining compact and cost-effective at the same time, they became suitable detectors for the field. Beginning with a brief introduction to the semiconductors and detection principles, this thesis provides an overview of current and future implementations of SiPMs and progresses to an examination of SiPMs and their compatibility with plastic scintillators. Experimental evaluation of the SiPMs is conducted through a basic laser laboratory setup and measurements of the scintillator bar with the cosmic rays. The synthesis of findings aims to underscore the suitability of the SiPMs for diverse HEP experiments.

Key words: SiPM, photodetectors, HEP

Název práce:

Evaluace křemíkových fotonásobičů pro současné a budoucí detektory fyziky vysokých energií

Autor: Timea Szöllösová

Studijní program: Jaderná a částicová fyzika

Druh práce: Bakalářská práce

Vedoucí práce: Solangel Rojas Torres Ph.D.
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Abstrakt: Táto práca skúma využitie kremíkových fotonásobičov (SiPMs) v detektoroch požívaných v oblasti fyziky vysokých energií. Vzhľadom na neustály rýchly rozvoj polovodičovej techniky sa javí využitie SiPMs v oblasti vysokých energií ako zaujímavá a nádejná alternatíva k iným konštrukčným materiálom detektorov. Vďaka ich vysokej efektívnosti a rozlišovacej schopnosti, pri zachovaní kompaktnosti a cenovej dostupnosti, umožňuje použitie tohto typu detektorov v spomínanej oblasti. Úvod tejto práce je venovaný všeobecnému opisu polovodičov fotodetektorov. Ďalej ponúka prehľad súčasného využitia SiPMs a popisuje možnosti ich implementácie v budúcnosti. V experimentálnej časti je popísaný spôsob samotného testovania SiPMs a ich porovnanie a kompatibilita s plastovými scintilátormi. Merania boli prevedené pomocou interakcií s laserovým zväzkami a kozmickým žiarením. Zhrnutím týchto zistení je snaha poukázať na vhodnosť použitia kremíkových fotonásobičov pri konštrukcii detektorov pre rôzne aplikácie v experimentoch fyziky vysokých energií.

Klíčová slova: křemíkové fotonásobiče, fotodetektory, fyzika vysokých energií

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Preface

Understanding the fundamental building blocks of the universe represents one of humanity's most significant endeavours. Within this challenge, high-energy physics (HEP) stands at the forefront of scientific discoveries, and the crucial part lies in detection technologies unravelling the strange petite world of particles and their interactions, otherwise remaining hidden.

This thesis explores the relatively new and quickly evolving silicon detectors, seeking out the silicon photomultipliers (SiPMs). SiPMs have emerged as a promising technology for photodetection with high efficiency and precision while remaining compact and cost-effective. The unique properties of these photodetectors and their evaluation are the goal of this thesis, with an overview of their current and future uses in the HEP.

To facilitate a fluent passage through this work, Chapter 1 explains the fundamental concepts of HEP and particle detectors. By clarifying the title of the thesis itself, it allows the reader to perceive the ideas further in detail and presents motivation for the experimental part of this work.

Chapter 2 describes the foundation of semiconductor detectors, starting from the band theory, and provides an overview of the photodetectors and their principles. These concepts provide a necessary introduction to the SiPMs, and their characteristics, such as photon detection efficiency, dark count rate and other noise factors, are discussed in detail.

Delving into the current landscape of the HEP detectors and experiments employing the SiPMs in Chapter 3, their key designs and implementation techniques are discussed. Further developments in this sector are also investigated, and future experiments relying on this technology are outlined.

Chapter 4 details the experimental evaluation of SiPMs conducted. The SiPMs were tested with laboratory-based laser setup and cosmic rays detection, implementing their compatibility with scintillating materials. This elucidates their behaviour in conditions similar to many of the HEP experiments.

Through performed experiments and analysis, this thesis aims to contribute to the knowledge regarding the SiPM applications and limits for the HEP uses in large experiments, which play pivotal roles in this field, as well as demonstrate the various methods and techniques available for the work with these sensor arrays.

Chapter 1

High Energy Physics and particle detectors

This chapter provides an introduction of concepts for the scope of this thesis. It briefly introduces the Standard Model of particle physics, mentions accelerator technology and describes a modern detector system example. The structure for this chapter was inspired by Ref. [1].

1.1 Elementary particle physics

High Energy Physics (HEP), also known as Elementary Particle Physics, is a study of fundamental forces, particles and interactions described by the Standard Model (SM) and searches for physics beyond this description.

The Standard Model has been developed and tested over decades with high accuracy and is based essentially on symmetry principles. Figure 1.1 shows the fundamental particles described by the SM. The set contains three generations of quarks and leptons, and together with bosons are considered without any inner structure. The gauge bosons responsible for the electromagnetic, weak, and strong interactions are the photons, Z and W bosons, and the gluons, respectively, are considered carriers of the fundamental forces. The Higgs boson provides the mechanism for the elementary particles to generate mass. All elementary particles have corresponding antiparticles with the same exact properties but opposite electric charges, which, in the case of zero-charge particles, become indistinguishable.

Despite the SM being a theoretically completed theory, it still does not describe all the natural phenomena and requires further investigation. For instance, the model does not describe various astrophysical observations as dark matter and matter-antimatter asymmetry. Furthermore, the gravitational force and the neutrino mass also lack their explanations. This leads to many Beyond Standard Model (BSM) theories, which state the need for experimental verification, enriching the experimental physics to precision measurements for the SM and search for new particles and mechanisms [3].

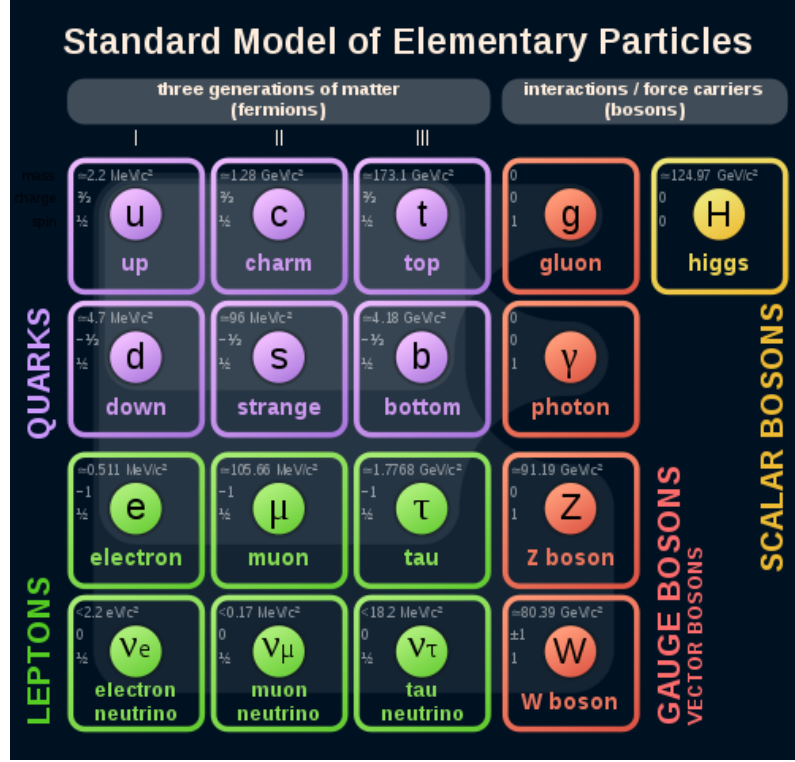


Figure 1.1: The classification of elementary particles described in the Standard Model with their basic properties. *Taken from Ref. [2].*

1.2 Particle accelerators

Particle accelerators are essential tools in probing the fundamental particles and processes. Colliding particles at near-light speeds recreate conditions similar to those just after the Big Bang, allowing the exploration of the early universe through the quark–gluon plasma (QGP). There are various types of accelerators, including linear accelerators (linacs) and circular accelerators, each designed for specific purposes and experiments, which are further divided into fixed–target and collider experiments. The fixed target experiments use one particle beam to hit the stationary target, while the collider experiments collide two beams of particles (the beams may consist of different particle species and cocktails).

Apart from the astrophysics experiments acquiring the highly energetic particles from cosmic rays, the HEP experiments utilize the particle accelerators to achieve the desired energies. Accelerated particles such as electrons, protons, or heavy ions must be charged, while often (especially in collider physics) antiparticles are also required. The interaction rate ϕ is one of the most crucial parameters describing the number of events expected for a particular reaction. For fixed target experiments, it depends on the rate of beam particles n hitting the target, the cross section of the observed reaction σ , and the target thickness d and may be expressed followingly

$$\phi = \sigma \cdot N_A \cdot \rho \cdot n \cdot d = \sigma \cdot L, \quad (1.1)$$

where N_A is the Avogadro's number, ϱ the density of the target material, and the luminosity L can be used to rewrite the formula. In the collider experiments, the luminosity depends on the cross section of the two beams in both transversal directions, σ_x , σ_y , and the number of particles in the second beam instead of the properties of the target as in the previous case. This brings us a relation for the luminosity on colliders as

$$L \propto \frac{n_1 \cdot n_2}{\sigma_x \sigma_y}, \quad (1.2)$$

where the determination of the cross section is non-trivial, nevertheless, the known processes may be used for fixing the luminosity [1]. This parameter describes the likelihood of collisions resulting in a desired interaction and, therefore, is an important metric in accelerator physics.

1.2.1 Current and future accelerators in HEP

Accelerator physics is a broad field, and therefore, only a brief overview of accelerators further mentioned in this work will be presented in this section. The author recommends for further overview with historical context Ref. [4].

Large Hadron Collider (LHC) at CERN

The Large Hadron Collider (LHC) is located at CERN (Conseil Européen pour la Recherche Nucléaire - European Council for Nuclear Research) near Geneva, on the border of France and Switzerland and at the moment (2024), is the largest particle accelerator on the world with a circumference of 27 km. It replaced the Large Electron Positron (LEP) collider in its original tunnel and was designed for finding the Higgs boson which required larger energies than the LEP was allowing. The LHC accelerates protons and heavy ions at energies at the centre-of-mass of 13 TeV and more for protons and 5 TeV for lead ions [5]. Currently, the lead program is ongoing, while in the past, there were xenon beams during Run 2, and there are future calls for oxygen [6].

The LHC interaction points host the four major experiments of the collider ATLAS (A Toroidal LHC Apparatus), CMS (Compact Muon Solenoid), ALICE (A Large Ion Collider Experiment), and LHCb (LHC beauty experiment). Each of the experiments has unique capabilities and agendas. The CMS and ATLAS experiments are oriented towards the precision measurements of the SM after their joint discovery of the Higgs boson in 2012. The ALICE focuses on the QGP studies, and the LHCb observes the CP symmetry violation via beauty quark reactions.

The near future of the LHC leads towards the High Luminosity LHC (HL-LHC), which is to be installed during the LHC's Long Shutdown 3 (LS3) [5]. During installation, all the experiments undergo major (ATLAS, CMS) or minor (LHCb, ALICE) upgrades to keep up with the HL-LHC integrated luminosity (see formula (1.2)). The upgrade plan in detail is in Figure 1.4, and it will prolong the potential of the research program up to 2040.

Further development and use of the LHC may lie in pre-accelerating particles for the Future Circular Collider (FCC), which would collide e^+e^- in its first runs and

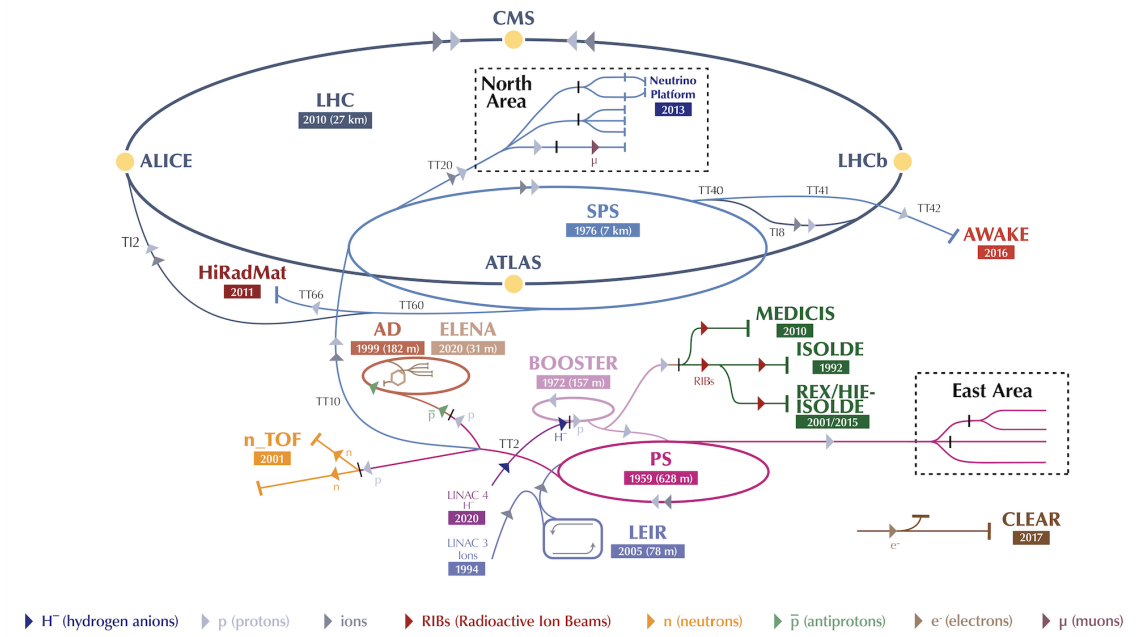


Figure 1.2: Layout of the CERN accelerator complex (2022) with colorly distinguished particle accelerated (see the legend). *Taken from Ref. [7].*



Figure 1.3: Timeline of the LHC with luminosity upgrades from 2022. The schedule has been shifted a few times, notably due to the COVID-19 world pandemic. *Taken from Ref. [8].*

later upgrade towards hadron collisions. Nevertheless, the project is still waiting for its approval, the Feasibility Study for the FCC is currently undergoing until 2027 [9].

Relativistic Heavy Ion Collider (RHIC) at BNL The Relativistic Heavy Ion Collider (RHIC) is located at Brookhaven National Laboratory (BNL) in New York, USA, and focuses on understanding the fundamental aspects of QCD (Quantum Chromodynamics) and the dynamics of high-energy nuclear collisions. RHIC accelerates heavy ions to energies up to 200 GeV per nucleon pair, allowing the study of the near-ideal gas of quarks and gluons, the QGP [10]. The experiments at RHIC currently taking data are the STAR (Solenoidal Tracker at RHIC) and sPHENIX (super Pioneering High Energy Nuclear Interaction eXperiment), which replaced the PHENIX experiment, and the commissioning was done only recently (2023) [11].

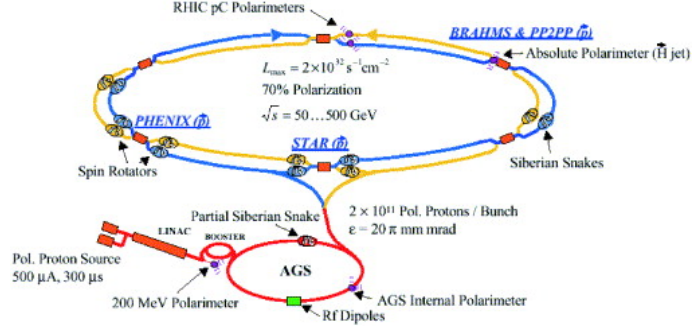


Figure 1.4: The original layout of the accelerator complex at BNL from 2003. The interaction point for the PHENIX experiment is currently occupied by its successor, sPHENIX. *Taken from Ref. [12].*

Electron Ion Collider (EIC) at BNL

The Electron-Ion Collider (EIC), the future project at BNL, is designed to explore the structure of protons and nuclei with unprecedented precision. The EIC will collide spin-polarised beams of electrons with ions from deuterons to the heaviest stable nuclei with centre-of-mass ~ 20 GeV to 100 GeV. This facility aims to study the properties of matter originating from the deeply fundamental constituents of QCD, which is the central motivation for polarized electron-proton and electron-ion collisions at the EIC. The collider is designed to be able to answer the question of the characteristic nucleon spins of $\frac{1}{2}$. The project also aims to make large contributions in instrumentation with the R&D for advanced detectors and accelerator technology to achieve the high luminosity and precision required [13]. The planned layout of the accelerator complex can be seen in Figure 1.5. Only one of the possible detector locations is at the moment assigned to an experiment. Namely, it will be the ePIC experiment at IR6.

1.3 Particle detectors and systems

Nowadays, the interactions induced by the accelerated particles are studied by enormous detector systems combined with multipurpose and dedicated experimental

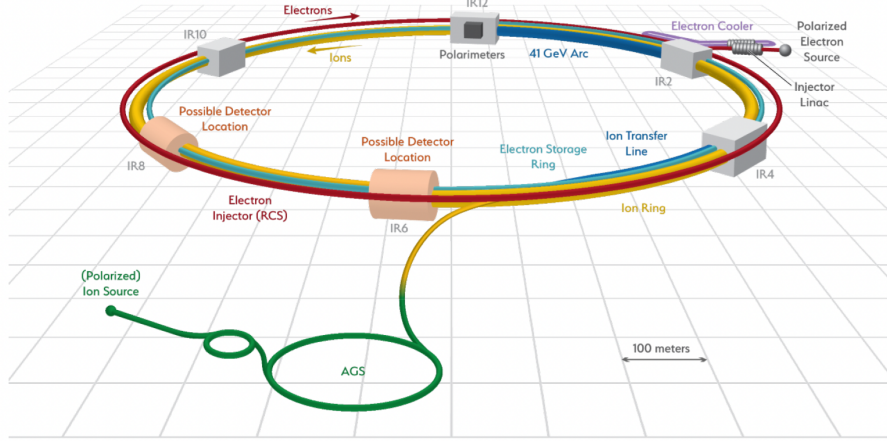


Figure 1.5: Schematics of the future EIC in the BNL accelerator family. *Taken from Ref. [13].*

setups. The detector consists of multiple sensitive channels measuring the characteristics of particles produced in collisions and decays of the initial particles. The usual architecture of a general-purpose detector comprises tracking, vertexing, energy loss and momenta measuring, and particle identification subdetectors. For these complex systems, a trigger is an essential subsystem to identify the measurements in the time dimension with the events observed. In the next section, a brief overview of the upgrade of the ALICE experiment is set to state the example of the general-purpose detector and its current triggering system is discussed later on.

1.3.1 The ALICE experiment as an example of general-purpose detector

As stated previously, the ALICE experiment is an experiment at the LHC focused on studies of the QGP in heavy ion collisions and further finding the QGP also in small systems. The detector will undergo a full refurbishment during the LS4 before the LHC Run 5, introducing the new detector ALICE 3 [14].

The subdetectors of the ALICE 3 are shown in the layout in Figure 1.6. The schematics show the system situated inside a magnet yoke already used in previous runs, dating back to the L3 experiment at LEP. ALICE 3 will include a new **superconducting magnet system** that will provide a magnetic field of 2 T and will consist either of a single solenoidal magnet or of its combination with dipoles. The magnetic system of the detector is necessary for curving the paths of charged particles and, therefore, allowing observation of their change and distinction from the neutral particles from the momenta calculated through the curvature.

The **Vertex detector** and the **Outer tracker** will consist of eleven barrel layers and 2×12 discs installed retractably in the secondary vacuum, allowing its insertion closer to the beampipe when taking data and keeping the detector protected from the radiation while the beam tuning. The technology proposed for this detector is

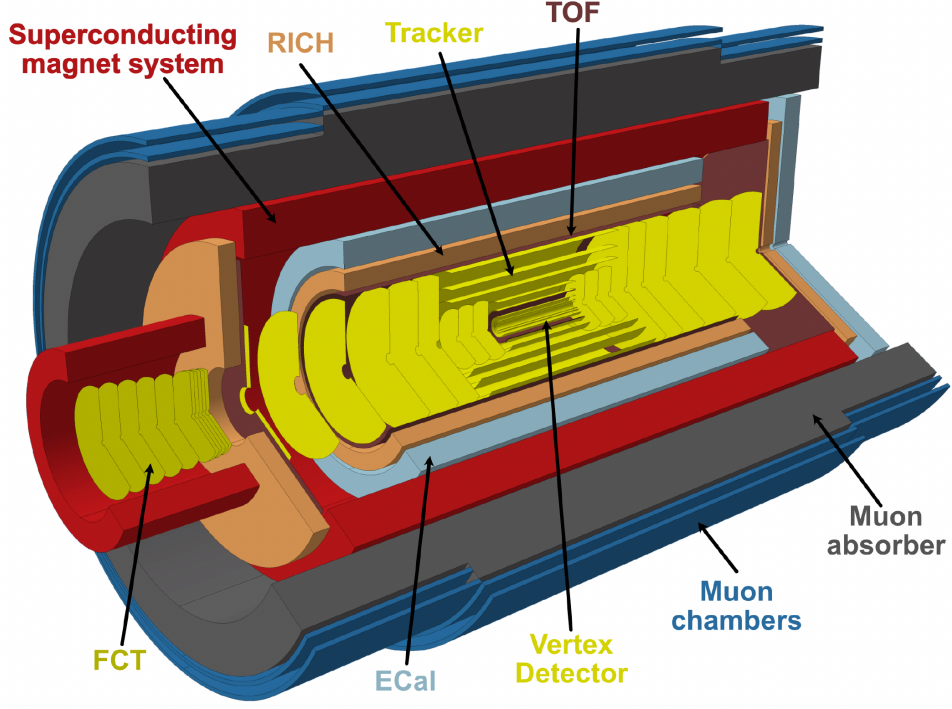


Figure 1.6: Schematic concept of the ALICE 3 detector. *Taken from Ref. [14].*

the CMOS already explored for the Inner Tracking System (ITS) upgrade, the ITS3. The challenge is to withstand the large amounts of radiation while avoiding robust structures in order to keep low material budget and high spatial precision.

The **Time of Flight (TOF)** system provides particle identification over the full acceptance ($|\eta| < 4$). Similarly to the tracking system, it comprises the central barrel layers and forward disks on both sides of the experiment. The main request on the detector is to provide a time resolution of 20 ps or better. This is to be achieved by the Monolithic Active Pixel Sensors (MAPS) technology, which is also explored for the ITS3. The TOF detector is typically used for particle identification (PID) and triggering.

The **Ring Imaging Cherenkov (RICH)** detector is to be used to extend the particle identification capabilities to transverse momenta out of reach for the outer TOF detector. The refractive index of the radiator determines the transverse momenta (p_T) window, in which the detector provides effective separation. The refractive index of the radiation sets the p_T range, which is for $n = 1.03$ ensuring the continuity in the PID capabilities beyond the TOF is in the barrel region and can be achieved conveniently by using an aerogel radiator material. However, the Lorentz boost affecting the particles in the forward direction limits the radiator to a smaller refractive index for adequate p_T coverage in the forward region. For the detector architecture, various layouts with a mirror and multiple layers of radiator are in consideration, as shown in Figure 1.7. For the photodetector, the most promising option so far is a further development of the digital silicon photomultipliers (dSiPM), combining the readout with the CMOS technology rather than the use of the conventional vacuum PMTs.

