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Doctoral Programme of National Interest
in
Space Science and Technology (SST)

Characterisation and calibration of silicon photomultipliers for next-generation space detectors

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মা

আমার এই পিএইচডি ডিগ্রিটি আমি আমার মাকে উৎসর্গ করছি। তুমি যদি পাশে না থাকতে, তবে আজ আমি এখানে পৌঁছাতে পারতাম না। আমাকে একা হাতে বড় করে তোলা এবং বাবার অভাব আমাকে কখনোই বুঝতে না দেওয়া। আমার সারাটা জীবন ধরে তুমি যেসব কষ্ট ও প্রতিকূলতা নীরবে সহ্য করেছ—তার কোনো আঁচই আমাকে লাগতে দাওনি। আমার ব্যাগ শুষ্কিয়ে আমাকে পুনেতে পাঠিয়ে দিয়েছিল, যাতে আমি নিজের জন্য একটি সুন্দর ভবিষ্যৎ গড়ে তুলতে পারি। আমার মনে আত্মবিশ্বাস ও দৃঢ় প্রত্যয় জাগিয়ে তুলেছ এবং সবসময় আমাকে সবার আগে একজন 'ভালো মানুষ' হতে উৎসাহিত করেছ। এখন আমি মর্মে মর্মে উপলব্ধি করি যে, একজন ভালো মানুষ হওয়াটা আসলে কতটা গুরুত্বপূর্ণ। বাকি সবকিছু তো পরে এমনিতেই চলে আসে। আমার জন্য কতই না আত্মত্যাগ করেছ, যাতে এই পৃথিবীতে আমি একজন আর্থিকভাবে স্বাবলম্বী মানুষ হিসেবে মাথা উচু করে দাঁড়াতে পারি। এটি এক অলৌকিক ঘটনা এবং অবিশ্বাস্য কাকতালীয় ব্যাপার যে, আমি 'মাতৃদিবস'-এর দিন এই গবেষণাপত্রটি জমা দিচ্ছি। এটি বিষয়টিকে আরও অনেক বেশি বিশেষ করে তুলেছে। আমার মনের ডাব প্রকাশ করার জন্য কেবল শব্দই যথেষ্ট নয়; তাই আমি সংক্ষেপে শুধু এটুকুই বলব: তোমার ভালোবাসা, সমর্থন, গভীর বোঝাপড়া এবং আমার জীবনের সেবা মা ও বন্ধু হয়ে পাশে না থাকলে—আমার জীবনে আমি যা কিছুই অর্জন করেছি বা করবো —তার কিছুই কোনোভাবেই আমার পক্ষে করা সম্ভব হতো না। আমি তোমাকে ভীষণ ভালোবাসি এবং তোমার প্রতি আমার শ্রদ্ধা অসীম।

ধন্যবাদ, ধন্যবাদ, এবং অসংখ্য ধন্যবাদ।

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List of Abbreviations

ACC	Anti-coincidence Counter
ADC	Analogue to Digital Converter
AGN	Active Galactic Nuclei
AMS	Alpha Magnetic Spectrometer
ANTARES	Astronomy with a Neutrino Telescope and Abyss environmental REsearch
APD	Avalanche Photodiodes
ASAPP	Advances in Space Astroparticle Physics
ASIC	Application-Specific Integrated Circuit
ATIC-2	Advanced Thin Ionization Calorimeter (Flight 2)
BC	Bonding Curve
BETA	fiBer trackEr readouT
BGO	Bismuth Germanate Oxide
C	Collective efficiency
CALET	Calorimetric Electron Telescope
CALO	Calorimeter
CERN	European Organisation for Nuclear Research
CITIROC	Cherenkov Imaging Telescope ReadOut Chip
CMB	Cosmic Microwave Background
CMOS	Complementary Metal-Oxide-Semiconductor
CRs	Cosmic Rays
CREAM	Cosmic Ray Energetics And Mass
CT	Cherenkov Telescope
CTA	Cherenkov Telescope Array
CTAO	Cherenkov Telescope Array Observatory
DAMPE	DARk Matter Particle Explorer
DN	Dark noise

EAS Extensive Air Shower

EBL Extragalactic Background Light

ECAL Electromagnetic CALorimeter detector

EM ElectroMagnetic

FAMOUS First Auger Multi pixel photon counter camera for the Observation of UHECR air Showers

FBK Fondazione Bruno Kessler

FD Fluorescence Detector

FIT Fiber Tracker

FOV Field-of-view

FPGA Field Programmable Gate Arrays

FRBs Fast Radio Bursts

FT Fluorescence Telescope

FTK Fiber Tracker

G Gain

GAGG Gadolinium Aluminium Gallium Garnet

GECAM Gravitational wave High-energy Electromagnetic Counterpart All-sky Monitor

GRBs Gamma Ray Bursts

GZK Greisen-Zatsepin-Kuzmin

HEP High Energy Physics

HERD High Energy cosmic Radiation Detection facility

HESS High Energy Stereoscopic System

HG High Gain

ICCUB-SiUB Electronics Instrumentation Service of the Institute of Cosmos Science of the University of Barcelona

IEL Ionising Energy Loss

IFAE Institut de Física d'Altes Energies

INFN Istituto Nazionale di Fisica Nucleare

ISM Interstellar Medium

ISS International Space Station

JEM-EUSO Joint Exploratory Missions for an Extreme Universe Space Observatory

KASCADE KArllsruhe Shower Code and Array Detector

LACT Large Array of Imaging Atmospheric Cherenkov Telescopes

LAT Large Area Telescope

LED Light Emitting Diode

LEO Low Earth Orbit

LG Low Gain

LHAASO Large High-Altitude Air Shower Observatory

LIDAR Light Imaging and Detection Ranging

LIGO Laser Interferometer Gravitational-Wave Observatory

LIROC Liquid argon Integrated ReadOut Chip

LSTs Large-Sized Telescopes

LYSO Lutetium-Yttrium Oxyorthosilicate

PAMELA Payload for Antimatter Matter Exploration and Light-nuclei Astrophysics

RD Radio Detector

RF Radio Frequency

RICH Ring Imaging Cherenkov detector

MAGIC Major Atmospheric Gamma Imaging Cherenkov for CTA

MAPMTs Multi Anode Photomultiplier Tubes

Mini-EUSO Multiwavelength Imaging New Instrument for the Extreme Universe Space Observatory

MPPC Multi-Pixel Photon Counter

MSTs Medium-Sized Telescopes

MUSIC Multiple Use SiPM Integrated Circuit

NASA National Aeronautics Space Administration

NIEL Non-Ionising Energy Loss

NUD NeUtron Detector

NUSES Neutrinos and Seismic Electromagnetic Signals

NUV-HD-MT Near Ultra Violet - High Density - Micro-Trench

PCB Printed Circuit Board

PCL Plastic Condensing Lens

PDM Photo Detector Module

PMMA Poly Methyl Meth Acrylate

PMTs Photo Mutiplier Tubes

POEMMA Probe of Extreme Multi-Messenger Astrophysics

POLAR-2 POLARimetric Gammar-ray Burst Detector 2

PS PolyStyrene

PS Proton Synchrotron

PSD Plastic Scintillator Detector

PST Plastic Scintillator Tower

PVT Poly Vinyl Toluene

QE Quantum Efficiency

RADIOROC RADIO ReadOut Chip

R&D Research and Development

RF Radio Frequency

SCD Silicon Charge Detector

SCT Schwarzschild-Couder Medium-Sized Telescope

SD Surface Detector

SiPMs Silicon Photomultipliers

SNR Signal-to-Noise Ratio

SPACIROC Spatial Photomultiplier Array Counting Integrated ReadOut Chip

SPAD Single Photon Avalanche Diode

SPB Stratospheric Balloon

SPHIRA SiPM Photon-counting High-resolution Integrated Readout ASIC

SPS Super Proton Synchrotron

SSDs Silicon microStrip Detectors

SSTs Small-Sized Telescopes

STK Silicon-Tungsten trackER

TA Telescope Array

ToF Time of Flight

TRD Transition Radiation Detector

TRL Technology Readiness Level

TTL Transistor Trigger Logic

UFA Ultra-Fast Astronomy Telescope

UHECRs Ultra-High-Energy-Cosmic-Rays

UV Ultra Violet

VERITAS Very Energetic Radiation Imaging Telescope Array System

WCD Water Cherenkov Detector

WLS Wavelength Shifters

WLSFs Wavelength Shifting Fibres

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"I'll tell you a secret: we don't read and write poetry because it's pretty. We read and write poetry because we belong to the human race; and the human race is filled with passion. Medicine, Law, Commerce, Engineering... they are noble and necessary races to dignify human life. But poetry, beauty, romance, love are things that keep us alive"

Dead Poets Society 1989

Introduction

The High Energy Cosmic Radiation Detection Facility (HERD) is a planned future space-based detector to study CRs at very high energies. It is scheduled to be launched in the near future and will be placed in the Chinese space station. HERD will be the first astroparticle detector of its kind to measure particles in the TeV region using state-of-the-art technologies such as silicon photomultipliers (SiPMs) and LYSO crystals. The SiPMs have been planned to be equipped to the Plastic Scintillator Detector (PSD), which is one of the sub-detectors of HERD, as shown in Figure 1. In the interest of this thesis, I will adhere to discussing only the technology to be used for the PSD.

SiPMs have been proposed as a new photosensor to replace conventional PMTs because of their low cost, small size, and high photon detection efficiency. However, SiPMs require a high-performance signal readout system to operate effectively. The BETA-ASIC readout board was developed at ICCUB, Spain, for the PSD and FIT subsystems. In space missions, where volume, power and cost are the deciding factors, the BETA-ASIC readout board is capable of reading multiple channels with limited power consumption. Additionally, it provides high detection efficiency, good energy resolution and a broad dynamic range, which are critical parameters for the PSD. For high-energy particle detection, a complete characterisation of the readout system is imperative. Parameters such as the calibration factor, signal-to-noise ratio and crosstalk are some of the critical parameters that need to be studied.

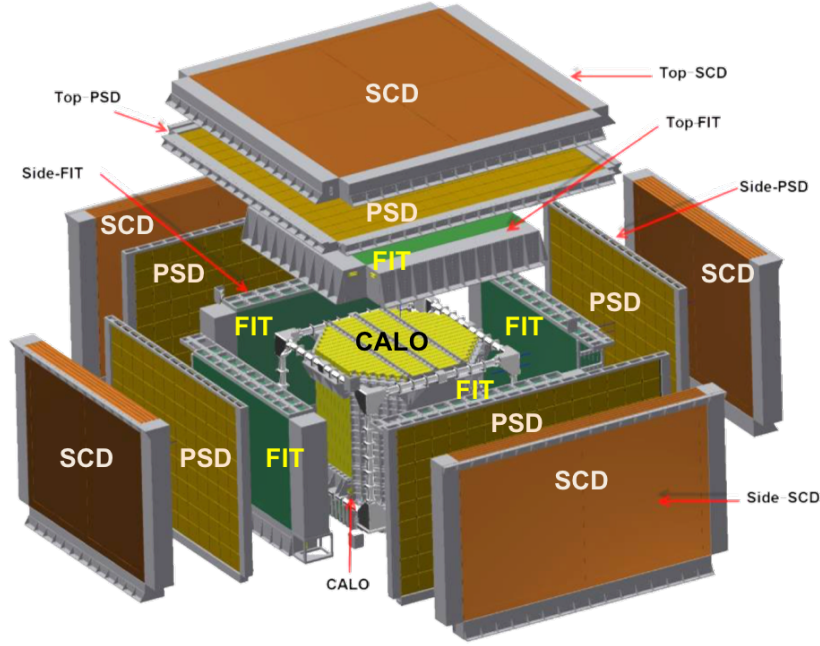


Figure 1: The HERD detector

This thesis will report the calibration of the BETA-ASIC readout board and the characterisation of the two kinds of SiPMs for low-Z and high-Z particles. The calibration of two different ASICs and results from the characterisation of the SiPMs, such as calibration factor, signal-to-noise ratio and crosstalk results for the two SiPMs, will be reported. The thesis is structured in the following chapters:

- Chapter 1 provides an overview of CRs and their interaction with matter. It will describe both the indirect and direct measurement of CRs, utilising ground-based and space-based telescopes, respectively. Lastly, it will describe the DAMPE detector and my contributions to the DAMPE and HERD collaborations.
- Chapter 2 describes the methods to detect CRs using scintillators and photosensors. A description of scintillators, PMTs and SiPMs is provided. Lastly, the state-of-the-art experiments that utilise SiPMs in ground-based and space-borne applications are discussed.
- Chapter 3 is the description of HERD with a detailed description of its components. There are two versions of this detector described in this chapter. The first design shows the detector as it was at the start of this PhD and its latest evolution. Lastly, this chapter also reports the CERN

SPS test beam for HERD that was conducted during the course of this PhD.

- Chapter 4 describes the experimental setup used for the calibration of the BETA-ASIC readout board and characterisation of the SiPMs.
- Chapter 5 discusses the methodology of the calibration procedure of the two different ASICs followed by the three different characterisation tests performed on the SiPMs. They are calibration factor performed using two different methods, signal-to-noise ratio and crosstalk characterisation using the Vinogradov model. Finally, the results from each of them are presented and discussed.

The aim of this thesis was to observe single distinguishable photoelectron peaks to establish a low SNR and check the number of distinguishable peaks. The performance parameters that will be validated in this thesis are calibration factor, SNR, crosstalk and threshold calibration of the two kinds of SiPMs. By providing the first results obtained from the characterisation of these two kinds of SiPMs with their custom-built readout system, this thesis aims to establish a good foundation for further tests and calibration to make the SiPMs ready for future space-based astroparticle detectors. The operational impact of these measurements will directly impact the data analysis framework of HERD.

to my favorites in heaven...

Chapter 1

Cosmic Rays

1.1 Introduction to Cosmic Rays

Cosmic Rays (CRs) are high-energy particles that enter the Earth's atmosphere. Since their discovery in 1912 by Victor Hess, CRs have played an important role in the discovery of new and unstable particles. The electron, proton and neutron were discovered in 1897, 1917, and 1932, respectively. Between the 1920s and the 1950s, the new particles and the interactions among elementary particles were studied using CRs.

Source candidates for CRs are associated with the endpoints of stellar evolution, which release a large amount of gravitational or rotational energy. Galactic candidates are supernova remnants, star cluster winds, stellar wind binaries, and micro-quasars. Extragalactic CR candidates are Active Galactic Nuclei (AGN) that include blazars, radio galaxies, gamma-ray bursts, and starburst galaxies. These particles reach Earth, and their arrival direction, composition, and spectrum can be studied.

Primary CRs are directly accelerated at astrophysical sources such as AGNs, pulsars, and supernova remnants, whereas secondary CRs are produced during the propagation of primary CRs through interactions with the interstellar medium. These high-energy interactions produce gamma rays and neutrinos. Gamma rays are high-energy photons and are electrically neutral. They can travel long distances without being deflected by galactic or extragalactic magnetic fields. Therefore, primary gamma rays allow us to directly study the emission sources. Figure [1.1](#) shows the CRs in the Universe.

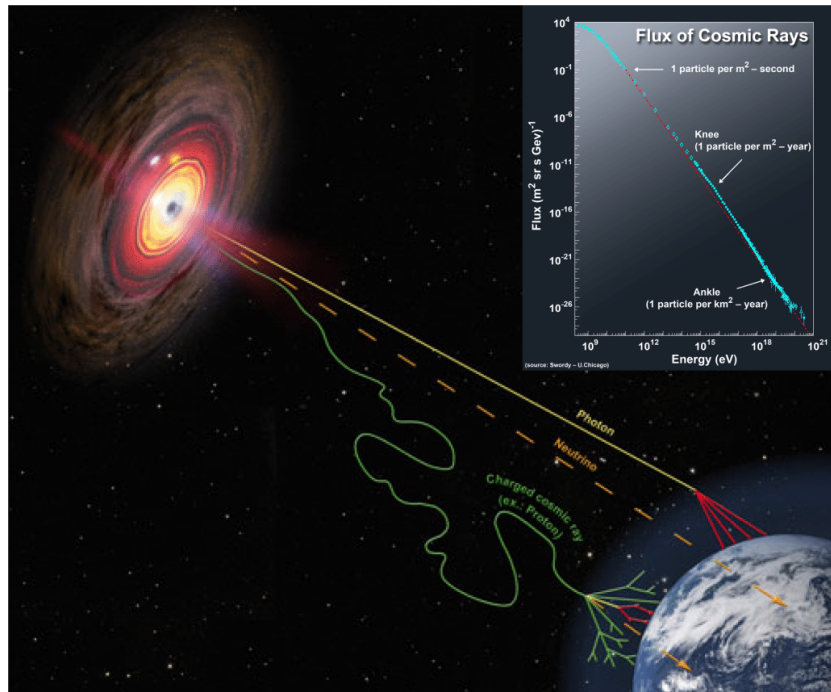


Figure 1.1: CRs crossing the universe from the sources to Earth 1

Cosmic accelerators such as supernova remnants, AGNs, and black holes use intense magnetic fields to propel particles to nearly the speed of light. The mechanism behind this acceleration remains one of the most important and unsolved problems in astrophysics. To understand CR sources and their propagation within the Galaxy, it is important to measure their chemical composition at the highest energies. This composition is determined by the relative percentage of protons and the heavier nuclei in the cosmic radiation. Electrons constitute a minor part of the primary component, whereas positrons are the secondary products of CR interactions in the Galaxy. The majority of high-energy particles in CRs are protons (hydrogen nuclei), approximately 10% are helium nuclei (also known as α particles), and 1% are nuclei of heavier elements.

The process of CR transport in the Milky Way is primarily via diffusion. It is observed in the arrival directions of CRs and by certain abundance ratios of nuclear species. These include radiative losses for electrons and positrons, ionisation, and Coulomb losses for nuclei, electrons, and positrons. Spallation produces lighter nuclei mostly by inelastic collisions of heavier ones during propagation in the interstellar and intergalactic space. Protons and heavier nuclei undergo inelastic collisions with the Cosmic Microwave Background (CMB) and Extragalactic Background Light (EBL). For protons above 10 EeV, pion production limits the propagation distance to approximately 100 Mpc. The heavier nuclei photodisintegrate into lighter ones, limiting the spatial reach. These processes lead to the Greisen-Zatsepin-Kuzmin (GZK) effect. The stable gamma rays and neutrinos are used to study the origin and transport of Ultra-High-Energy CR (UHECRs). The combined observations of gravitational waves, gamma rays, neutrinos and charged CRs form multi-messenger astrophysics. Together, they provide insight into the extreme astrophysical environment.

Due to the power-law dependence $E^{-\gamma}$, the differential spectrum of incoming CRs decreases steeply with energy Figure 1.2. Two striking features are present: the "knee" spectral feature at a few PeV, where the spectral index γ changes from ~ 2.7 to ~ 3.0 , and the second "knee" at $\sim 100\text{PeV}$, with a change at ~ 3.3 . A third spectrum structure, the "ankle", occurs at a few EeV where γ changes to ~ 2.7 . The flux suppression occurring above a few EeV is shown in Figure 1.2. Thus, the energy for the charged CRs ranges from tens of MeV to approximately 1 ZeV. However, the intensity of the particles is approximately $10^4\text{m}^{-2}\text{s}^{-1}\text{sr}^{-1}$ above 1 GeV [1, 2, 3].

¹<https://www.ctao.org/news/pevatrons-hunt-for-galactic-cosmic-rays/>

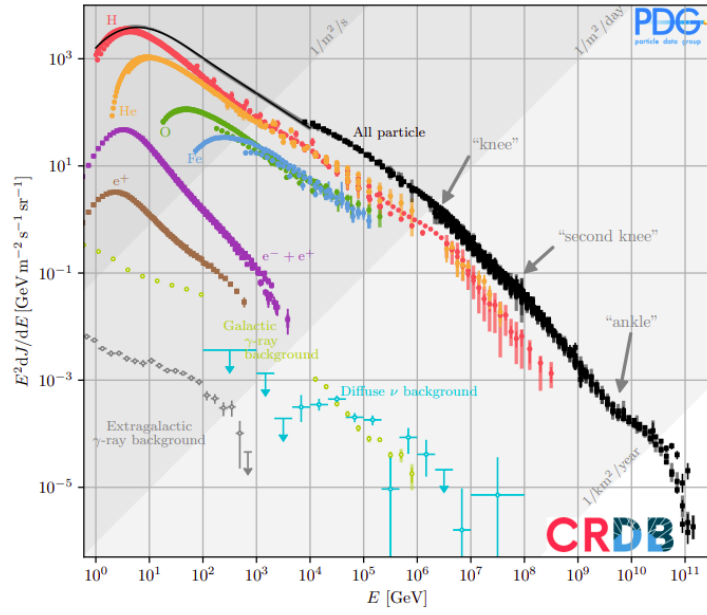


Figure 1.2: Differential energy spectrum of CRs as measured by different experiments [\[2\]](#)

There are two methods to detect the components of the CRs:

1. Direct measurement of CRs
2. Indirect measurement of CRs

Direct measurement involves placing a detector in space (Section 1.5) to capture the primary CRs to identify their charge and energy before they interact with the atmosphere. Indirect measurement of CRs uses large ground-based instruments (Section 1.4) to observe Extensive Air Showers (EAS) and secondary particles produced when primary particles interact with the Earth's atmosphere.

Some of the main properties that can be studied in direct observations consist of detailed spectral information and the identification of species on an event-by-event basis. The standard model of CR acceleration is described by power laws with similar spectral indices for protons and heavier nuclei up to energies of $\sim 10^{15}$ eV. CRs in this energy range are thought to be of Galactic origin. Figure 1.2 shows the CRs from different experiments.

Protons dominate the CR flux below ~ 10 TeV approximately, with a precise measurement of their spectrum. Most of the primary species, like helium, carbon, oxygen, neon, magnesium, and silicon, show a similar spectral shape. Moreover, a combined analysis of protons and helium nuclei has been performed by DAMPE, which extends the light CR component up to several hundred TeV of total energy, thus joining the ground indirect measurements.

The measurement of stable secondary nuclei provides information regarding their abundance in CRs. There is a notable difference between the spectral shapes of the primaries and the secondaries. Some of the secondaries that can be identified from their soft spectra are lithium, beryllium, boron, and fluorine. Aluminium, sodium, and neon exhibit different spectral indices that are intermediate between those of the pure primary and secondary components of the CR. This is because the contribution from secondaries is mixed with the harder primary source component. Some of the experiments dedicated to direct measurements are described in Section 1.5. Below the energy range of direct measurement techniques, the solar energetic particles dominate the flux. This flux is too low to be observed directly using space-based instruments [12].

When the cosmic ray flux drops to a few tens of particles per m^2 per year above 10^{15} eV, it is no longer possible to detect the incident particles before they interact with the atmosphere. As a consequence of the limited geometrical acceptance of space detectors due to size and weight restrictions, the ground-based experiments are utilised to detect CRs on Earth. They are different from their space counterparts, especially in terms of size. They cover a vast area and conduct long-duration experiments to study the parameters such as the nature, flux, mass, and arrival direction of the primary CRs up to the highest energies. These are called EAS arrays. EAS measures the all-particle spectrum, which is the summation of all nuclei species. Some of the experiments using indirect methods are listed in Section 1.4.

1.2 Interaction of photons with matter

The interaction of particles with matter is used to measure the momentum, energy, and velocity of incoming and outgoing particles from the detector. For photons, the interaction mechanisms vary by energy. They interact with matter via the photoelectric effect, Compton scattering and electron-positron pair production.

At low energies, specifically up to a few hundred keV, photoelectric absorption dominates.

Above a few hundred keV, an incident photon transfers a part of its initial energy E_γ to an electron in the atomic shell, then scattered at an angle θ with respect to its original direction [3]. The energy of the recoil electron is given by this formula:

$$E_e = E_\gamma - E'_\gamma - E_{\text{binding}} \quad (1.1)$$

Where E'_γ is the energy of the scattered photon, calculated as

$$E'_\gamma = \frac{E_\gamma}{1 + \frac{E_\gamma}{m_e c^2} (1 - \cos \theta)} \quad (1.2)$$

Above 1.02 MeV, electron-positron pair production takes place. This happens in the electric field of nuclei. Similar to the other two interactions, this process has a higher probability for high-Z materials [3]. The cross-section is given by the formula:

$$\sigma_{\text{pair}} \propto Z^2 \ln(2E_\gamma) \quad (1.3)$$

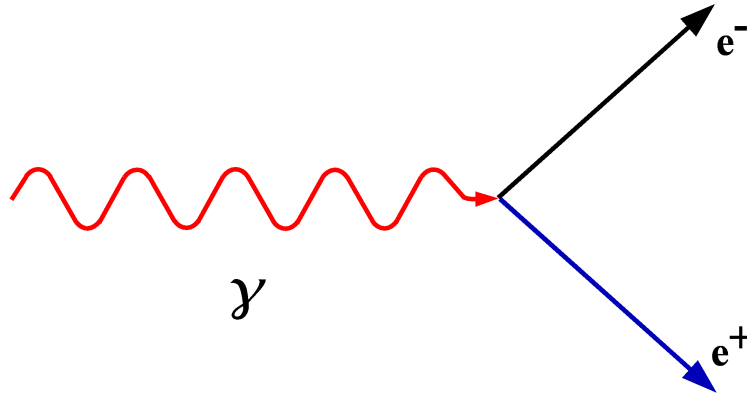


Figure 1.3: Pair production [2]

²https://commons.wikimedia.org/wiki/File:Pair_Production.png

1.2.1 Energy Loss

Particles interact with atoms either by expelling electrons or by moving electrons to higher energy levels. Light charged particles radiate photons through the Bremsstrahlung process.