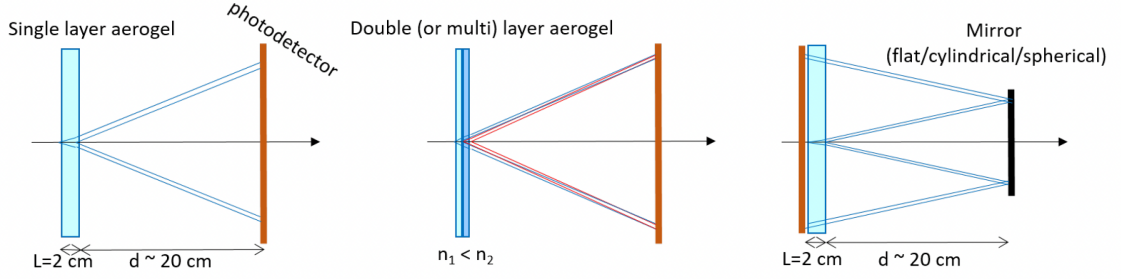


Figure 1.7: Schematic view of the aerogel RICH baseline layout (left), multi-layer (focusing) aerogel layout (centre) and mirror layout (right). Taken from Ref. [14].

The **Electromagnetic Calorimeter (ECal)** is to cover one forward and the full barrel regions, most of which will be instrumented with a sampling calorimeter. A fraction of the central barrel will reuse the PbWO_4 crystals from the ALICE PHOS and the CMS ECal, with SiPM readout. The remaining part of the acceptance will be covered with a lead–scintillator sampling calorimeter. A challenge arises from the relatively low light yield Y of the crystals, which shows a strong temperature dependence. For this reason, the ALICE PHOS is operated at a temperature of $t = -25^\circ\text{C}$ to increase the light yield by a factor of 3 compared to operation at room temperature. This problem shall be mitigated to acceptable levels by the front-end electronics (FEE).

The **Muon Identifier (MID)** will provide muon tagging for particles reconstructed in the tracker. It is to be composed of chambers to track charged particles that pass through the hadron absorber of about 1 kt. The physics performance, i.e. the matching of muons, can be achieved in various ways, so the muon absorber material is still under discussion. The muon chamber is currently under consideration between the scintillating paddles coupled with the SiPMs or the multiwire proportional chambers (MWPCs) [15]. The MID is further discussed in section 3.3.1.

The **Forward Conversion Tracker (FCT)** is to measure photons only accessible by exploiting the Lorentz boost in the forward direction, which is observed by their creation of the e^+e^- pairs. The Magnetic field perpendicular to the (forward) direction of flight is required for sufficient p_T resolution. Thus, the design can only be finalized after the magnet system design is decided. The detector will try to adapt the ITS3 bend silicon technology; nevertheless, it is still to be tested on large flat areas as the discs of the FCT will be.

This overview discusses only the very basic concepts of the detector, and the author advises further reading in the Letter of Intent for the ALICE 3 [14].

1.3.2 Fast Interaction Trigger of ALICE

As mentioned at the beginning of this section, an important part of the data acquisition, the event distinction, lies in the triggering system. The main trigger mode of ALICE is since the Run 3 (starting in 2022) continuous mode, which is triggerless [16]. Nevertheless, some of the detectors still need the traditional trigger mode,

which is provided at the lowest level by FIT [17]. This led to the development of the Fast Interaction Trigger (FIT), also aiming to provide the multiplicity trigger, useful especially for detectors with limited readout-rate capabilities that focus on highly energetic processes, for example, related to jet physics. FIT generates a minimum bias and a multiplicity trigger with a maximum latency below 425 ns and measures the collision time with a resolution of 40 ps. In the offline analysis, FIT assists in the reconstruction of the vertex position, assesses forward particle multiplicity, centrality, and event plane, and allows the study of diffractive physics at forward rapidity. Additionally, it provides a luminosity monitor in real-time and sends feedback directly to the LHC for beam tuning.

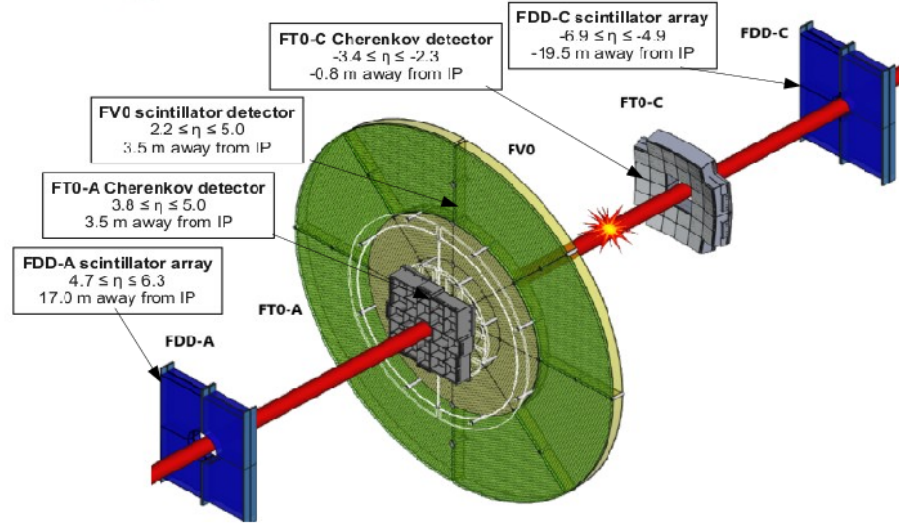


Figure 1.8: FIT detectors layout. From bottom-left FDD-A, FT0-A connected with FV0, interaction point, FT0-C, FDD-C. The distances along the beamline are not up to scale *Taken from Ref. [18]*.

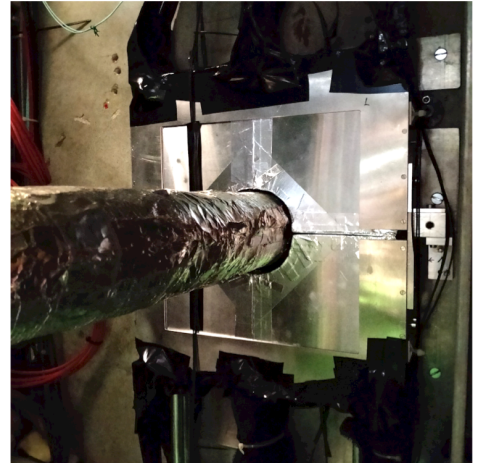
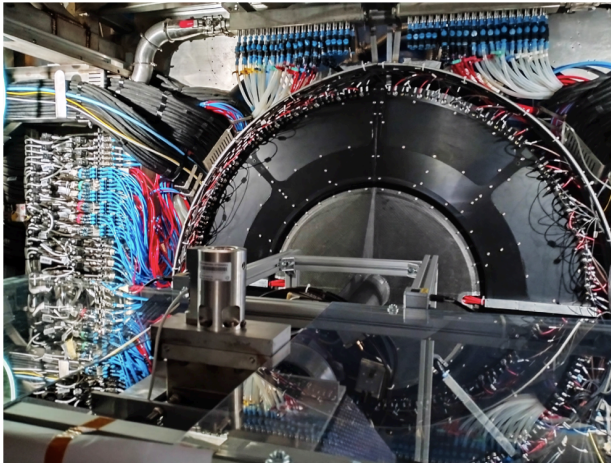


Figure 1.9: FIT detectors FV0 (left) and FDD-A (right) installed in the ALICE experiment. *Photos taken in February 2024.*

The FIT design balances between performance and cost and consists of 3 components: FT0, FV0 and FDD, see Figure 1.9. Each of them is optimized for different functions and operational regimes. The FT0 is a Cherenkov array with good timing properties and signal-to-background ratio. Around the FT0-A, the scintillator FV0 seeks to enlarge acceptance towards midrapidities, improving the trigger efficiency and dynamic range. The scintillator FDD (Forward Diffractive Detector) covers the forward pseudorapidity range. The author would like to note here that the C-side and A-side are common labels throughout all the LHC experiments, meaning clockwise and anti-clockwise, respectively [19].

The FT0 and FDD detectors comprise each of the two arms located on both sides of the interaction point (IP), allowing the background rejection using the vertex trigger (defined as a coincidence of signals in both arms). On the C-side, the small space available between the IP and the absorber makes it impossible to install an FV0 array; therefore, only the Cherenkov array is installed. Furthermore, the Cherenkov arrays themselves use, in comparison with standard PMT, much thinner MCP-PMT technology for light detection, given the operation in a strong magnetic field. On the A-side, further away from the IP, the dimensional constraints are more relaxed, so the Cherenkov array is accompanied by a scintillator ring [20].

Chapter 2

Semiconductors and photodetectors

This chapter provides an overview of the photodetectors used in the HEP and dives deeper into the solid-state technology with semiconductors. The semiconductors are introduced from their basics in band theory, and the description of a silicon photomultiplier is then built upon this concept and further steps in the development of the sensor. This chapter took a large amount of inspiration and information from the Ref. [21].

2.1 Photodetectors

Photodetectors are sensors converting incoming light into electric signals. In HEP they are primarily used with scintillators or to detect Cherenkov radiation. The operating range is usually from vacuum-ultraviolet (VUV) to near-infrared (NIR), where the photon energy is only a few eV. Photodetectors rely on the photoelectric effect, where the photon energy exceeds the electron binding energy, thus ejecting electrons. The distinction between internal and external photoeffects is important. Common materials include *photocathodes*, made from alkali substances like CsI, and *semiconductors*: in semiconductors, the internal photoeffect moves electrons from the valence to the conduction band, making them free electrons, while external photoelectric effects involve electron ejection from metal surfaces, which is the case for photocathodes.

Vacuum-based photodetectors produce free electrons through the external photoelectric effect. This category includes photomultiplier tubes (PMTs), hybrid photodetectors, and microchannel plates. PMTs consist of a photocathode that emits electrons when hit by photons, followed by a series of dynodes for electron amplification, ultimately resulting in a measurable electric signal. Hybrid photodetectors combine aspects of PMTs with semiconductor technologies to enhance performance. Microchannel plates use a dense array of microscopic channels to multiply electrons through secondary emission.

Gaseous-based photodetectors use photosensitive gas molecules or a solid photocathode to release primary electrons using the external photoelectric effect as well. The

electron subsequently drifts towards the anode and triggers an ionization avalanche in the gas in the high electric field. Thanks to the low mobility of produced charge carriers, the detector can operate in magnetic fields, which is beneficial with respect to the previous type. Compared with the solid-state sensors, their noise levels are lower, and they have higher gain, which, together with their cost-effectiveness, makes them an excellent competitor for large-area detectors. A notable example is the ALICE RICH detector, which uses segmented CsI-coated photocathodes in a multi-wire proportional chamber, optimizing performance for particle identification in high-energy collisions [22].

Solid-state photodetectors utilize semiconductors to detect incoming photons through the internal photoelectric effect and will be discussed further in the next Section 2.2.

2.1.1 Important parameters of the photodetectors

To characterize photodetectors for HEP uses, various parameters are discussed, although the emphasis is, as usual, specific to an application. The *Quantum Efficiency* (QE) is defined as the ratio of the number of photoelectrons emitted N_{PE} to the number of incident photons N_{tot} and is given by the equation

$$QE = \frac{N_{PE}}{N_{tot}}. \quad (2.1)$$

The *Dark Count Rate* (DCR), the rate of signals generated in the absence of light, directly impacts the noise level and overall accuracy of measurements. *Gain* is a crucial parameter for the detection of faint light signals, such as in Cherenkov detectors and states the amplification factor of one photon into photoelectrons. This can be expressed as

$$G = \frac{Q}{e}, \quad (2.2)$$

where G stands for the gain, Q for the charge collected and e for the charge of a single electron. The *timing resolution* is essential for time-of-flight and fast timing applications, often quantified by the full width at half maximum (FWHM) of the timing distribution. Spectral response defines the *range of wavelengths* to which the detector is sensitive to. *Linearity*, the consistency of response over a range of light fluxes, is the goal behaviour, nevertheless unachievable due to physical constraints of the detection probability smaller than 100%.

2.2 Semiconductors

Semiconductors are crucial materials in modern electronics widely used for their ability to behave both as conductors and insulators. The principle of this duality arises from their structure, so-called bands, which describe the allowed energetic states of the electrons and holes in the material. The crystalline material can be described as a periodic structure of atoms arranged with covalent bonds. The valence

electrons may break the bond, creating a free electron and a hole, both treated as particles in this theory. The free electron is no longer bound to the lattice, and the hole is its reminder to be filled by a neighbouring electron. Thus, both electron and hole are available for conduction (the hole moves by being filled).

2.2.1 Band theory

The electron in the material will occupy different energy levels depending on its state, whether it is bound to the lattice, in *conduction band*, or free, in *valence band*, see Figure 2.1. For metals, these bands overlap, which explains conductivity by the electrons not needing additional energy to move from the valence band to the conduction band. For semiconductive materials, however, the bands are not overlapping, and a *forbidden gap* between the bands exists, the size of which depends on the material. This results in electrons needing to change their energy by the gap size for jumping between the bands. Therefore, all the electrons in the semiconductor are in the valence band at low temperatures, and the material manifests itself as an insulator. With increased temperature (room temperature is sufficient for this process), the electrons are thermally agitated and excited to the conductive band, free to move. In this theory, insulators are described similarly as semiconductors by sufficiently large *forbidden gap* (3-4 eV) [23].

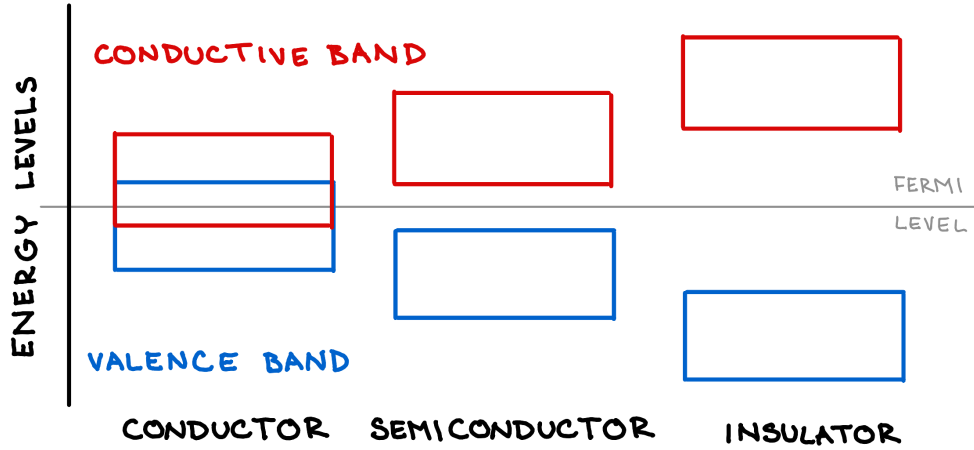


Figure 2.1: The band theory description of the energy levels and overlapping bands for metals, semiconductors and insulators. *Inspired from [24].*

Electrons and holes in semiconductors, being indistinguishable particles with spin $1/2$, obey the Fermi–Dirac statistics. That leads to a distribution $f(E)$ for occupied states with energy E at the temperature T as follows

$$f(E) = \frac{1}{1 + \exp\left(\frac{E - E_F}{kT}\right)}. \quad (2.3)$$

The E_F in this expression denotes the Fermi energy, which is defined as the chemical potential of the particles in the structure. It describes the amount of energy needed

to add a particle to the system from its initial distance infinitely far away. Note that at thermodynamic equilibrium, this chemical potential is the same for all the particles in the system [25].

2.2.2 Intrinsic and extrinsic semiconductors, junctions

Materials with no or very few impurities in their lattice structure are classified as *intrinsic*, and the thermally agitated electrons are the only free carriers. The intrinsic semiconductors are used very rarely due to the complexity of the manufacturing process. Adding a well-defined fraction of impurities to the material, *doping*, is favourably altering the material properties so that it is more suitable for the application. Depending on the *dopant*, the material becomes n-type, with an excess of electrons, or p-type, with an excess of holes. An example of doping is shown in Figure 2.2. To the base consisting of pure silicon with four valence electrons, boron (phosphorus) is added, and thus, an extra hole (electron) is created while the matrix remains neutral [24]. This modification to the material has a consequence of a shift in the Fermi level. The E_F in the doped semiconductor can then be described by the energy level of the conduction band E_c and densities in the conduction band N_c and of the dopants N_D followingly

$$E_F = E_c - kT \ln \frac{N_c}{N_D}. \quad (2.4)$$

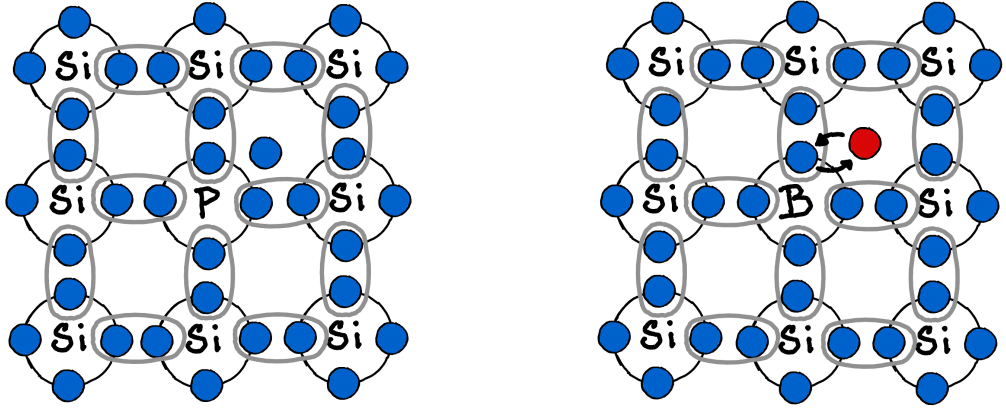


Figure 2.2: Schematics of silicon base with phosphorus as an n-type dopant (left) and boron as a p-type (right). The blue circles represent the electrons, and the red is a hole. Inspired from [24].

Different doping allowed the creation of semiconductor structures beginning with the simplest *p-n* junction. The *p-n* junction consists of two extrinsic semiconductors with opposite doping, creating a diode structure which conducts current only in one direction as seen in Figure 2.3.

The absence of free-charge carriers of the opposite sign in the material causes diffusion, and the holes and electrons start recombining around the border. That leaves

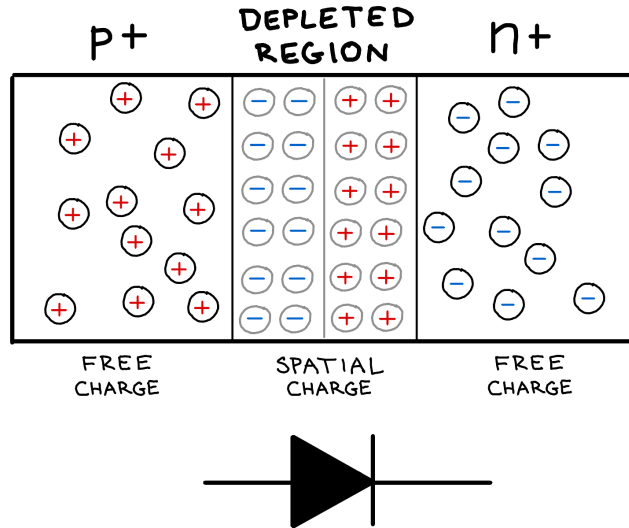


Figure 2.3: Schematics of the p-n junction, a basic semiconductor structure. The grey circles represent the ions in the lattice, and the black circles represent the free charge carriers - the electrons and holes. *Inspired from [24].*

the region free of the carriers, but the static charge in the lattice remains in its place. This creates an electric field stopping further diffusion and leaves the border region depleted from moving charges. The size of the depleted region is proportional to the concentrations of the charge carrier in both joint materials and can be modified by applying an external voltage.

2.3 Photodiodes and avalanche photodiodes

Irradiation with light generates electron-hole pairs in semiconductors. This effect occurs when the transversing photon has energy larger than the energy of the band gap. The photon is subsequently absorbed, lifting the electron from the valence band to the conduction band, thus leaving a hole in the conduction band. If the pair is created in the depleted region and, therefore, affected by the electric field, the pair is separated, and each free charge moves towards a different side of the depleted region, creating a photocurrent. Important to note here is the relationship between the photon energy $h\nu$, h being the Planck's constant and ν its frequency, its wavelength λ , and the transitioned energy ΔE

$$\lambda = \frac{hc}{\Delta E} = \frac{1.24}{\Delta E(\text{eV})}, \quad (2.5)$$

giving the wavelength in μm (c is the speed of light). This wavelength is the minimal to cause excitations since usually also photons with large ΔE can cause them. The minimal energy is given by the forbidden gap [26].

2.3.1 Avalanche mechanism

If a free charge occurs in a region with a high electric field, it is accelerated. This may provide sufficient energy to create an electron–hole pair, which will be subsequently accelerated, allowing the creation of new pairs and creating an avalanche. A region with a sufficiently strong field to cause multiplication is characteristic of the avalanche photodiodes (APD). The strength of the electric field is moderated by doping, which is often gradual for the charge amplification. Important to note here is that the holes, by their definition, require higher electric fields than the electrons for avalanche creation. This also results in a non–linear response to the signal as opposed to the moderate–high voltage mode in which only the electrons are liable for the multiplication. As the depleted region of the photodiode is the sensitive area of the detector, it may be intuitive to have it as large as possible. Nevertheless, a large volume allows the thermally agitated electrons to create more false avalanches in the detector, thus increasing the signal–to–noise ratio (SNR).

2.3.2 Single Photon Avalanche Diodes

The simple APDs are suitable for the HEP detectors; an example from this category can be the electromagnetic calorimeter, ECAL, at the CMS experiment [27]. Nonetheless, the APDs deliver relatively low signals while operating with linear response, which is indeed a result of low intrinsic amplification that is proportional to the thickness of the $p+$ layer. This can be improved by increasing the voltage so that the hole begins to contribute to the multiplication process, shifting the operation mode to the Geiger mode (above the breakdown voltage), and arriving at the Single Photon Avalanche Diode (SPAD). This modification results in increased photon sensitivity, making the detector suitable even for low–light–yield environments. The use of this detector commonly goes beyond the HEP research since the light capture efficiency is crucial for tomography imaging.

2.4 Silicon photomultipliers

Silicon photomultipliers (SiPMs) are cutting–edge photodetectors that work in the non–linear amplification region of a p – n junction, sometimes referred to as the Geiger–Müller region, similar to gaseous detectors. These devices are pixelated arrays of SPADs connected in parallel. SiPMs are operated in reverse bias V_{bias} with a voltage exceeding the linear amplification region, and at the breakdown voltage V_{br} , the avalanche regime transitions from linear to self–sustaining mode. The pairs produced in SPAD avalanches result in a fast–rising current, which is stopped with the avalanche by quenching. This is possible either by reducing the voltage across the diode (active quenching) or by limiting the current below a critical value using a quenching resistor (passive quenching), as shown in Figure 2.4. The temperature dependence of the avalanche process requires a higher electric field as temperature increases, leading to a linear increase of with temperature, typically 20–60 mV/K

depending on the SiPM technology. The difference between bias voltage together with the overvoltage $\Delta V = V_{bias} - V_{br}$ significantly influences many characteristics of SiPMs.

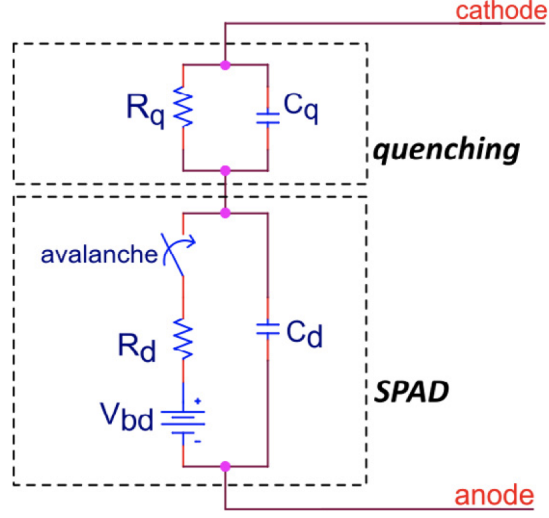


Figure 2.4: Equivalent circuit of the SPAD cell with quenching. *Taken from [28].*

Silicon Photomultipliers (SiPMs), also known as multiple-pixel photon counters (MPPCs), replace traditional photomultiplier tubes (PMTs) without the need for a photocathode and dynodes, making them less sensitive to magnetic fields while maintaining high photon sensitivity and low dark count rates. SiPMs offer single-photon sensitivity and high gain (up to 10^6), providing a very fast rise time on the order of hundreds of picoseconds while operating at low voltages (orders of tens of volts). These features make SiPMs highly suitable for applications requiring precise timing and high sensitivity, such as in high-energy physics experiments and medical imaging. The advanced design of SiPMs ensures robust performance, combining the benefits of traditional PMTs with modern semiconductor technology to deliver superior performance in a compact form.

2.4.1 Electric structure

The most common representation of the SiPM equivalent electrical circuit can be seen in Figure 2.5. The N_{tot} represents the number of total available cells in the SiPM, and the N_f represents the triggered cells. Unlike the SPAD equivalent circuit, the SiPM circuit includes additional passive components from non-triggered SPADs ($N_{tot} - N_f$), along with grid inductances and capacitances (parasitic part). In a SiPM, the output current generated by the triggered cells, particularly the fast component in C_q , is divided by the parasitic capacitance C_g (mainly from the metal grid and bonding pads) and the series connection of the passive capacitances. The grid capacitance and inactive cells can cause a noticeable drop in the single SPAD signal amplitude, depending on the input impedance of the front-end electronics.

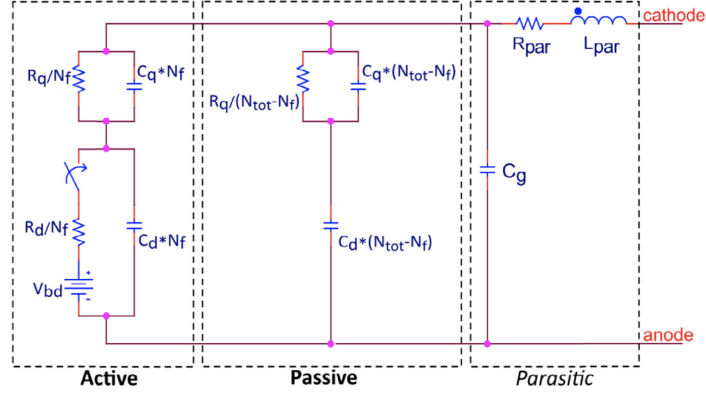


Figure 2.5: SiPM equivalent circuit including the switch that mimics avalanche triggering, the diode series resistance R_d , the diode capacitance C_d the quenching part R_q and C_q , the parasitic part from the not triggered cells and the series and parallel parasitic components. *Taken from [28].*

Using an amplifier with very low input impedance, such as a trans-impedance amplifier, helps in extracting the current signal since the impedance of the passive and parasitic components is generally higher than that of the amplifier. Additionally, the parasitic trace (and bonding) inductance L_{par} and resistance R_{par} can limit the SiPM signal rise time, emphasizing the importance of minimizing these in PCB design to benefit from the intrinsically fast rise time of SiPM signals [28].

The timing properties of the SiPMs are divided into two components: fast and slow. The fast signal discharge is a product of the load resistor R_L and the total capacitance of N_{tot} cells C_{tot} , which depends on the capacitance of each individual cell and the grid capacitance from the connector

$$\tau_{fast} = R_L \cdot C_{tot} = R_L \cdot (N_{tot}(C_d + C_q) + C_g). \quad (2.6)$$

The slow component τ_{slow} is given by the recovery time τ_{rec} , which is the full recharge of the capacitors C_d and C_q through R_q in the active pixels.

There is also a possible enhancement of the SiPM uses by the fast output explored by the ONSEMI manufacturer, which has enriched the traditional structure of SiPM by incorporating a third terminal coupled with a small value capacitor. This modification enables the transmission of ultra-fast output signals in addition to the standard anode-cathode output. This modification allows shorting the signal to only tens of nanoseconds or even less, in comparison to the standard output of hundreds of nanoseconds [29]. The circuitry of this incorporation can be seen in Figure 2.6.

Another breakthrough in faster timing was achieved by the digital SiPMs (dSiPMs). The signal from the single SPADs (or groups of a few) is directly digitized as opposed to the sum of the signal's digitization in conventional analogue SiPMs. The advantage of the solution lies in the integration of all the components in one chip, providing compactness and high speed and also in the possibility of disabling noisy cells [31]. The disadvantages are manifested in larger electronic noise and power

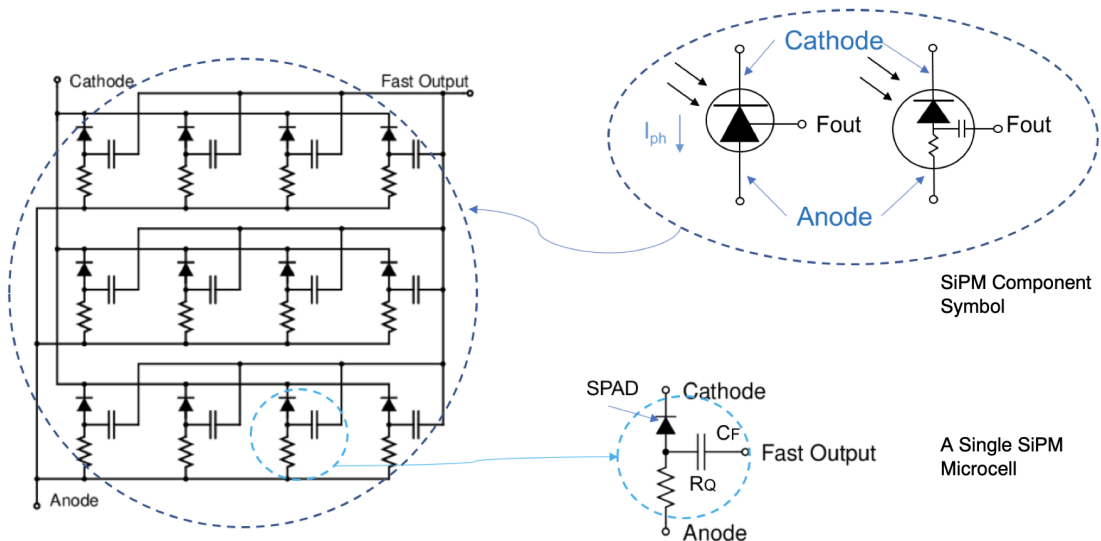


Figure 2.6: The circuit of a SiPM with the fast output. The SiPM consists of an array of SPAD microcells with resistor R_Q and capacitor C_F connected in parallel. Taken from [30].

consumption. The block diagram is presented in Figure 2.7, where it can be seen that each pixel consisting of four SPADs delivers one bit very fast for the on-chip trigger, which is used for synchronous cell read-out.

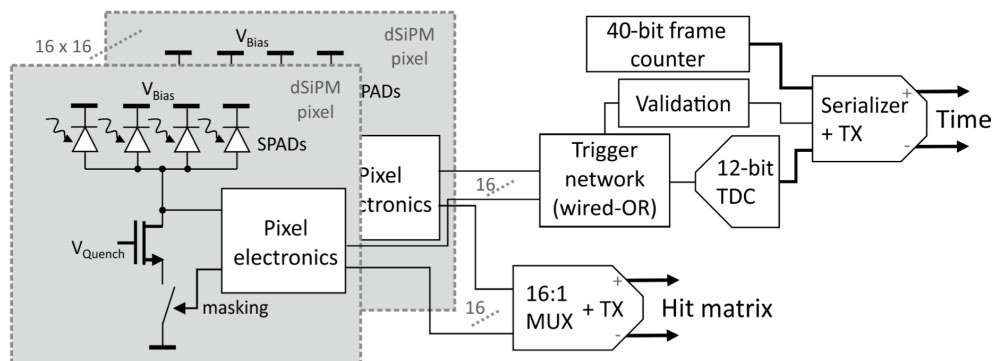


Figure 2.7: Block diagram of the digital SiPM from DESY. *Taken from [31].*

2.4.2 SiPM characteristics

The SiPMs are characterized by various properties that are also used for comparison with other types of photodetectors, which were briefly introduced already in Section 2.1.

2.4.2.1 Gain

Gain of the SiPM can be further expressed from the equation (2.2) using the capacitance C_d and overvoltage ΔV , from which subsequently an expression using the latch current I_{latch} and recovery time $\tau_{rec} \approx R_d \cdot C_d$ can be derived by the Ohm's law

$$Q = \frac{\Delta V \cdot C_d}{e} = \frac{I_{latch} \cdot \tau_{rec}}{e}. \quad (2.7)$$

This describes the gain linearly proportional to the overvoltage; however, it is possible for the depletion of the epitaxial layer to cause deviations in this behaviour.

The measurements of the gain are typically affected by the bandwidth and shaping time of the front-end electronics, and for fast shaping times, a high signal-to-noise ratio is difficult to achieve. From the equation (2.7), it is visible that the real-life measurements will use numerical integration of the signal produced by one photon as

$$G = \frac{1}{e} \int I dt = \frac{1}{R_L \cdot G_a \cdot e} \int U dt, \quad (2.8)$$

where the R_L and G_a label the resistance and gain of the pre-amplifier.

2.4.2.2 Photon Detection Efficiency

The photon detection efficiency (PDE) is the ratio of the detected number of photons to the total number of incoming photons. This is in the case of SiPMs bounded to the QE , geometry fill factor (GFF), and the probability of an avalanche originating from the electron-hole pair P_a and can also be fitted by a phenomenological function dependent on the V_{bias} [32]. The expressions are

$$QE \cdot P_a \cdot GFF = PDE = PDE_{max} \left(1 + \exp \left(-d \cdot \frac{\Delta V}{V_{br}} \right) \right) \quad (2.9)$$

where the d factor is a phenomenological factor reflecting the dependence on the P_a , and the PDE_{max} is the fitting constant representing the maximal possible PDE in theory. This variable can saturate for high voltages and create a plateau. It is a consequence of the saturation of the charge carrier ionization rate.

2.4.2.3 Dark noise

Dark noise in SiPMs is defined as signals generated in the absence of incident light, primarily due to thermally generated carriers, tunnelling effects and diffusion from the bulk region. These dark counts are a significant source of noise, affecting the signal-to-noise ratio and overall performance of the detector. The dark count rate (DCR) is, by definition, dependent on temperature, rising with its increase. To mitigate DCR, SiPMs are often operated at lower temperatures, especially when large doses of irradiation are expected. The dark count pulses in time follow the Poisson distribution and are used to characterize SiPMs. This behaviour is for room temperatures described by the Shockley-Read-Hall mechanism [33], while for

extremely low temperatures, the tunnelling effects are dominant. In the limited range of ΔV , the DCR is linearly proportional to it, and it has proportionality to the active area of the sensor.

2.4.2.4 Correlated noise

The correlated noise in the SiPM comprises the signal propagation between neighbouring cells, crosstalk, and within the same cell, the afterpulses.

In **direct crosstalk**, the mechanism is an emittance of infrared photons which can travel long distances due to their low absorption coefficient in silicon and, when reaching the neighbouring cells, create a signal not corresponding to a new incident photon. The prevention of this phenomenon is optical opaque trenches. Nevertheless, the likelihood of such crosstalk is still proportional to the gain.

An **afterpulse** occurs when a charge carrier released by an avalanche is trapped by impurities or lattice defects in the silicon and subsequently released after a delay, causing a second avalanche in the same pixel with a time delay of a few hundred nanoseconds. It can also happen due to incomplete quenching, which leaves free charges in the avalanche region and limits the stable operation range of a SiPM, especially at high ΔV .

The **delayed crosstalk** is a combination of the two and emerges from trapped avalanches propagated to the neighbouring cells.

Chapter 3

SiPMs in current and future HEP experiments

The SiPMs became a valuable competitor to the traditional PMTs in HEP detectors. The semiconductor nature combines the high sensitivity of PMTs with the benefits of solid-state technology, such as compact size, low operating voltage, and resistance to magnetic fields. These characteristics are particularly advantageous in large experiments operating in strong magnetic fields [34].

Over the past decades, the spread of their applications has been significant, confirmed by the applications in laboratories worldwide. For instance, the CMS experiment has integrated SiPMs into its calorimeters [27, 35], enhancing their ability to measure the energy of particles with greater precision and reliability. Similarly, they have become a crucial technology explored for the Compressed Baryonic Matter (CBM) experiment at the FAIR accelerator centre [36]. Further research is being conducted on their use in Cherenkov detectors like in the future ePIC [37].

SiPMs are further explored for their excellent photon detection efficiency, fast response time, and ability to operate in cryogenic temperatures, which are often the case in HEP experiments. These features are crucial for experiments that demand precise timing and high resolution, such as the Belle II experiment at the SuperKEKB accelerator in Japan [38], where SiPMs are to be used in the Time of Propagation (TOP) detector for particle identification. Another advantage of these sensors is the capability to handle high data rates, a critical requirement for many future HEP projects, such as the HL-LHC, where the SiPMs are set to play a pivotal role.

In this chapter, a few more detailed examples of selected current and future HEP experiments utilizing the SiPMs are provided and discussed with the aim of setting the motivation behind the measurement for this thesis, as well as a selection of monitored properties of the sensors. The subchapters are organized by types of conventional large HEP experiment subdetectors, as discussed in section 1.3 and the last subchapter will discuss also the neutrino detection.

3.1 Tracking, Particle Identification, and Timing detectors

3.1.1 SciFi tracker at LHCb

Among the trackers, a pioneering scintillating fibre detector is installed at the LHCb at CERN (commissioned during the LHC Long Shutdown 2 in 2021). The SciFi tracker consists of three stations of four detector planes each, as shown in Figure 3.1. The modules comprise 8 individual fibre mats serving as the active material of the detector. Within this part, blue (400 to 600 nm) scintillation light is radiated and propagated towards the multi-channel SiPM on one side and reflected by a mirror on the other. The 128 channels with a width of 250 μm will, together with the fibre positioning, allow a hit-position resolution better than 100 μm .

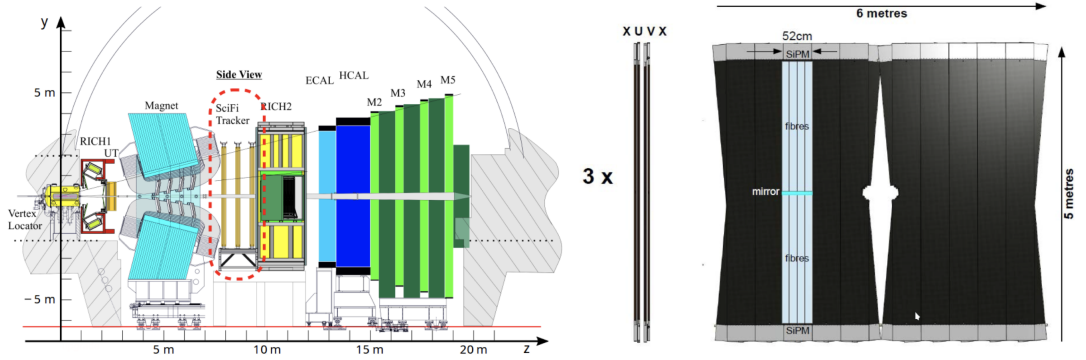


Figure 3.1: The side view of the LHCb experiment with the position of the SciFi tracker circled in red (left) and schematics of one detector station (right). *Taken from Ref. [39].*

The active layers are read out by Hamamatsu SiPM arrays (model MPPC S13552 – H2017 [40]) with custom adjustments for detector performance. The photon detection efficiency is about 45 % at the overvoltage 3.5 V with relatively small crosstalk. Large efforts were made to suppress the dark noise by the modules operating in -40 $^{\circ}\text{C}$. This solution leads to a DCR of 13 MHz per channel after receiving neutron fluence of 6×10^{11} neq/ cm^2 , corresponding to half of the expected fluence for the lifetime of the detector in operation, monitored because the DCR is known to increase significantly with irradiation. While the readout is at 40 MHz, the DCR at such a level does not significantly narrow down the detector use as opposed to the original (without cooling) DCR of 550 MHz after irradiation.

3.1.2 Mighty Tracker for LHCb

In Upgrade II of the LHCb during the LHC Long Shutdown 4 (LS4) in 2032-2034, the SciFi technology will be merged with a silicon pixel detector, forming a new detector, the Mighty Tracker. The combination of the two technologies will enhance

tracking efficiency in the region with the highest occupancy. Initial changes will be already performed during the LS3 (Upgrade Ib in 2026-2028) when both the inner tracking part of CMOS technology will be installed, and the SciFi detector will be adjusted limitedly, and the fibres most exposed to the radiation will be exchanged to prevent error caused by the radiation damage [21].

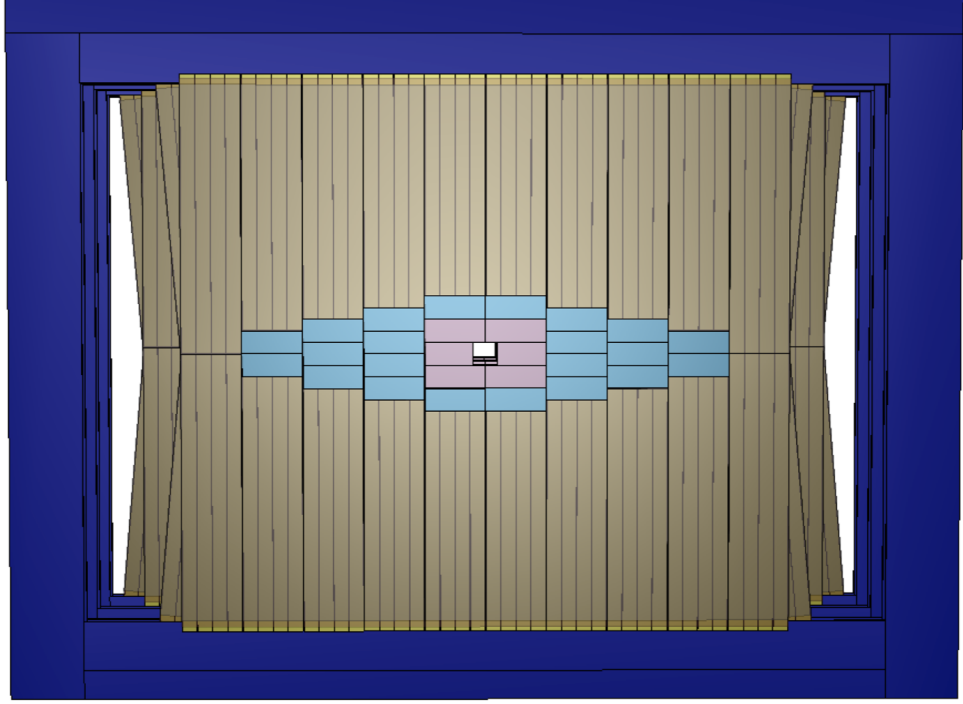


Figure 3.2: Geometry simulation of the layout of the Mighty Tracker detector. The HV-CMOS region consisting of the Inner Tracker (pink) and Outer Tracker (light blue) is the closest to the beampipe. The outer region (brown) is tiled from the SciFi modules. *Taken from Ref. [41].*

The design of the detector is shown in Figure 3.2. This text will discuss only the upgrades of the SciFi modules, focusing on the SiPM; for further reference, see Ref. [41].

The main challenges in the upgrade arise from the increase by a factor of 10 in luminosity at LHC in Run 5 (after LS4) compared to the current Run 3 (2024). The integrated luminosity causes the DCR to rise beyond the acceptable levels and the current operating temperature (-40°C). The only suitable option is foreseen to be the application of cryogenic cooling, setting the operational temperature down to -120°C and lower. This leads to an expected decrease of DCR to 1.5 MHz, allowing detector operation in lower light yield at the same hit detection efficiency.

The upgrade also introduces the microlensing technique commonly used for sensor enhancement in industry. The light yield for a minimal ionising particle is expected to decrease with radiation damage to both SiPMs and the fibres. In order to compensate for the subsequential increased DCR, focusing is used to avoid inactive regions, as shown in Figure 3.3. This leads to a larger ratio between the active and total area

of the device without changing its mechanical and electronic properties. Successful simulations for microlens-enhanced SiPM were done in ROOT and promise an improvement in the light collection up to 23% [42].

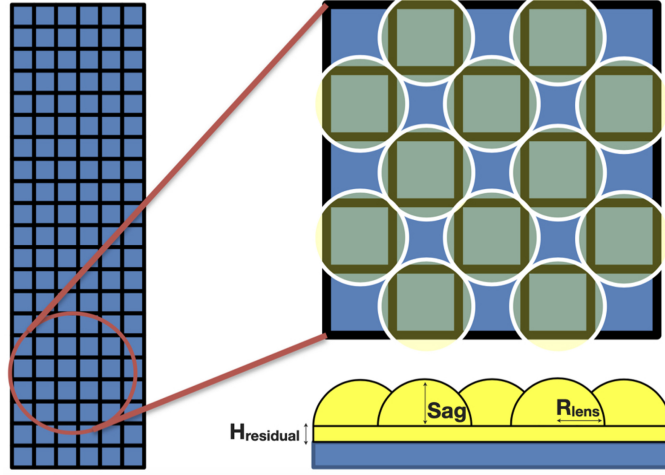


Figure 3.3: Visualisation of microlens-enhanced SiPM for the LHCb SciFi modules. The microlenses (placed on every other pixel) are characterised by residual height H_{residual} , sag, and radius R_{lens} . *Taken from Ref. [42].*

Following prototype production showed a reduction in the gain of the light yield with increasing GFF of the sensor [42]. Further experiments achieved a favourable increase of 32% in light yield for SiPM with 50% GFF. Nevertheless, SiPMs with larger GFF tested indicated no significant increase; the next steps thereafter lead to customised production of silicon [21].