The value of the specific energy loss per unit length caused by ionisation and excitation as a particle passes through a material of density ρ is given by the Bethe-Bloch formula. This formula calculates the energy loss with an accuracy of 0.1% for materials with intermediate atomic number: [3].

$$-\frac{dE}{dx} = \rho D \left(\frac{Z}{A} \right) \frac{(z_p)^2}{\beta^2} \left[\frac{1}{2} \ln \left(\frac{2m_e c^2 \beta^2 \gamma^2 T_{\max}}{I^2} \right) - \beta^2 - \frac{\delta(\beta, \rho)}{2} \right] \quad (1.4)$$

where,

1. ρ is the material density in g/cm^3 ,
2. Z and A are the atomic and mass numbers of the material respectively,
3. z_p is the charge of the incoming particle in electron charge unit,
4. $D \simeq 0.307 \text{ MeVcm}^{-2}/g$,
5. $m_e c^2$ is the energy corresponding to electron mass $\sim 0.5 \text{ MeV}$,
6. I is the mean excitation energy in the material. It is approximated as $I \simeq 16eV X Z^{0.9}$ for $Z > 1$,
7. δ is the correction term important for high energy. It accounts for the reduction in energy loss due to the so-called density effect. As the incident particle velocity increases, media become polarised, and their atoms can no longer be considered as isolated.

Since the Bethe-Bloch primarily describes the mean energy loss of heavy charged particles, it becomes inadequate at very low energies and does not apply well to electrons and positrons. To study these light particles, Bremsstrahlung is considered.

1.3 Loss by Bremstrahlung

Bremsstrahlung is the dominant mechanism for explaining the energy loss of electrons and positrons through the emission of electromagnetic radiation. The fractional energy loss of a high-energy electron ($E \gg mc^2$) is independent of the energy and can be described with this formula:

$$\frac{1}{E} \frac{dE}{dx} \simeq -\frac{1}{X_0} \quad (1.5)$$

[3]

where X_0 is the radiation length, which depends on the material. The average energy loss through radiation increases rapidly with the increase in energy, but the average energy loss due to collision is comparatively constant. At high energies, energy loss due to radiation is more important than energy loss due to collisions. Consequently, critical energy (E_c) is defined as the energy where the radiation loss is equivalent to the collision energy loss. E_c decreases with increasing atomic number [3].

Above a few GeV, a nuclear force is felt by both charged and neutral hadrons. The inelastic cross-section for hadrons is dominated by nuclear interaction. The final products of inelastic high-energy hadron collisions are mostly pions, which are the lightest hadrons. The interactions of neutrinos differ from hadronic and electromagnetic interactions. Since they are subject only to weak interaction, and because of their extremely low interaction cross-section with matter, they are very difficult to detect and are electrically neutral.

1.3.1 Electromagnetic Showers

When high-energy electrons interact with matter, they produce high-energy photons and dissipate a small fraction of their energy. The secondary photons produced undergo either pair production Figure 1.3 or Compton scattering at lower energies. Electrons and positrons produced during pair production can radiate. This phenomenon continues generating cascades of electromagnetic particles. The number of particles increases with a decrease in energy till the energy falls below the critical energy [3]. These formulas for the scaled distance and the scaled energy are:

$$t = \frac{x}{X_0}$$

for the scaled distance, where X_0 is the radiation length

$$\epsilon = \frac{E}{E_c}$$

for the scaled energy, where E_c is the critical energy. A comparison between the hadronic and the electromagnetic interaction is shown in Figure 1.4.

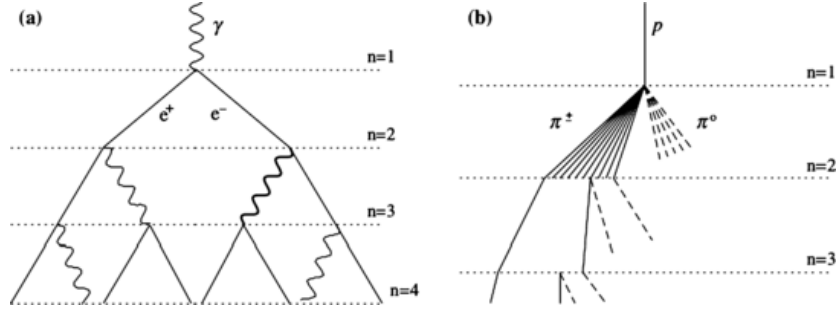


Figure 1.4: Comparison between the Electromagnetic shower and the Hadronic shower ³

1.3.2 Hadronic Shower

When primary hadrons undergo a sequence of interactions and decays, the process is called a hadronic shower. This shower contains both electromagnetic and nuclear reactions. At the end of the cascade, most of the particles are pions; one-third of them are neutral, which decay almost instantly ($\tau \sim 10^{-16}$ s) into a pair of photons ³. On the ground, the cascade contains muons, electrons and photons. Consequently, a hadronic air shower at ground level can be seen as the superposition of several electromagnetic showers.

1.4 Indirect Measurement of Cosmic Rays

Indirect measurements of CRs are conducted using ground-based experiments that study the electromagnetic (EM) and hadronic cascades. The Figure ^{1.5} represents an EAS which is studied using the ground-based instruments described below:

1.4.1 EAS-TOP

³https://www.researchgate.net/figure/Schematic-diagram-of-an-electron-initiated-electromagnetic-shower-This-multiplication_fig1_221911282

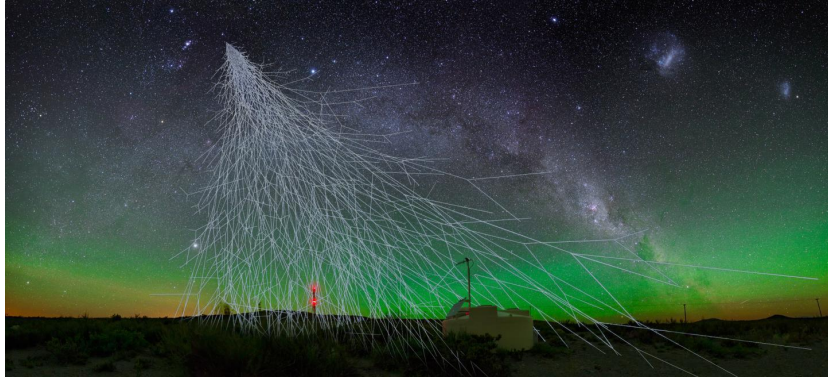


Figure 1.5: Extensive Air Showers ⁴

The Extensive Air Shower on Top (EAS-TOP) array was located in central Italy and operated between 1989 and 2000. The E.M. array consisted of 35 modules of scintillator detectors, each $10m^2$ over a total area of approximately 10^5m^2 . The $10m^2$ module were split into 16 individual scintillators. Each scintillator was viewed by two photomultipliers for timing and particle density measurements ⁴. The detector achieved trigger efficiency for an electromagnetic shower size of $N_e > 10^5$. It consisted of nine layers of 13cm thick iron absorbers and limited streamer tubes as active elements. Particles with energies exceeding 1GeV were identified as muons ².

1.4.2 KASCADE

⁴<https://vr.mephi.ru/en/eas>

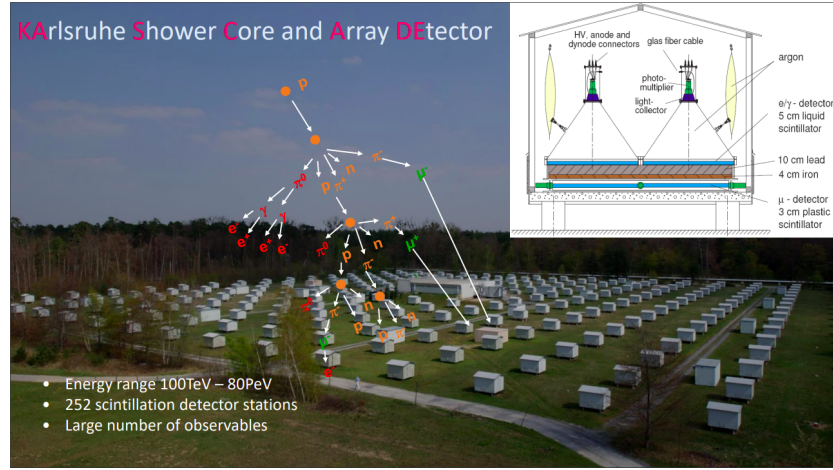


Figure 1.6: The KASCADE-GRANDE at KIT in Karlsruhe ⁵

The Karlsruhe Shower Core and Array Detector (KASCADE) experiment is shown in Figure 1.6. It started operations in 1996 and studied CRs within the energy range of $10^{14} - 10^{17}$ eV. It consisted of a field array, a central detector, and a muon-tracking detector. It detected electrons and muons at four different energy thresholds, as well as total energy and hadronic content ². KASCADE-Grande was an extension of the KASCADE project and stopped operations on March 30, 2009 ⁶.

1.4.3 PIERRE AUGER OBSERVATORY

⁵https://indico.cern.ch/event/1370326/contributions/5766334/attachments/2788109/4861528/Seminar_CERN_KoreaCMS_2024_DKang.pdf
⁶<https://cr.iap.kit.edu/kascade/>

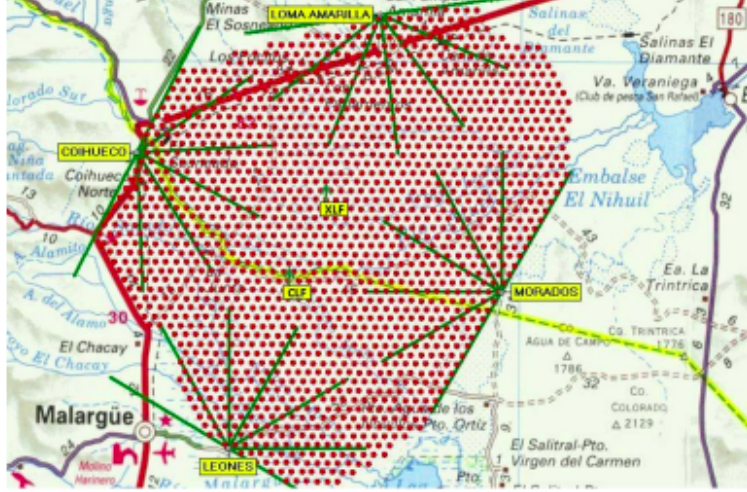


Figure 1.7: The Auger Observatory representing 1660 surface detector stations with the four fluorescence detectors. Each of them has a 30° field of view of its six telescopes. The laser facilities CLF and XLF are also shown [5]

The Pierre Auger Observatory is the world's largest cosmic-ray observatory probing the origin and characteristics of CRs above 10^{17}eV . The observatory consists of 1,660 water Cherenkov particle detectors distributed over $3,000\text{km}^2$ and 24 air fluorescence telescopes. Additionally, there are three high-elevation fluorescence telescopes overlooking an infill array of 61 detectors which covers 23.5km^2 with a spacing of 750m. A bird's-eye view of the observatory is shown in Figure [1.7]

1.5 Direct Measurement of Cosmic Rays

Direct measurements of CRs are performed using space-based telescopes to study the primary CRs before they interact with the Earth's atmosphere. Some of the past and present experiments are described below.

1.5.1 Balloon Experiments

Balloon experiments were integral in determining the presence of extraterrestrial radiation. The scientific balloons are made up of $20\text{ }\mu\text{m}$ thick polyethylene film and are filled with helium gas. They have the capacity to carry a payload of up to 3,600 kg and fly at an altitude of up to 42 km. The payloads are attached to a parachute, and the flights are terminated by remotely firing an explosive squib that separates the payload from the balloon [2]. They are dedicated to the



Figure 1.8: a. The CREAM ballooncraft with a $10^6 m^3$ balloon at Williams Field near McMurdo, Antarctica. b. The balloon trajectory for a lifetime of 37 days, from December 1, 2008 to January 8, 2010 at the South Pole [2].

study of cosmic ray composition below the knee region, antimatter, and dark matter in our galaxy. One example is shown in Figure 1.8

1.5.2 PAMELA

The Payload for Antimatter Matter Exploration and Light-nuclei Astrophysics (PAMELA) was devoted to antimatter studies up to the hundreds of GeV region. It measured both neutral and charged components up to the TeV region and was launched from Baikonur Cosmodrome in Kazakhstan in June 2006, and operations were terminated in 2016 [2].

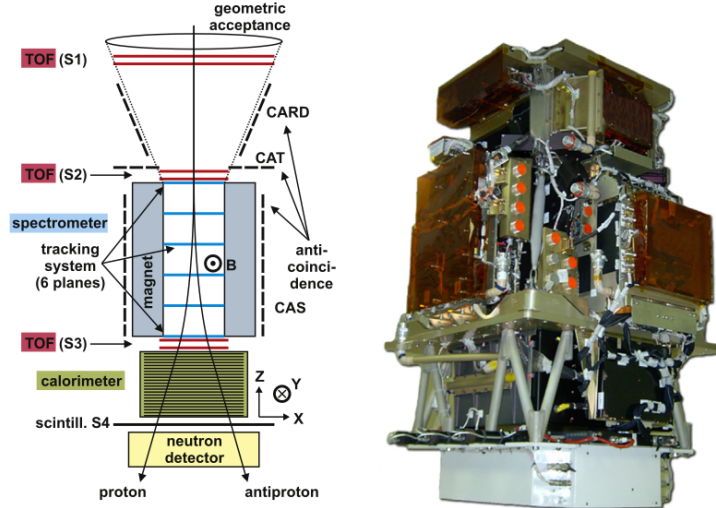


Figure 1.9: A schematic view of PAMELA on the left and the flight model of PAMELA on the right [6].

The PAMELA apparatus, shown in Figure [1.9](#), consists of a magnetic spectrometer with a 0.43T permanent magnet and a silicon microstrip tracker with a Maximum Detectable Rigidity (MDR) exceeding 1TV which provides charge and track deflection data. A scintillator system provides the data acquisition trigger, time of flight, and charge information for particles. It also includes a silicon-tungsten imaging calorimeter for hadron-lepton separation, a scintillator and a neutron detector for particle recognition, and an anti-coincidence system of plastic scintillators to reject spurious events.

PAMELA measured the antiproton spectrum up to 200GeV, positrons up to 300GeV, and electrons up to 600GeV, protons up to 1.2TeV/N, helium up to 0.6TeV/n, and nuclear spectra from Li to C up to 100GeV/n [\[6\]](#).

1.5.3 AMS-02

AMS-01 was the prototype that flew in space for 10 days in 1998, proving that the detector concept worked. The Alpha Magnetic Spectrometer (AMS) is a space-based particle physics experiment for high-precision measurement of CRs and gamma-ray fluxes. It is mounted as an external module on the International Space Station (ISS) in Low Earth Orbit (LEO). It consists of a large superconducting magnet at 18K cooled with superfluid helium. This produces a strong magnetic field (0.8T) over a large volume. This magnetic field bends the paths of the charged cosmic-ray particles. The detector, along with its components [\[2\]](#) [\[7\]](#), is shown in Figure [1.10](#)

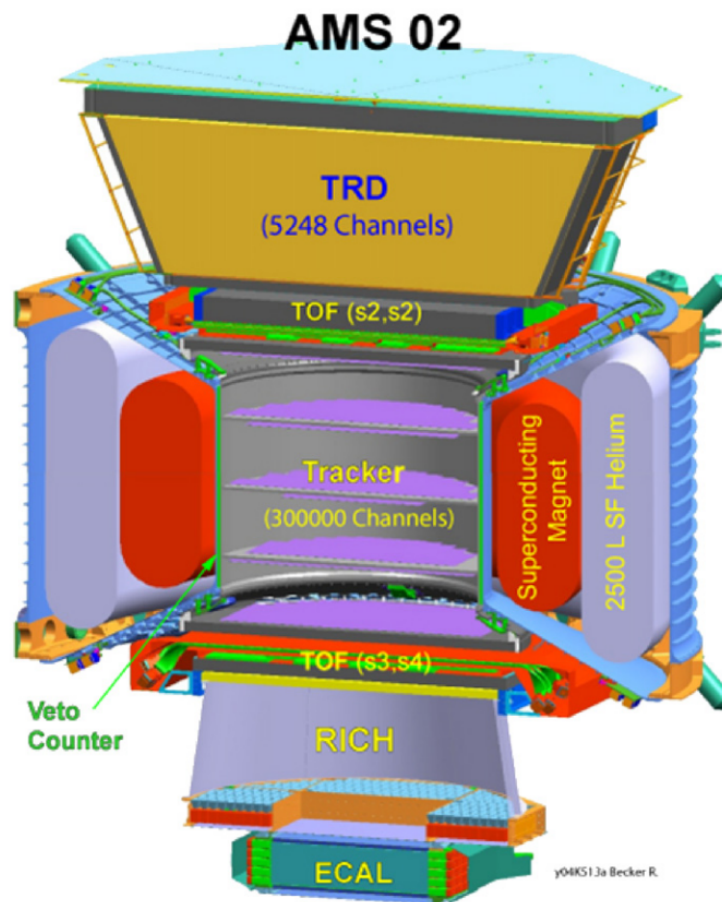


Figure 1.10: The AMS-02 Spectrometer along with its components [7].

A brief description of its subdetectors is as follows:

1. The Transition Radiation Detector (TRD) is used to separate e^+/e^- p^+/p^- up to 300 GeV .
2. The Ring Imaging Cherenkov detector (RICH) provides Z measurements up to iron.
3. The Time of Flight (ToF) provides a fast trigger for protons and charge identification up to $Z=20$.
4. Eight layers of silicon micro-strip detectors measure the position and energy loss in silicon along the particle trajectory.
5. The Electromagnetic CALorimeter detector (ECAL) consists of nine layers of lead foils with glued scintillating fibres for shower development.
6. The Anti-Coincidence Counter (ACC) consists of 16 plastic scintillator paddles. It detects the particles that pass through the magnetic aperture and are not scattered in the tracker [7](#).

1.5.4 FERMI

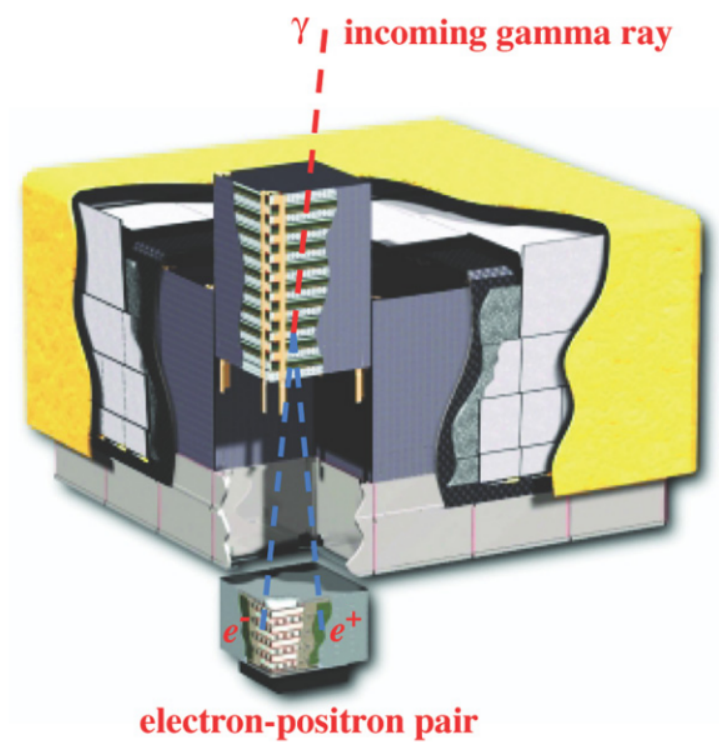


Figure 1.11: A schematic diagram of FERMI-LAT Telescope [8]

The Large Area Telescope (LAT) is an imaging high-energy gamma-ray telescope. It has a wide Field-of-View (FOV) and was built by an international collaboration, as shown in Figure 1.11. It covers the energy range from 20MeV to over 300GeV . It is a pair-production telescope with a precision converter-tracker and a calorimeter arranged in a 4×4 array of 16 modules supported by a low-mass aluminium grid structure. A segmented anti-coincidence detector covers the tracker array and a data acquisition system that manages the data flow via a programmable trigger [8].

1.6 DAMPE

The DArk Matter Particle Explorer (DAMPE) is a space-based detector that was launched from the Jiuquan Satellite Launch Centre (China) on December 17, 2015. The main goals are to study galactic CRs, indirect dark-matter search, electron-positron energy spectrum and gamma-ray astronomy [9]. An exploded view of DAMPE, along with its sub-detectors, is shown in Figure 1.12.

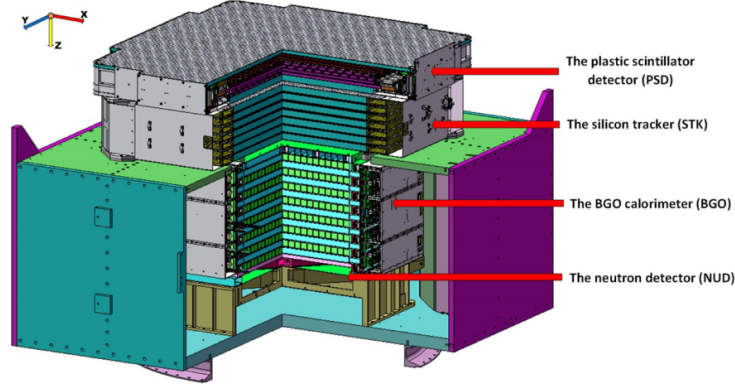


Figure 1.12: DAMPE along with its subdetectors [9].

DAMPE consists of a BGO imaging calorimeter, a NeUtron Detector (NUD), a Plastic Scintillator strip Detector (PSD), and a Silicon-Tungsten track-converter (STK). The functions of these detectors is briefly described below:

1.6.1 Plastic Scintillator strip Detector

The PSD has a high detection efficiency, large dynamic range, and good charge resolution. It has an active area of $82.5 \times 82.5\text{cm}^2$, and consists of 82 plastic scintillator bars arranged in two planes, each with a double-layer configuration. Two Hamamatsu R4443 PMTs are coupled to the ends of each scintillator bar for signal readout. The bars at the top and bottom are perpendicular to each other, allowing full coverage of the detector with the active scintillator area.

without any gaps. The overall efficiency of the detector is ≥ 0.9975 for charged particles [10]. A schematic diagram is shown in Figure 1.13.

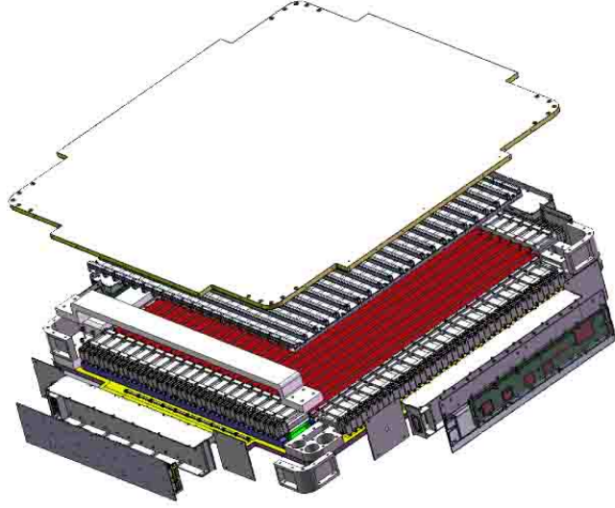


Figure 1.13: The PSD strips of DAMPE detector [10]

1.6.2 Silicon Tungsten tracker

The STK is composed of six position-sensitive double-layer (X and Y) planes of silicon detectors with a total area of approximately 7m^2 . Multiple layers of thin tungsten are interleaved within the tracker structure to enhance the photon conversion rate while keeping electron-positron pair scattering negligible. It is equipped with 768 single-sided AC-coupled silicon microstrip detectors (SSDs). Four SSDs are assembled with a wire-bonded strip-to-strip connections to form a silicon detector ladder. These ladders form 12 STK silicon layers. These microstrip sensors are manufactured by Hamamatsu Photonics, are stacked to form the complete tracker system. An exploded view of STK is shown in Figure 1.14 [10].