3.1.3 dRICH detector at ePIC

The ePIC experiment is to be located at future EIC at BNL (see Section 1.2.1). For separation between the 3σ K/π at a wide range of momenta (up to 50 GeV/c) in the ePIC experiment, a dual radiator ring imaging Cherenkov detector (dRICH) is to be installed, see Figure 3.4. The two-radiator system is the key component, which allows separation at a wide range of momentum. Specifically, the aerogel with a refractive index of 1.02 facilitates the exploration of the lower momenta range while the gaseous C_2F_6 with a refractive index of 1.0008 allows distinction for particles at higher momenta. The crucial element for the compactness of the detector is the spherical mirror focusing the Cherenkov light with Fresnel lenses to the photodetector. Given the experiment's position and the experiment's precision requirements, the SiPMs are a natural choice due to their functionality in high magnetic fields (1 T required) and their compactness, photon detection efficiency and timing resolution [43].

An extensive study of suitable prototypes of the SiPM was conducted with the aim of their evaluation after irradiation and annealing. Different models by different vendors were compared while operating at -40°C with fluences up to 10^{11} neq/cm².

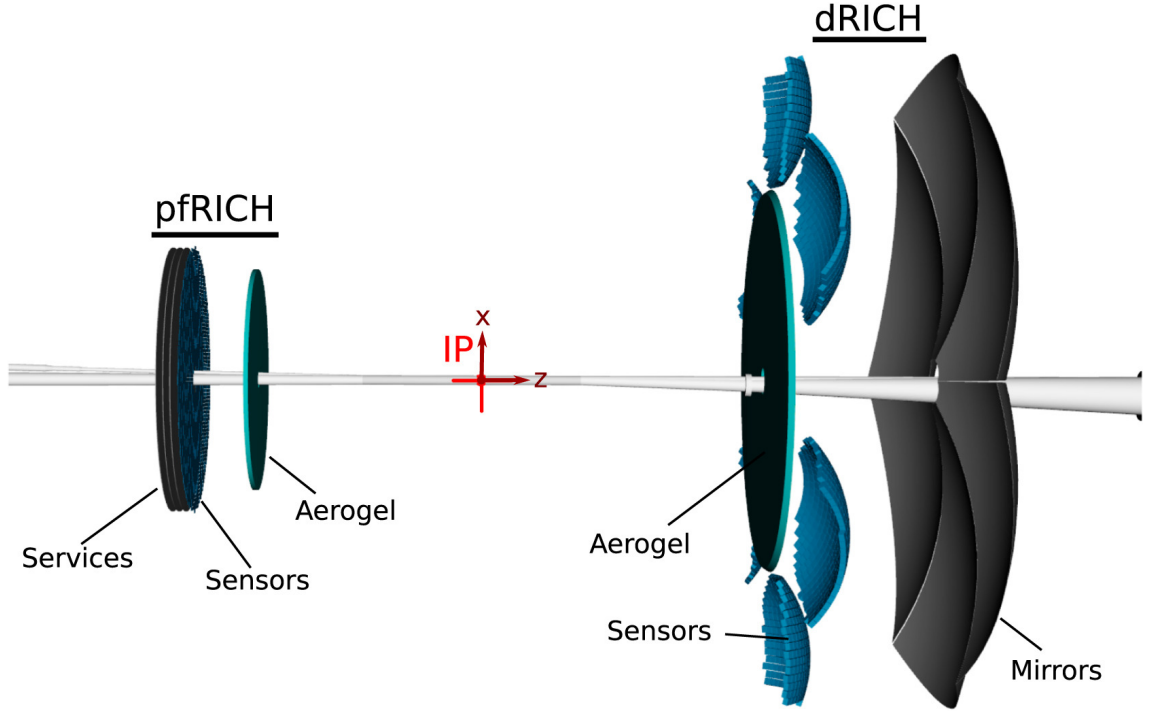


Figure 3.4: Schematics of the dRICH detector (right) together with proximity focusing RICH detector (left) to be installed at the ePIC experiment of the EIC. The interaction point (IP) is also marked at the beampipe. *Taken from Ref. [44].*

Custom boards for the 3 mm^2 SiPMs were designed to withstand the annealing phases (temperatures up to 175°C) and the irradiation cycles. The sensors were produced by Hamamatsu, FBK, and Sensl with cell pitches from $15 \text{ }\mu\text{m}$ to $50 \text{ }\mu\text{m}$; for further details, see [43]. The DCR showed a linear rise with increasing fluence, but after the annealing phase, decrease factors of 10 and 100, for temperatures of 125°C and 150°C , respectively, were achieved. The annealing phase in this part of the experiment took 150 hours, and attempts with shorter periods of time at higher temperatures were endeavoured. A factor of 10 was achieved at 175°C during only 2.5 hours of annealing. This result shows worse performance than with 150°C , but it is achieved only during a small fraction of time, which is a non-negligible benefit of the procedure.

3.1.4 MTD at CMS

For the HL-LHC, the upgrade of the CMS experiment includes a new high-precision timing detector - the Minimal Ionizing Particle (MIP) Timing Detector (MTD). This detector consists of the Barrel Timing Layer (BTL) and the Endcap Timing Layer (ETL) covering pseudorapidity regions $|\eta| < 1.5$ and $1.6 < |\eta| < 3.0$ respectively. Both are restricted in dimensions by CMS architecture to fit between the tracker and electromagnetic (endcap) calorimeter. Aside from compactness, the architecture also poses requirements on both subdetectors to withstand magnetic fields and survive in operation during the whole HL-LHC phase, while the radiation damage affects the

time resolution. Thus, to reduce the pileup to acceptable levels, a time resolution of 30-40 ps is intended at the beginning of the operation, which degrades to 50-60 ps by the end of the operation [45].

BTL is a thin cylindrical detector made of LYSO:Ce scintillators coupled double-sided with the SiPMs with the area of $3 \times 3 \text{ mm}^2$ and cell pitch of $25 \times 25 \text{ }\mu\text{m}^2$. The scintillating crystals provide signals of 40 ns decay time read by the SiPM with a peaking time of 30 ns, of unipolar signal, with a tail of 200 ns. Reduction of DCR (the integrated fluence is expected up to $2 \times 10^{14} \text{ neq/cm}^2$) will be accomplished by operation at -45°C and periodical annealing at 60°C , together with noise suppression circuitry furtherly discussed in [46].

ETL covers regions with higher radiation levels where integrated fluence reaches beyond 10^{15} neq/cm^2 , which restrains from the use of the SiPMs. Instead, Low Gain Avalanche Diodes are used (LGADs) [35]. This illustrates that despite the many excellent properties of the SiPMs, they are not a universal solution for light collection.

3.2 Calorimetry

Scintillators such as PWO or LYSO, in homogeneous calorimeters, or plastic scintillators, serving as active layers in inhomogeneous, are often used in calorimetry, creating a great demand for photodetectors in the field. As stated earlier, the SiPM provide a suitable option, either coupled directly to the scintillator or via wavelength shifting or optical fibre [47].

3.2.1 Crystal calorimeter at Mu2e

The Muon-to-Electron Conversion (Mu2e) experiment at Fermilab is planned to investigate Charged Lepton Flavour Violation (CLFV) by measuring the ratio of neutrinoless, coherent conversion of muons into electrons in the field of a nucleus. The CLFV was previously studied in the SINDRUM II experiment at PSI, observing not only the μ, e transitions but also significant results were reached in τ decay and other leptonic decays. [48] Mu2e intends to probe four orders of magnitude beyond the SINDRUM II single-event-sensitivity (SES), aiming for unambiguous evidence for physics beyond the Standard Model and reach of the LHC [49].

The SES of 3×10^{-17} at energies $\sim 100 \text{ MeV}$ states the requirement for the calorimeter to consist of a homogeneous medium, reducing the design options to gases and crystals. The extensive R&D phase concluded with an option of high-quality undoped CsI crystals with the SiPMs arranged in two annular disks. The combination proved to be the best due to the mechanical properties and cost-effectiveness of the crystals and matching emission spectra (310 nm) to the PDE of UV-extended SiPM (Hamamatsu) [50].

The most important characteristics for the photodetector selection were in $\text{PDE} > 20\%$, recovery time less than 100 ns for each sensor cell, reasonable operation voltage and

its spread between the cells, gain of 10^6 together with the DCR withstanding 3×10^{12} neq/cm² without significant changes at 20°C, and the Mean Time To Failure (MTTF - representing the time of operation until the device stops working properly) better than 10^6 hours at 0°C. The Hamamatsu UV-extended SiPMs of 6×6 mm² were used and proved satisfactory in various tests in testing facilities in Germany and USA and set a limit on operation temperature less than -10°C to fulfil all the requirements [50].

3.2.2 sPHENIX calorimeter

The sPHENIX experiment is built for high-precision measurements of jets and heavy flavour observables. There are two calorimeters for sPHENIX: the electromagnetic calorimeter (EMCal), which prototype is composed of scintillating fibres embedded in a mixture of tungsten powder and epoxy and the hadronic calorimeter (HCal), with the prototype composed of tilted steel plates alternating with the plastic scintillator [51] and for both was designed a specific readout system using the SiPMs [52].

The EMCal prototype tested in [53] consist of towers, where each tower has a light guide epoxied to one side and an aluminium reflector on the other. The light guides are of UV-transmitting acrylic and are coupled with silicone adhesive to a 2×2 array of SiPM.



Figure 3.5: EMCal blocks (back), light guides, SiPMs, electronics (front), and part of the cooling system (copper pipe) as used for the beamtest. *Taken from Ref. [53].*

Each SiPM (Hamamatsu S12572-015P) had an active area of $3 \times 3 \text{ mm}^2$ with photon detection efficiency of 25%. The signals from each of the four SiPMs were summed to give a single output signal from each tower. For thermal compensation to avoid SiPM performance perturbations, a cooling system for the electronics was used, as visible in Figure 3.5 and provided satisfactory stability for the SiPMs to keep the gain at 2.3×10^5 . The tests resulted shown satisfactory performance for the energy resolution for the range of energies from 2 GeV to 28 GeV [53].

3.3 Muon Systems

3.3.1 MID for ALICE 3

The Muon IDentifier (MID) is a proposed detector for the ALICE 3 to efficiently reconstruct J/ψ a rest, which corresponds to the reconstruction of muon tracks down to $p_T \approx 1.5 \text{ GeV}$ for $|\eta| < 1.3$. The modest particle flux favours the plastic scintillators equipped with wavelength-shifting fibres and SiPM readout, or lightweight Multi-Wire Proportional Chambers (MWPCs) that are currently under investigation [15] although the original proposal also included the Resistive Plate Chamber (RPC) technology same as its predecessors [14]. The layout of a module for the plastic scintillator option is shown in Figure 3.6. This option considered a baseline due to its simplicity, comprises two layers of crossed scintillator paddles (5 cm wide) with a 10 cm gap between the two layers. Both MWPCs and scintillators represent a cost-effective solution to cover a detection area of around 360 m^2 .

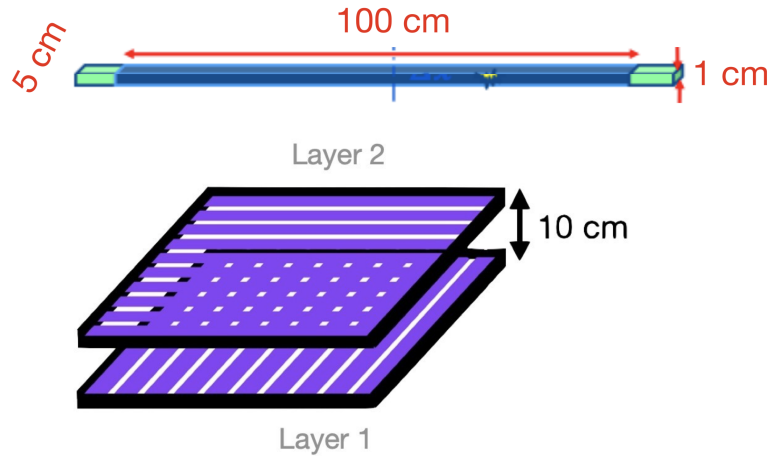


Figure 3.6: Scintillator bar specification and its planned layout in one of the MID modules. *This scheme is a property of Dr Solangel Rojas Torres.*

Regarding the SiPMs used, the Hamamatsu S13360-6050CS were used in the competitive bars investigated for this detector. Together with the scintillator bars - the extruded FNAL-NICADD scintillator bar equipped with WLS fibre and only one SiPM at one side of the bar and the ELJEN EJ-208 - deliver better than 2 ns

time resolution and light yield of 40 photoelectrons and provide a sufficient and cost-effective solution for the future detector.

3.4 Neutrino physics

The neutrino experiments using both the cosmic neutrinos or the neutrino beams produced from primary beams after transversing the targets also use state-of-art detectors, which, to a large extent, copy the structure of general-purpose detectors. The neutrino interactions are rarer than the collision described earlier, and therefore, the neutrino experiments tend to be enormous in size. Large water tanks used as Cherenkov radiators are very common for neutrino detection [54]. The Cherenkov light is then detected with photodetectors which opens possibilities of uses for the SiPMs.

3.4.1 The Deep Underground Neutrino Experiment

The Deep Underground Neutrino Experiment (DUNE) is to be hosted by Fermi National Accelerator Laboratory (Fermilab) in Illinois (near detector and beamline) and Sanford Underground Research Facility (SURF) in South Dakota (far detector), as shown in Figure 3.7. DUNE promises a broad exploration of the three-flavour neutrino model with unbeatable precision and discoveries revolving around the matter-antimatter asymmetries in neutrino flavour mixing [55].

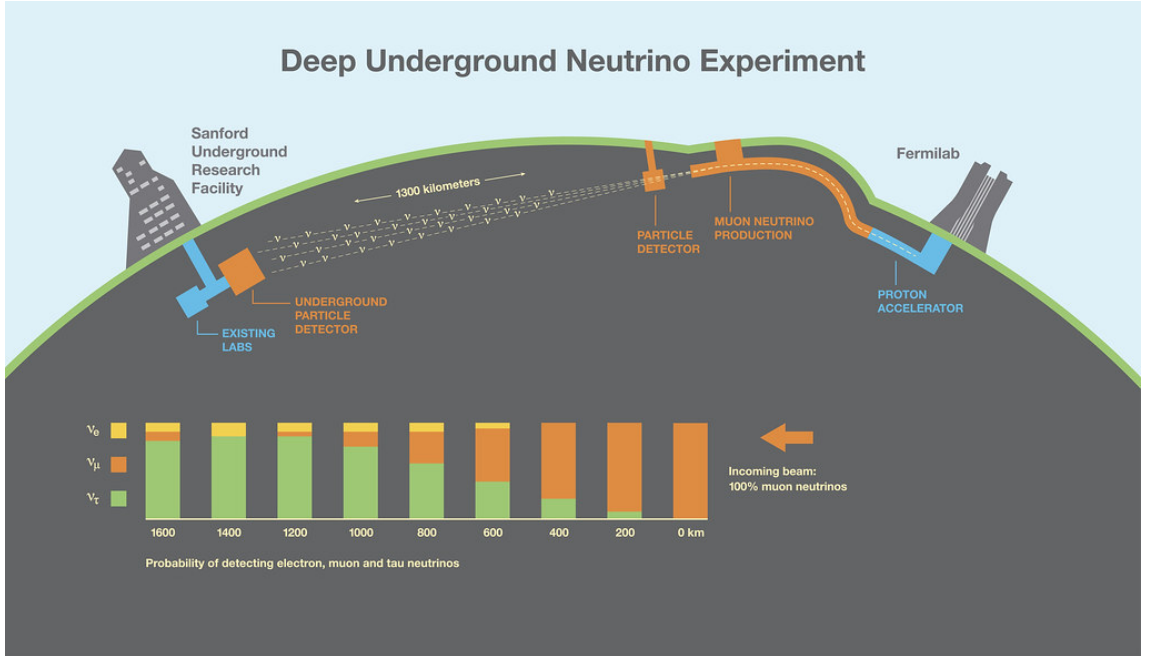


Figure 3.7: DUNE graphic of the detector situating and probabilities of detection of different neutrino flavours. *Taken from Ref. [56].*

The far detector (at SURF) will be a modular liquid argon time-projection chamber (LArTPC) with a sensitive mass of 40 kt of liquid argon (LAr), a cryogenic liquid that must be kept at 88 K. The LAr typically allows not only the anode readout for the TPCs but also the scintillation light readout. This light will be collected by ARAPUCA modules consisting of layers of dichroic filter and wavelength shifter transporting the light to the SiPMs. The modules are architectures to cover large areas and focus the faint light signal to the photodetectors while also adjusting the wavelength from the vacuum ultraviolet to the range visible to the SiPMs. Note that the low temperature will allow the peak performance of the SiPM devices, which are customary developed by Hamamatsu [57].

The near detector (at Fermilab) will comprise also a multipurpose detector (MTD) to complement its LArTPC measurements for the muon momenta, crucial for neutrino energy determination. The MTD will consist of a high-pressure gaseous TPC and an electromagnetic calorimeter (ECAL). The ECAL will use SiPM in a conventional way in sampling calorimetry, as shown in Figure 3.8. The Further development for this detector is still ongoing, given the later commissioning in Phase II, while the far detector modules are to be completed by 2025 in Phase I [58].

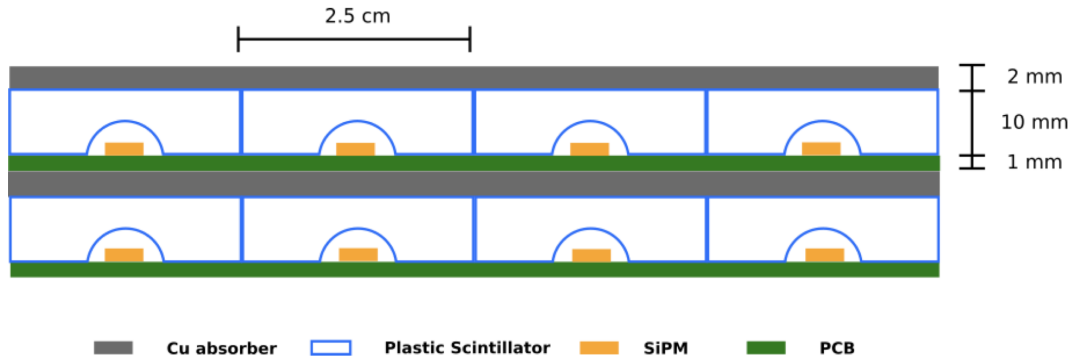


Figure 3.8: Conceptual layout of the DUNE's ECAL showing the absorber structure, scintillator tiles, SiPMs, and PCB. *Taken from Ref. [55].*

Chapter 4

Evaluation of the SiPMs in the lab environment

This chapter guides the reader through the experimental part of this work performed in the Laboratory of Experimental Nuclear Physics of the FNSPE CTU in Prague, the Laboratory of the University of Kansas at CERN, and previous work performed in the CERN East Area Facility. The beginning of the chapter is focused on the introduction of the SiPMs and their readout and power electronics and is followed by the measurements with the laser and cosmic rays, and the temperature-dependent measurement of the dark court rate (DCR). For every measurement is formost introduced the setup, used components, and devices. Afterwards, a description of the analysis method and subsequent results are presented.

The measurements of this chapter concentrate on the performance of four SiPMs with various methods and approaches to the evaluation of such devices.

4.1 SiPMs and their front-end electronics

Four SiPMs were used for the evaluation, as shown in Table 4.1, where are noted the identifying information about the SiPMs and their label further used in this work.

label	manufacturer	model	area [mm ²]	outputs*
S1	ONSEMI (SensL)	MICROFJ-60035	6×6	dual
S2	ONSEMI (SensL)	MICROFC-30035	3×3	std
S3	ONSEMI (SensL)	MICROFJ-30020	3×3	dual
Hamamatsu	Hamamatsu	S13360-6050CS	6×6	std

Table 4.1: Overview of the SiPMs used in this work with their basic properties.

*Some SiPMs have a dual output, the standard (std) and an additional fast output.

The SiPM signal can have, in general, different polarities depending on the front-end electronics, particularly the pre-amplifier. The onboard amplification also affects

label	VME amplification	V_{bias} [V]	V_c [V]	signal polarity
S1	$\times 10$ std & $\times 10$ fast	26 - 30	27	both positive
S2	$\times 10$	26 - 31	27	negative
S3	$\times 3$ std & $\times 10$ fast	26 - 30	28	std positive, fast negative
Hamamatsu	$\times 1$	54 - 58	57	positive

Table 4.2: Overview of the amplifications used for the setup with the VME crate, the operational voltages used for the laser measurements V_{bias} , the bias voltages used for the cosmic measurements V_c , and the signal polarities.

the need for an additional amplifier, which was, in fact, used for the measurements using the VME modules. A VME (Versa Module Europa) crate is a type of standardized hardware and bus and communication protocol often used in industrial control systems providing modular data acquisition and processing. The VME modules conform to the VME bus standard and enable the modularity of such a system [59]. The modules are adjusted to work reliably with a large number of devices, and undoubtedly, this approach is a great option in large tests with extensive amounts of devices; nonetheless, for the purposes of the sensitive measurements device-by-device, the oscilloscope was shown to be a more suitable option. For the measurements with the sensors used, this solution was proven to induce excessive noise levels, which, in some cases, completely eradicated the possibility of acquiring useful data. In fact, in the case of the measurements performed, the mostly empty (i.e., many unused channels) modules were creating large reflections of the electric signal, destroying the original signal. However, this setup was used for the measurement with the cosmic rays, where the signal-to-noise ratio had an acceptable level needed for the measurement.

During the evaluation, different operational voltages were used for the SiPMs that were in the ranges suggested by the manufacturer in their corresponding datasheet and also measured with the oscilloscope since the differences are also observed in SiPMs within the same series or type; hence, it is standard practice to characterize each of the SiPM individually to utilise each at its best performing configuration. The observed SiPM-specific properties mentioned in the last two paragraphs can be found in Table 4.2.

4.1.1 SiPM S1

The SiPM S1 came on a development board with 3 SMA connectors for the powering, fast, and standard outputs. The board model is corresponding to the SiPM type, MICROFJ-SMA-60035-GEVB. The board with the SiPM can be seen in Figure 4.1, and its detail can be found in the datasheet [60].

4.1.2 SiPM S2

The SiPM S2 was donated for this work by Dr Nicola Minafra, together with his custom-designed board shown in Figure 4.2. The amplifier is 20dB, 3 GHz wide

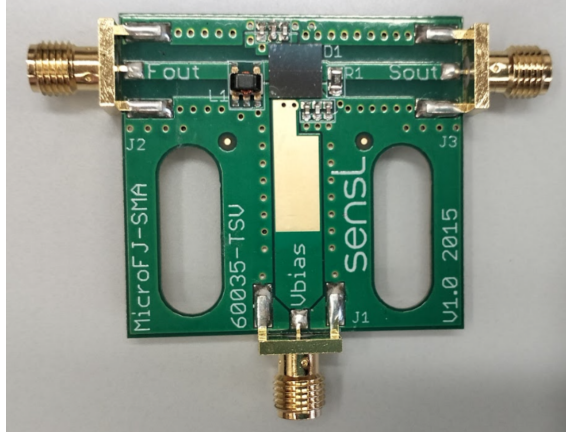


Figure 4.1: Photo of the SiPM S1 on its development board.

bandwidth, 2.4 dB noise figure, and 50 Ohm matched. Further details on the SiPM itself can be found in its datasheet [61].