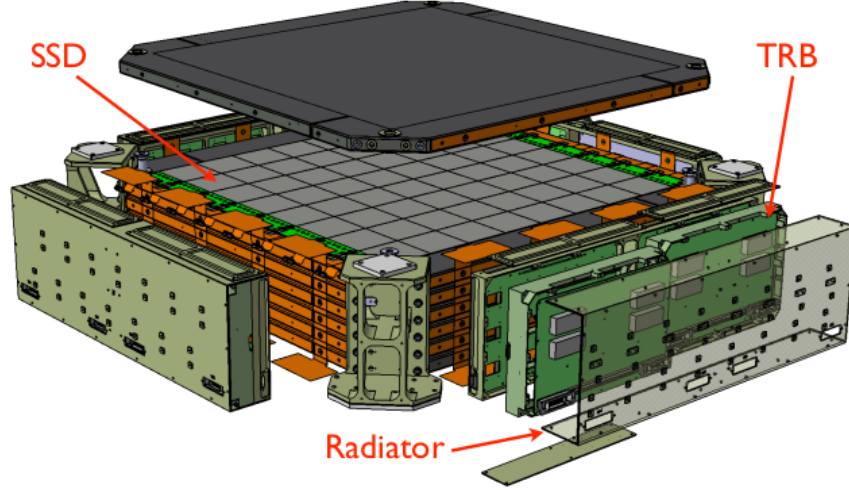


Figure 1.14: Exploded view of STK [10]

1.6.3 Calorimeter

The BGO calorimeter consists of fourteen layers of bars with dimensions of $25 \times 25 \times 600\text{mm}^3$, with seven layers in the X direction and seven layers in the Y direction in a hodoscopic arrangement [11]. The crystals are read out by two Hamamatsu R5610A-01 PMTs mounted at both ends. It has an active area of $60 \times 60\text{cm}^2$ (on-axis) and a thickness equivalent to 32 radiation lengths. The PMTs are coupled to the crystals with optical filters that attenuate the scintillation light produced in the BGO. A schematic diagram of the calorimeter is shown in Figure 1.15 [10].

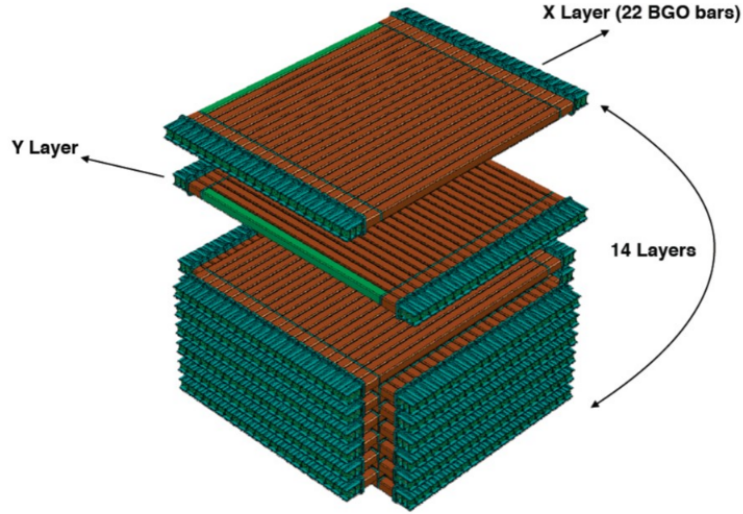


Figure 1.15: The BGO calorimeter arranged in the X-Y plane [10]

1.6.4 NeUtron Detector

The NUD performs electron/hadron identification; the neutron content of a hadronic shower is expected to be one order of magnitude higher than that of an electromagnetic shower. The created neutrons are thermalised in the BGO calorimeter, and the total neutron signal is measured over a few microseconds by the NUD. It consists of four blocks of boron-laden plastic scintillator. Each of them is wrapped with a layer of aluminium film for photon reflection and read out by a PMT. The scintillators contain wavelength-shifting fibres for optical transmission to reduce the fluorescence attenuation and increase the photon collection efficiency. The NUD detector is shown in Figure 1.16 [10].

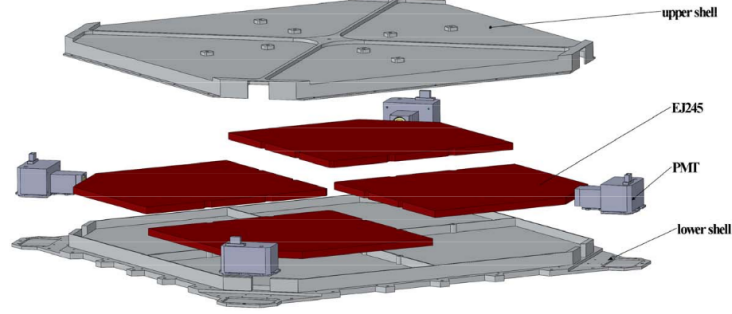


Figure 1.16: Exploded view of the NUD [10]

1.6.5 Performance parameters of DAMPE

The overall DAMPE payload weighs 1.3 tonnes. It has a power consumption of 130 W. The rate of data transmission to the ground is 12 Gb/day [11]. It was built to study CRs and γ rays up to 10 TeV. Some of the performance parameters of DAMPE are listed in Table 1.1.

1.6.6 Recent results from DAMPE

To understand CR acceleration and its propagation through the interstellar medium, it is important to study the composition and flux of individual CR species. The experiment also provides new high-precision data. A recent publication by the DAMPE collaboration reports the direct measurement of carbon, oxygen and iron spectra up to petaelectron volts (PeV) [12]. The spectra for neon, magnesium and silicon as observed by DAMPE are shown in Figure 1.17.

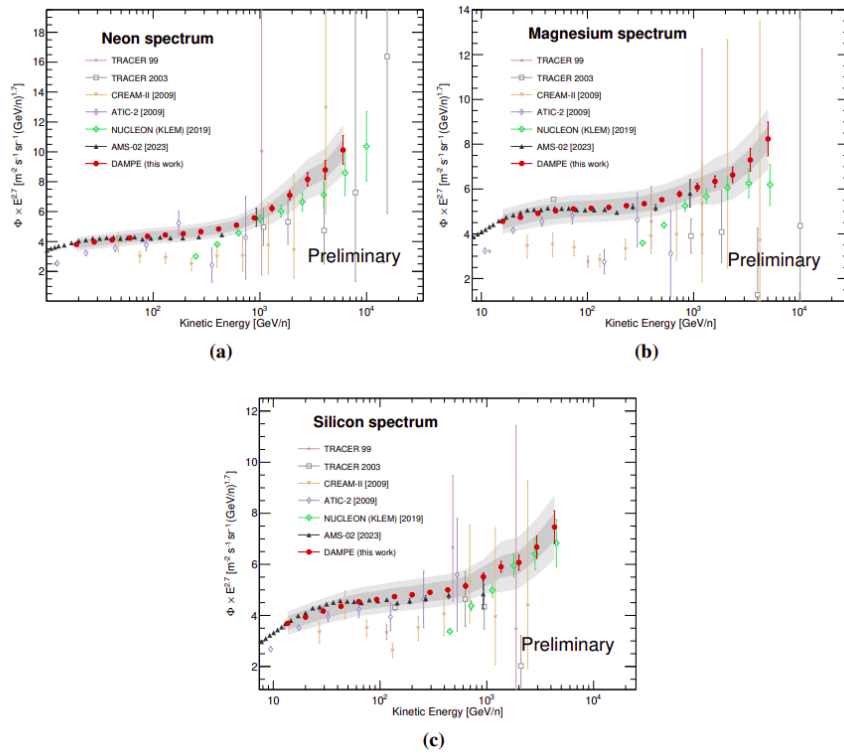


Figure 1.17: Preliminary results of Neon, Magnesium and Silicon spectra as seen by DAMPE from January 1, 2016, to December 31, 2023, and compared with other detectors [13]

Performance Parameters for DAMPE	
Parameters	Values
Energy range of γ -rays/electrons	5 GeV – 10 TeV
Energy resolution of γ -rays/electrons ^a	$\leq 1.5\%$ at 800 GeV
Energy range of protons/heavy nuclei	50 GeV – 100 TeV
Energy resolution of protons ^b	$\leq 40\%$ at 800 GeV
Effective area at normal incidence (γ -rays)	1100 cm ² at 100 GeV
Geometric factor for electrons	0.3 m ² sr above 30 GeV
Photon angular resolution ^c	$\leq 0.2^\circ$ at 100 GeV
Field of View (FoV)	~ 1.0 sr

Table 1.1: List of the design parameters of DAMPE [10].

^a σ_E/E assuming Gaussian distribution of energies
^b σ_E/E assuming Gaussian distribution of energies
^cThe 68% containment radius

Another significant result is the measurement of the boron-to-carbon ratio and the boron-to-oxygen flux ratios using a nine-year DAMPE in-orbit dataset. This is crucial because carbon and oxygen nuclei remain relatively unchanged when they travel from their source to their location of detection, whereas boron is a secondary CR and it changes its nature when it interacts with the interstellar medium. Therefore, knowledge of secondary CRs and secondary-to-primary ratios provides valuable information to probe the galactic CRs. A spectral hardening was suggested by AMS-02 and CALET at ~ 200 GeV/ n , which was confirmed by DAMPE [14]. Preliminary results of boron-to-carbon and boron-to-oxygen ratios are shown in Figure 1.18.

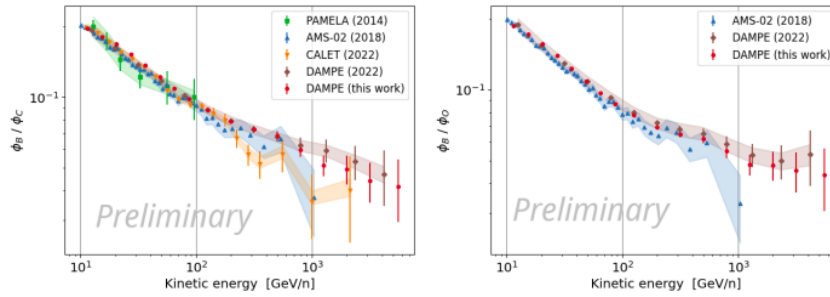


Figure 1.18: Preliminary results of Boron-to-Carbon and Boron-to-Oxygen flux ratio seen by DAMPE from January 1, 2016, to December 31, 2023 and compared with other detectors [14].

An important result about the spectral hardening in the boron spectrum

was also reported using DAMPE observations [15]. The analysis uses eight years of DAMPE data and provides improved precision at high energies above $1\text{ TeV}/n$. This observation of spectral hardening, a first for DAMPE, is shown in Figure 1.19

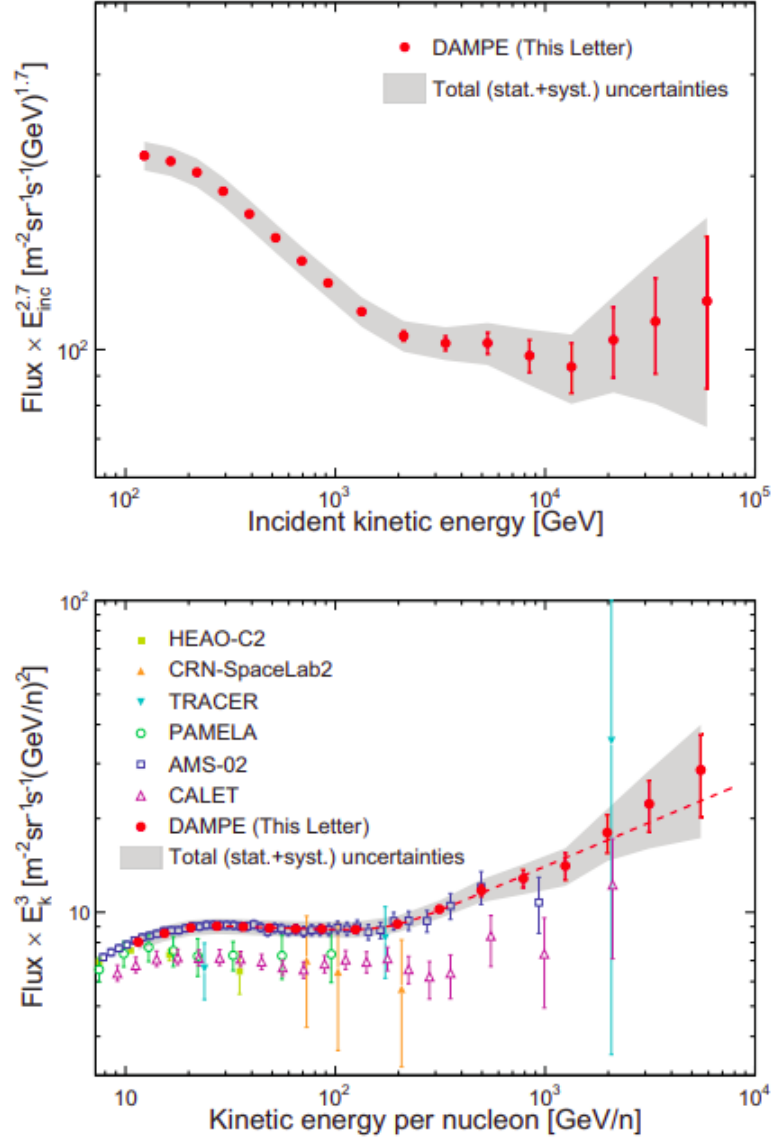


Figure 1.19: Spectral hardening of Boron as compared with previous measurements from different experiments [15].

DAMPE has recently reported the $p + He$ spectrum, which is in agreement with other direct-detection experiments. This is a significant result that suggests a second hardening at about 150 TeV. Using 72 months of in-orbit data confirming the softening feature with a significance of 6.6σ . The measurement of $p + He$ is shown in Figure 1.20 that is compared with different detectors, providing an important link between direct and indirect measurements.

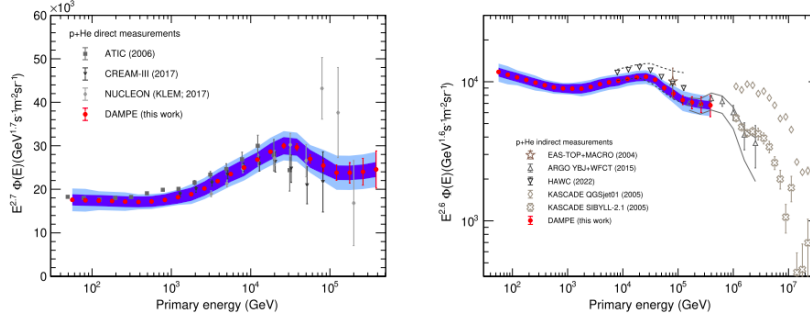


Figure 1.20: Direct measurement of $p + He$ spectrum by DAMPE and compared with direct measurements (left) and with indirect measurements (right) [16].

1.6.7 DAMPE Shifts

To obtain the results mentioned in Section 1.6.6, the observational data and the Monte Carlo simulations must be in good agreement. To ensure a robust comparison, "DAMPE shifts" are performed independently by the Chinese and European counterparts. As a member of this collaboration, I participated in executing and maintaining the Monte Carlo simulations, which has further enabled me to be a part of the DAMPE collaboration papers.

1.6.8 DAMPE and HERD Collaboration

My main work is on the HERD project, and the idea of HERD was partially conceived by the same Chinese-European collaboration as DAMPE. HERD aims to detect CRs at higher energies using novel technologies, as will be described from Chapter 3 onwards.

After discussing CRs and the on-ground and in-space experiments, this thesis will report on methods of detecting CRs in Chapter 2 with a focus on scintillators and photosensors.

***"It doesn't stop being magic just because you know
how it's done."***

Terry Pratchett

Chapter 2

Methods to detect Cosmic Rays

One of the most important components of a cosmic-ray detector is a scintillator equipped with a photosensor. In this chapter, scintillators, photosensors, and their applications in different ground-based and space-based instruments are discussed.

2.1 Scintillators

A scintillator is a radiation detectors that also acts as an absorbing material. A fraction of the energy deposited by ionising radiation in the material is converted into light. Scintillators act as wavelength shifters that convert the energy (or wavelength) of the incident particle or energetic photon such as UV, X-rays or γ rays into a number of photons with much lower energy in the visible or near-visible range. This can be detected by photomultipliers, photodiodes, or avalanche photodiodes [17]. The photosensors are generally coupled to the material to translate these photons into electrical signals.

2.2 Why scintillators in High Energy Physics (HEP)?

Scintillators have plenty of applications in different fields, such as high-energy particle detectors, medical imaging, safety systems, and astrophysics, among others. Scintillators are used in HEP for the compact and high-precision measurement of electrons, photons and the decay of unstable heavier particles over a wide energy range. Traditionally, there is no single "ideal" scintillator material. It depends on the application and is a trade-off between physico-chemical properties and optical parameters such as density, scintillation properties, radiation hardness and cost. Since the density and compactness of a detector are

essential to reduce detector volume and cost, this is achieved by using a high stopping power and therefore a high-density material. High-density materials reduce the shower size of high-energy gamma rays, electrons and the range of Compton-scattered photons for low-energy gamma rays. They also reduce the lateral spread of the shower, a critical factor for high-energy physics detectors. Fast scintillation is also an important parameter in the search for rare events and at hadron colliders. High light yield is less important at high energies (GeV range), as even a poor scintillator can produce a lot of scintillation photons. Consequently, they can be paired with silicon photomultipliers, along with being compact and immune to strong magnetic fields [17].

2.2.1 Types of Scintillators

Scintillators are broadly classified into two classes:

1. Inorganic scintillators.
2. Organic scintillators.

2.2.2 Inorganic Scintillators

In inorganic scintillators, the scintillation mechanism depends on the electronic band structure determined by the crystal lattice of inorganic materials. When energy is absorbed, electrons are elevated from their valence band into the conduction band. This leaves a hole in the valence band. In the case of pure crystals, the emission of a photon when the electrons return to the valence band is an inefficient process. To enhance the process of emission of the visible photons, small amounts of impurities, also known as activators, are added to inorganic scintillators [18].

2.2.3 Organic Scintillators

Organic scintillators use ionisation produced by charged particles to generate optical photons in the blue to green wavelength region [18]. There are three kinds of organic scintillators - crystals, liquids and plastics. Organic scintillators have a wide range of applications because of their good time resolutions. Plastic scintillators are relatively cheap, have a low density, and can measure particles with precision [19].

Because of their fast time response, relatively low cost, easy manufacturing, versatility, and high detection efficiency for charged particles, they have found applications in medicine, particle physics, and astrophysics. They exhibit significant radiation tolerance and have been used in various space missions such as AMS or DAMPE. Furthermore, they have also been used in Phobos, Lunar Prospector, or Mars Odyssey [20]. The properties of different kinds of scintillators are described in Table 2.1.

Material	Light Yield ($\phi(\text{photons})/\text{keV}$)	$\lambda_{peak}(nm)$	Decay time (s)
Plastic scintillators	8–10	420	$\simeq 10^{-9}$
Liquid scintillators	11–13	420	$\simeq 10^{-9}$
Glass scintillators	3–5	400	$\simeq 10^{-9}$
Inorganic scintillators	40–90	415–480	$\simeq 10^{-7}$

Table 2.1: Parameters for different scintillator materials [18]

2.2.3.1 Plastic Scintillators

When an organic scintillator is dissolved in a solvent and polymerised, the product is a solid solution. The base materials used for making plastic scintillators are Polystyrene (PS), PolyVinylToluene (PVT) or PolyMethylMethAcrylate (PMMA).

Plastic scintillators are a common form of organic scintillators, available commercially in different shapes, and are relatively inexpensive. The composition for plastic scintillators is generally PS or PVT for detectors.

Properties such as attenuation length, decay time and light yield are functions of fluors⁷. Ionisation produces UV photons with a short attenuation length of a few millimetres. To obtain longer attenuation lengths, primary fluor is dissolved in a high concentration, approximately 1% by weight (wt.), into the base. The other function of the fluor is to have a short decay time and increase the total light yield [18]. The operating mechanism of a plastic scintillator is shown in Figure 2.1.

⁷They act as a primary emitter, and secondary fluors act as a wavelength shifters that convert radiation energy into detectable light

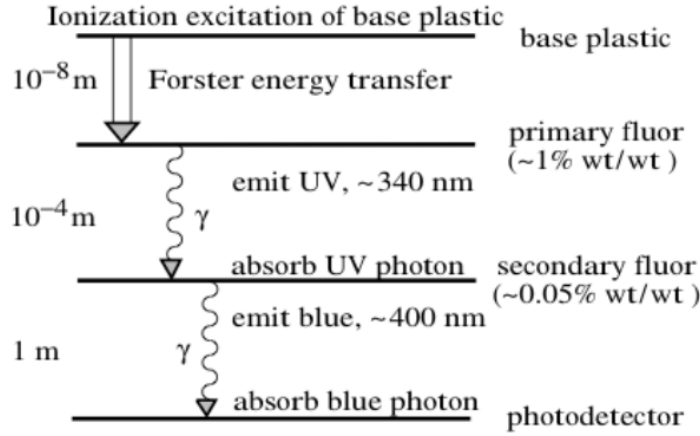


Figure 2.1: Operating mechanism of a Plastic Scintillator where the fluor is added in different concentrations into the base by their weight (wt) [18]

Radiation damage in plastic scintillators is mainly caused due to the creation of optical absorption centres that absorb more light in the ultraviolet and blue regions as compared to longer wavelengths. Although this effect is not well understood, it reduces the light yield and attenuation length. These materials degrade after receiving cumulative doses of the order of $10^3 - 10^4 Gy$ (gray). Some specially formulated plastic scintillators can tolerate radiations up to $10^5 Gy$ before it shows a small decrease in light output [18]. The plastic scintillators that were tested at the CERN SPS test beam (Section 3.4) were BC-404 plastic scintillators. It is used for alpha, beta and fast-counting applications with 1.8 ns decay time. These types of scintillators contain a high concentration of primary and WLS fluors, and light is emitted in a short distance at its final wavelength [8].

Scintillators are equipped with photosensors for light detection. The two most commonly used photosensors are PMTs and silicon photomultipliers (SiPMs). PMTs were widely used in space experiments, as shown in Section 1.6, while SiPMs are being increasingly considered for future space experiments. They will be discussed in the following sections.

2.3 Working principle of photomultipliers

Many detectors are designed to detect photons sensitive in the visible part of the electromagnetic spectrum. This range covers scintillation and Cherenkov radiation, as well as light emitted by many astronomical sources. Only a mea-

⁸<https://luxiumsolutions.com/radiation-detection-scintillators/plastic-scintillators/bc400-bc404-bc408-bc412-bc416>

measurable signal needs to be extracted from a small number of incident photons. It is achieved by generating a primary photoelectron or electron-hole pair by an incident photon and amplifying the signal to a detectable level through a sequence of avalanche processes and collecting the secondary charges to form the electrical signal. The resulting secondary charge is then collected to form a measurable electrical signal [3]. Some of the characteristics of the photodetectors are:

1. Quantum Efficiency (QE), or the probability that a primary photon generates a photoelectron.
2. Collection efficiency (C), or the geometrical factor.
3. Gain (G) - number of electrons collected for each photoelectron generated.
4. Dark Noise (DN) – electrical signal where there is no incoming photon.
5. Intrinsic response time of the detector.