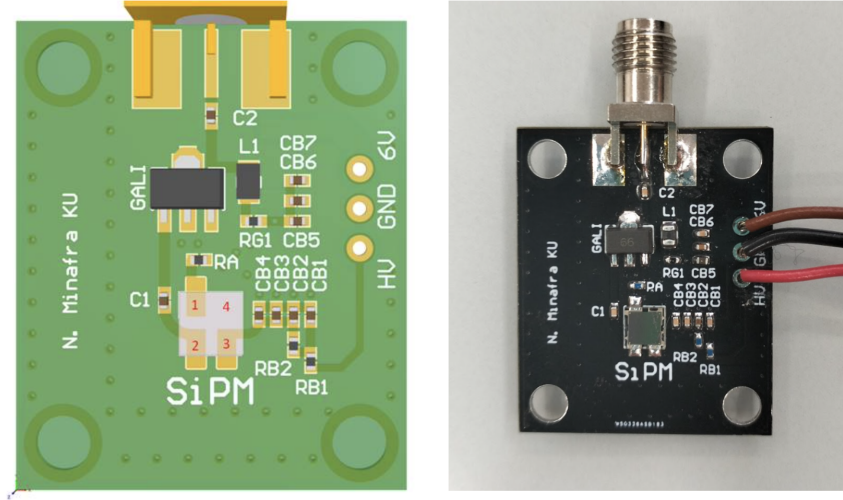


Figure 4.2: Photo of the SiPM S2 (right) and its board schematics (left).

4.1.3 SiPM S3

The SiPM S3 was provided for this work by Dr Petr Chaloupka on a custom-designed board for the tests for the CBM experiment and can be seen in Figure 4.3.

4.1.4 Hamamatsu SiPM

The Hamamatsu SiPM came with a PBC board and a separate board for power management, and the readout was connected to the SiPM board via flex cable. The specification of the driver board is its datasheet [62], which is, however, separate from

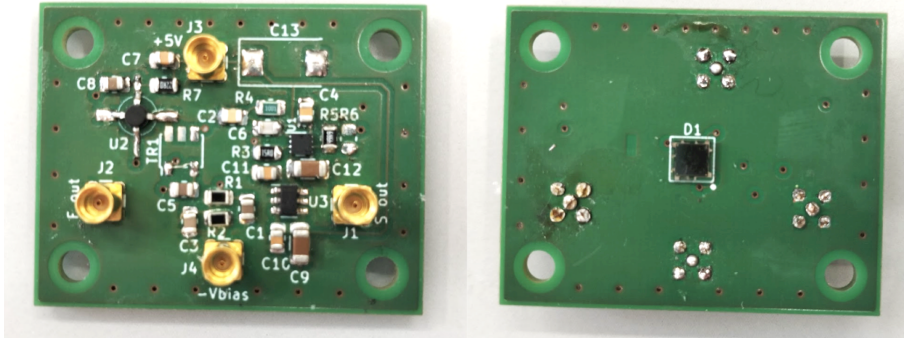


Figure 4.3: Photo of the SiPM S3 (right) and the opposite side of its board with visible components (left).

the SiPM datasheet[63]. The power management of the SiPM is done additionally by software from Hamamatsu running on a Windows machine.



Figure 4.4: Photo of the Hamamatsu SiPM (left) connected to its powering board (right).

4.2 Tests with laser

For evaluation of the SiPMs and their comparison, they were tested with a picosecond laser in the black box.

4.2.1 Holder

For the purpose of this test, a holder for the SiPM and the laser was printed on a 3D printer 3ntr A4v4. The holder consists of the body, a laser support, and possibly a SiPM adapter. The SiPM adapter was designed for each of the SiPMs, except for the Hamamatsu one, which fitted to the holder directly. In fact, the Hamamatsu having the largest board was the reason for the holder design to fit it directly; thus,

the reduction adapters were designed only for the smaller boards. The holder is shown in Figure 4.5.

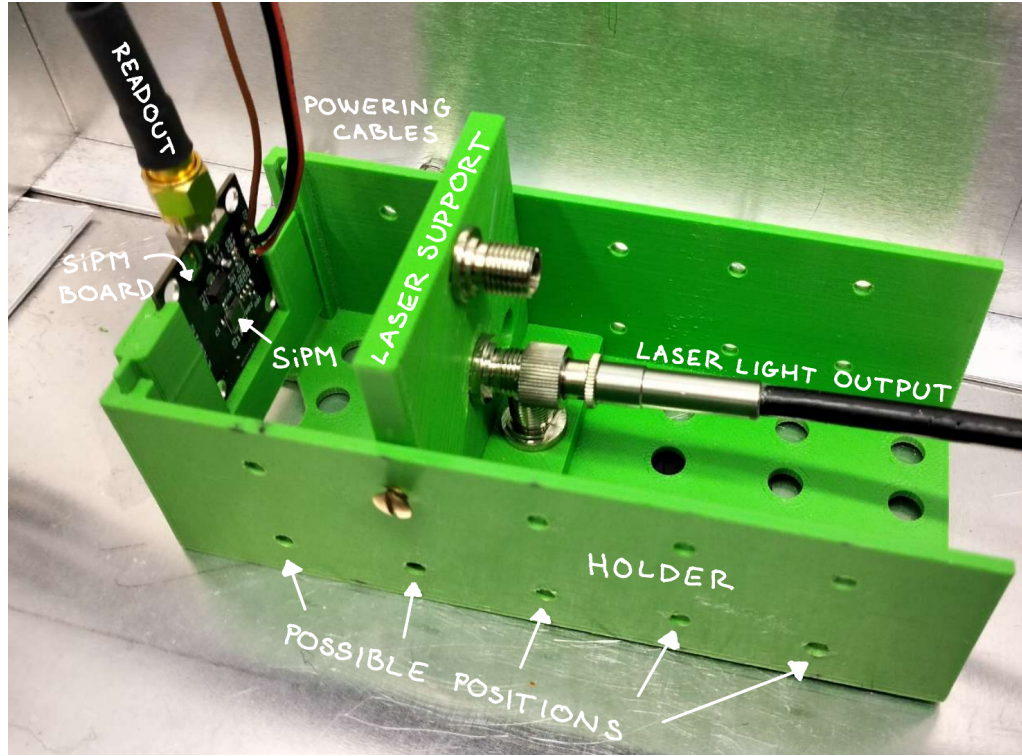


Figure 4.5: Photo with the description of the holder for the laser and the SiPM with the adapter.

The laser support was also printed in multiple versions in order to adjust to the SiPM position within its board. The holder was designed to allow multiple different distances between the laser and the SiPM, out of which 2 cm was chosen and was kept through all the measurements.

4.2.2 Initial setup for the laser measurements

Before further analysis of the acquired data, it is necessary to go over the immediate signal responses as will be shown in the next Section 4.2.5.1 in order to not overlook any obvious mistakes in the data acquisition. The author complements this approach by including the data from the first measurements performed for this task, which were later evaluated as unsatisfactory, and the measurement was repeated with a different setup. The initial setup for this measurement is shown in Figure 4.6.

The main aim of this setup was to observe the single photon distribution. However, this became a major problem, as was already discussed in section 4.1 and the clarity of the data was not satisfactory due to a large electronic noise pollution.

A human error also added to the unsuitability of the data acquired, where for some of the acquired data, an improper sampling rate was chosen. Thus, parts of the waveforms were cut precociously for longer signals.

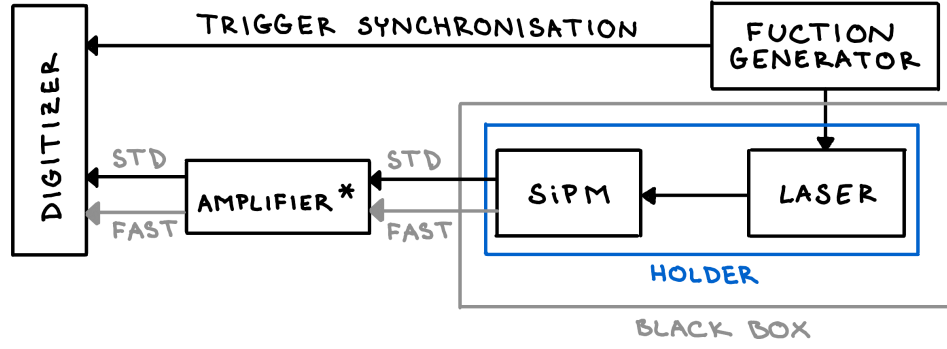


Figure 4.6: Schematics of a setup for the first measurement with the laser.

4.2.3 Full setup for the laser measurements

The full setup comprised the holder, laser PicoQuant PDL 800-D driver and LDH-P-C-405 laser head, function generator GW Instek AFG-3051, oscilloscope Lecroy TELEDYNE HDO 6104B and the evaluated SiPM; each of the four were tested.

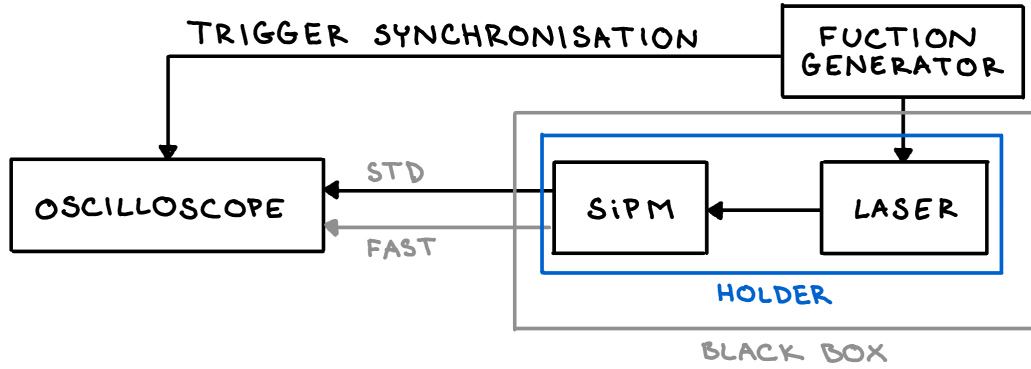


Figure 4.7: Schematics of a setup for measurement with the laser.

4.2.4 Method

The data were acquired and preprocessed in the oscilloscope. The function generator, having two outputs, was used as a trigger for the data acquisition. With the functions on the oscilloscope, the histograms of amplitude, charge (area under the waveform) and rise times (20 % to 80 %) were taken. Afterwards, the Gaussian distributions were fitted to the individual peaks with Python 3.

4.2.5 Results

The measured and analysed results are divided into three sections, starting from the plain observation of the signal and followed by a comparison of the timing properties. The last part discusses the single photon distributions.

4.2.5.1 Waveforms of the SiPM signals

For this section, only selected waveforms are included. The selection was made to comment on the repeating structures of the singles yet not overwhelm the content. The waveforms were obtained by the persistence display and screenshot from the oscilloscope. The structure looked for in these plots is formed from equidistant lines representing the waveforms of a small number of photons. This structure is, however, clearly visible only for the SiPM S2; see Figure 4.9.

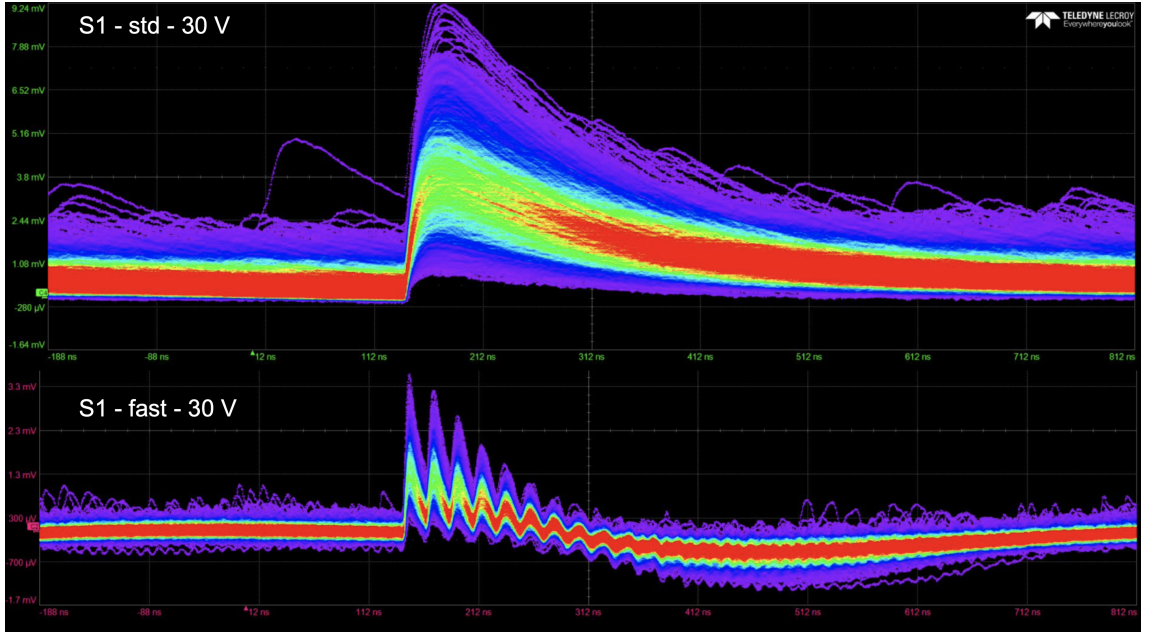


Figure 4.8: Waveforms for the SiPM S1 for the run with laser at 30 V for both its outputs.

In Figure 4.8, waveforms of the same run (at 30 V) from both outputs of the SiPM S1 are shown. For the standard output, due to the persistence setup, hints of the single photon distribution are manifesting as separate, equidistant red lines around 212 ns. On the other hand, the fast output does not show the desired behaviour and the parasitic sine structure in the signal can also be observed. This structure most probably comes from electronics reflection since it is too repeating to come from the sensor noise phenomena such as crosstalk discussed in section 2.4.2.4. The possible source of the electronic reflections may be improper coupling, a damaged connector, as well as the signal cable. Similar behaviour was observed previously for a broken adapter LEMO–BNC; nevertheless, in this case, the author was not able to find the source of this discrepancy.

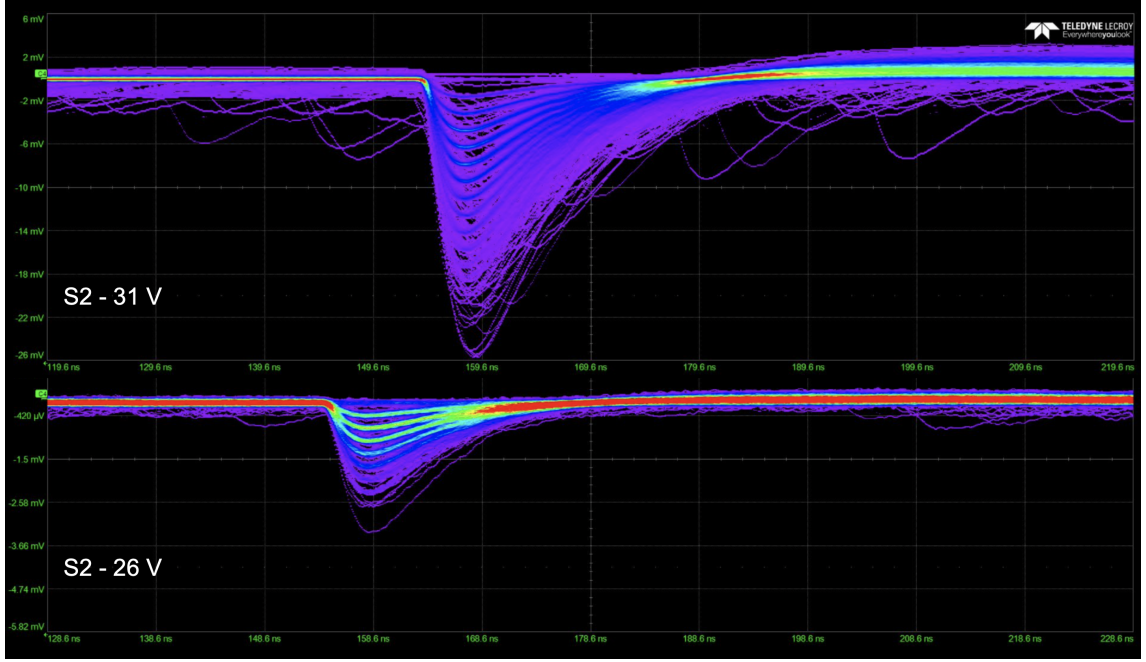


Figure 4.9: Waveforms for the SiPM S2 for the runs with laser at 31 V and 26 V, which are the maximal and minimal voltages used for this measurement.

Figure 4.9 compares the runs of the SiPM S2 with the highest and lowest bias voltage measured. For both cases, the single photon structure is very well visible. In the case of the $V_{bias} = 31$ V, the difference between the lines and the rest of the distribution is not so articulated as seen for the $V_{bias} = 26$ V, which is a result of higher gain at larger bias voltages. With higher gain, the variance of the signal also increases and results in seemingly less precise measurements.

For the SiPM S3, the comparison of fast and standard output at 29 V is shown in Figure 4.10. The standard output, similarly to the SiPM S1, shows rather faint yet visible lines of the single photon structure. The fast output due to its briefness does not demonstrate this feature; rather, it draws attention to its positive overshoot after the initial negative response. This is a usual feature of fast outputs due to their electronic structure and fast pulse compensation.

The Hamamatsu SiPM was compared for boundary voltage levels, namely 54 V and 58 V. The shapes of the signal are the same, and the amplitude is naturally higher only for the higher voltage. A notable insight is provided by the persistent view; for the higher bias voltage, more blended shapes are observed, the same as for the S2. Additionally, for the lower voltage, more reflection-like disturbances are visible.

4.2.5.2 Rise times

The rise time distributions were obtained for each of the measurements, giving two options for the determination of the rise time for the given SiPM output at a given voltage. A calculation of the statistical mean and, subsequently, the mean and the standard deviation calculation was done as visible on an exemplary

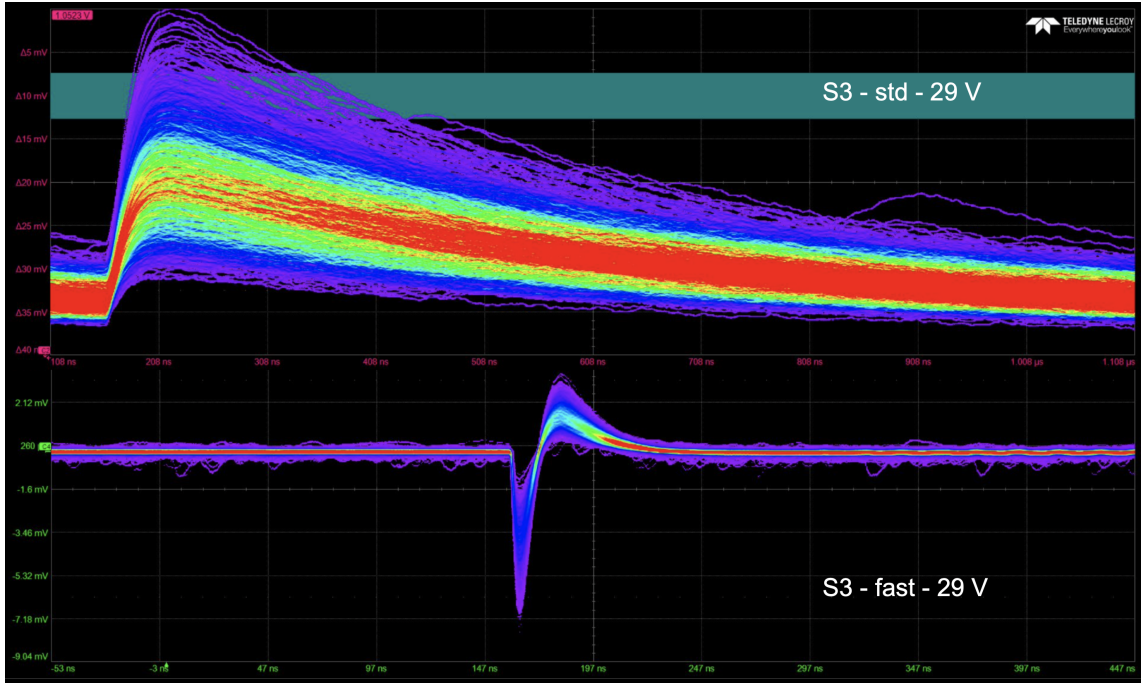


Figure 4.10: Waveforms for the SiPM S3 for the run with laser at 29 V for both its outputs. *Note that the green line has no relation to the message of the figure; it is only a relict from the previous oscilloscope settings.*

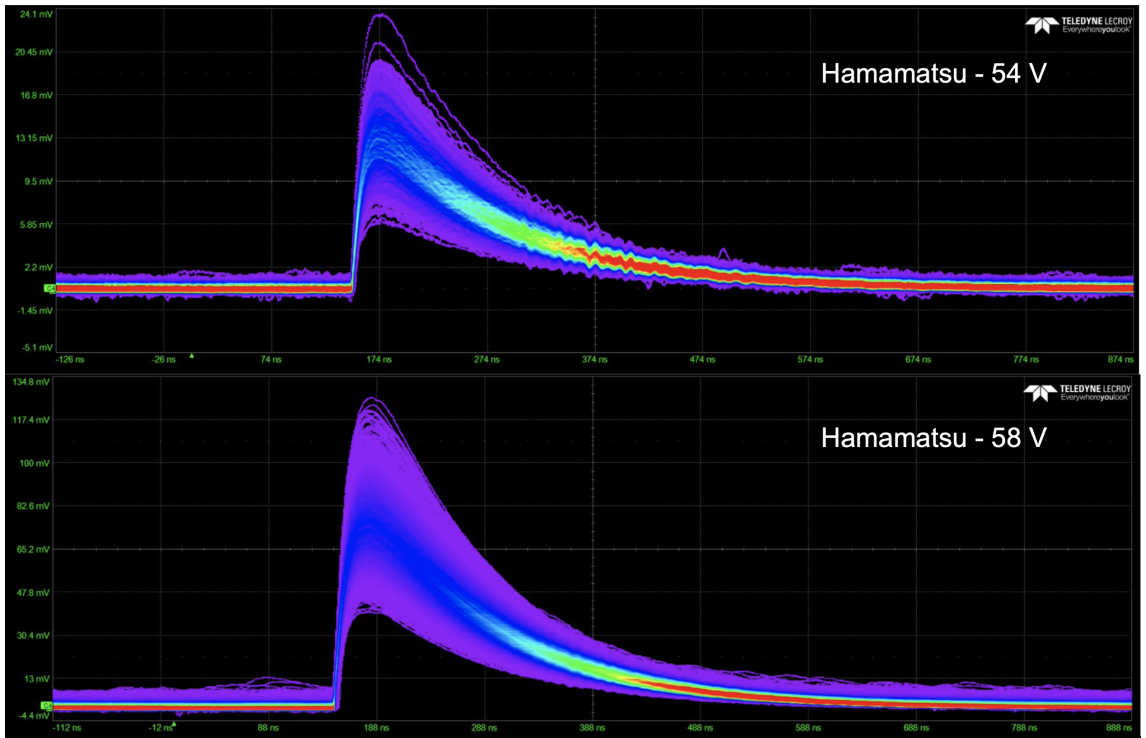


Figure 4.11: Waveforms for the Hamamatsu SiPM for runs with laser at 54 V and 58 V, which are the minimal and maximal voltages used for this measurement.

run in Figure 4.12. Nevertheless, from most of the distributions, was visible, that the Gaussian distribution is dominating, hence, a Gaussian fit was performed a well. Both approaches were performed in order to see which one leads to a better description of the data and compare the two since both of them were seen used for timing performance evaluation [64, 65]. The results of the calculations are shown in Tables 4.3 and 4.4.

V_{bias} [V]	std S1 _{gauss}	std S1 _{mean}	fast S1 _{gauss}	fast S1 _{mean}	S2 _{gauss}
26	n/a	100 ± 110	n/a	110 ± 130	12 ± 2
27	10 ± 2	20 ± 50	n/a	130 ± 115	11 ± 2
28	7 ± 3	10 ± 20	n/a	40 ± 60	11.1 ± 1.3
29	8 ± 3	8 ± 3	2.3 ± 0.3	3 ± 2	11.2 ± 1.2
30	10 ± 1	12 ± 6	3 ± 2	20 ± 30	10.3 ± 1.5
V_{bias} [V]	fast S3 _{gauss}	fast S3 _{mean}	std S3 _{gauss}	std S3 _{mean}	S2 _{mean}
26	7.1 ± 0.5	7.3 ± 0.7	n/a	100 ± 120	13 ± 6
27	7.1 ± 0.3	7.2 ± 0.5	14 ± 5	15 ± 5	12 ± 3
28	7.0 ± 0.2	7.2 ± 0.5	19 ± 1	20 ± 4	12 ± 3
29	7.1 ± 0.3	7.3 ± 0.5	19 ± 1	20 ± 3	12 ± 3
30	7.2 ± 0.4	7.5 ± 0.9	16 ± 4	17 ± 4	11 ± 3

Table 4.3: The rise times for each measurement in nanoseconds (ns), for the SiPMs S1, S2, and S3, calculated as Gaussian fit and statistical mean.

V_{bias} [V]	Hamamatsu _{gauss} [ns]	Hamamatsu _{mean} [ns]
54	9.1 ± 0.3	9.1 ± 0.4
55	9.1 ± 0.3	9.1 ± 0.4
56	9.4 ± 0.4	9.5 ± 0.5
57	10.4 ± 0.7	10.5 ± 0.8
58	10.2 ± 0.6	10.5 ± 0.8

Table 4.4: The rise times, for each measurement of the Hamamatsu SiPM, calculated as Gaussian fit and statistical mean.

From the table, it is visible that despite the fact that the Gaussian fit does not always converge, the only option is to take the statistical mean, the Gaussian; every time it converges, it has a smaller error. The Gaussian shape dominated the distribution for the vast majority of cases. Therefore, this approach can be evaluated as more plausible.

4.2.5.3 Single photon distribution

Apart from the pure waveforms, the single photon distribution is also observable in the amplitude and charge distributions. The appearance in the amplitude distribution is a direct result of the observation in the waveform with persistent display. However, the charge distribution, calculated as an integral of the signal, may show

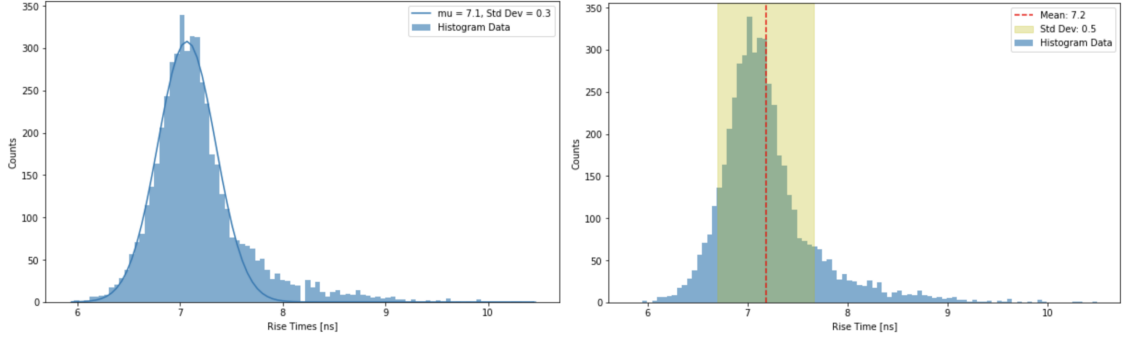


Figure 4.12: The rise time distribution for the fast output of the SiPM S3 at 27 V fitted with Gaussian (left) and with statistically calculated parameters (right).

more sensitive behaviour to this phenomenon since the number of photons is directly translated into the amount of charge, while the amplitude is only a secondary feature. This might not be true in cases when the charge amplifier is used with the SiPM, then the integration is already included in the amplitude, and its repetition will not bring any additional information.

As it is visible from the waveforms shown in section 4.2.5.1, the SiPM S2 single photon distribution is very extremely clear. The amplitude distribution indeed inherited this behaviour, as seen in Figure 4.13. The equidistant peaks can be used for the determination of an amplitude response for a single photon for each of the measured voltages.

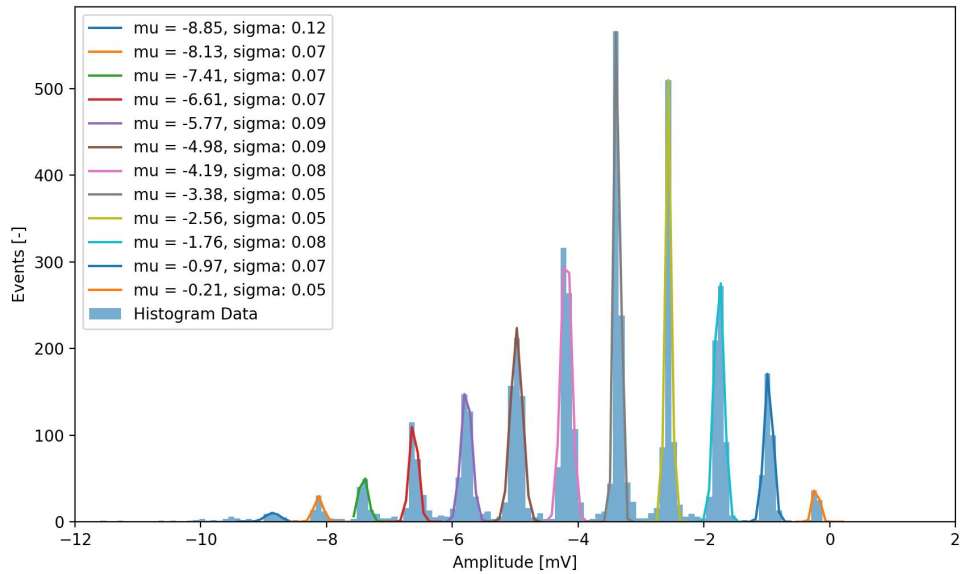


Figure 4.13: A single photon distribution in amplitudes with fitted Gaussians for the individual peaks. The data used are for the SiPM S2 at 27 V.

Each peak for each measurement was fitted with a Gaussian, and the differences between the peaks were averaged in order to obtain one representative value for each bias voltage. These values are plotted in Figure 4.14 and fitted linearly as it is the expected behaviour [31].

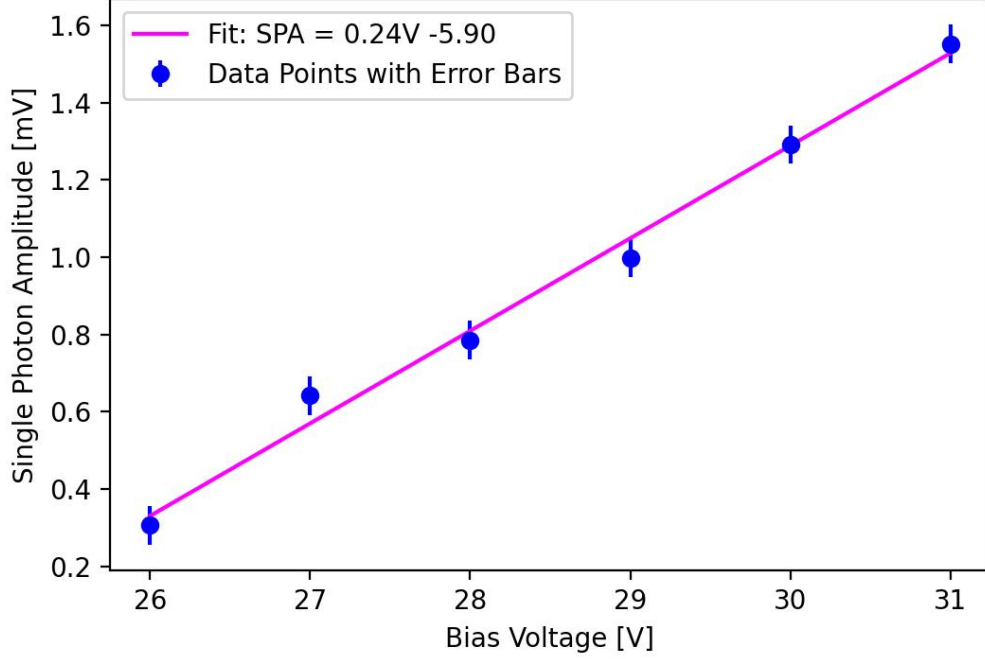


Figure 4.14: A single photon amplitude with respect to the bias voltage plotted with a linear function.

In order to prove the quality of the data, the run with the same voltage and laser intensity is shown in Figure 4.15. The additional Gaussian-like structure can be observed on the top of which the single photon distribution is visible. This additional noise in the amplitude distribution is visible, deforming even the possible perfectly clear measurement endorses the move to the oscilloscope setup from the one using the VME crate.

4.2.5.4 Gain dependency on the overvoltage

The gain is dependent on the overvoltage and can be calculated as $const. \int U dt$ according to the formula (2.8). This opens an easy possibility of its calculation in arbitrary units (since the constant is unknown and SiPM-specific). The method of this calculation will take the distribution of the areas from the waveforms and fit the full distribution with a Gaussian. The means will be then plotted with respect to the bias voltages, similarly as was done for the Single Photon Amplitudes, in Figure 4.16.

The linear behaviour was confirmed for all the standard outputs, while the fast outputs were discluded from this analysis because the error of the Gaussian fit was

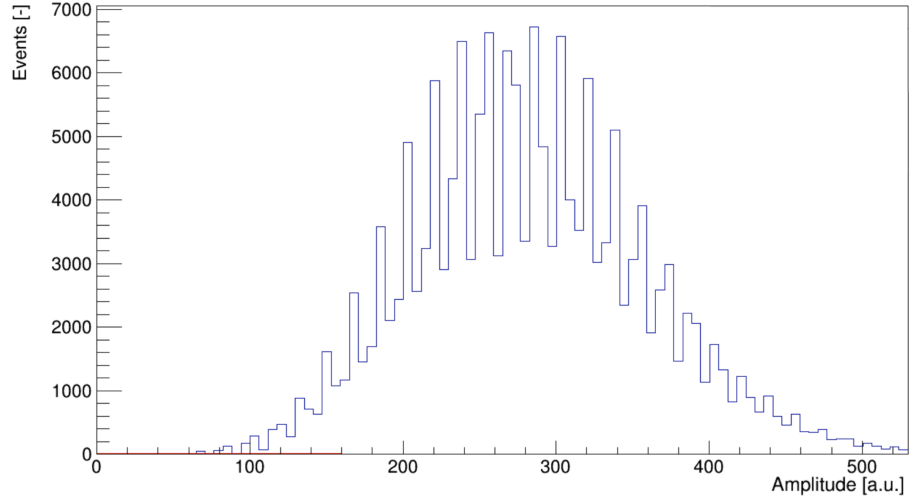


Figure 4.15: A single photon distribution in amplitudes with fitted Gaussians for the individual peaks. The data used are for the SiPM S2 at 27 V from the initial setup, discarded from further analysis.

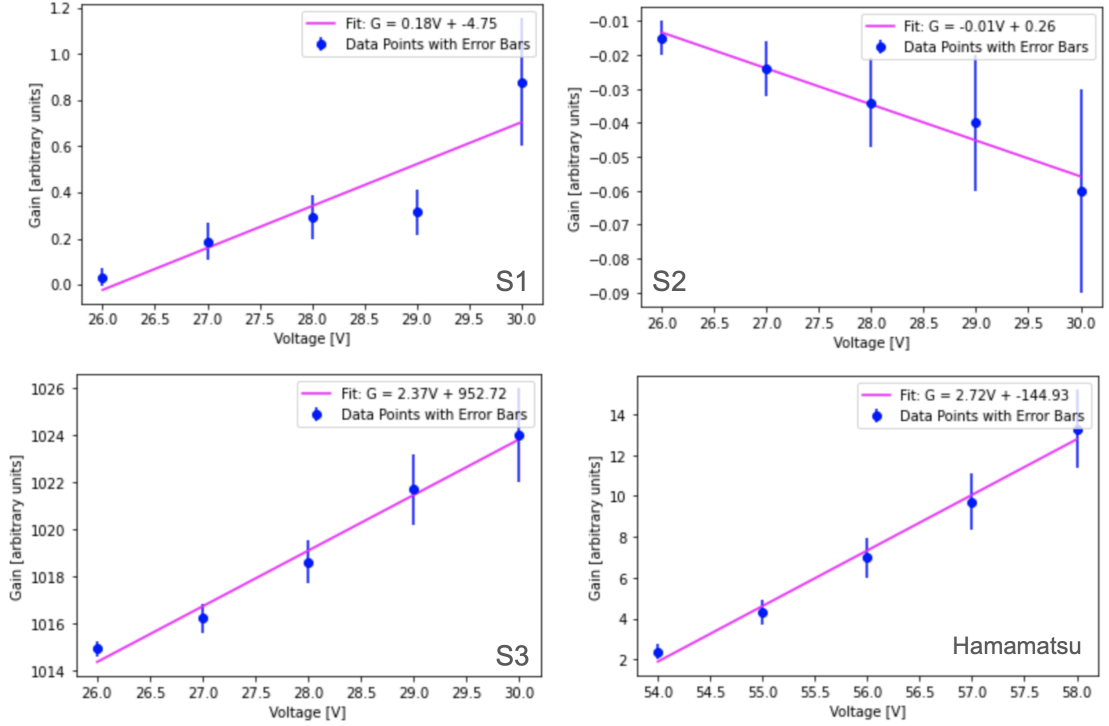


Figure 4.16: Gain in arbitrary units plotted against the bias voltage of the standard outputs of all four tested SiPMs.

by at least one order of magnitude larger than the shift of the peak between the two voltages. This analysis was also performed on the data acquired with the initial setup for the laser measurements with the VME crate 4.2.2. The standard outputs of the 3 SiPMs were taken, neglecting the rest of the data due to their low quality or incompatibility with the method. The plots demonstrating the same behaviour are shown in Figure 4.17.

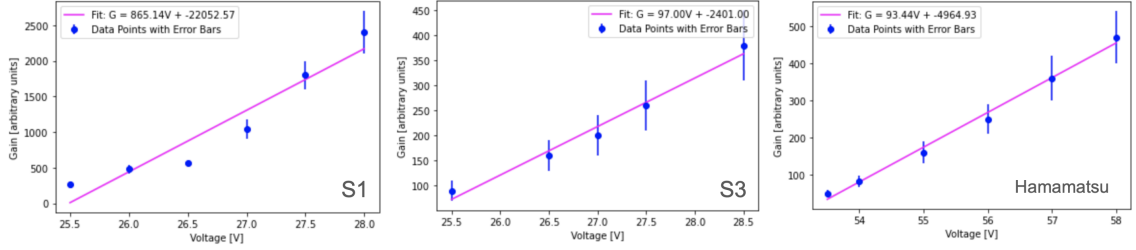


Figure 4.17: Gain in arbitrary units plotted against the bias voltage of the standard outputs of S1, S2 and Hamamatsu SiPMs.

The data points, except for the SiPM S1, are in all cases agreeing with the fitted curve within their errorbars. Since the breakdown voltage is temperature-dependent, the gain follows this proportional behaviour as well. To unravel this consistent discrepancy, appearing in two plots of the seven analysed while both belong to the same SiPM, the author decided to examine the timestamps of the measurements.

This step was motivated by an attempt to measure the DCR in the CTU lab, which, despite being unsuccessful in obtaining suitable data for the DCR frequency calculation (this was done later at CERN, see section 4.4), provided an insight on the effect of overheating due to the continuous monitoring of the temperature while the SiPMs were in operation. From the four tested SiPM, this board showed the largest increase in temperature, up to 5°C, while the other boards were during the same period showing no increase, only up to 2°C.

The conclusion of this investigation, unfortunately, disproves this hypothesis since the times of operation would suggest rather opposite behaviour. The gain, however, increases with lower temperatures [66]. Thus, the earlier measurements being below the curve, and vice verse, only confirm the need for further study of this device.

4.3 Evaluation of scintillator bar with cosmic rays with the SiPMs

As stated in previous chapters, the SiPM are widely used as photodetectors in larger detector systems. To demonstrate the capabilities of the devices, a scintillator bar was characterized with a cosmic ray setup. For cosmic ray detection, a standard technique of twofold coincidence was used.

4.3.1 Cosmic ray setup

The cosmic ray setup comprised two scintillator bars with photomultiplier tubes attached, working together as a coincidence trigger for the measurement. The setup components were in a custom foam holder, as shown in Figure 4.18.

Standard VME modules were used for data acquisition and PMT powering. Namely the Low Threshold Discriminator (LTD) Caen V814, amplifier Caen V925, power

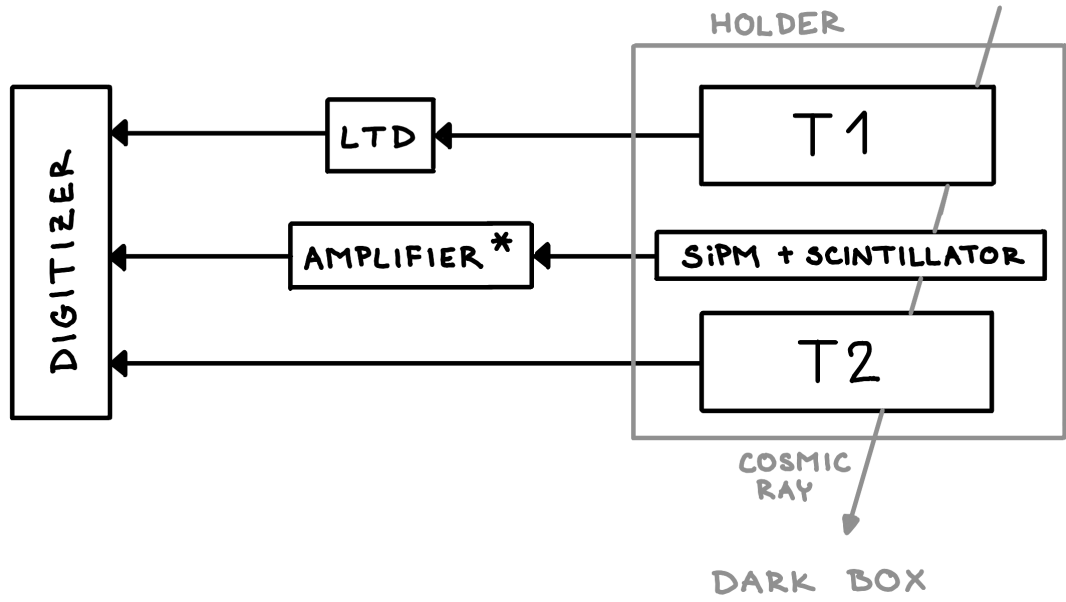


Figure 4.18: Schematics of a setup for measurement with the cosmic rays. The asterisk denotes that the amplifier was not used for all the measurements.

module Caen V6533P, and digitizer Caen V1718. Both triggering PMTs were controlled using the GECO software to power them at 1.7 kV, and their signal was not amplified. The signal from the top bar was used for a hardware trigger after going through the LTD module. The coincidence with the signal from the bottom trigger was done in the software. A photo of the setup is in Figure 4.19.

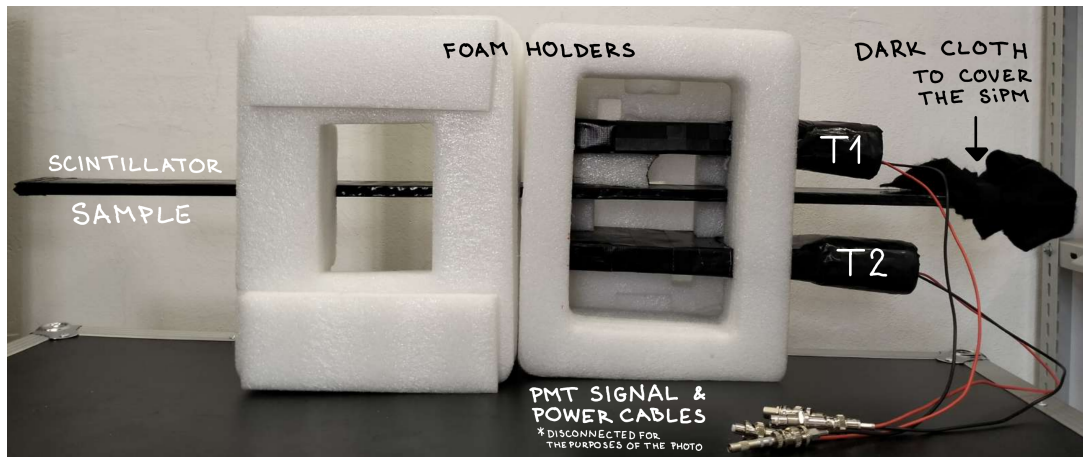


Figure 4.19: Photo of the setup for the cosmic ray measurements, taken away from the electronic to provide enough detail clarity for the picture.

4.3.2 Scintillator bar

The scintillator bar was provided (free sample donation) by NuviaTech and tested during the MID beamtest at CERN Proton Synchrotron East Area Facility, control room T10, in June 2023, which resulted in the publication of a technical report in JINST [15]. The bar was polished and wrapped in reflective aluminium foil on the long sides, and the short side, which was not used for the SiPM attachment, was covered with Teflon tape; the process is seen in Figure 4.20. The outer layer was made of black tape, and the remaining short side was kept naked for the SiPM coupling. The bar dimensions are $100 \times 5 \times 1 \text{ cm}^3$.