Photomultipliers are the oldest photon detectors used in high-energy particle and astroparticle detectors. They operate across ultraviolet, visible, and near-infrared ranges of the electromagnetic spectrum. They are made up of a glass envelope with a high vacuum inside. They consist of a photocathode, several intermediate electrodes called dynodes, and an anode. When an incident photon hits the photocathode material (a thin deposit on the entry window of the device), electrons are produced via the photoelectric effect. These electrons are directed by focusing electrodes towards the electron multiplier chain, where they are multiplied by secondary emission. The electrons produced in the photocathode have the energy of an incoming photon, and as they enter the multiplier chain, they are accelerated due to the electric field. Each dynode inside the electron multiplier has a higher voltage than the previous one. As they hit the first dynode with a much higher energy, they are accelerated towards the second dynode and low-energy electrons are emitted. They are arranged such that at each dynode an increasing number of electrons is produced. Finally, when they reach the anode, due to the accumulation of these electrons, a sharp pulse is produced and indicates the arrival of a photon at the photocathode [3]. The working principle is described in Figure 2.2

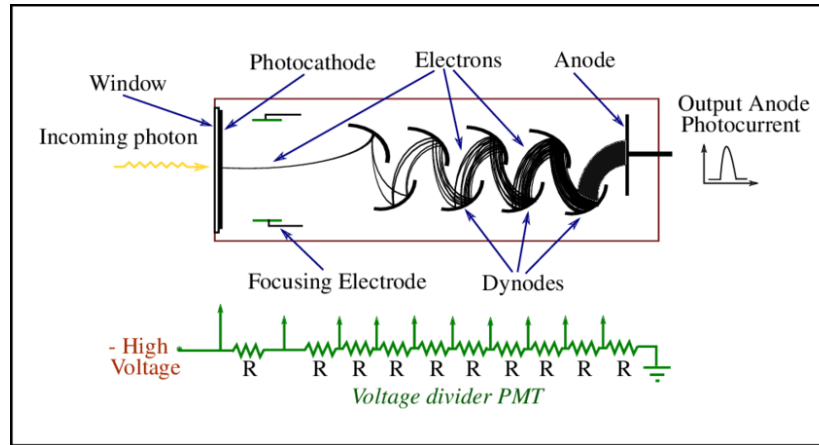


Figure 2.2: A schematic diagram of a Photomultiplier Tube (PMT) ⁹

They have diverse applications in medical imaging ^[21], Light Imaging and Detection Ranging (LIDAR) ^[22], hard X-ray astronomy ^[23] ^[24] ^[25], planetary exploration ^[26] and particle physics ^[27]. An ideal photon detector provides a response proportional to the incident photon flux, has a good internal gain, a broad spectral sensitivity, and yields a good signal for further processing and analysis ^[28]. A PMT's output signal is linearly proportional to the number of detected photons. These vacuum tubes operate at high voltages with a gain of up to 10^6 to 10^7 . The photodetection efficiency is approximately 20% at 420nm and their operation is affected by magnetic fields ^[28]. Considering these drawbacks along with the size and shape of the PMTs - they are not optimal for compact designs. Hence, this void was filled by solid-state photodetectors - enter SiPMs!

2.4 What is a Silicon Photomultiplier (SiPM)?

To understand SiPMs, it is essential to understand fundamental concepts such as a diode, reverse bias, avalanche photodiode, quenching resistor and breakdown voltage.

2.4.1 Diodes

A "diode", as shown in Figure ^[2.3] refers to a device with two electrodes, the cathode (n-type) and the anode (p-type). Semiconductors such as silicon and germanium are used for diode fabrication ^[10].

⁹https://www.researchgate.net/figure/shows-an-example-of-the-construction-of-a-PMT-with-the-input-window-photocathode-the_fig3_266740323

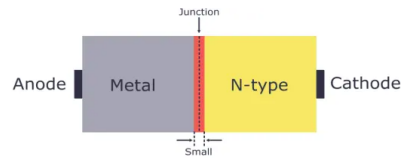


Figure 2.3: The basic construction of a diode ¹⁰.

A silicon diode is the most common type of semiconductor diode. It consists of a p -type and n -type semiconductor. The p -type contains excess holes that act as positive charge carriers. The n -type contains excess electrons that act as negative charge carriers. Therefore, a semiconductor diode is formed by creating a junction between these p and n regions. Semiconductors often work in two conditions:

1. Forward Bias
2. Reverse Bias

When the anode is connected to the positive terminal and the cathode to the negative terminal, it is called forward bias.

When the anode of the diode is connected to the negative terminal and the cathode to the positive terminal, it is called 'reverse bias'. The negative terminal attracts holes from the p -region, and the positive terminal attracts electrons from the n -region. This makes electrons and holes move away from the junction which increases the depletion layer ¹¹.

2.4.2 Avalanche Photodiodes (APD)

An avalanche photodiode consists of a positively doped p region and a negatively doped n region sandwiching an area of neutral charge, which is called the depletion region. These diodes provide gain due to electron-hole pair generation from an energetic electron that creates an 'avalanche' of electrons in the substrate ¹².

¹⁰<https://www.blikai.com/blog/diodes/diode-construction-types-working>

¹¹<https://www.geeksforgeeks.org/physics/reverse-bias/>

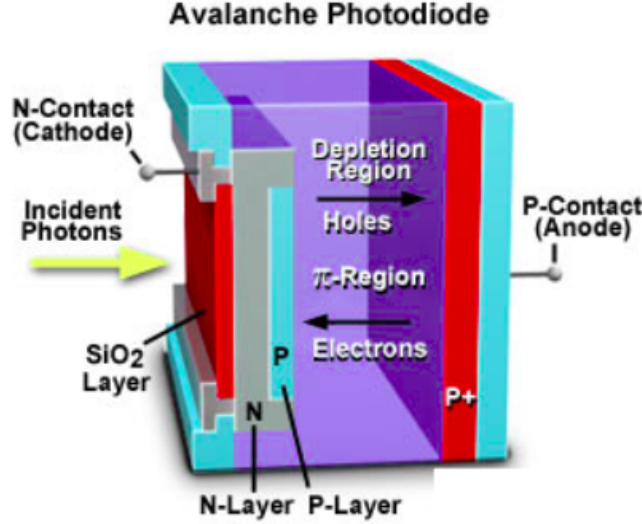


Figure 2.4: An avalanche photodiode ¹²

In Figure 2.4, an APD is shown. The photons enter the diode, pass through the silicon dioxide, and then through the p and n layers. Eventually, they pass through the depletion region. Here, the photons excite the free electrons and holes that migrate to the cathode and the anode, respectively. When a semiconductor diode has a reverse bias voltage applied and the junction between p and n is illuminated, then the current flow is proportional to the number of photons incident upon the junction.

2.4.3 Quenching resistor

A single photon triggers an avalanche breakdown with high internal gain. This discharge of one microcell is independent of the incident light. With the help of a quenching resistor, the bias voltage is lowered. This happens because of the voltage drop across the resistor. Once this process is complete, the microcell is restored and ready to detect another photon. The quenching resistor, along with the junction capacitance, C_j , is responsible for the recovery time of the microcell. The quenching resistors of the microcells are connected in parallel; therefore, the current is proportional to R_q/N where, N = total number of microcells in the SiPM [28] as shown in Equation (2.1) where V_{bias} is the bias voltage.

$$V_{bias} = \frac{I \times R_q}{N} \quad (2.1)$$

¹²<https://micro.magnet.fsu.edu/primer/digitalimaging/concepts//avalanche.html>

2.4.4 Breakdown Voltage

The breakdown voltage of a silicon photomultiplier is the minimum reverse bias required to trigger a self-sustaining avalanche in the device's internal microcells. The breakdown voltage is temperature-dependent. Depending on temperature and technology, the breakdown voltages are different for different SiPMs. Since the breakdown voltage changes with temperature, a temperature coefficient is assigned to regulate the breakdown voltage as shown in Equation (2.2) where V_{bd} is the breakdown voltage and V_{OV} is the overvoltage.

$$V_{bias} = V_{bd} + V_{OV} \quad (2.2)$$

To maintain the breakdown voltage, the temperature coefficient of the particular SiPM is provided in their respective datasheets. The formula is shown in Equation (2.3) where β is the temperature coefficient, ΔT is the change in temperature and ΔV_{bias} is the corresponding change in the bias voltage

$$\Delta V_{bias} = \beta \times \Delta T \quad (2.3)$$

2.4.5 Working principle of SiPMs

A silicon photodiode is formed when the $p - n$ junction creates a depletion region which is free from mobile charge carriers. When a reverse bias voltage is applied, it sets up an electric field in the depletion zone that accelerates the charge carriers toward the cathode (electrons) or anode (holes). So, this absorbed photon will cause a net flow of current in the reverse-biased photodiode. When the electric field is sufficiently high in the depleted region, a charge carrier will be accelerated to a point where it carries sufficient kinetic energy to create secondary charge pairs through impact ionisation. In this way, a single absorbed photon can create a self-perpetuating ionisation cascade that spreads throughout the silicon volume. Eventually, the silicon breaks down and becomes conductive [29]. This amplifies the electron-hole pair into a macroscopic current flow – the Geiger discharge Figure 2.5.

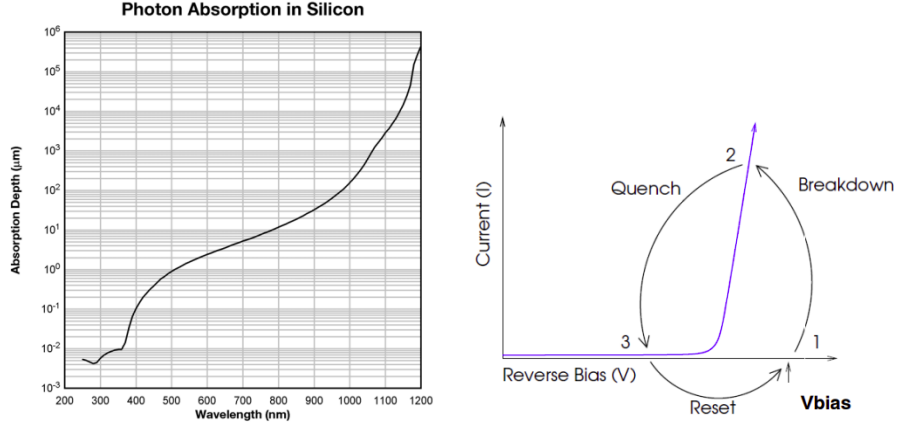


Figure 2.5: photon absorption in SiPM w.r.t wavelength (left) and SPAD operation in Geiger mode(right) [29]

When a photodiode operates in Geiger discharge mode and employs this mechanism of breakdown to achieve a high gain, it is called the Single Photon Avalanche Diode (SPAD) Figure 2.5. Since current flows during breakdown, it must be stopped. This is achieved through a process called passive quenching by using a series of resistors that limit the current drawn by the diode during breakdown.

The diode then recharges back to its bias voltage to detect subsequent photons. This creates a cycle of breakdown, avalanche, quenching and recharge back to the bias voltage.

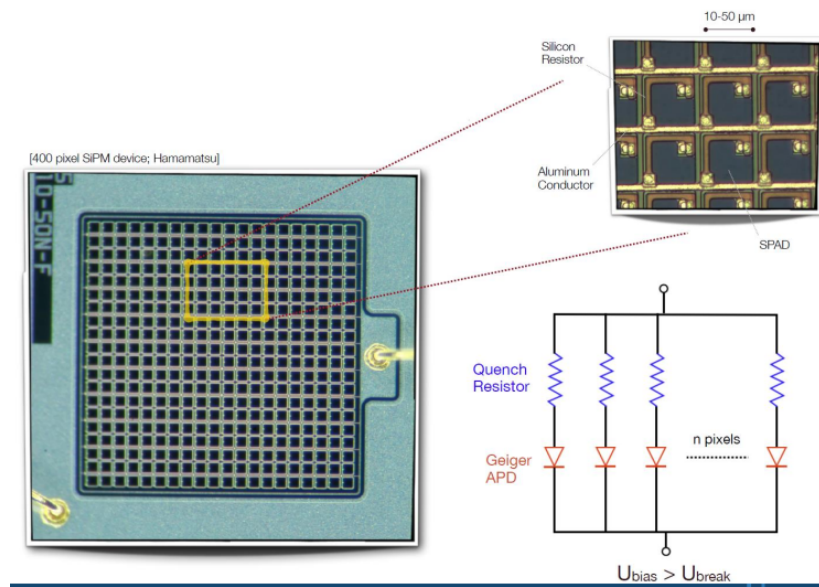


Figure 2.6: The structure of a Silicon Photomultiplier is characterised by an array of SPADs connected in parallel. Every SPAD has its silicon resistor. Every microcell contains a SPAD and its resistor, and it is divided by the others through an aluminium conductor that is not photon-sensitive [29]

Thus, SiPMs integrate a dense array of small, independent SPADs – each with its own quenching resistor. This is called a "microcell". When a photon is absorbed, a Geiger avalanche is initiated inside the microcell, causing current to flow through the microcell. A typical SiPM has microcell densities between 100 and 1000 per mm² depending on the size of the microcell. Each microcell generates a charge proportional to the overvoltage. The gain of the SiPM is defined as the ratio of the output charge to the charge of the electron [28] with a gain of approximately 10⁶, equivalent to PMTs with additional advantages. To obtain a good gain of 10⁶ the APDs are operated above the breakdown voltage. The design determines the breakdown voltage and can range between 20V and 100V.

2.4.6 Why SiPMs for HEP?

SiPMs are the new low-cost alternatives to the Photomultiplier Tube (PMT) because of their capability to handle the challenges of sensing, timing, and quantifying low-light signals down to a single photoelectron [29]. They also offer low bias voltage, high gain, high photon detection efficiency, fast transient response, excellent time resolution and a wide spectral range [30]. All of these features make it a very lucrative option to be used in different fields, such as medical imaging, threat and hazard detection, biophotonics and high energy physics [29].

2.4.7 Effect of radiation damage on SiPMs

The use of SiPMs in space will inevitably expose them to high doses of radiation. There are two kinds of radiation – ionising and non-ionising radiation – that can worsen their performance over time [31] [32]. These radiations cause surface and bulk damage, respectively.

The surface damage is caused by ionising energy loss (IEL) due to X-rays and electrons with energies below 300 keV and results in charge accumulation at the Si-SiO₂ interface. Due to this, the leakage current and breakdown voltage are altered.

Bulk damage is caused by non-ionising energy loss (NIEL). It is caused by electrons, protons, neutrons and gamma rays with energy above 300 keV. It causes lattice defects, which lead to increased dark count rate and afterpulsing effects [33].

Recovery of SiPMs from the radiation damage is widely studied using the annealing procedure. "Annealing" means heating the SiPM and then cooling it slowly to remove internal defects. Previously, long-term annealing procedures, both at room temperature and high temperature, have shown that the SiPM performance can be restored. A special study called the in-situ annealing is used for space applications, colliders or other applications where maintenance of SiPMs is particularly difficult. It does not require an additional heating device or disassembly of the device and can be achieved through circuit design [34].

2.5 State-of-the-Art: On-ground Experiments

Several experiments used SiPMs as their photodetectors for ground experiments as well as for space. The ground experiments are discussed in this section.

2.5.1 FAMOUS

The First Auger Multi-pixel photon counter camera for the Observation of Ultra-high-energy-cosmic-ray (FAMOUS) air showers is a compact refractor with a camera built using SiPMs [35]. Each pixel contains a light concentrator, a 1 mm thin UV-pass filter, and a Hamamatsu-S10985-100C - an array of four $3 \times 3 \text{ mm}^2$ Hamamatsu S10363-33100C SiPMs yielding a total area of $6 \times 6 \text{ mm}^2$. After FAMOUS was assembled, the result of the first-test measurement is shown in Figure 2.7

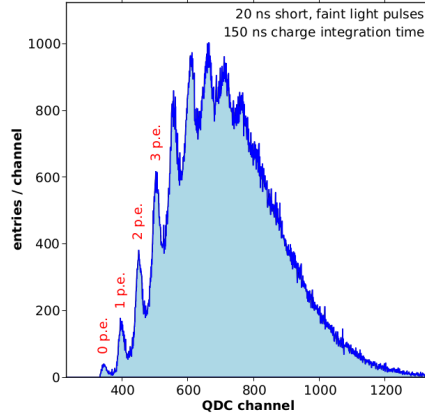


Figure 2.7: The charge spectrum of a single pixel of FAMOUS with a 400nm LED light [35]

2.5.2 Ultra-Fast Astronomy (UFA) Telescope

The UFA searches for Fast Radio Bursts (FRBs) at the Assy-Turgen Astrophysical Observatory near Almaty, Kazakhstan. FRBs are high-energy radio transients of unknown origin with millisecond durations, and an optical counterpart probably exists on the sub-millisecond timescale; due to dispersion and specific timescales, which can be used to study the origin of FRBs. The characterisation of S13360-3050CD Multi-Pixel Photon Counter (MPPC) Hamamatsu SiPMs for the UFA to study FRBs can be found in [36].

2.5.3 Pierre Auger Observatory

AugerPrime is an upgrade of the Pierre Auger Observatory, located in Argentina. The Underground Muon Detector of this upgrade will consist of three scintillator modules with a total active area of 30.72m^2 . It will consist of 64 scintillator bars with wavelength-shifting fibres with 64 SiPMs embedded in them [37]. To improve the mass sensitivity of the Surface Detector (SD), detectors will be added to provide complementary responses to different components of the EAS. This will be achieved by installing the Scintillator Surface Detectors (SSDs) with the radio antennas known as Radio Detectors (RDs) on top of the Water Cherenkov Detector (WCD). The SD array occupies a $1,500\text{m}$ -spaced isometric triangular grid over a $3,000\text{km}^2$ area. The addition of the SSDs provides mass sensitivity such that the response to the electromagnetic and muonic shower components differs from that of the WCD [37]. The fully deployed SD for AugerPrime is shown in Figure 2.8. A small photomultiplier was also installed in the WCD to extend the dynamic range and the new SD electronics. An underground muon detector was also deployed inside each WCD in the infill region of the observatory to measure muons directly. It will also extend the measurements of the Fluorescence Detectors (FD) to increase their duty cycle [38].

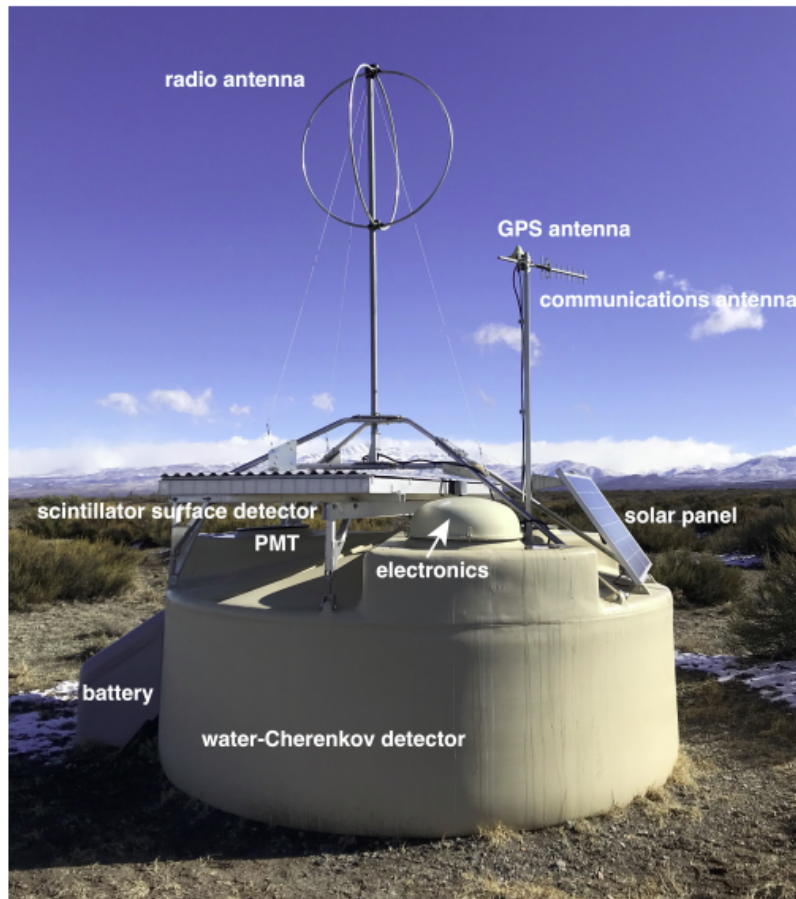


Figure 2.8: The upgraded AugerPrime (Phase II) surface detector station [37].

2.5.4 LHAASO

The Large Array of Imaging Atmospheric Cherenkov Telescopes (LACT) will be situated at the Large High Altitude Air Shower Observatory (LHAASO) site on Haizi Mountain, Daocheng, Sichuan Province, China. The array will consist of 32 six-metre aperture imaging atmospheric Cherenkov telescopes with a SiPM camera system with a 16×16 pixels and a 0.2° per pixel with a field of view. The SiPMs will be placed at the focal point of the telescope and will measure the shape and intensity of the Cherenkov light cone after the Cherenkov light is reflected and focused by the mirror disc onto the camera's surface [39].

2.5.5 Cherenkov Telescope Array (CTA)

The Cherenkov Telescope Array Observatory (CTAO) will be the world's largest ground-based gamma-ray observatory operating at very high energies. It is being built at the Roque de los Muchachos Observatory on La Palma, Spain, in the Northern Hemisphere, and at the Paranal Observatory in the Atacama Desert, Chile, in the Southern Hemisphere. It has three classes of telescopes. There are four Large-Sized Telescopes (LSTs) in the Northern Hemisphere for a low-energy range of 20 GeV to 3 TeV; up to 23 Medium-Sized Telescopes (MSTs) at the two array sites covering an energy range of 80 GeV to 50 TeV; and up to 37 Small-Sized Telescopes (SSTs) in the Southern Hemisphere to extend the energy range above two TeV [13]. To understand the origin of CRs particle acceleration mechanisms, it is very important to study the very high-energy gamma rays. CTA is the most sensitive in the energy range between 20 GeV and 300 TeV energies and is one of the largest ground-based gamma-ray observatories for high-energy CRs.

For the detection of Cherenkov emission, SiPM sensors that are sensitive to the near-UV light were developed by FBK in collaboration with INFN. They are made up of 16 pixels with a $6 \times 6 \text{ mm}^2$ effective area for the upgrade of the Schwarzschild-Couder Medium-Sized Telescope (SCT) [40]. The SiPMs used for the two CTAO systems are discussed below:

2.5.6 Large-Sized Telescope (LST) for CTA

The LSTs are planned to be built in each hemisphere for an all-sky coverage. At each of these sites, the Imaging Atmospheric Cherenkov Telescopes (IACTs) will be focusing between 20 GeV and 200 GeV. Currently, the LSTs use 1,855 PMTs with a 1.5-inch diameter photocathode. Due to their high photon detection efficiency and tolerance to high illumination, SiPMs are a good alternative to PMTs in IACTs [41]. The aim is to replace the PMTs with SiPMs. Figure 2.9 shows the LST camera module where the photosensors, power supply, as well as the pre-amplification stages are modified, keeping the rest of the camera intact [41]. An optical feasibility of SiPMs has been reported in [42].

¹³<https://www.ctao.org/emission-to-discovery/telescopes/>

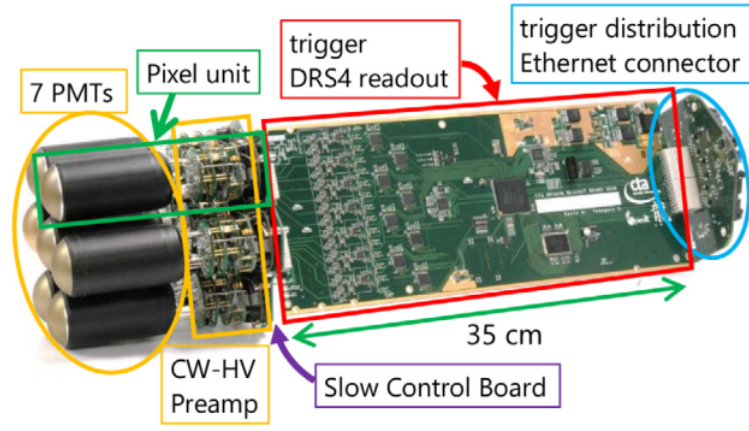


Figure 2.9: The LST camera module where the Pixel Unit of the PMT is replaced with the SiPM pixel [41].

2.5.7 Major Atmospheric Gamma Imaging Cherenkov (MAGIC) for CTA

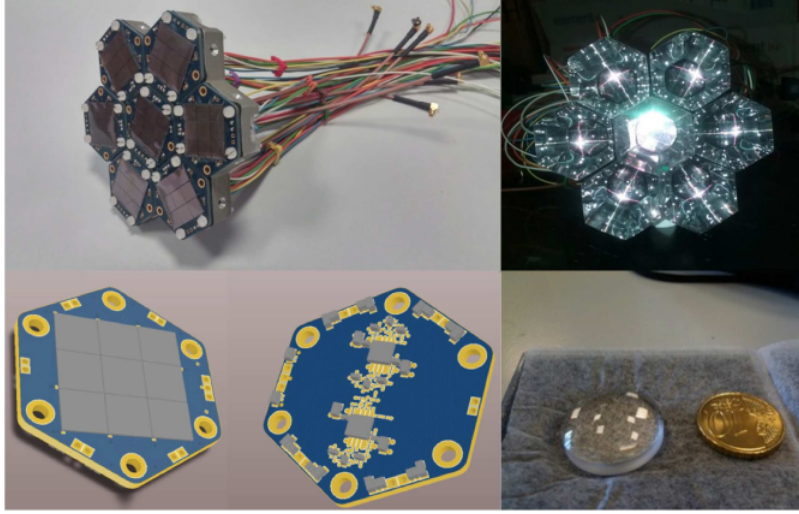


Figure 2.10: The SiPM module prototype for MAGIC [43].

SiPM modules are being installed by the MAGIC Collaboration to compare their performance with PMTs in one of the two telescopes. The SiPM-based prototype designed for the MAGIC cluster is seen in Figure 2.10 with a $6 \times 6 \text{ mm}^2$ size for each channel for nine channels. The top-left image shows the pixel cluster that will be glued to the PCB (bottom left). It will be equipped with the MAGIC Winston cones shown in the top-right, and a fused silica Plastic Condensing Lens (PCL) (bottom right) is placed on all the pixels except for the central one [43].

2.6 State-of-the-Art: In-space Experiments

Some of the previous and ongoing experiments in space that have used SiPMs are discussed in this section.

2.6.1 SiPMs in-space

The Joint Exploratory Missions for an Extreme Universe Space Observatory (JEM-EUSO) Program consists of several telescopes and experiments operated in space such as ISS-Mini-EUSO on the International Space Station [44]; stratospheric balloons (EUSO-Balloon [45], EUSO-SPB1 [46], and EUSO-SPB2 [47]; and on the ground (EUSO-TA) [48].

They are dedicated to detecting Ultra-High Energy CRs (UHECRs) from space. These missions are dedicated to observing fluorescence and Cherenkov light from space and on Earth. The method of detection to observe UHECRs and skimming neutrinos is measuring the Cherenkov light that develops in the atmosphere dur-

ing the EASs.

Some of the SiPMs in the JEM-EUSO experiments are Hamamatsu S13360-1325CS and S13360-6075CS. They are compact and light, and thermal noise can be mitigated with the help of a cooling system to maintain low operating temperatures. The cost of industrially produced SiPMs makes them financially feasible [49].

2.6.2 Mini-EUSO - Ancillary Sensors and Day/Night Transition

The Multiwavelength Imaging New Instrument for the Extreme Universe Space Observatory (Mini-EUSO) is the first telescope of the JEM-EUSO program to observe from space on board the ISS [44] [50]. Its scientific objectives include observing EASs from UHECRs with energies exceeding 10^{21} eV, detecting artificial showers generated by ground-based lasers; searching for nuclearites and strange quark matter, studying transient luminous events, meteors, and meteoroids; and observing sea bioluminescence, artificial satellites, and space debris. It also maps the ultraviolet (UV) light at night to study the background. Finally, it utilises a single-pixel SiPM (Hamamatsu C13365) to evaluate the day-night transition [49] and a 64-channel SiPM array (Hamamatsu C14047-3050EA08) to test them in space.



Figure 2.11: The photo-detector module (PDM) is composed of 36 MAPMTs each with 64 independant channels [44] (left) and Mini-EUSO installed inside the the Zvezda module of ISS (right) [50]

2.6.3 EUSO-SPB1 - SiECA

The first experiment of the JEM-EUSO program that operated with the SiPM camera onboard was the Extreme Universe Space Observatory on a Super Pressure Balloon (EUSO-SPB1 — formerly called EUSO-SPB) [46]. It was launched

by NASA in 2017 and installed on a Super Pressure Balloon (SPB). The scientific goal was to observe UHECRs by monitoring the atmosphere with a UV fluorescence detector from an altitude of 33 km to measure the background UV light at night. Due to a helium leak that necessitated an early controlled termination of the mission, it could complete only 12 days and four hours of flight instead of the originally planned hundred-day target. Despite the mission being terminated, the EUSO-SPB1 instrument operated successfully and returned with 60GB data.

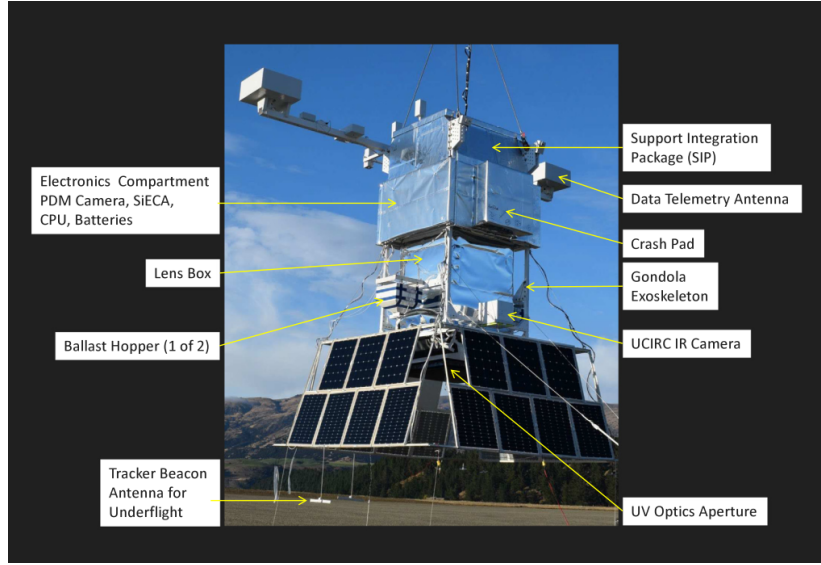


Figure 2.12: EUSO-SPB1 in flight-ready configuration [46].

2.6.4 EUSO-SPB2 - Cherenkov Telescope

EUSO-SPB2 flew on May 13 and 14, 2023 [51]. It was launched from Wanaka Airport in New Zealand and ended after 1.5 days because of a balloon leak [14]. This experiment is the successor to EUSO-SPB1 and a pathfinder for POEMMA, a dual satellite mission, to detect UHECRs with energy above 1 EeV and very high energy neutrinos with energies above 1 PeV. It will detect UHECRs from fluorescence light as well as Cherenkov light from EAS to identify neutrinos due to their interaction or decay of charged leptons in the atmosphere after the neutrino propagates through Earth and interacts near the surface. Since it has two different scientific objectives, it uses a hybrid focal surface. EUSO-SPB2 has a Fluorescence telescope (FT) and a Cherenkov Telescope (CT). The CT has an elongated camera constructed with SiPM arrays, designed to observe Earth's limbs. It consists of an 8×4 SiPM array (Hamamatsu S14521-6050AN-04) horizontally and vertically, respectively, and 4×4 channels for 512 channels. Since there are fewer pixels - it will reduce the power

consumption in the readout electronics. The MUSIC chip is a low-power eight-channel ASIC designed only for SiPM applications in Cherenkov telescopes [52] that monitors the current output of SiPM channel and digitised with a 24-bit ADC. The temperature is controlled with a thermistor mounted at the back of the SiPM array which is used to correct the temperature-dependent gains of the SiPMs [49] [53].

2.6.5 POLAR-2

POLAR-2 is being built to study the polarisation of the Gamma Ray Bursts and is a space-borne polarimeter. It is testing S13361-6075NE-04 and S14161-6050HS-04 SiPM models from Hamamatsu. GRBs are highly energetic and have a short prompt emission followed by an afterglow ranging from radio waves to TeV energies [54].

2.6.6 Terzina

The NUSES project has two payloads – Terzina and Zirè – for monitoring the low-energy cosmic flux $\leq 250\text{MeV}$ in the Van Allen belts, space weather, lithosphere-ionosphere-magnetosphere couplings, and gamma-ray bursts in the 1-10 MeV range. In these payloads, the SiPMs will be coupled with LYSO or GAGG crystals in the calorimeter (CALog), in the Plastic Scintillator Tower (PST) as the readout for the scintillating tiles, and in the Fiber Tracker (FTK). The SiPMs under consideration are produced by FBK; specifically NUV-HD-MT SiPMs with active areas of $3 \times 3\text{mm}^2$ and $1 \times 1\text{mm}^2$ and microcell sizes of 25, 30, 35, 40, 50 μm have been tested [55].

2.6.7 GECAM

The Gravitational wave High-energy Electromagnetic Counterpart All-sky Monitor (GECAM) was launched from the Xichang Satellite Launch Centre on December 9, 2020 [15]. It has two microsatellites that operate on opposite sides of the Earth. Each of them is named GECAM-A and GECAM-B. Due to an unexpected power anomaly, GECAM-A has not been able to observe yet, while GECAM-B has been able to observe 21 hours per day since May 30, 2022. The Gamma-Ray Detectors (GRD) fitted on GECAM cover an energy range of 8keV to 2MeV and are equipped with a three-inch SiPM array to fit within the microsatellite. This provides a quasi-real-time early warning available to facilitate all-sky monitoring for gamma-ray bursts [56].

2.6.8 LabOSat

The Laboratory On a Satellite (LabOSat) aims to increase the Technological Readiness Level (TRL) for electronic components and sensors for satellite mis-

¹⁴https://heasarc.gsfc.nasa.gov/docs/heasarc/missions/euso_spb.html

¹⁵http://www.nssc.cas.cn/gecam_en/sai/

sions. They are using SiPM sensors to increase the TRL [\[57\]](#).

After the discussion of the state-of-the-art experiments, the HERD experiment, which is the framework of this thesis, will be discussed in Chapter [3](#).

"Technology, like art, is a soaring exercise of the human imagination"

Daniel Bell

Chapter 3

The High Energy Cosmic Radiation Detection Facility

Following the discussion on CRs and their methods of detection, let's focus on HERD - a future space-based telescope that will employ novel photosensors (SiPMs).

HERD, also known as the High Energy Cosmic Radiation Detection facility, shown in Figure [3.1](#), is a future space-borne detector designed to directly study features of the cosmic-ray nuclei spectra with extreme precision and at energies up to a few PeV. It will also detect gamma rays above 100 MeV, the electron and positron spectrum up to tens of TeV, and study annihilation of decay products and search for dark matter, owing to its wide FOV [\[58\]](#). HERD is not only aiming for measurements at such high energies but also planning to do so using innovative technologies such as silicon photomultipliers (Section [4.2.2](#)) and LYSO crystals (Section [3.1.1](#)).

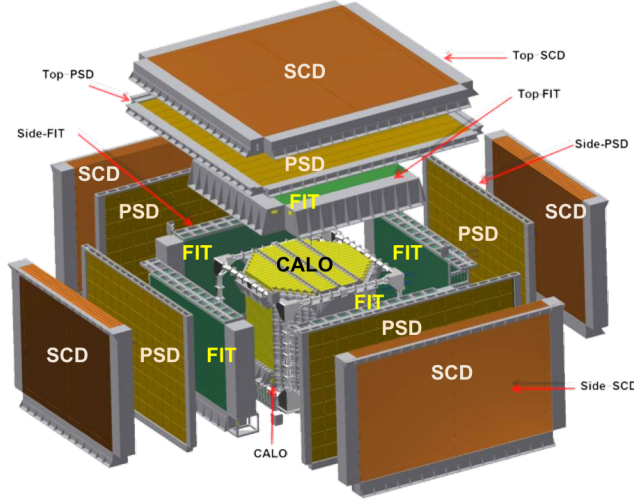


Figure 3.1: The exploded view of HERD with all its sub-detectors. Starting from the innermost detector - CALORIMETER, surrounded by FIT, surrounded by PSD, and the outermost being SCD [59]

3.1 The Initial Design of HERD

HERD was initially designed to be composed of five sub-detectors, that will be described in subsections below. As the design has evolved during the course of this PhD, an updated design will also be discussed in Section 3.2. It is important to describe both designs, because the initial design of PSD used the same SiPMs and the readout board that is the foundation of this thesis, which were tested at the CERN test beam and are discussed in Section 3.4.

3.1.1 Calorimeter - CALO

The calorimeter is the innermost detector of HERD. It consists of about 7,500 LYSO scintillating cubic crystals of 3cm side, as shown in Figure 3.2. This innovative detector was studied under the CaloCube R&D project [60] [61].

The calorimeter is three-dimensional, segmented, homogeneous, and isotropic with a depth of 55 radiation lengths and three hadronic interaction lengths for particles passing near the centre of the detector with a good energy resolution. It is surrounded on five sides by other sub-detectors, which will increase the effective geometric factor of HERD.

The readout is based on Wavelength Shifting Fibres (WLSFs) coupled to intensified scientific CMOS. Each crystal is connected to high-gain and low-gain CMOS channels to reach a good dynamic range [62]. Another alternative readout method of the calorimeter is the addition of the Double Photodiode readout system alongside the WLSF. In this case, the two photodiodes would have dif-

ferent active areas connected to a front-end readout electronics board, providing a good check for the independent triggers and redundancy [63].

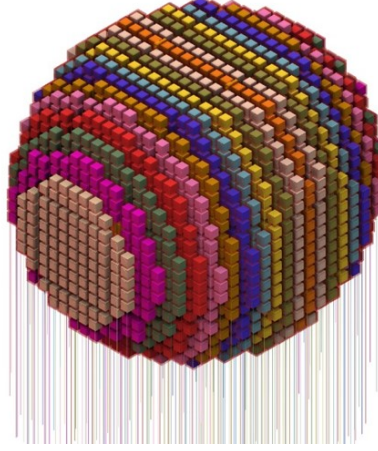


Figure 3.2: The LYSO crystal of the CALORIMETER [62]

3.1.2 The Scintillating Fiber Tracker - FIT

The FIT envelopes the CALO and is designed to reconstruct the trajectories of the low-energy gamma rays and the tracks of generated electrons and positrons. The main design parameters for this tracker are the geometric acceptance, angular resolution and the conversion capability while remaining consistent with the thermal and power supply requirements. The current geometry of the FIT consists of five tracking sectors that are made up of seven tracking planes. These seven planes measure the positions of the traversed charged particles. Each tracking plane consists of two layers of the FIT modules for measuring the two orthogonal spatial coordinates. A FIT module is a fiber mat composed of six layers of plastic scintillating fibres [64]. More information about the FIT can be found here [65]. The FIT module and the tracker is shown in Figure 3.3. The miniFIT prototype is under test with the Hamamatsu S13552¹⁶ and BETA-ASIC readout board at IFAE, Barcelona, Spain [66].

¹⁶https://www.hamamatsu.com/content/dam/hamamatsu-photonics/sites/documents/99_SALES_LIBRARY/ssd/s13552_kapd1083e.pdf

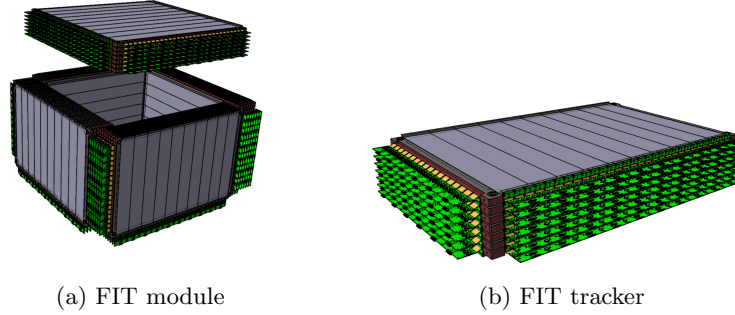


Figure 3.3: The FIT module and the FIT tracker for the FIT sub-detector [64]

3.1.3 The Plastic Scintillator Detector - PSD

The Plastic Scintillator Detector encloses both the CALO and the FIT sub-detectors. It is designed to discriminate the incident photons from the charged particles as well as provide charge measurements for the incoming charged particles from $Z = 1$ to $Z = 26$. The main requirements for the PSD design are high detection efficiency, wide dynamic range and a good energy resolution [58]. The PSD was designed such that trapezoidal bars are placed orthogonally to each other. This was the prototype tested at the CERN test beam that is described in Section 3.4. This provides a good hermeticity for the PSD. Furthermore, the bar is equipped with multiple SiPMs for uniform light collection [67]. The PSD bar is shown in Figure 3.4.



Figure 3.4: The trapezoidal bar of PSD equipped with SiPM bar.

3.1.4 Silicon Charge Detector - SCD

The Silicon Charge Detector encloses the PSD and is designed to provide additional charge measurements of incoming particles. It has four superlayers in the X and Y directions, as shown in Figure 3.5. It consists of 500,000 strips and 768 ladders with a $150\mu\text{m}$ pitch and $320\mu\text{m}$ thickness [67].

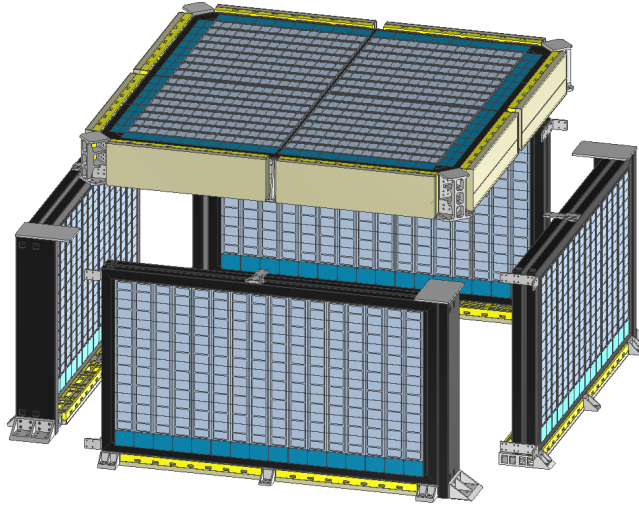


Figure 3.5: The SCD envelope outside the PSD [67]

3.1.5 The Transition Radiation Detector - TRD

It is dedicated to the calibration of protons in the energy range of 1-10 TeV and is located on one of the lateral sides of HERD [68]. An image of the TRD is shown in Figure 3.6

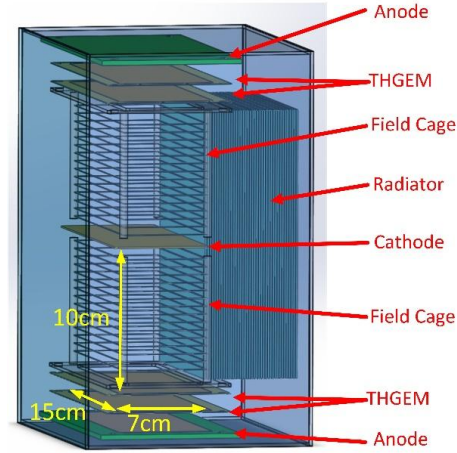


Figure 3.6: The Transition Radiation Detector for HERD [67]

3.2 The new design of HERD

The design described in the preceding section was the preliminary design, and the most recent design has since been reported at a recent conference [69]. In the subsections below, only the changes from the previous design will be reported. The new payload is shown in Figure 3.7

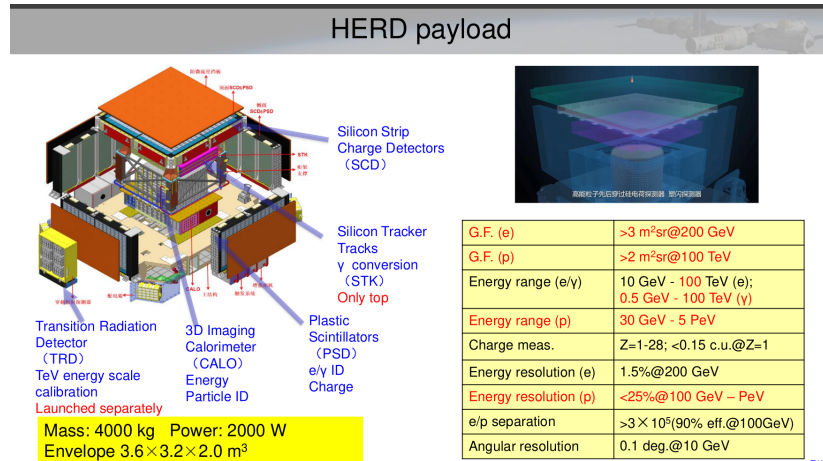


Figure 3.7: The new HERD Payload design presented at the ASAPP Conference [69]

3.2.1 Calorimeter - CALO

The calorimeter is designed to be an octagon with 7,489 LYSO crystals instead of a sphere.

3.2.2 Silicon Tracker - STK

STK is replacing the FIT sub-detector. It is designed to track incident particles and provide charge measurements [70]. It is a top covering with seven superlayers with tungsten plates inserted in between these layers, as shown in Figure 3.8. The pitch and the thickness of each superlayer are $250\mu m$ and $500\mu m$ respectively [67].



Figure 3.8: The STK layer [67]

3.2.3 Plastic Scintillator Detector - PSD

The detector will use a single layer of $(4 \times 50 \times 1)\text{cm}^3$ plastic parallelogram bars, as shown in Figure 3.9 to improve its hermeticity. The Hamamatsu SiPMs will be used, combined with the CITIROC ASIC for the readout.



Figure 3.9: A schematic diagram of the PSD equipped with its SiPMs [67]

The schematic diagram shows a PSD bar with the two kinds of SiPMs attached to it, as shown in Figure 3.10

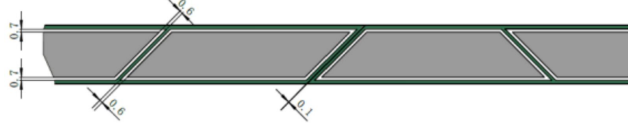


Figure 3.10: A schematic diagram of the PSD bar designed to attain maximum hermeticity [67]

3.3 The Scientific Objectives of HERD

There are several scientific objectives that HERD is aiming to achieve:

3.3.1 Properties of the cosmic ray nuclei spectra

One of the most important scientific objectives of HERD is to perform the spectral measurements at the highest energies, up to iron and beyond. This will enable HERD to measure the cosmic ray propagation mechanisms as well as the hardening and softening of the nuclei spectra, along with their eventual signatures [71]. In addition to this, HERD will be integral in enhancing the study of all the elements in the 'knee' region in the PeV region [68] is shown in fig. 3.11.

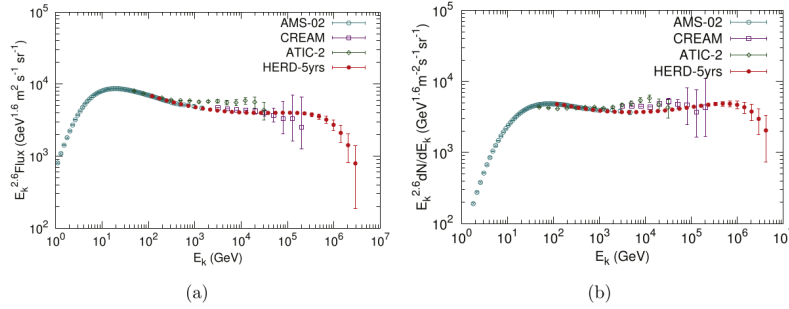


Figure 3.11: Predicted observation of proton-helium flux of HERD as compared to ASM-02, CREAM, ATIC-2 [68].

3.3.2 The electron+positron spectrum

The electron+positron spectrum can provide valuable information regarding sources located within a few hundred parsecs. Due to large energy losses during particle acceleration/propagation, the electron spectrum can be approximated by a single power law, consistent with observations made using different detectors. The first direct evidence of a spectral break in the all-electron spectrum was published by DAMPE in 2017 [72] at 1 TeV and extending it up to 5 TeV.

Apart from DAMPE, these results were predicted by VERITAS [73], and HESS [74] and later on validated by CALET [75]. HERD will be integral in verifying such features with great precision and at the same time extend the current measurement to a few tens of TeV, owing to its large acceptance [68]. Measuring this spectrum at tens of TeV focuses on local sources, as shown in Figure 3.12. This is because high-energy particles experience continuous energy losses and cannot reach Earth from distant sources [71].

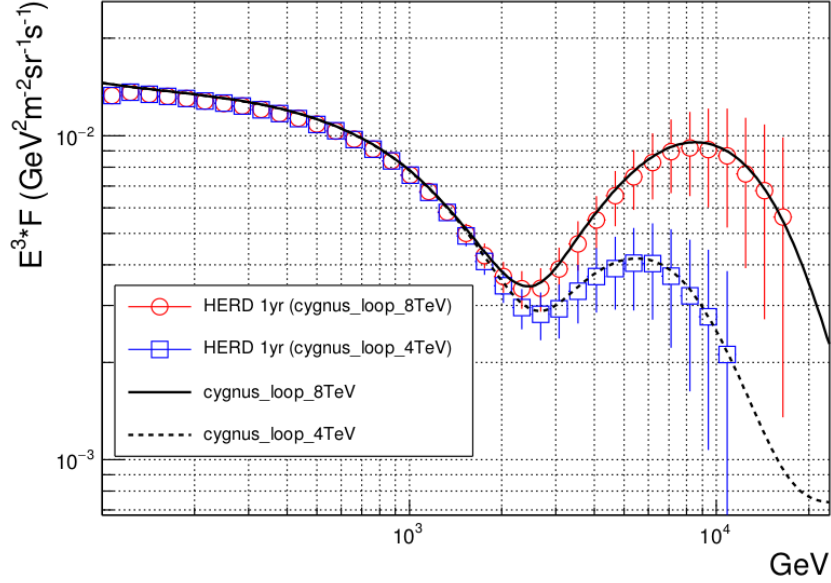


Figure 3.12: Prediction of electron+positron flux if the SNR Cygnus loop can accelerate high-energy electrons and positrons. The two curves represent the different source energy cut-offs [71].