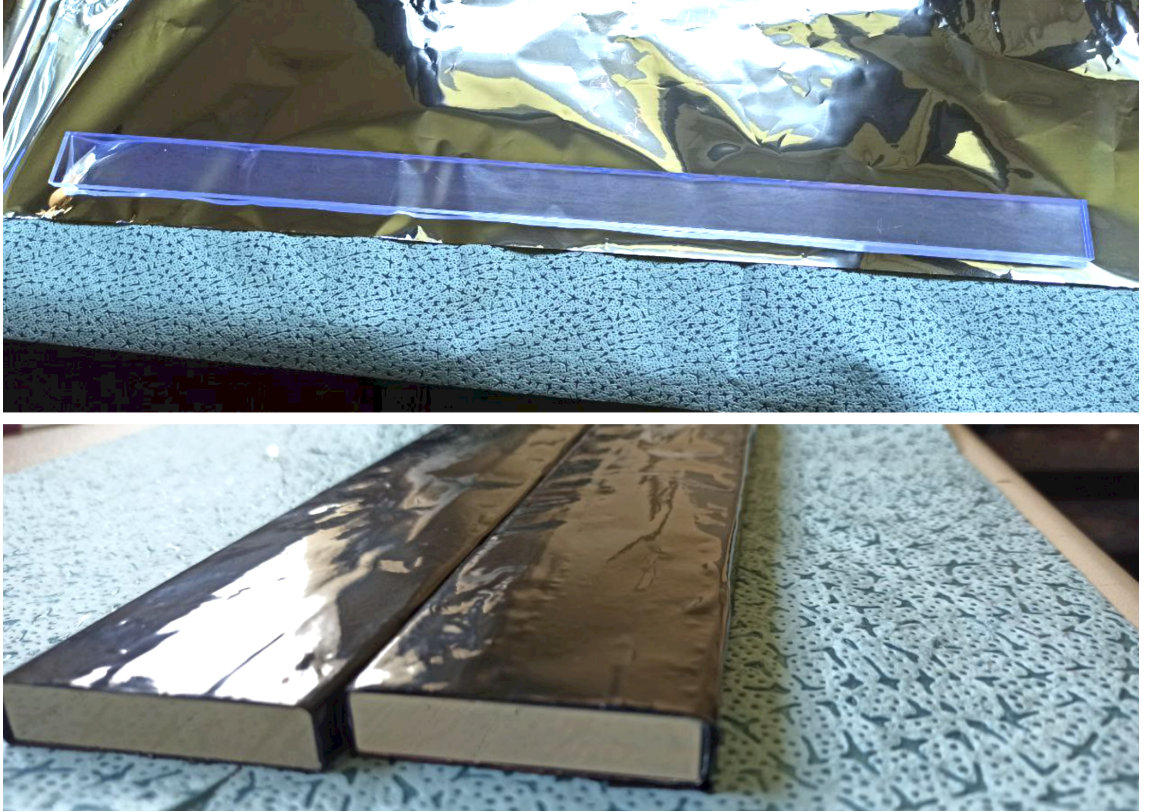


Figure 4.20: Photo of the Nuvia scintillator bar on the aluminium refractive foil before being wrapped in it (top) and the two Nuvia bars already wrapped and photographed from the side on which the SiPMs are to be attached. *The photos are property of Dr Solangel Rojas Torres.*

During the beamtest in 2023, the light from the bar was collected by the Onsemi MICROFC-SMTPA-30035 $3 \times 3 \text{ mm}^2$ SiPM [61] with a customarily soldered board on the site, since prior preparation was not possible due to the time constraints. The SiPM was likewise attached to the bar directly; for details of the board and attachment, see Figure 4.21.

However, this solution was not proven to provide a satisfactory quality signal, and consequently, after a discussion within the collaboration group, the performance results of this bar were decided not to be included in the paper. Nonetheless, the bar was selected after further study and characterisation in order to be contained in the

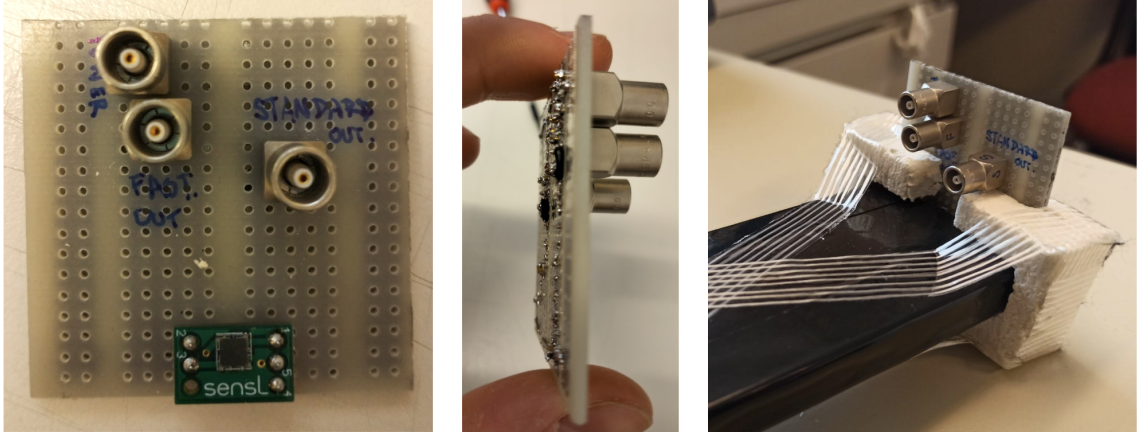


Figure 4.21: Photos of the SiPM on the on-site soldered board (left and centre) and its attachment to the scintillator bar.

full-module beamtest planned in October 2024. The method for its characterisation is explored in this section. The author would also like to note here that the original SiPM with the board used at the aforementioned beamtest was initially intended to be one of the four SiPMs used in this thesis; however, due to the lack of a suitable signal response, it was substituted by the SiPM S3.

4.3.3 Triggering modules

The triggers comprised the scintillator bars with PMTs attached on one side. The dimensions of the top scintillator, part of the trigger T1, are $20 \times 5 \times 3.5 \text{ cm}^3$ and for the bottom one, T2, are $20 \times 10 \times 2.5 \text{ cm}^3$. Due to the exceeding length of T2, the T1 was positioned only 3 cm above the examined scintillator bar in order to provide reasonable triggering, even though there is still a region in which the cosmic rays passed only through T1 and T2, excluding the sample. Calculation of these false triggers was performed using the drawing in Figure 4.22.

The setup is symmetrical; thus, the ratio was calculated as the number of hits hitting the T1 and left half of T2, bypassing the sample to the number of total hits in T1 and left half of T2. Each hit is defined by its coordinates in T1 and T2. In Figure 4.22 is marked a cone of rays not hitting the sample with first coordinate x ; the possible second coordinates are in the interval from 0 to $2.5 - \frac{5}{6.5} \cdot x$, calculated from the geometric similarity of triangles ABC and ADE . With this reasoning, the desired ratio can be written down as

$$\frac{\int_0^{\frac{13}{4}} (2.5 - \frac{5}{6.5} \cdot x) dx}{\int_0^5 5 dx} = \frac{[2.5 \cdot x - \frac{5}{6.5} \cdot \frac{1}{2} x^2]_0^{\frac{13}{4}}}{[5 \cdot x]_0^5} = \frac{\frac{65}{16}}{25} = 16.25 \%. \quad (4.1)$$

Note that the upper limit $\frac{13}{4}$ was taken from the right-most coordinate in T1, which is possible for the bypassing ray. This bias of 16.25 % is nevertheless neglected from further analysis.

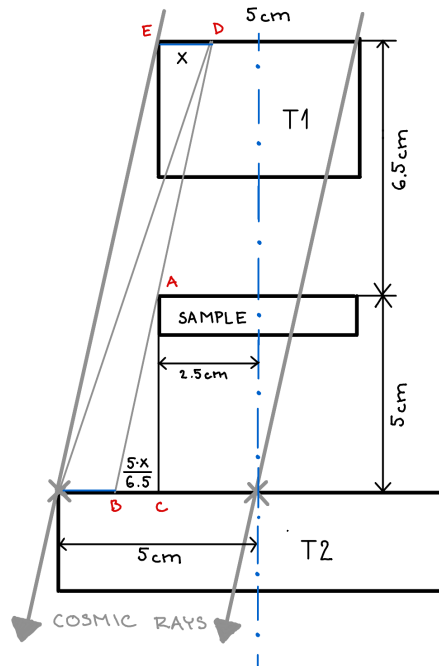


Figure 4.22: Schematics of the front view of the setup for the calculation of the false triggers.

The T1 and T2 were aligned in a vertical position and centred horizontally, creating the symmetrical situation seen in Figure 4.22. The horizontal alignment in the direction of the examined scintillator bar was done in two positions that will be further noted as *far* and *near*. The near position denotes the distance between the SiPM and the closer edges of T1 and T2 being 33 cm. The far position similarly denotes the distance of 78 cm, resulting in the difference between the two being $\Delta d = 45$ cm.

4.3.4 Connecting the SiPMs

Each of the SiPMs was coupled directly to the bar with a custom foam holder that was taped to the end of the bar. After this instalment, the whole part of the bar with the SiPM was covered in multiple layers of black fabric in order to avoid light leaks. Each SiPM was then connected to the electronics, and the signal was, except for the Hamamatsu SiPM, amplified, as shown in Table 4.2.

4.3.5 Method

The number of events acquired was given by the time of measurement, which was for all of them 8 hours with variation of tens of minutes for each of the SiPMs. During this time, $100\,000 \pm 10\,000$ triggers were done by the T1. After applying the second trigger selection from T2, only $15\,000 \pm 1000$ event passed for further analysis.

The next step was to find the maximum amplitude spectra and fit it with a convolution of Gaussian and Landau functions (in literature, also known as Landau convoluted Gaussian). This convolution was done due to the emergence of the two signals of different shapes - the one from the scintillator and the one from the SiPM itself. From this fit, the most probable value (MP) is taken as the parameter to compare the measurements obtained.

4.3.6 Measured data

The results show the expected behaviour for all of the SiPMs and their outputs in the sense of the peak amplitude dependence on the distance between the SiPM and the particle hit. The amplitude distributions with their fits and the MP rounded to the first digit of the error are in Figures 4.23, 4.24, and 4.25.

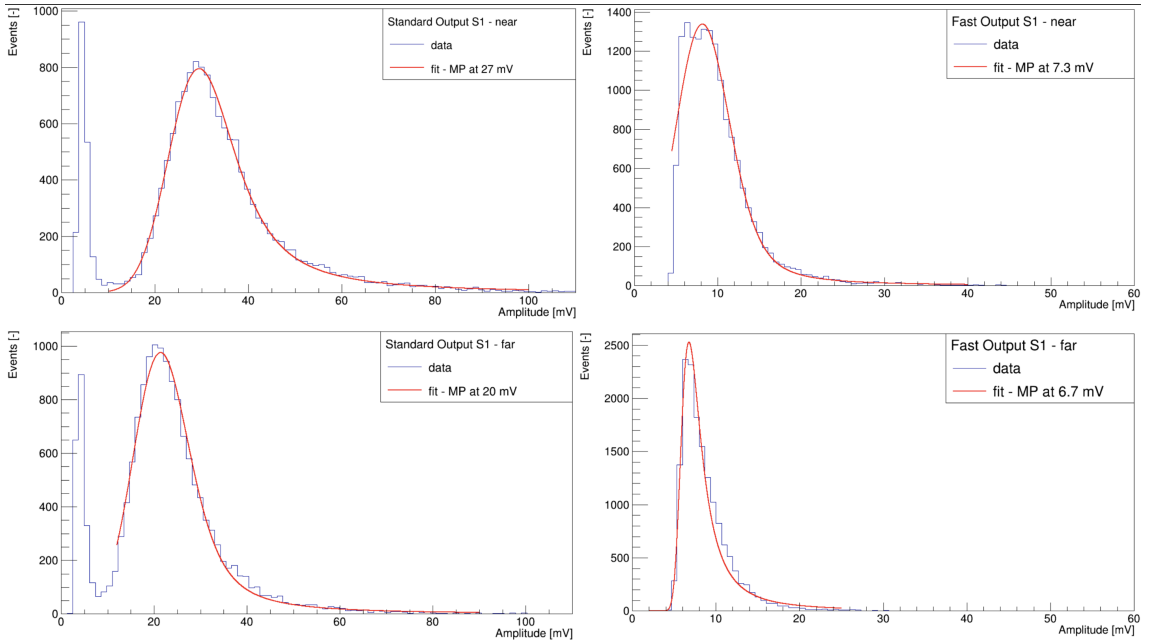


Figure 4.23: Plotted amplitude distribution for the SiPM S1 for both outputs in two positions, together with their fitting functions, which MP is noted in the legend.

Note that for the S2-near in Figure 4.25, the fit was done on the full distribution regardless of the visible single photo distribution since, for the far measurement, the distribution was already blended, and therefore, the full spectra had to be fitted together. The author is aware that this approach is adding discrepancies to the results of this large neglect of the distribution structure. The author, nonetheless, believes that this method approaches the distribution in a similar way as the blend of the single photon distribution that appeared for the far position and brings, therefore, not an unreasonable result.

The summary of the MP for each distribution is in Table 4.5 together with the error parameters from the fits.

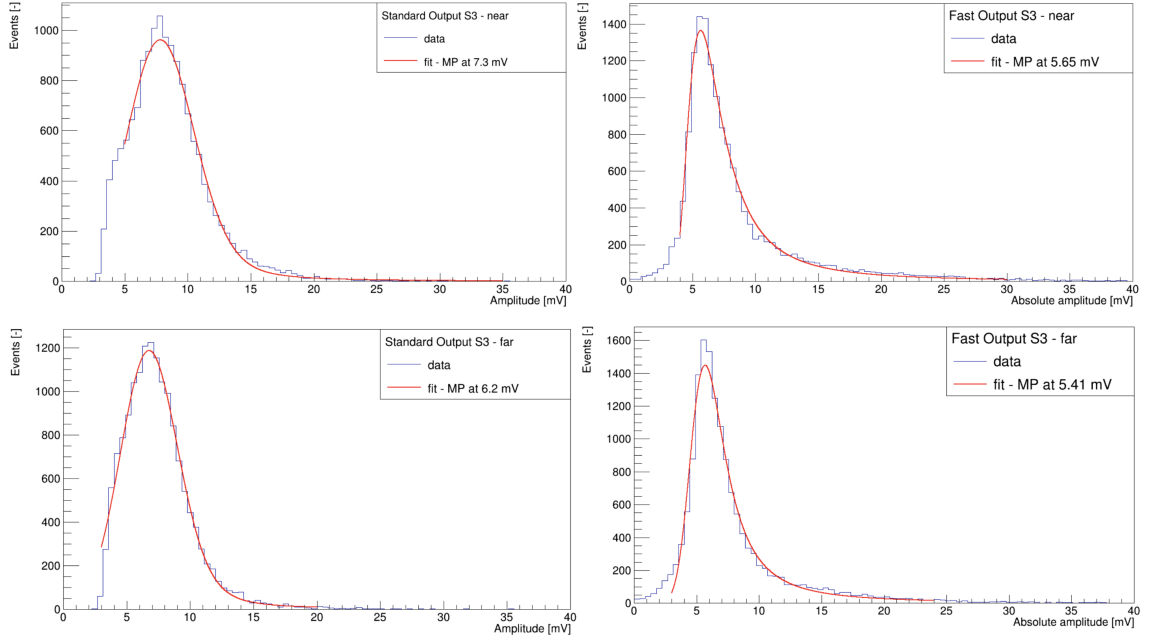


Figure 4.24: Plotted amplitude for the SiPM S3 for both outputs in two positions, together with their fitting functions, which MP is noted in the legend. Note that the fast output was signal negative, but its distribution was done for the absolute values in order to allow better visual comparison.

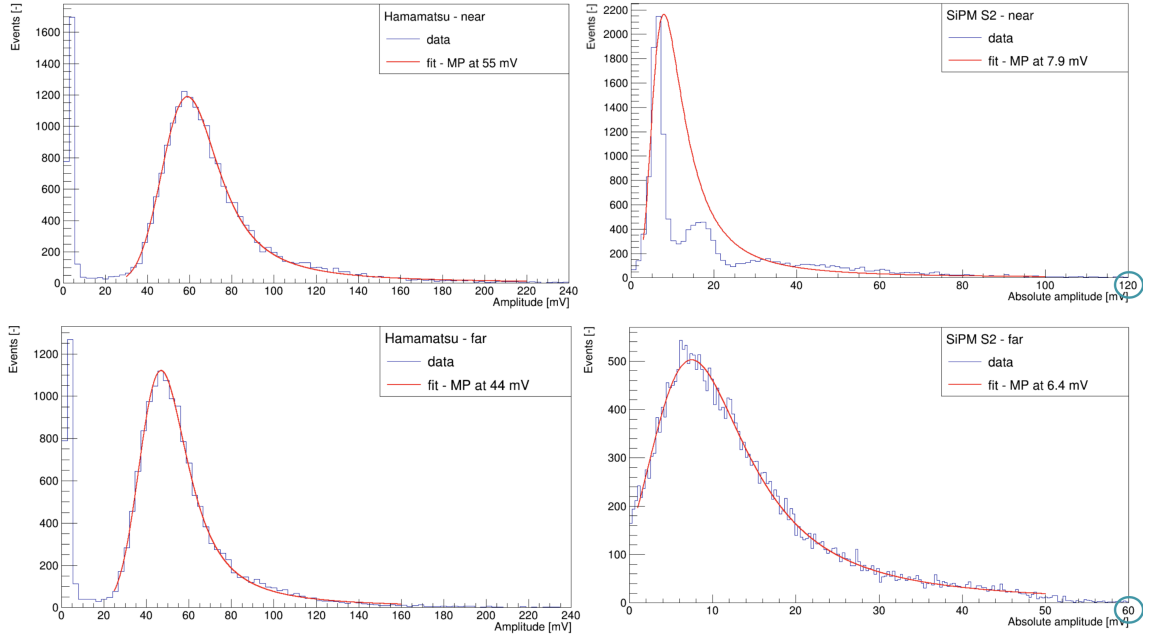


Figure 4.25: Plotted amplitude for the SiPMs S2 and Hamamatsu together with their fitting functions, which MP is noted in the legend. Note that these two SiPMs have only the standard output, and for S2, the amplitude is given in absolute values to allow visual comparison despite the signals being negative. The change in the horizontal scale for the S2 is highlighted.

SiPM	near [mV]	far [mV]
S1 std	27 ± 0.1	20 ± 0.1
S1 fast	7.3 ± 0.1	6.7 ± 0.2
S2	7.9 ± 0.8	6.4 ± 0.1
S3 std	7.3 ± 0.1	6.2 ± 0.1
S3 fast	5.64 ± 0.02	5.41 ± 0.2
Hamamatsu	55 ± 0.2	44 ± 0.2

Table 4.5: Most probable values (peaks) in the amplitude distribution of the evaluated SiPMs for all the outputs and both near and far positions.

4.3.7 Attenuation length

The attenuation length μ is defined as a length in which the light decreases to $\frac{1}{e}$ of its original intensity I_0 while the attenuation itself follows the exponential law written as

$$I(x) = I_0 \exp\left(-\frac{x}{\mu}\right), \quad (4.2)$$

where x stands for the distance from the origin of the incident light and $I(x)$ is the intensity with respect to this distance [67].

From this, we can derive a formula for calculating the attenuation length knowing intensities in two positions as follows

$$\frac{I_1}{I_2} = \frac{\exp\left(-\frac{x}{\mu}\right)}{\exp\left(-\frac{x+\Delta d}{\mu}\right)} = \exp\left(\frac{\Delta d}{\mu}\right), \quad (4.3)$$

$$\mu = \frac{\Delta d}{\ln \frac{I_1}{I_2}}. \quad (4.4)$$

For determination of the attenuation length of the examined scintillator bar, the ratio of the MP of the amplitudes was taken as the ratio between the intensities, and from that, the μ of the bar was calculated. For this calculation, an average ratio was taken throughout all the different for both fast and standard outputs. The average value of $\frac{I_1}{I_2} = 1.19 \pm 0.09$ was obtained, and using the formula (4.4), the final value of $\mu = (260 \pm 20)$ cm was calculated.

4.4 Dark Count Rate measurements

The DCR measurements were done for the SiPM S2 for different temperatures varying from 18 °C to 34 °C and different overvoltages. For the temperature modification, a Peltier element was used with a heat sink, and it was measured with a thermal camera as shown in Figure 4.26. These components were placed together with the SiPM in the dark box, and the signal was read by the Lecroy TELEDYNE HDO6000B oscilloscope. The scheme of the setup is shown in Figure 4.27.

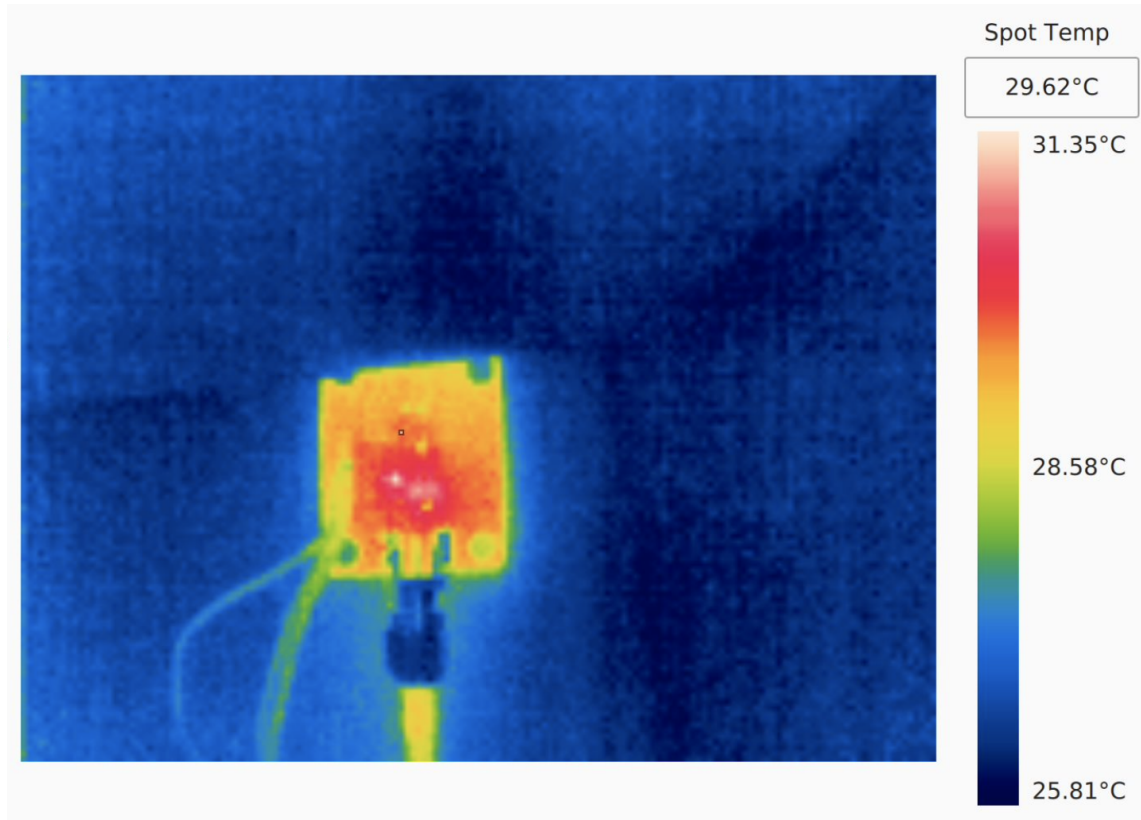


Figure 4.26: Monitoring of the temperature of the SiPM (selected by the cross) with the thermal camera.