3.3.3 Search for Gamma Rays

HERD will search for indirect dark matter signals through the detection of photons, dark-matter annihilation in gamma-ray couples causing high-energy gamma-ray flux, cosmic-ray acceleration sources, and diffuse gamma-ray emission [71]. Identifying gamma-ray diffusion sources can lead to enhanced understanding of cosmic-ray intensities by studying the particle interactions between protons and electrons in the Interstellar Medium (ISM) [68]. HERD will make important contributions to multi-messenger astronomy [71]. Furthermore, HERD can provide additional information on transient studies by complementing observations from ground-based and space-based instruments such as the Cherenkov Telescope Array (CTA), Virgo and Advanced LIGO experiments [68]. Combining the data from both ground and space-based instruments will

lead to a wide coverage of the spectral measurements and solidify gamma-ray studies. A projection of a 5-year all-sky map of gamma rays as will be seen by HERD is shown in Figure 3.13.

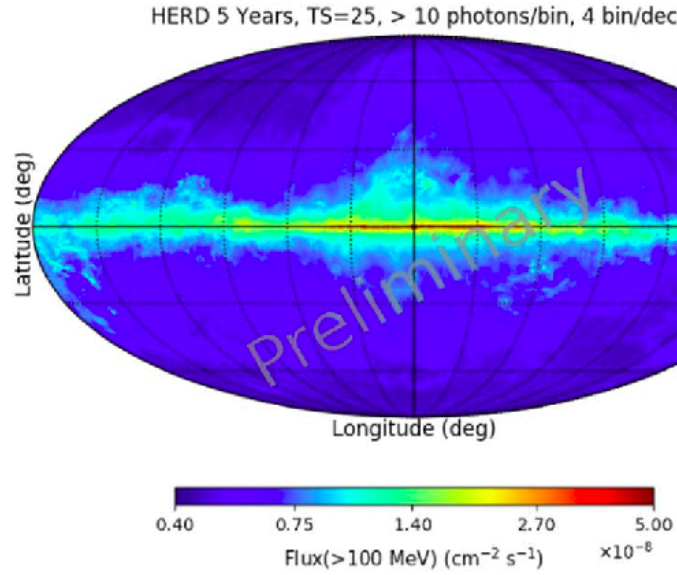


Figure 3.13: A 5-year all-sky map of gamma-ray observation by HERD above 100 MeV energies [68].

3.4 CERN SPS TEST BEAM 2023

CERN, which stands for the European Organisation for Nuclear Research, is the world's largest particle physics laboratory. It is located in the Franco-Swiss laboratory near Geneva, Switzerland. It provides test beam facilities that are a key infrastructure for developing high-energy particle detectors. Test beams are important to assess the performance of new detectors and are the only source of well-defined GeV-scale particles. There are two kinds of test beam facilities provided by CERN. The Proton Synchrotron (PS) and the Super Proton Synchrotron (SPS) test beam facility. The SPS facility provides high-energy particle beams ranging from 10 GeV to 400 GeV for a wide variety of particles such as electrons, muons, hadrons, and both primary and secondary protons and ions. There are four multipurpose beamlines, and each beamline serves multiple well-equipped experimental areas with adjacent control rooms housing data acquisition systems and electronics [76]. At the CERN SPS test beam, prototypes of all HERD subdetectors were tested. The entire setup of all the subdetectors is shown in Figure 3.14.

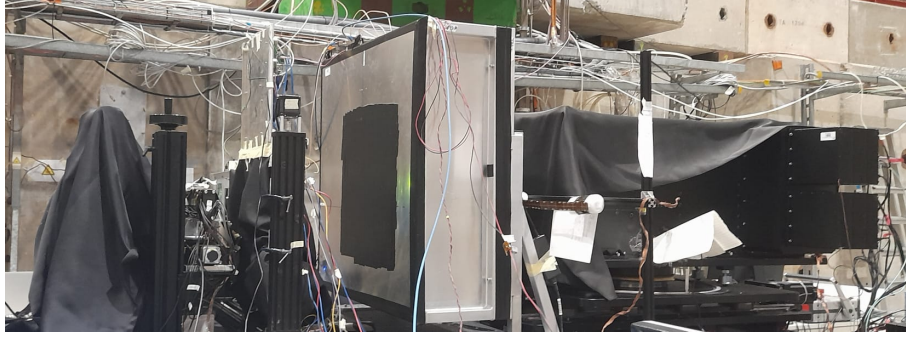


Figure 3.14: The complete view of CERN SPS test beam setup 2023

3.4.1 The PSD design

In Figure 3.15, a single trapezoidal bar equipped with the SiPM bar is seen on the top, and the SiPM bar, along with its two kinds of SiPMs, is seen at the bottom.

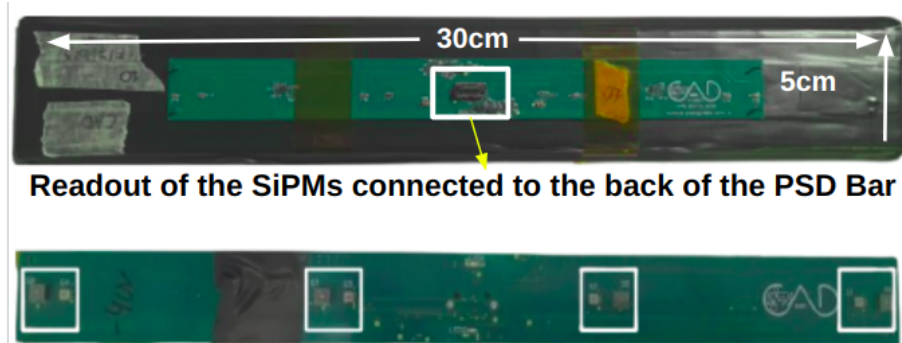


Figure 3.15: The PSD bar equipped with the SiPMs

The PSD prototype shown in Figure 3.16 consisted of eight BC404 plastic scintillator trapezoidal tiles. There were two variants called "long (L)" and "short (S)" tiles. The length of L and S tile was 40cm and 30cm, respectively. Each of these tiles was coupled with two kinds of Hamamatsu SiPMs – the S14160-1315PS [77] for the detection of high-Z particles and the S14160-3050HS [78] for low-Z particles, referred to as S1 (small SiPMs) and S3 (large SiPMs), respectively. They were read out by the BETA-ASIC board, developed by Electronics Instrumentation Service of the Institute of Cosmos Science of the University of Barcelona (ICCUB-SiUB) [79] that was originally developed as a readout for the FIT (see Section 3.1.2).



Figure 3.16: Trapezoidal bars of the PSD configuration arranged orthogonally.

The red dot in the figures represents the irradiation area at the test beam. It is placed between L2 and S1 bars. A trigger system was used to trigger particles with $Z \geq 3$, and two square tiles, T1 and T2, were placed on the beam axis upstream and downstream to monitor the beam composition and particle fragmentation caused by subsystems and between the beam pipe and the PSD prototype. The configuration is shown in Figure 3.17. The four short trapezoidal tiles are labelled as S0, S1, S2 and S3, and the four long trapezoidal tiles are labelled as L0, L1, L2 and L3.



Figure 3.17: Trapezoidal bars of the PSD configuration with a red dot [80].

3.4.1.1 Preliminary results from the test-beam

A scatter plot in Figure 3.18 shows the correlated data in ADC counts between T1 and L2. On the right, the spectrum for the PSD L2 bar displays all the primary particles that were inferred from the scatter plots. Different colours represent ions of different Z [81].

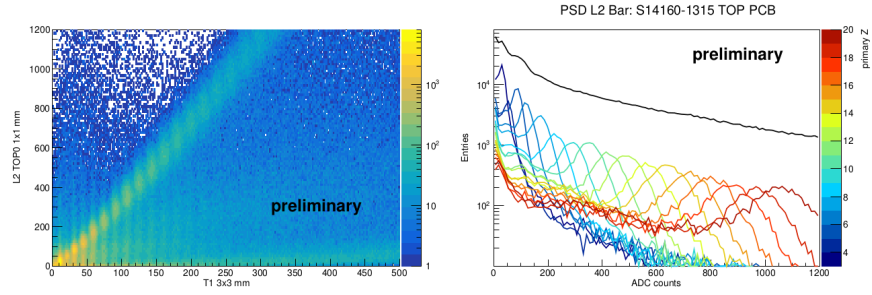


Figure 3.18: Observed spectra on TI and L2 tile of the PSD prototype as a scatter plot on the left and the spectra of each Z ion on the right [81]

Now that the overview of the HERD experiment has been discussed, let us now focus on the core chapter of the thesis in Chapter 4



to copius amounts of coffee, chocolates and music

Chapter 4

The Experimental Setup

To configure and characterise the SiPMs, an experimental setup was established at the Institute for High Energy Physics (IFAE), Spain. The primary objectives were to configure the BETA-ASIC readouts for the low-Z and high-Z SiPM separately. The complete setup is shown in Figure [4.1](#). A broad view of the experimental setup is shown with the readout board on the left and the power supplies and the trigger generator placed below the black box. The LED and the SiPMs are placed inside the box with a black cloth covering the setup to reduce environmental light contamination.

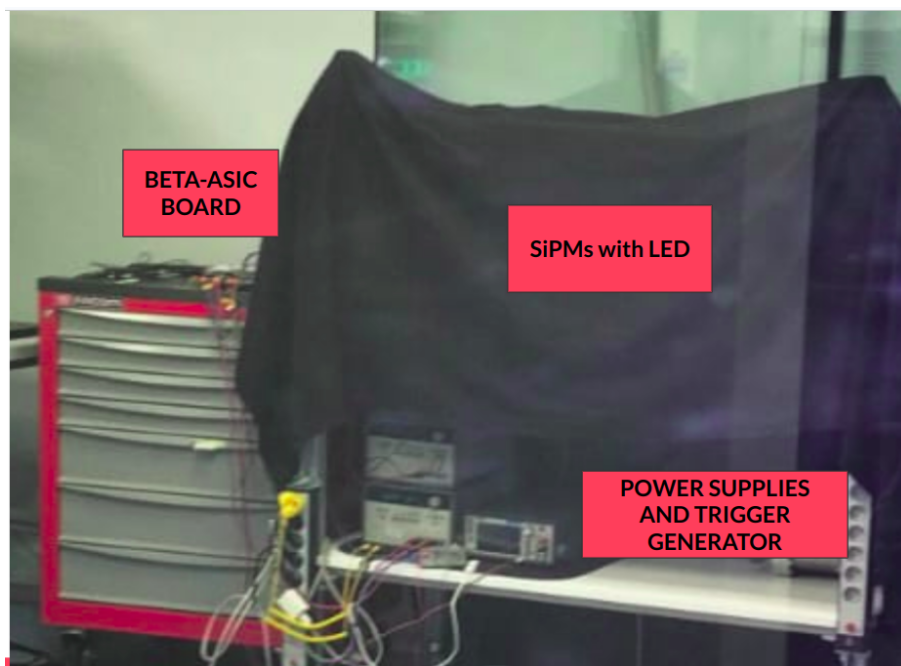


Figure 4.1: The complete setup for configuration of the BETA-ASIC readout and the characterisation of the SiPMs.

Once the configuration was complete, the characterisation of these SiPMs was performed by taking data at different intensities. Subsequently, gain calibration, threshold calibration, signal-to-noise ratio (SNR) and the crosstalk for each intensity were calculated.

4.1 The components of the experimental setup

The experimental setup is shown in Figure 4.2: 1. The LED and the SiPM board inside the black box. 2. The interface board between the SiPM bar and the BETA-ASIC board. The selection of the port determines which kind of SiPM is to be characterised. 3. A temperature sensor¹⁷ was used to monitor the temperature of the BETA-ASIC board, and another temperature sensor to correct the operating voltage of the SiPMs. 4. The power supplies and the trigger generator.

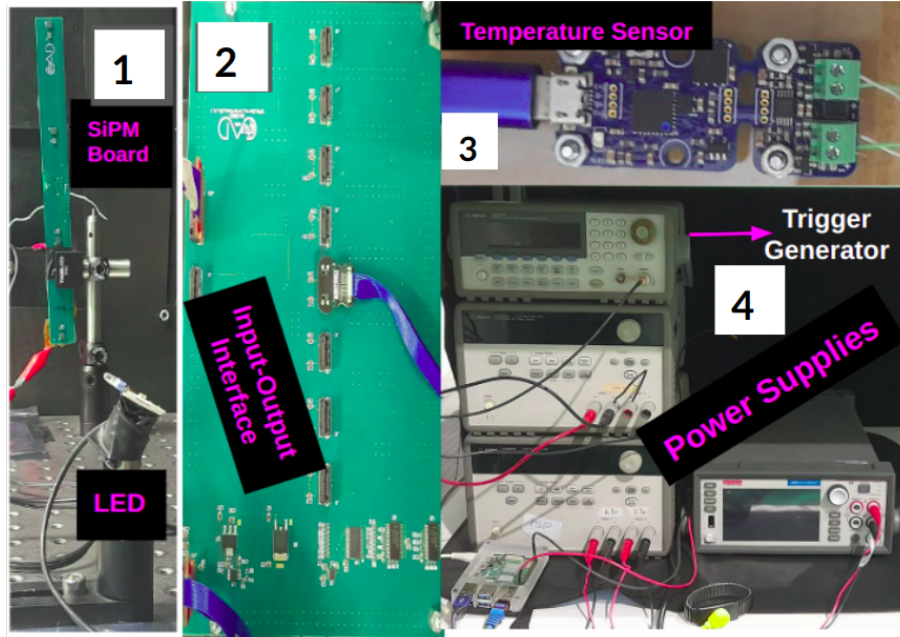


Figure 4.2: The components of the Experimental Set-Up

¹⁷<https://www.yoctopuce.com/EN/products/usb-environmental-sensors/yocto-thermocouple>

4.2 Description of the components of the setup

4.2.1 The LED circuit

The nanosecond LED pulser [82] used in this experimental setup is inexpensive and compact. It is based on a fast discharge of a small capacitor using a complementary pair of radio frequency (RF) transistors. We are using a blue LED with a peak emission spectrum at 470 nm. One of the advantages of this pulser is the possibility of adjusting the light pulse intensity of the LEDs by varying the power supply voltage [83]. It has been used in many astroparticle experiments, such as ANTARES in the Mediterranean Sea [84] and NT-200 in Lake Baikal [85] to study high-energy neutrinos, the imaging atmospheric Cherenkov telescope H.E.S.S., and the Pierre Auger Observatory for cosmic ray detection [83].



(a) The components of the Kapustinsky LED Pulsar [82].



(b) The configuration of the LED and the SiPM bar placed inside the black box.

The Figure 4.3a shows the components used to build the LED circuit. Figure 4.3b is a zoomed-in view of the LED and the SiPM bar placed inside the black box. Figure 4.4 shows the vertically placed SiPM bar and the position of the LED circuit. Due to this configuration, the different SiPMs (connected each to a channel) receive different amounts of light. The power supply for the LED circuit is provided by Agilent E3648A¹⁸.

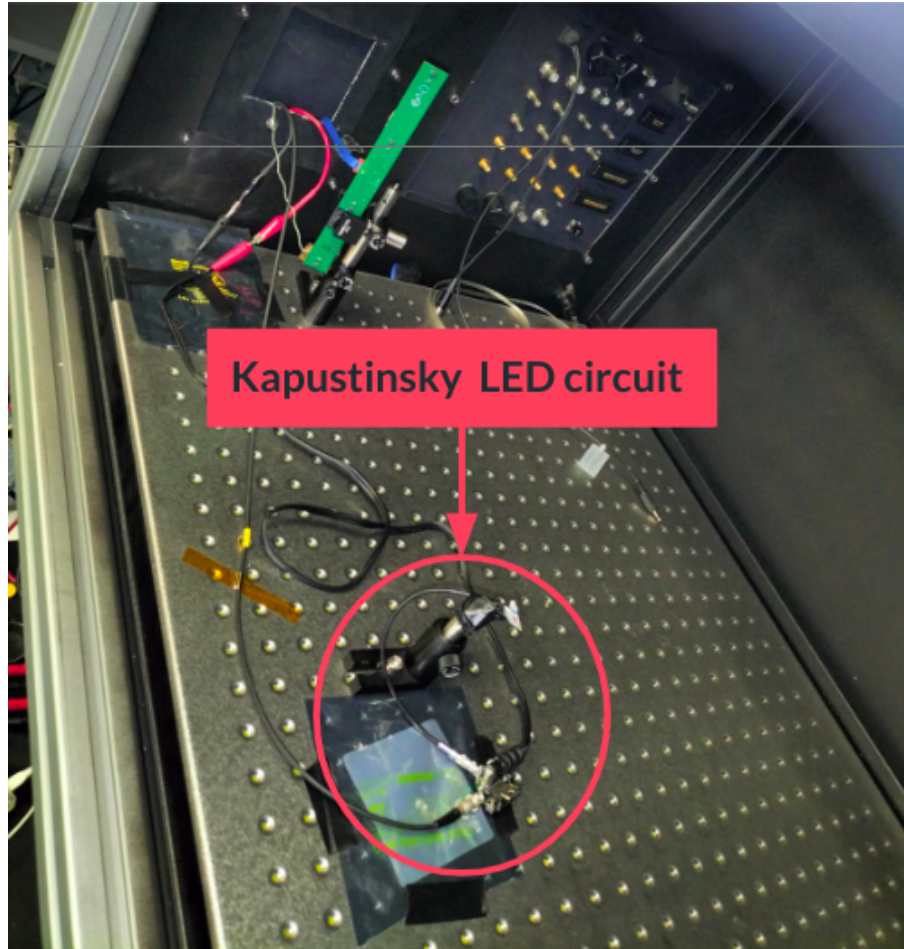


Figure 4.4: The LED circuit as used in the experiment.

¹⁸<https://www.keysight.com/es/en/product/E3648A/100w-dual-output-power-supply-two-8v-5a-20v-2-5a.html>

4.2.2 Silicon Photomultipliers

This specific kind of SiPM was selected to detect elements with a high Z number, as high as iron ($Z = 26$). Therefore, these two kinds of SiPMs were selected to justify the scientific objectives of the PSD of HERD. The low Z SiPM can detect elements such as hydrogen, helium and other subatomic particles. The high Z SiPM can detect elements with a higher Z number without saturation. The SiPM board contains four low Z ($3 \times 3 \text{ mm}^2$ - Hamamatsu S14160-3050HS [78]) SiPMs and four high-Z ($1.3 \times 1.3 \text{ mm}^2$ - Hamamatsu S14160-1315 [77]) SiPMs are shown in Figure 4.5. The voltage supply for the SiPM bar is Keithley 2450¹⁹.



Figure 4.5: The SiPM board with low-Z and high-Z SiPMs.

An exploded view of the two kinds of SiPMs labelled as 'High Z' and 'Low Z' SiPMs is shown in Figure 4.6.

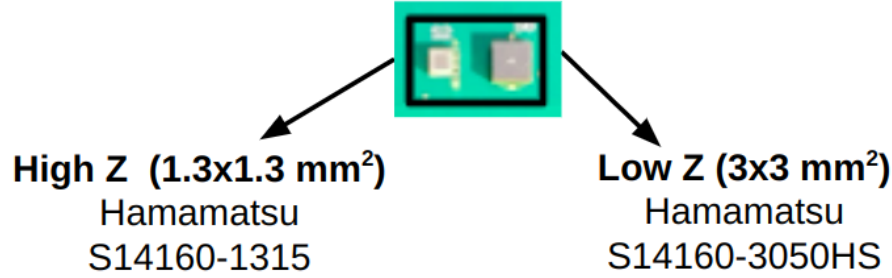


Figure 4.6: The 2 kinds of SiPMs.

The performance parameters of these SiPMs are shown in Table 4.1.

4.2.3 Readout

The complete readout for the SiPMs is performed by the Beta board with a programmable FPGA. The complete view of the readout is shown in Figure 4.7.

¹⁹https://download.tek.com/datasheet/2450-Datasheet_1KW-60904-0.pdf

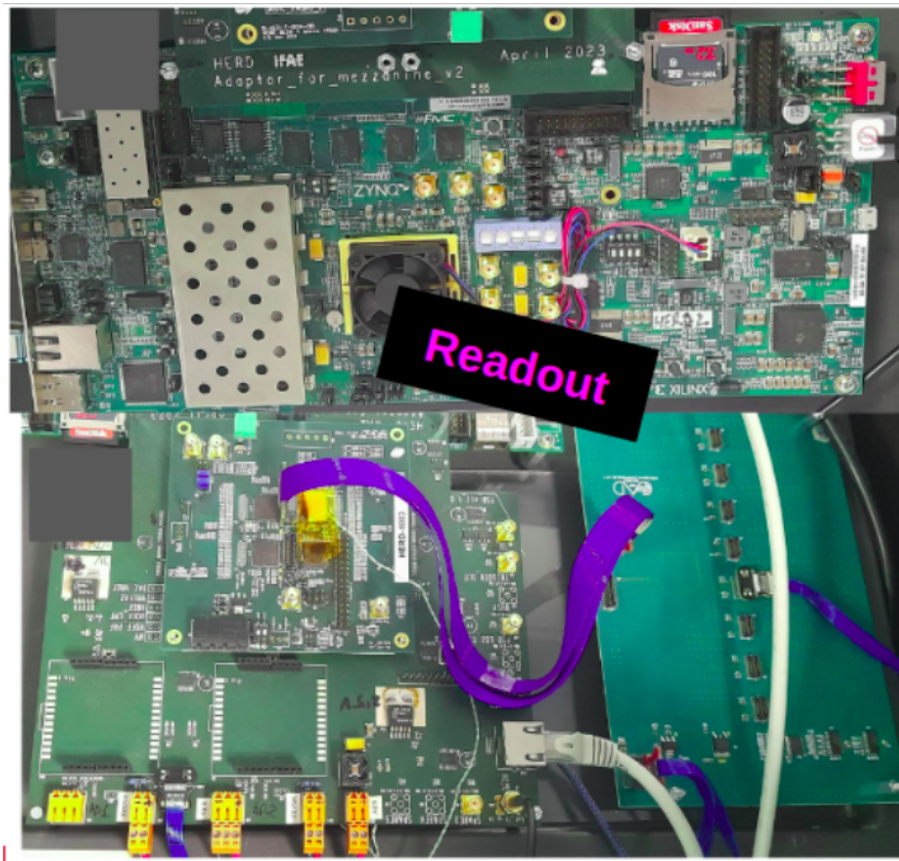


Figure 4.7: The BETA-ASIC readout board with its FPGA and their interface board.

Performance parameters of S14160-3050HS and S14160-1315		
Parameters	S14160-3050HS ^a	S14160-1315 ^b
Effective photosensitive area per channel	$3.0 \times 3.0 \text{ mm}^2$	$1.3 \times 1.3 \text{ mm}^2$
Pixel pitch	$50 \text{ }\mu\text{m}$	$15 \text{ }\mu\text{m}$
Number of pixels per channel	3531	7284
Operating temperature (T_{opr})	-40 to +85 °C	-40 to +60 °C
Spectral response range	270 – 900 nm	290 – 900 nm
Peak sensitivity wavelength (λ_p)	450 nm	460 nm
Photon detection efficiency at λ_p ^c	50%	32%
Breakdown Voltage (V_{BR})	38 V	$38 \text{ V} \pm 3 \text{ V}$
Recommended Operating Voltage	$V_{BR} + 2.7 \text{ V}$	$V_{BR} + 4 \text{ V}$
Gain	2.5×10^6	3.6×10^5
Temp. Coefficient of rec. reverse voltage	$34 \text{ mV}/^\circ\text{C}$	$34 \text{ mV}/^\circ\text{C}$

Table 4.1: Summary of the performance of the main parameters of Hamamatsu S14160-3050HS [78] and S14160-1315 [77].

^ahttps://www.hamamatsu.com/content/dam/hamamatsu-photonics/sites/documents/99_SALES_LIBRARY/ssd/s14160_s14161_series_kapd1064e.pdf

^bhttps://www.hamamatsu.com/content/dam/hamamatsu-photonics/sites/documents/99_SALES_LIBRARY/ssd/s14160-1310ps_etc_kapd1070e.pdf

^cPDE does not include crosstalk and afterpulses.

4.2.3.1 BETA-ASIC

The fiBer trackEr readout (BETA) - Application-Specific Integrated Circuit (ASIC) was developed at ICCUB, Spain, for two subsystems of HERD – the PSD and the FIT. There are two different versions of the BETA-ASIC – one with 64 channels for FIT and the other with 16 channels for PSD. It is a fully programmable chip designed to amplify, shape and digitise the signals from the SiPMs. The power consumption is approximately 1 mW/channel. It can be used for in-space SiPM readouts and other applications with a maximum rate below 10 kHz and has a dynamic range as large as 15 bits [86]. A top view of the BETA-ASIC board is shown in Figure 4.8.

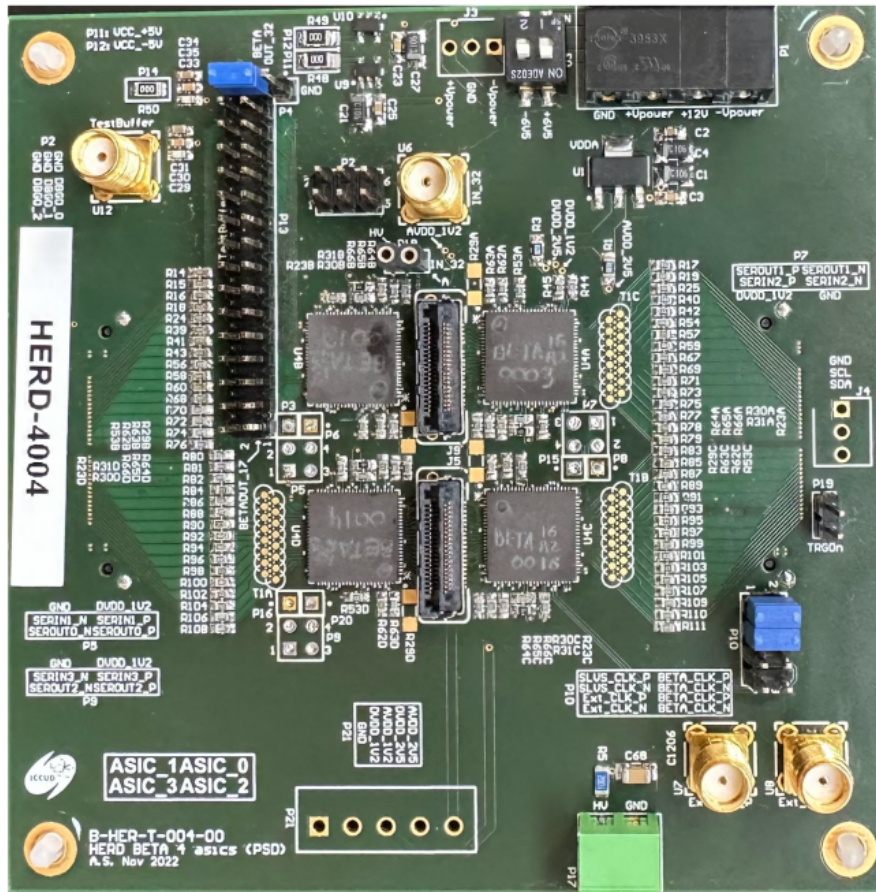


Figure 4.8: The BETA-ASIC board with its 4 ASICs

For this experimental setup, the "HERD-4004" board was used. The power supply for this board is Agilent E3648A ^[20]. It is the BETA-16R2 version, which has 16 channels with an individual trigger from each channel. It consists of four ASICs, has a dual-gain architecture with a high-gain setting (HG00 to HG15) and a low-gain setting (LG00 to LG15) and two different trigger modes: internal and external ^[87].

In space applications, where volume, cost, and power are always limited, an ASIC is capable of reading multiple channels with limited power consumption and providing a digitised output. For the PSD, the main requirements are high detection efficiency, good energy resolution, and a broad dynamic range. A BETA-ASIC with 16 channels was chosen to optimise the SiPM signal readout. Up until now, no integrated circuits have been available in the scientific community for SiPM readouts in space applications that provide a good dynamic range with low power consumption.

Some of the integrated chips developed for different experiments, such as the SPHIRA designed for gamma-ray spectroscopy, are 16-channel ASICs with a dynamic range of 12 bits and a power consumption of approximately 2 mW/channel. The 32-channel CITIROC ASIC has a dynamic range of 14 bits and a power consumption of 8 mW/channel. Other ASICs such as RADIOROC, SPACIROC and LIROC have a dynamic range below 8 bits and a power consumption of over 3 mW/channel. Apart from this, none of these ASICs – CITIROC, SPHIRA, LIROC, RADIOROC, or SPACIROC – have on-chip ADC integration ^[79]. Although it was developed in the interest of the FIT and PSD within the HERD framework, it is an ideal candidate for space because of its low cost, compact size, and low power consumption and it can find applications in different areas such as radiation monitoring for LISA ^[88], agriculture ^[89], environmental monitoring ^[90], drones, and other applications where power and compactness are crucial parameters ^[91].

4.2.3.2 FPGA

²⁰<https://www.keysight.com/es/en/product/E3648A/100w-dual-output-power-supply-two-8v-5a-20v-2-5a.html>

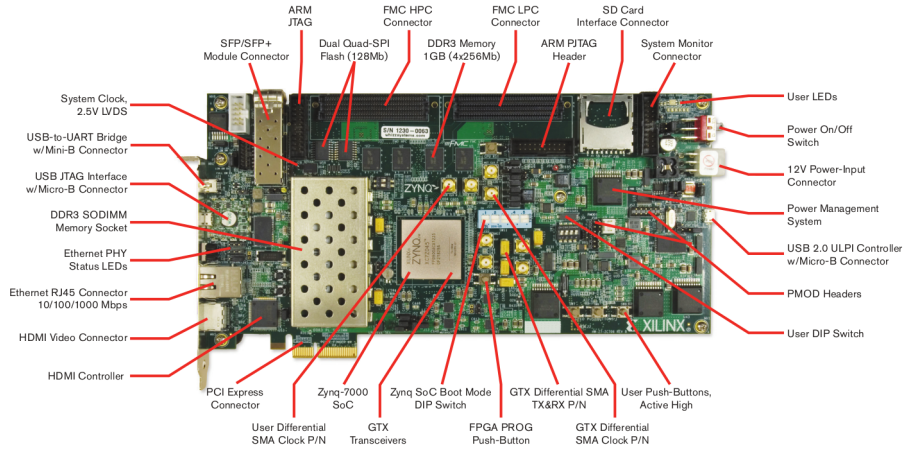


Figure 4.9: The Xilinx FPGA board that we are using for our setup ²¹.

Field Programmable Gate Arrays (FPGAs) are entirely programmable systems on a chip (SoC). They cover a wide range of applications. We are using the Xilinx EK-Z7-ZC706-G ²² FPGA. It is used to configure and read out the BETA-ASIC board. Additionally, the FPGA also manages the trigger counters, creates the internal trigger logic, and saves all the information from the BETA, such as the channel data needed for the analysis, timestamps, and trigger maps of the events. The FPGA board used in this work is shown in Figure 4.9.

4.2.4 Trigger Generator

The trigger modes used in the data-taking procedure are:

1. For dark-count measurements (when the LED is switched off) and there is no light on the SiPMs, an FPGA pulse trigger is used as an internal trigger, derived from the FPGA clock and operating at a frequency of 1 kHz.
2. For data acquisition with the light on (LED On) – the Kapustinsky LED pulser Section 4.2.1 ⁸² acts as the external trigger for the setup.

4.2.4.1 External Trigger for LED On Data

A schematic diagram of the external trigger operations in the setup is shown in Figure 4.10.

²¹<https://www.mouser.com/datasheet/2/903/ug954-zc706-eval-board-xc7z045-ap-soc-1596272.pdf?>

²²<https://www.amd.com/en/products/adaptive-socs-and-fpgas/evaluation-boards/ek-z7-zc706-g.html>

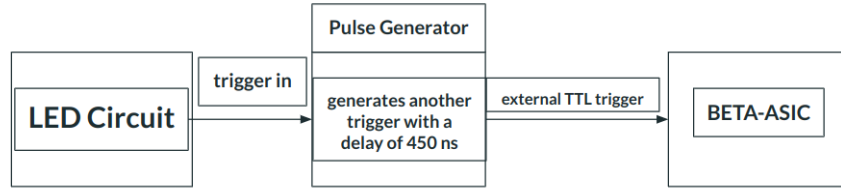


Figure 4.10: The external trigger schematic diagram

For the external trigger and for illuminating the SiPMs, the Kapustinsky LED Pulser (Section 4.2.1) is used. It works in the following way [92]:

1. The pulse trigger from the LED is taken and fed into the pulse generator as a "trigger-in" for the pulse generator device itself. The pulse generator used for triggering is Agilent 33250A [23].
2. This device then generates another pulse with a delay of 450ns.
3. This signal is then fed to the BETA-ASIC board as the TTL trigger for data acquisition.
4. Therefore, the timing to signal the sample is $450\text{ns} + D_WAIT_INTERNAL * 20\text{ns}$, corresponding to the time between the LED pulse and the peak of the shaper. The calculation of $D_WAIT_INTERNAL$ is shown in Section 5.1.4.

This experimental setup will be used to study the following and is discussed in Chapter 5:

1. Configuration of the BETA-ASIC readouts for low-Z and high-Z SiPMs
2. Calibration factor of SiPMs
3. Signal-to-Noise ratio of the SiPMs
4. Crosstalk of the SiPMs
5. Threshold calibration of the low-Z SiPM

²³<https://www.keysight.com/es/en/product/33250A/function--arbitrary-waveform-generator-80-mhz.html>

"If you wish to improve, be content to appear clueless or stupid" - Epictetus

Chapter 5

Results & Discussions

5.1 Configuration of the Beta-ASIC

In fig. 5.1, a zoomed-in view of the Beta board can be seen. The two different ASICs – ASIC03 and ASIC00 – have been configured. ASIC03 is configured for the low-Z SiPMs, while ASIC00 is configured for the high-Z SiPMs. Since they were configured individually, the configuration will be presented here simultaneously for both types of SiPMs. The configuration steps are presented in chronological order:

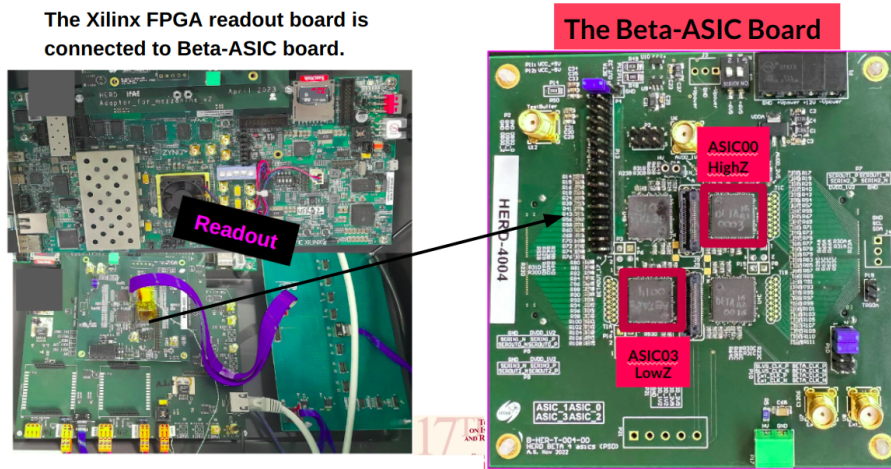


Figure 5.1: The Beta-ASIC board, along with its exploded view, showing the 2 different ASICs that have been configured for low-Z (ASIC03) and high-Z (ASIC00), respectively.

5.1.1 Reference Voltage Optimisation

The optimal working voltage for the ASICs is 500 mV. In the configuration script, the voltages correspond to register values from 0 to 255. After the initial measurement of the voltages of all the ASICs with a multimeter, the register values were adjusted, and the configuration script was run. Eventually, when the voltages were approximately 500 mV for all the ASICs, the corresponding register values were locked. This is a crucial first step to proceed with the following steps for obtaining optimal results. The voltages and their corresponding register values can be seen in Figure 5.2

Fine tuning of the Vref value:

- Initial values:

	D_Vref	Measured voltage [mV]
ASIC0	44	504
ASIC1	44	501
ASIC2	44	487
ASIC3	44	493

- Optimized values:

	D_Vref	Measured voltage [mV]
ASIC0	46	500
ASIC1	44	501
ASIC2	38	501
ASIC3	41	500

Figure 5.2: Reference Voltage Setup.

5.1.2 Voltage Full Scale (VFS)

This is the full ADC (Analog-to-Digital Conversion) range of the ASICs. The optimal range is between 1900 and 2040. These values correspond to a parameter called "D_Slope" in the configuration script. A script is run to change the D_Slope values from 0 to 8, and the corresponding mean value of one of the channels for each ASIC is calculated. The result is seen in Figure 5.3. The values of D_Slope just before saturation are set as the optimal values for each ASIC.

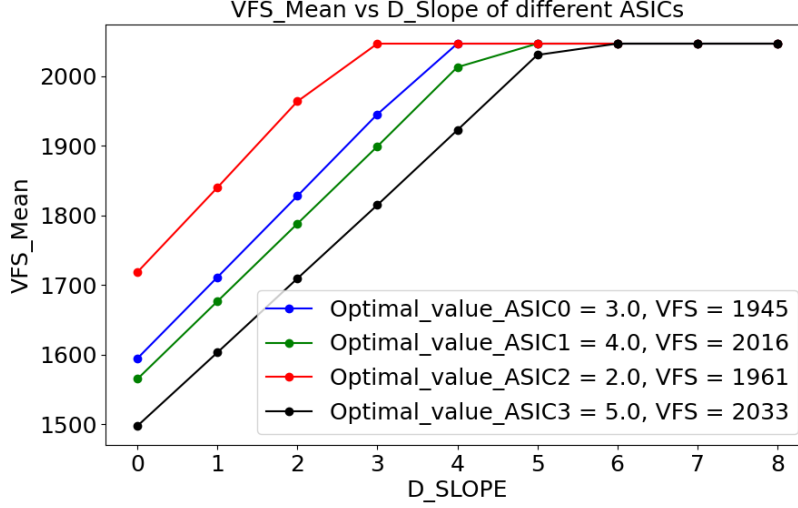


Figure 5.3: The voltage full-scale capacity of all the 4 ASICs.

5.1.3 Bias Voltage Selection

The bias voltage for the operation of the low-Z and the high-Z SiPMs is selected in this step. Taking the reference bias voltage mentioned in the datasheet, some data at a fixed intensity of light were collected by changing the voltages. The final value was selected to achieve a balance between good resolution of photoelectron peaks and a good ADC range without saturation. As seen in Figure 5.4 the dynamic range, or the ADC range, and the number of photoelectron peaks for the low-Z and high-Z SiPMs are starkly different.

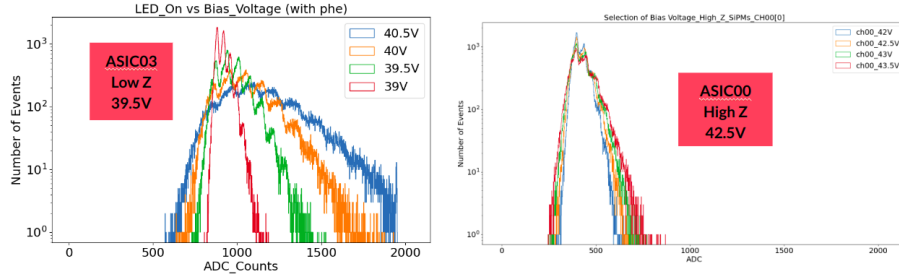


Figure 5.4: Comparison of Bias voltage for low-Z (left) and high-Z (right).

For the low-Z and high-Z SiPMs, 39.5V and 42.5V were selected as their respective bias voltages.

$$V_{\text{bias, corr}} = V_{\text{bias}} + 0.034 \times (T - 21.8^\circ\text{C}) \quad [\text{V}] \quad 93 \quad (5.1)$$

This formula for correcting the bias voltage with respect to temperature was provided in the datasheet, where 0.034 is the temperature coefficient, as seen in Table 4.1

5.1.4 Internal Time Delay

After the bias voltage is set, the time delay for signal sampling is determined. The internal time delay is the time difference between the external trigger and the Track-and-Hold signal. The corresponding name in the configuration file is D_WAIT_INTERNAL. A scan is run for all values between 20 and 100 in steps of 1, and the corresponding mean ADC values for one of the channels are calculated only for the two ASICs that we are configuring. The peak of the scan is selected as the optimal delay time. One clock corresponds to 20 ns. The final values set for low-Z and high-Z are 55 and 40, respectively. To convert these into units of time, these correspond to $55 \times 20 = 1100$ ns and $40 \times 20 = 880$ ns, respectively. The individual scans are shown in Figure 5.5

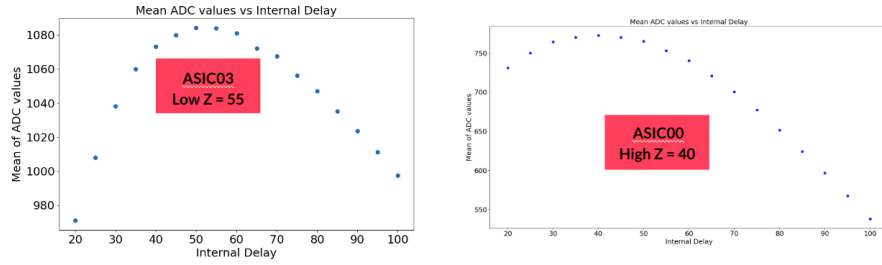


Figure 5.5: Comparison of Internal Delay Time for Low Z (left) and High Z (right).

5.1.5 Preamplifier Offset

This parameter is critical for setting a good value for the baseline to have a very low trigger just above the zero-photoelectron level. As seen in Figure 5.6, the dark counts for all four channels of the low-Z SiPM are shown. Since this parameter is set for the entire ASIC, the value of the most-shifted channel is considered. As "Channel 03" is the most shifted, the trade-off was to select a value at 50% after the peak of the pedestal, while the remaining channels had already reached the baseline. The final value selected is 40.

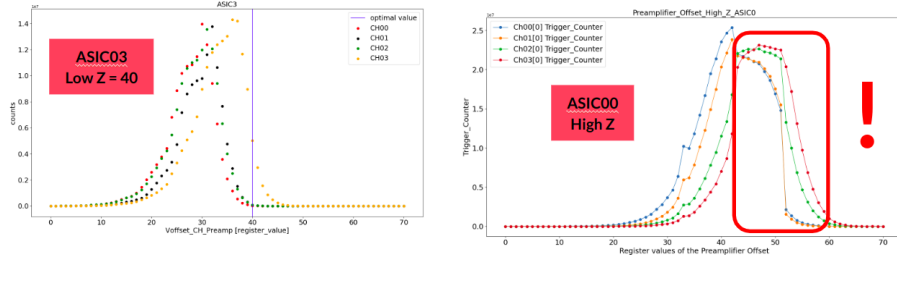


Figure 5.6: Comparison of Preamplifier Offset for Low Z (left) and High Z (right).

For the high-Z SiPMs, the dark count data show a strange pattern due to data mixing between channels and other parameters. Due to this reason, this parameter could not be set, and further configuration could not be completed. This parameter is critical for the threshold calibration, which is discussed in Section [5.2.7](#).

5.1.6 Low Pass Filter

This parameter can be set only if the preamplifier offset has been configured. Hence, only the low-Z has been configured. This parameter involves maximising the ADC range without distorting the signal. A scan was run from 114 to 122 in steps of 1, and the corresponding plots for only the initial and final values are shown in Figure [5.7](#). The pedestal peak for channel 03 was calculated for the entire scan and plotted as shown on the right-side of Figure [5.7](#). The peak values for channel 03 were considered because it was the most-shifted channel as seen on the left-side of Figure [5.7](#). This ensured a good dynamic range for all the channels.

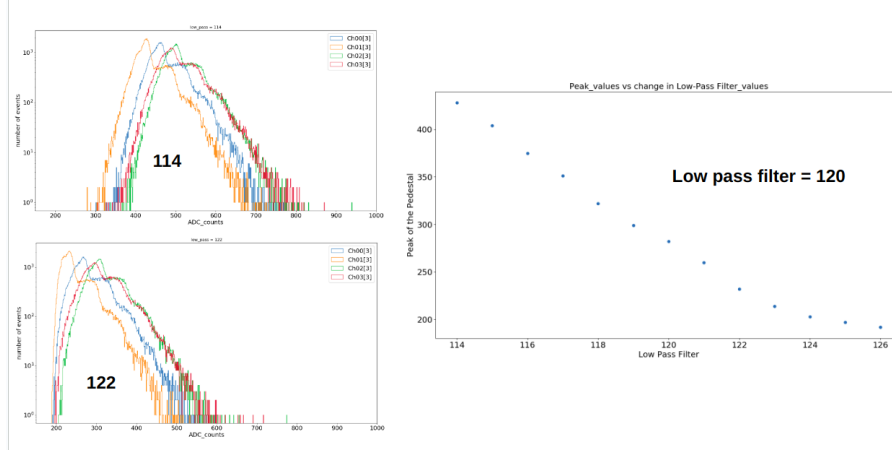


Figure 5.7: Left: The pedestals as observed for the extreme values of the Low Pass filter scan. Right: A complete scan of all the values of the Low Pass Filter.

5.2 Characterisation of SiPMs

To characterise the SiPMs, four key parameters – calibration factor, signal-to-noise ratio, crosstalk and threshold calibration – were evaluated. I will start with the calibration factor study using the betaPy software.

5.2.1 Calibration factor from the betaPy software

betaPy is a Python 3 module for configuration, data acquisition and analysis scripts for electronic setups based on the BETA ASIC produced by ICCUB. Initially developed for, but not restricted to, the HERD's PSD and FIT electronics system²⁴, betaPy was used to calculate the calibration factor across all the gain settings. To understand betaPy, it is important to define some core terms, like 'calibration factor' and the 'gain setting' of the experimental setup.

5.2.1.1 Definition of calibration factor

The calibration factor is defined as the mean distance between consecutive photoelectron peaks. It is measured in ADC counts, since these are related to the number of photoelectrons. Ideally, the distance between two consecutive peaks should be constant, starting from one-photoelectron peak. Therefore, it is important to know which ADC counts correspond to a single photoelectron for calibration purposes.

²⁴<https://gitlab.pic.es/herd-ifae/betaPy>

5.2.1.2 Gain setting of the experimental setup

The BETA-ASIC has a dual-gain architecture Section 4.2.3.1. One path is for High Gain (HG), ranging from HG00 to HG15, and the other is for the Low Gain (LG), ranging from LG00 to LG15. HG00 represents the maximum readout gain, providing the highest amplification of the SiPM signal. The peaks can be clearly resolved at HG00. As the gain setting is changed from HG00 to HG01, the amplification reduces. Eventually, HG15 has the lowest amplification. The dynamic range for HG is from 0 to 2048 ADC counts. The LG path follows the same logic (LG00 to LG15) as the HG path, but with a lower overall amplification. So it provides a wider dynamic range from 2048 to 4096 ADC counts.

5.2.1.3 Measurement & Analysis

For the data acquisition, dark count data and the LED-on data were taken for all the gain settings (HG00-HG15 and LG00-LG15).

Two sets of dark count data were taken for each gain setting: one before and one after the LED-on data acquisition. The mean and peak of the pedestal were calculated. The peak for the pedestal was used for further calculations.

The operating voltage of the LED is between 6V and 15V for taking data with LED-on. The intensity of light was controlled by adjusting the LED voltage. Data acquisition started at the lowest intensity, where the peaks could be resolved. Since the peaks are clearly resolved for HG00, data was taken by increasing the LED voltage in steps of 0.1V until saturation for HG00, as shown in Figure 5.8. This dataset was used to calculate the calibration factor (CF) using Equation (5.3) for HG00. At HG00 only, the calibration factor was calculated using the peak-finding method. The complete dataset for HG00 for Ch00 is shown in Figure 5.8. It shows the pedestal with the spectrum of different intensities at HG00.