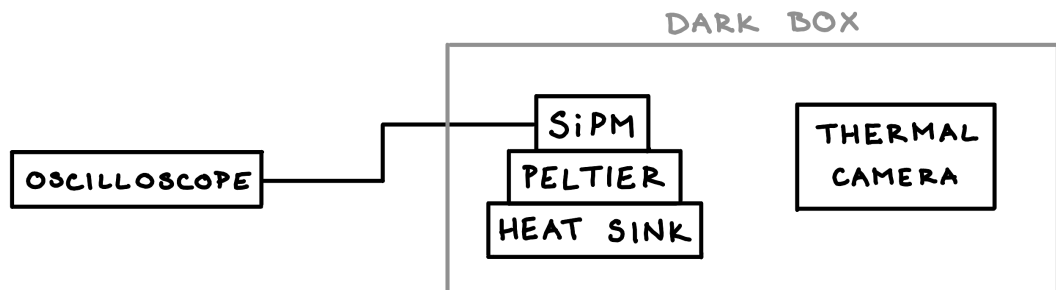


Figure 4.27: Schematics of a setup for measuring the DCR.

The data acquisition was done using a Python script that acquired the times of 5000 consecutive triggers induced by the dark count spikes. The time differences between the triggers define the DCR frequency. Therefore, the mean time difference was calculated, and by its reversed value, the desired frequency was achieved. The measurement was done for bias voltages within the operational range until the linear behaviour, foretold by the datasheet, was observed.

The results of this measurement are plotted in Figure 4.28. The data points were fitted with a linear fit, with slopes noted in the plot legend. An unexpectedly low

DCR, orders of ones of kHz as opposed to the orders of hundreds of kHz [61], can be observed for voltages lower than 28 V for all temperatures. A possible explanation for this phenomenon could be a higher breakdown voltage than stated on the data sheet by ~ 2 V. This may, in fact, be the case to some extent and requires further investigation to distinguish between the method precision limits and the sensor capabilities.

Nevertheless, for higher bias voltages, the expected rates were achieved, and a linear behaviour was observed with the slope parameter increasing with the temperature. This behaviour is comparable to the previous results of the SiPM characterisation [68].

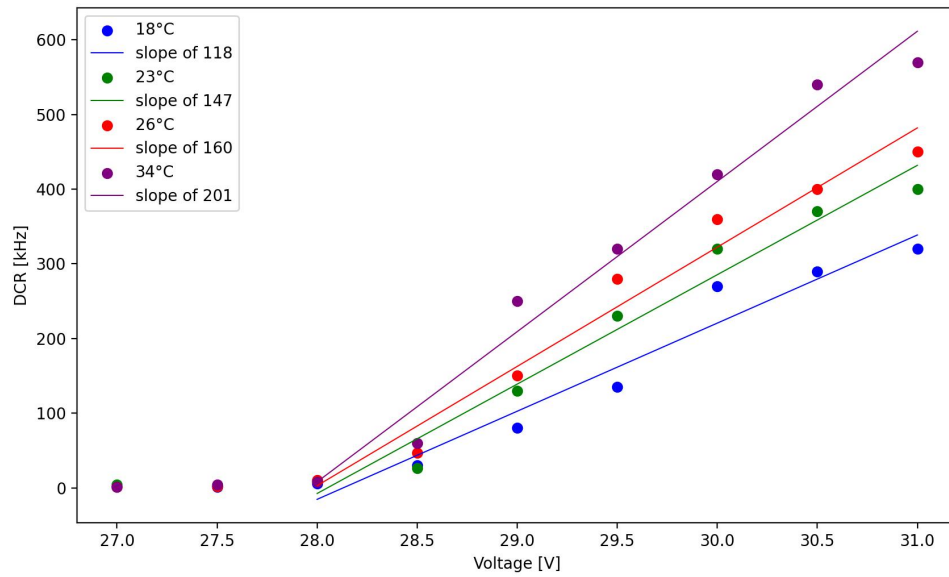


Figure 4.28: Schematics of a setup for measuring the DCR.

These results confirm the great competitiveness of this SiPM, already shown in previous measurements, and support is clean performance for single photon detection. Despite the demonstrated procedure being viable for any SiPM, measurements with the other models were not conducted due to the thermal coupling difficulties for the other boards to the Peltier element. The solution to this problem would be a differently shaped thermal conductor or a sufficient amount of a thermal paste. Nevertheless, neither was available at the time of the measurement. Therefore, the measurements with different boards were omitted. This complication does not cause additional problems since the board with the SiPM measured was, in fact, showing the most promising result; thus, the further characterisation of this custom board was the main objective of this measurement regardless of the circumstances.

Summary

This thesis aimed to overview the current and future engagement of silicon photomultipliers as a state-of-the-art alternative to conventional photomultiplier tubes and demonstrate their usability in lab measurements.

The first two chapters served introductory purposes. Chapter 1 presented the general concepts of high energy physics and a brief description of the Standard Model and particle detectors, showing the ALICE 3 detector upgrade as an example. Chapter 2 provided a more profound introduction to photodetectors and semiconductors, allowing a deeper insight into the concepts necessary for further applications and understanding the evaluation techniques.

Building on the stable ground, built on the preceding chapters, Chapter 3 introduced current and future detectors in high energy physics using the silicon photomultipliers for their light collection. This chapter provided a wide variety of applications in all parts of the large experiments, from trackers to muon chambers, from timing to energy measurements and from Cherenkov radiator to crystal scintillator light collection.

The experimental part is comprised in Chapter 4. The work included the evaluation of four different silicon photomultipliers based on their ability to detect the single photon distribution and their rise times. The evaluated photomultipliers were subsequently used to characterise the scintillator bar, which was meant to be used for an upgraded detector for the ALICE experiment at CERN. Furthermore, the dark count rate measurement was performed for one of the silicon photomultipliers. The test introduced a method for temperature measurements and demonstrated the temperature dependence of the noise induced by the dark current.

The Muon Identifier, an upgraded detector for ALICE, has scheduled the following tests at CERN beamline testing facilities in October 2024. The complete modules will be tested and the search for new solutions is still open. This presents an opportunity for the possible use of the results of this thesis, and mainly for applying the methods described and tested to be used in the real production of the high energy physics detector in one of the largest experiments built until now.

Bibliography

- [1] Claus Grupen and Boris Shwartz. *Particle Detectors*. Cambridge Unibersity Press, 2008.
- [2] Institute of Particle Physics and Riga Technical University Accelerator Technologies. *STANDARD MODEL*. URL: <https://www.rtu.lv/en/hep/particle-physics/standard-model>. (accessed: 26.07.2024).
- [3] Alexey Drutsky. *International Linear Collider (ILC) - The next mega-scale particle collider*. Morgan Claypool Publishers, 2018.
- [4] Andrew Sessler and Edmund Wilson. *Engines of Discovery, A Century of Particle Accelerators, Revised and Expanded Edition*. World Scientific Publishing Co. Pte. Ltd., 2014.
- [5] O. Aberle et al. *High-Luminosity Large Hadron Collider (HL-LHC): Technical design report*. CERN Yellow Reports: Monographs. Geneva: CERN, 2020. DOI: 10.23731/CYRM-2020-0010. URL: <https://cds.cern.ch/record/2749422>.
- [6] Michaela Schaumann et al. “First Xenon-Xenon Collisions in the LHC”. In: (2018), MOPMF039. DOI: 10.18429/JACoW-IPAC2018-MOPMF039. URL: <https://cds.cern.ch/record/2648699>.
- [7] Ewa Lopienska. “The CERN accelerator complex, layout in 2022. Complexe des accélérateurs du CERN en janvier 2022”. In: (2022). General Photo. URL: <https://cds.cern.ch/record/2800984>.
- [8] High Luminosity LHC Project. *LS3 schedule change*. URL: <https://hilumilhc.web.cern.ch/article/ls3-schedule-change>. (accessed: 26.07.2024).
- [9] Rebeca Gonzalez Suarez. *The Future Circular Collider (FCC) at CERN*. 2022. arXiv: 2204.10029 [hep-ex]. URL: <https://arxiv.org/abs/2204.10029>.
- [10] Thomas A. Trainor. “A critical review of RHIC experimental results”. In: *International Journal of Modern Physics E* 23.08 (Aug. 2014), p. 1430011. ISSN: 1793-6608. DOI: 10.1142/S0218301314300112. URL: <http://dx.doi.org/10.1142/S0218301314300112>.
- [11] Elke-Caroline Aschenauer et al. *The RHIC Cold QCD Program*. 2023. arXiv: 2302.00605 [nucl-ex]. URL: <https://arxiv.org/abs/2302.00605>.

- [12] M. Harrison, T. Ludlam, and S. Ozaki. “RHIC project overview”. In: *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* 499.2 (2003). The Relativistic Heavy Ion Collider Project: RHIC and its Detectors, pp. 235–244. ISSN: 0168-9002. DOI: [https://doi.org/10.1016/S0168-9002\(02\)01937-X](https://doi.org/10.1016/S0168-9002(02)01937-X). URL: <https://www.sciencedirect.com/science/article/pii/S016890020201937X>.
- [13] Ferdinand Willeke and J. Beebe-Wang. “Electron Ion Collider Conceptual Design Report 2021”. In: (Feb. 2021). DOI: 10.2172/1765663. URL: <https://www.osti.gov/biblio/1765663>.
- [14] *Letter of intent for ALICE 3: A next generation heavy-ion experiment at the LHC*. Tech. rep. 202 pages, 103 captioned figures, 19 tables. Geneva: CERN, 2022. arXiv: 2211.02491. URL: <https://cds.cern.ch/record/2803563>.
- [15] Ruben Alfaro et al. “Characterisation of plastic scintillator paddles and lightweight MWPCs for the MID subsystem of ALICE 3”. In: *Journal of Instrumentation* 19.04 (Apr. 2024), T04006. ISSN: 1748-0221. DOI: 10.1088/1748-0221/19/04/t04006. URL: <http://dx.doi.org/10.1088/1748-0221/19/04/T04006>.
- [16] S. Acharya et al. “ALICE upgrades during the LHC Long Shutdown 2”. In: *Journal of Instrumentation* 19.05 (May 2024), P05062. ISSN: 1748-0221. DOI: 10.1088/1748-0221/19/05/p05062. URL: <http://dx.doi.org/10.1088/1748-0221/19/05/P05062>.
- [17] Solangel Rojas Torres. “Status of the Fast Interaction Trigger detector of ALICE”. In: *PoS EPS-HEP2023* (2024), p. 541. DOI: 10.22323/1.449.0541.
- [18] Alla Maevskaya. “ALICE FIT data processing and performance during LHC Run 3”. In: *Phys. At. Nucl.* 84.4 (2021), pp. 579–584. DOI: 10.1134/S1063778821040189. arXiv: 2012.02760. URL: <https://cds.cern.ch/record/2746992>.
- [19] Communications Education and Outreach Group. *LHC the Guide, CERN-Brochure-2021-004-Eng*. September 2021. URL: <https://cds.cern.ch/record/2809109/files/CERN-Brochure-2021-004-Eng.pdf>.
- [20] Maciej Slupecki. “The Fast Interaction Trigger for the ALICE Upgrade”. Presented 12 Jun 2020. Jyvaskyla U., 2020. URL: <https://cds.cern.ch/record/2741462>.
- [21] Carina Trippel. “Development of microlens-enhanced SiPMs for a radiation-hard scintillating fibre tracker at LHCb”. In: (2023), p. 160. DOI: <https://doi.org/10.5075/epfl-thesis-10215>. URL: <http://infoscience.epfl.ch/record/302104>.
- [22] Giacomo Volpe. “The High Momentum Particle IDentification (HMPID) detector PID performance and its contribution to the ALICE physics program”. In: *Nucl. Instrum. Methods Phys. Res., A* 876 (2017), pp. 133–136. DOI: 10.1016/j.nima.2017.02.037. URL: <https://cds.cern.ch/record/2710033>.
- [23] Hermann Kolanoski and Norbert Wermes. *Particle detectors*. Oxford University Press, 2020.
- [24] Gerhard Lutz. *Semiconductor Radiation Detectors*. Springer, 2007.

- [25] Emmanuel Rosencher and Borge Vinter. *Optoelectronics*. Cambridge University Press, 2002.
- [26] S. M. Sze, Kwok Kwok Ng, and Yiming Li. *Physics of semiconductor devices*. John Wiley Sons, Inc., 2021.
- [27] “The CMS electromagnetic calorimeter project: Technical Design Report”. In: (1997).
- [28] Fabio Acerbi and Stefan Gundacker. “Understanding and simulating SiPMs”. In: *Nucl. Instrum. Methods Phys. Res., A* 926 (2019), pp. 16–35. DOI: 10.1016/j.nima.2018.11.118. URL: <https://cds.cern.ch/record/2692477>.
- [29] Yi Guo et al. “Optimization of fast output from SiPM array for pulse shape discrimination techniques at high counting rates”. In: *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* 1066 (2024), p. 169611. ISSN: 0168-9002. DOI: <https://doi.org/10.1016/j.nima.2024.169611>. URL: <https://www.sciencedirect.com/science/article/pii/S0168900224005370>.
- [30] ONSEMI. *AND9782/D, Biasing and Readout of ON Semiconductor SiPM Sensors*. URL: <https://www.onsemi.com/pub/collateral/and9782-d.pdf>. April, 2019 Rev. 3.
- [31] Inge Diehl et al. *A Digital Silicon Photomultiplier*. 2024. arXiv: 2402.12305 [physics.ins-det]. URL: <https://arxiv.org/abs/2402.12305>.
- [32] Robert Klanner. “Characterisation of SiPMs”. In: *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* 926 (May 2019), pp. 36–56. ISSN: 0168-9002. DOI: 10.1016/j.nima.2018.11.083. URL: <http://dx.doi.org/10.1016/j.nima.2018.11.083>.
- [33] Thierry Goudon, Vera Miljanovic, and Christian Schmeiser. “On the Shockley-Read-Hall Model: Generation-Recombination in Semiconductors”. In: *SIAM Journal of Applied Mathematics* 67 (Jan. 2007), pp. 1183–1201. DOI: 10.1137/060650751.
- [34] Frank Simon. “Silicon photomultipliers in particle and nuclear physics”. In: *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* 926 (May 2019), pp. 85–100. ISSN: 0168-9002. DOI: 10.1016/j.nima.2018.11.042. URL: <http://dx.doi.org/10.1016/j.nima.2018.11.042>.
- [35] Valentina Sola. “Precision Timing with the CMS MTD Endcap Timing Layer for HL-LHC”. In: *JPS Conf. Proc.* 34 (2021), p. 010013. DOI: 10.7566/JPSCP.34.010013.
- [36] V. Mikhaylov et al. “Characterisation of SiPM radiation hardness for application in hadron calorimeters at FAIR, CERN and NICA”. In: *Journal of Instrumentation* 15.02 (Feb. 2020), p. C02005. DOI: 10.1088/1748-0221/15/02/C02005. URL: <https://dx.doi.org/10.1088/1748-0221/15/02/C02005>.

- [37] Roberto Preghenella et al. “SiPM photosensors for the ePIC dual-radiator RICH detector at the EIC”. In: *PoS EPS-HEP2023* (2024), p. 515. DOI: 10.22323/1.449.0515.
- [38] Francesco Forti. *Snowmass Whitepaper: The Belle II Detector Upgrade Program*. 2022. arXiv: 2203.11349 [hep-ex].
- [39] Plamen Hopchev. *SciFi: A large Scintillating Fibre Tracker for LHCb*. 2017. arXiv: 1710.08325 [physics.ins-det].
- [40] Sune Jakobsen on behalf of the LHCb SciFi collaboration and with material from the full collaboration. *LHCb Scintillating fiber tracker: From performance requirements to operational detector*. 30-09-2022. URL: <https://indico.in2p3.fr/event/27569/attachments/72818/109387/0bf08408-ca15-4935-a2e9-09524fa8afdf.pdf>.
- [41] *Framework TDR for the LHCb Upgrade II: Opportunities in flavour physics, and beyond, in the HL-LHC era*. Tech. rep. Geneva: CERN, 2021. URL: <https://cds.cern.ch/record/2776420>.
- [42] C. Tripl et al. “Microlens-enhanced silicon photomultiplier arrays for LHCb SciFi Tracker Upgrade Ib”. In: *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* 1040 (2022), p. 167216. ISSN: 0168-9002. DOI: <https://doi.org/10.1016/j.nima.2022.167216>. URL: <https://www.sciencedirect.com/science/article/pii/S016890022200571X>.
- [43] Luigi Pio Rignanese et al. “A readout system based on SiPM for the dRICH detector at the EIC”. In: *JINST* 19.02 (2024), p. C02062. DOI: 10.1088/1748-0221/19/02/C02062.
- [44] D.S. Bhattacharya et al. “Simulation studies related to the particle identification by the forward and backward RICH detectors at Electron Ion Collider”. In: *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* 1056 (2023), p. 168591. ISSN: 0168-9002. DOI: <https://doi.org/10.1016/j.nima.2023.168591>. URL: <https://www.sciencedirect.com/science/article/pii/S0168900223005818>.
- [45] Collaboration CMS. *A MIP Timing Detector for the CMS Phase-2 Upgrade*. Tech. rep. Geneva: CERN, 2019. URL: <https://cds.cern.ch/record/2667167>.
- [46] E. Albuquerque et al. *TOFHIR2: The readout ASIC of the CMS Barrel MIP Timing Detector*. 2024. arXiv: 2404.01208 [physics.ins-det]. URL: <https://arxiv.org/abs/2404.01208>.
- [47] W. Baldini et al. “Measurement of parameters of scintillating bars with wavelength-shifting fibres and silicon photomultiplier readout for the SHiP Muon Detector”. In: *Journal of Instrumentation* 12.03 (Mar. 2017), P03005–P03005. ISSN: 1748-0221. DOI: 10.1088/1748-0221/12/03/p03005. URL: <http://dx.doi.org/10.1088/1748-0221/12/03/P03005>.

- [48] Wilhelm H. Bertl et al. “A Search for muon to electron conversion in muonic gold”. In: *Eur. Phys. J. C* 47 (2006), pp. 337–346. DOI: 10.1140/epjc/s2006-02582-x.
- [49] L. Bartoszek et al. *Mu2e Technical Design Report*. 2015. arXiv: 1501.05241 [physics.ins-det]. URL: <https://arxiv.org/abs/1501.05241>.
- [50] Nikolay Atanov et al. “The Mu2e Crystal and SiPM Calorimeter: Construction Status”. In: *IEEE Transactions on Nuclear Science* 70.7 (July 2023), pp. 1281–1287. ISSN: 1558-1578. DOI: 10.1109/tns.2023.3264757. URL: <http://dx.doi.org/10.1109/TNS.2023.3264757>.
- [51] C. A. Aidala et al. “Design and Beam Test Results for the sPHENIX Electromagnetic and Hadronic Calorimeter Prototypes”. In: *IEEE Transactions on Nuclear Science* 65.12 (2018), pp. 2901–2919. DOI: 10.1109/TNS.2018.2879047.
- [52] Eric J. Mannel. “An SiPM based readout for the sPHENIX calorimeters”. In: *2013 IEEE Nuclear Science Symposium and Medical Imaging Conference (2013 NSS/MIC)*. 2013, pp. 1–4. DOI: 10.1109/NSSMIC.2013.6829439.
- [53] C. A. Aidala et al. “Design and Beam Test Results for the 2-D Projective sPHENIX Electromagnetic Calorimeter Prototype”. In: *IEEE Transactions on Nuclear Science* 68.2 (Feb. 2021), pp. 173–181. ISSN: 1558-1578. DOI: 10.1109/tns.2020.3034643. URL: <http://dx.doi.org/10.1109/TNS.2020.3034643>.
- [54] Thierry Stolarsczyk. *Le NEUTRINO. particule ordinaire?* Le Pommier, 2008.
- [55] B. Abi et al. *Deep Underground Neutrino Experiment (DUNE), Far Detector Technical Design Report, Volume I: Introduction to DUNE*. 2020. arXiv: 2002.02967 [physics.ins-det]. URL: <https://arxiv.org/abs/2002.02967>.
- [56] Fermi National Accelerator Laboratory. *DUNE graphic*. URL: <https://lbnf-dune.fnal.gov>. (accessed: 28.07.2024).
- [57] Niccolò Gallice et al. “Development of a design for SiPMs readout in cryogenic environment for large area photon detectors”. In: *2021 IEEE International Instrumentation and Measurement Technology Conference (I2MTC)*. 2021, pp. 1–6. DOI: 10.1109/I2MTC50364.2021.9459995.
- [58] Martin Tzanov. *The Deep Underground Neutrino Experiment Status and Prospects*. URL: https://indico.cern.ch/event/1303630/contributions/5626510/attachments/2767654/4821212/231207_TAU2023_tzanov_final.pdf. 07.12.2023 (accessed: 28.07.2024).
- [59] G Bianchetti et al. *Specification for VMEbus Crate Type V430*. Geneva: CERN, 1990. URL: <https://cds.cern.ch/record/1110249>.
- [60] ONSEMI. *Silicon Photomultipliers (SiPM), High PDE and Timing Resolution Sensors in a TSV Package*. URL: <https://www.onsemi.com/pdf/datasheet/microj-series-d.pdf>. August, 2021 Rev. 7.
- [61] ONSEMI. *Silicon Photomultipliers (SiPM), Low-Noise, Blue-Sensitive C-Series SiPM Sensors*. URL: <https://www.onsemi.com/download/data-sheet/pdf/microc-series-d.pdf>. February, 2022 Rev. 9.

- [62] Hamamatsu. *Simple evaluation starter kit for non-cooled MPPC*. URL: https://www.hakuto.com.tw/tw/products_d.php?p=441. March 2020 accessed on 04.08.2024.
- [63] Hamamatsu. *MPPCs for precision measurement*. URL: https://www.hamamatsu.com/content/dam/hamamatsu-photonics/sites/documents/99_SALES_LIBRARY/ssd/s13360_series_kapd1052e.pdf. October 2020 accessed on 04.08.2024.
- [64] Stefan Gundacker et al. “Measurement of intrinsic rise times for various L(Y)SO and LuAG scintillators with a general study of prompt photons to achieve 10 ps in TOF-PET”. In: *Physics in Medicine Biology* 61.7 (Mar. 2016), p. 2802. DOI: 10.1088/0031-9155/61/7/2802. URL: <https://dx.doi.org/10.1088/0031-9155/61/7/2802>.
- [65] Sen QianOn Behalf of the PMT Lab. *Time performance of the large dynamic range SiPM*. URL: https://indico.cern.ch/event/818783/contributions/3598454/attachments/1951224/3239252/Time_performance_of_large_dynamic_range_SiPM_v5.0.pdf. 26. 11. 2019, accessed on 04.08.2024.
- [66] Evgeny Kuznetsov. “Temperature-compensated silicon photomultiplier”. In: *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* 912 (2018). New Developments In Photodetection 2017, pp. 226–230. ISSN: 0168-9002. DOI: <https://doi.org/10.1016/j.nima.2017.11.060>. URL: <https://www.sciencedirect.com/science/article/pii/S0168900217312895>.
- [67] Gerhard Martens. “Attenuation Length and Penetration Depth of X-rays”. In: (Feb. 2022). DOI: 10.13140/RG.2.2.29785.90727.
- [68] A. Vacheret et al. “Characterization and simulation of the response of Multi-Pixel Photon Counters to low light levels”. In: *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* 656.1 (2011), pp. 69–83. ISSN: 0168-9002. DOI: <https://doi.org/10.1016/j.nima.2011.07.022>. URL: <https://www.sciencedirect.com/science/article/pii/S0168900211014513>.