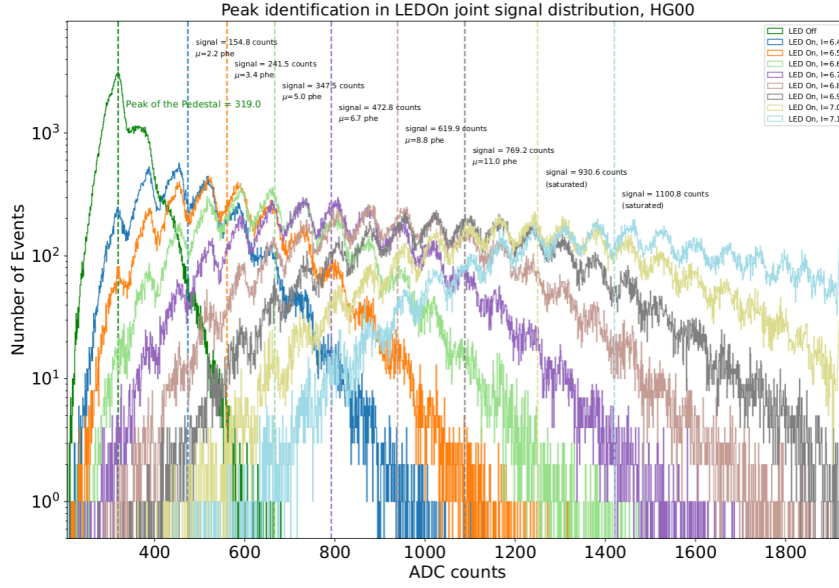


Figure 5.8: Photoelectron peaks at different intensities of light for HG00 and the pedestal of HG00 for CH00

The spectra from Figure 5.8 were summed and interpolated to form a joint signal distribution, improving the statistical precision and increasing the visibility of photoelectron peaks as shown in Figure 5.9. The signal, mean number of photoelectrons (μ) and the calibration factor using the peak-finding method for HG00 were calculated from Figure 5.9.

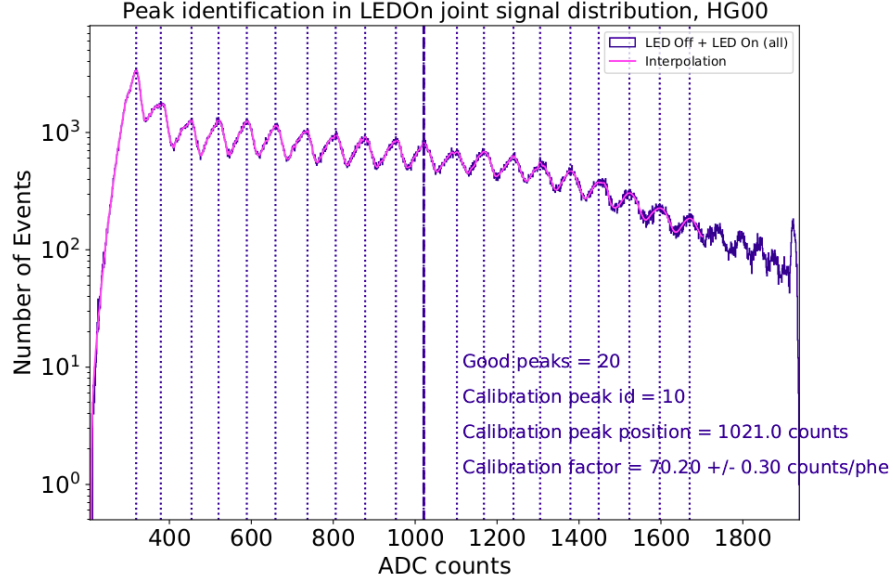


Figure 5.9: Interpolation of the overlap of all the spectra taken at different light intensity for HG00 for CH00

Using the peak-finding algorithm from the SciPy Python library²⁵, the peaks from the HG00 dataset were identified, as shown in Figure 5.9. A central peak near 1000 ADC counts was selected to minimise distortions and non-linearities in the electronics, as most of the peaks up to these ADC counts were clear and resolvable. This is called the "reference peak" as seen in Figure 5.9. A different reference peak could be selected, but selecting a peak towards the right of 1000 ADC counts might risk selecting noisy peaks, whereas selecting a reference peak towards the left of 1000 ADC might be too close to the pedestal with fewer photoelectron peaks.

The signal at the reference peak is calculated by subtracting the pedestal from the peak value closest to the reference peak, written as "calibration peak position = 1021.0 counts" in Figure 5.9 and using the Equation (5.2) where the "i-th" peak is the peak closest to the reference peak.

$$Signal_{HG00} = Peak_i - Pedestal \quad (5.2)$$

The calibration factor for HG00 is calculated by dividing the signal obtained from Equation (5.2) by the peak found closest to the reference peak denoted as "Calibration peak id = 10" in Figure 5.9 and using the formula in Equation (5.3) for the "i-th" peak:

²⁵https://docs.scipy.org/doc/scipy/reference/generated/scipy.signal.find_peaks.html

$$CF_{HG00} = \frac{\text{Signal}_{HG00}}{i} \quad (5.3)$$

Since the peak-finding algorithm does not provide us with an error, the error is calculated using the Asimov simulation [94] to ensure statistical reliability. It is a simulation mimicking and creating 300 pseudo-datasets derived from the experimental dataset with a Poissonian fluctuation to imitate the statistical fluctuations of the real measurement. The uncertainty reported in Table 5.1 and Table 5.2 is calculated using Equation (5.4):

$$CF_{error} = \frac{\sqrt{\sigma_{S_i}^2 + \sigma_{pedestal}^2}}{i} \quad (5.4)$$

Where σ_{S_i} and $\sigma_{pedestal}$ are the uncertainties of the $i - th$ peak and the pedestal, respectively.

Once the CF_{HG00} is calculated, the remaining calibration factors for the gain settings (HG01-HG15 and LG00-LG15) are calculated using the "connecting intensity" as shown in Figure 5.10. As we start losing the resolution of peaks (Figure 5.10), the calibration factor using the peak-finding method cannot be used anymore. Consequently, starting from HG01 two LED-On datasets are taken. The first dataset is taken at the same intensity as the previous gain setting (HG00) before saturation and another dataset for an increased intensity before saturation for HG01. To explain it better, I will refer to Figure 5.10. There are two datasets - one at 6.9V and another at 7.4V - both at HG01. Since data were already available for 6.9V at HG00, another dataset at 6.9V is taken for HG01. Therefore, 6.9V is the connecting intensity between HG00 and HG01. 6.9V is the intensity before saturation for HG00.

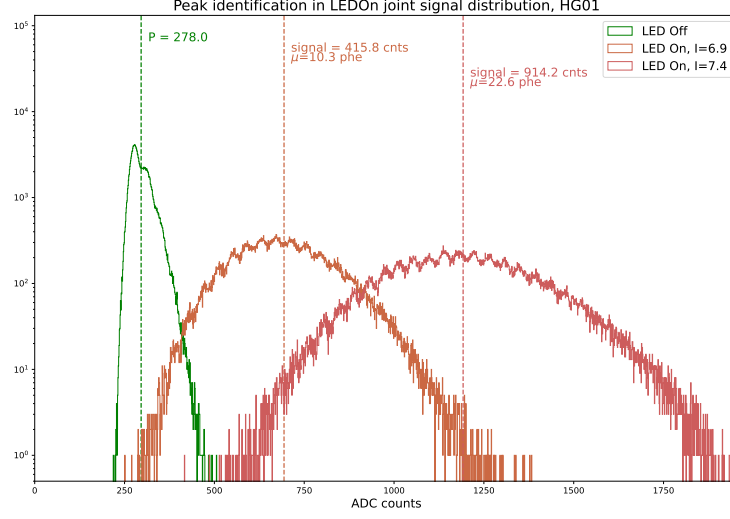


Figure 5.10: The connecting intensity between HG00 and HG01 for CH00.

Since the intensity remains the same and only the gain setting changes, we can get the ADC counts for these consecutive gains. From this we can calculate the signal at this intensity both for HG00 and HG01 using the formula shown in Equation (5.5).

$$\text{Signal_Ratio}_{6.9V} = \frac{\text{Signal}_{HG01}}{\text{Signal}_{HG00}} \quad (5.5)$$

The ratio of the signal is calculated and then multiplied by the calibration factor obtained from HG00 in Equation (5.6). The second dataset taken at 7.4V for HG01 is the dataset before saturation for HG01. This will serve as the connecting intensity between HG01 and HG02. This procedure of "connecting intensity" is followed from HG01 to HG15. As for the gain setting from LG00 to LG15, only one dataset at the maximum intensity (15V) is measured, as saturation is never reached and the maximum intensity that can be reached is 15V for this experimental setup. Therefore, the calibration factor for the remaining gain setting is propagated from CF_{HG00} to progressively lower gain settings through the relative calibration factor (RCF). The RCF for HG01 is calculated using the formula in Equation (5.6):

$$\text{RCF}_{HG01} = CF_{HG00} \times \left(\frac{\text{Signal}_{HG01}}{\text{Signal}_{HG00}} \right) \quad (5.6)$$

To detect saturation for HG01, datasets at 7.3V, 7.4V, 7.5V, 7.6V, and 7.7V are taken. It was run using the betaPy code. The intensities where 30% or more

data accumulates at the upper limit of the ADC range, is flagged as saturated. Therefore, the lowest intensity before saturation has to be searched for and selected. For Ch00 for HG01, it is 7.4V as seen in Figure 5.10. This intensity before saturation is different for different channels for the same gain-setting. The process of finding this intensity before saturation is repeated from HG01 to HG15. The complete set of plots generated by the betPy software can be found in ??.

A generalised version of eq. (5.6) where j is the gain setting, is shown in Equation (5.7):

$$RCF_j = CF_{j-1} \times \left(\frac{Signal_j}{Signal_{j-1}} \right) \quad (5.7)$$

The uncertainty for the relative calibration factor is calculated below:

$$\Delta RCF_j = CF_j \sqrt{\left(\frac{\Delta CF_{j-1}}{CF_{j-1}} \right)^2 + \left(\frac{\Delta Signal_Ratio}{Signal_Ratio} \right)^2} \quad (5.8)$$

Where ΔCF_{j-1} is the uncertainty of the previous gain setting, and $\Delta Signal_Ratio$ is the uncertainty in the measured signal ratio.

And the mean number of photoelectrons μ is calculated using Equation (5.9):

$$Mean_number_of_pe(\mu) = \frac{Signal\ of\ the\ spectrum}{CF_j} \quad (5.9)$$

Where pe = photoelectrons. RCFs are calculated for the entire dataset (HG01-HG15 and LG00-LG15).

This procedure is repeated for all the channels. Ch00, Ch01, Ch02 and Ch03 for the Low Z SiPMs. The calibration factors for Ch00 for the high gain setting and low gain setting are shown in Figure 5.11 and Figure 5.15, respectively. Similarly, plots for Ch01 are shown in Figure 5.12 and Figure 5.16, Ch02 in Figure 5.13 and Figure 5.17 and Ch03 in Figure 5.14 and Figure 5.18 respectively. The table for the calibration factors for Ch00, Ch01, Ch02 and Ch03 are listed in Table 5.1 and Table 5.2.

Low Z Calibration Factors				
Gain Set- ting	Ch00	Ch01	Ch02	Ch03
HG00	70.20 ± 0.30	71.90 ± 0.35	71.25 ± 1.95	70.78 ± 0.45
HG01	34.22 ± 0.23	40.40 ± 0.16	39.49 ± 0.20	39.67 ± 0.22
HG02	25.93 ± 0.17	27.60 ± 0.11	27.45 ± 0.14	27.74 ± 0.15
HG03	19.83 ± 0.13	21.17 ± 0.08	20.66 ± 0.10	21.37 ± 0.12
HG04	15.96 ± 0.11	17.14 ± 0.07	16.75 ± 0.08	17.24 ± 0.10
HG05	13.48 ± 0.09	14.44 ± 0.06	14.23 ± 0.07	14.32 ± 0.08
HG06	11.70 ± 0.08	12.44 ± 0.05	12.26 ± 0.06	12.36 ± 0.07
HG07	10.69 ± 0.07	10.89 ± 0.04	10.81 ± 0.05	10.67 ± 0.06
HG08	9.60 ± 0.07	9.77 ± 0.04	9.60 ± 0.05	9.55 ± 0.05
HG09	8.51 ± 0.06	8.84 ± 0.04	8.71 ± 0.04	8.56 ± 0.05
HG10	7.78 ± 0.05	8.10 ± 0.03	7.96 ± 0.04	7.82 ± 0.04
HG11	7.04 ± 0.05	7.44 ± 0.03	7.32 ± 0.04	7.19 ± 0.04
HG12	6.40 ± 0.04	6.93 ± 0.03	6.75 ± 0.03	6.65 ± 0.04
HG13	5.85 ± 0.04	6.45 ± 0.03	6.27 ± 0.03	6.17 ± 0.03
HG14	5.31 ± 0.04	6.06 ± 0.02	5.87 ± 0.03	5.81 ± 0.03
HG15	4.86 ± 0.03	5.67 ± 0.02	5.49 ± 0.03	5.48 ± 0.03

Table 5.1: Calibration factors for HG00 to HG15 for the four channels

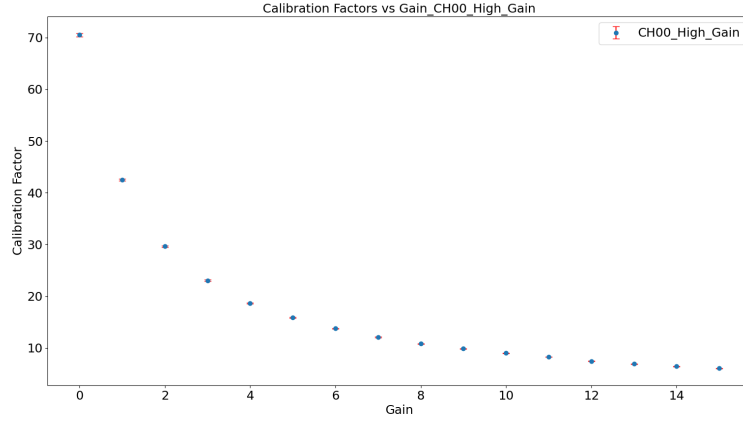


Figure 5.11: Calibration factor for HG00-HG15 for Ch00 for low-Z SiPM

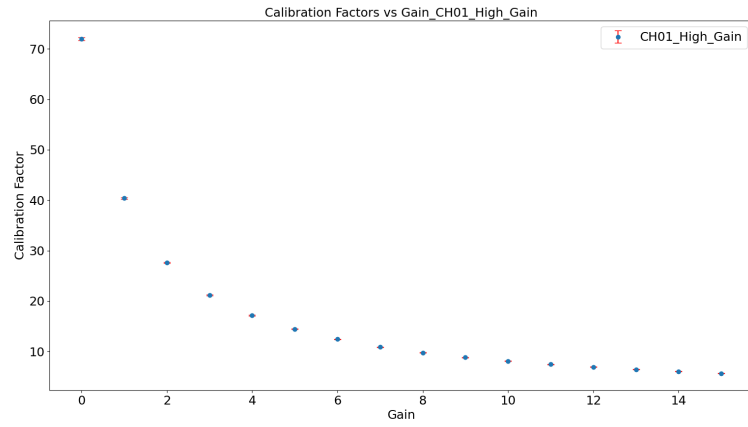


Figure 5.12: Calibration factor for HG00-HG15 for Ch01 for low-Z SiPM

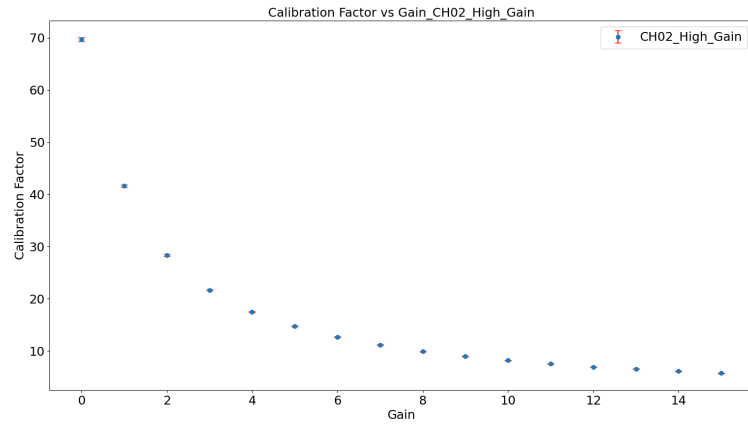


Figure 5.13: Calibration factor for HG00-HG15 for Ch02 for low-Z SiPM.

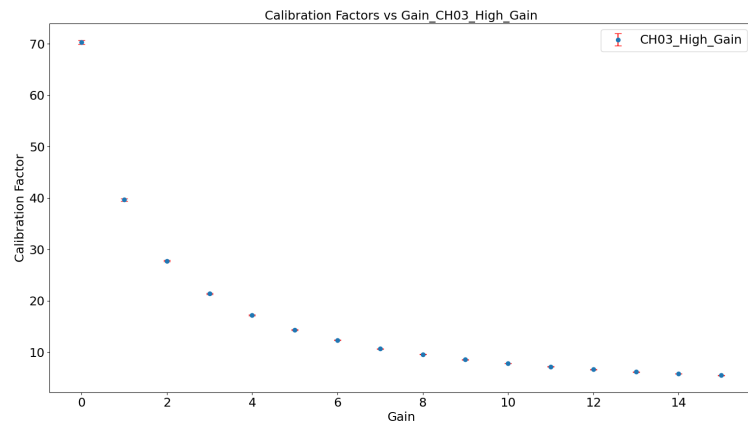


Figure 5.14: Calibration factor for HG00-HG15 for Ch03 for low-Z SiPM.

Low Z Calibration Factors				
Gain Setting	Ch00	Ch01	Ch02	Ch03
LG00	2.779 ± 0.019	3.133 ± 0.013	3.056 ± 0.016	3.087 ± 0.017
LG01	1.501 ± 0.010	1.682 ± 0.007	1.628 ± 0.008	1.668 ± 0.009
LG02	1.018 ± 0.007	1.155 ± 0.005	1.105 ± 0.006	1.142 ± 0.006
LG03	0.769 ± 0.005	0.883 ± 0.004	0.844 ± 0.004	0.838 ± 0.005
LG04	0.549 ± 0.004	0.696 ± 0.003	0.687 ± 0.004	0.712 ± 0.004
LG05	0.464 ± 0.003	0.579 ± 0.002	0.573 ± 0.003	0.614 ± 0.003
LG06	0.413 ± 0.003	0.512 ± 0.002	0.515 ± 0.003	0.551 ± 0.003
LG07	0.373 ± 0.003	0.464 ± 0.002	0.445 ± 0.002	0.500 ± 0.003
LG08	0.343 ± 0.002	0.426 ± 0.002	0.413 ± 0.002	0.463 ± 0.003
LG09	0.319 ± 0.002	0.391 ± 0.002	0.362 ± 0.002	0.425 ± 0.002
LG10	0.299 ± 0.002	0.370 ± 0.002	0.335 ± 0.002	0.404 ± 0.002
LG11	0.280 ± 0.002	0.347 ± 0.001	0.303 ± 0.002	0.378 ± 0.002
LG12	0.267 ± 0.002	0.332 ± 0.001	0.284 ± 0.001	0.364 ± 0.002
LG13	0.253 ± 0.002	0.311 ± 0.001	0.260 ± 0.001	0.341 ± 0.002
LG14	0.243 ± 0.002	0.297 ± 0.001	0.249 ± 0.001	0.323 ± 0.002
LG15	0.229 ± 0.002	0.278 ± 0.001	0.232 ± 0.001	0.303 ± 0.002

Table 5.2: Calibration factors for LG00 to LG15 for the four channels

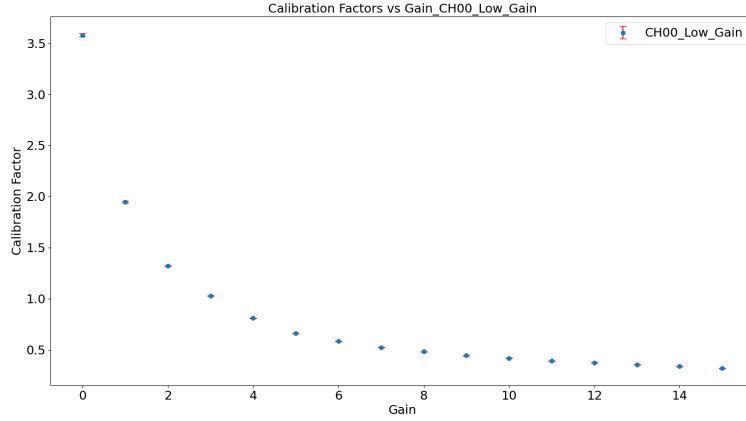


Figure 5.15: Calibration factor for LG00-LG15 for Ch00 for low-Z SiPM

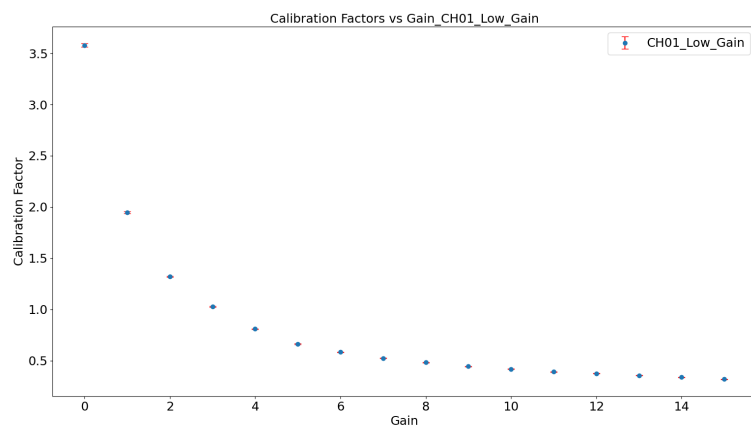


Figure 5.16: Calibration factor for LG00-LG15 for Ch01 for low-Z SiPM

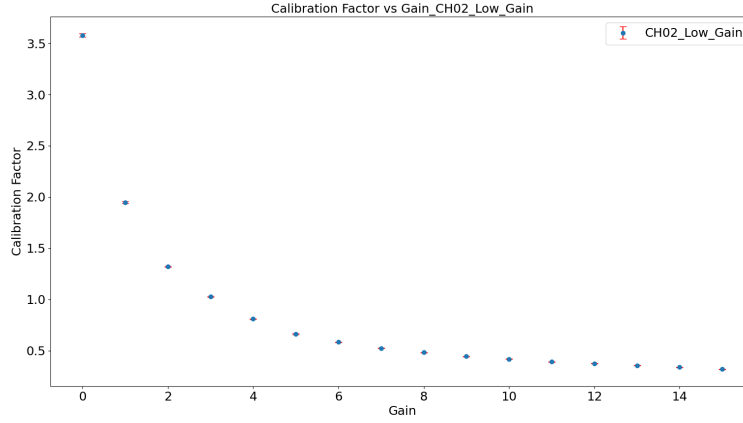


Figure 5.17: Calibration factor for LG00-LG15 for Ch02 for low-Z SiPM

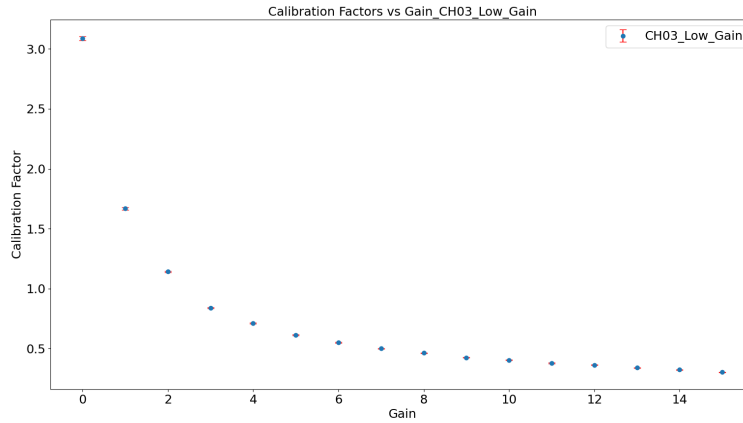


Figure 5.18: Calibration factor for LG00-LG15 for Ch03 for low-Z SiPM.

5.2.1.4 Results from betaPy measurement

The complete range of calibration factors for the high-gain setting is approximately between 72 and 5, whereas for the low-gain setting, it is approximately between 3 and 0. The high-gain calibration factors show a very sharp initial decrease, with the HG01 values being approximately half of the HG00 value. The trend is non-linear, as shown in Figure 5.11, Figure 5.12, Figure 5.13 and Figure 5.14. The plots demonstrate a gradual decrease and eventual flattening of the curve as HG15 is reached. For the LG values, the calibration factors

are much smaller than the initial HG values. It also shows the same non-linear trend as shown in Figure 5.15, Figure 5.16, Figure 5.17 and Figure 5.18. Both of them show a steep-to-flat pattern, and this behaviour is consistent across all the channels for all the gain settings.

Once these measurements were performed, plots for $1/C$ vs gain for the four channels were generated for the high-gain setting as well as the low-gain setting. The corresponding plots for Ch00 are shown in Figure 5.19 and Figure 5.20, Figure 5.21 and Figure 5.22 for Ch01, Figure 5.23 and Figure 5.24 for Ch02, and Figure 5.25 and Figure 5.26 for Ch03.

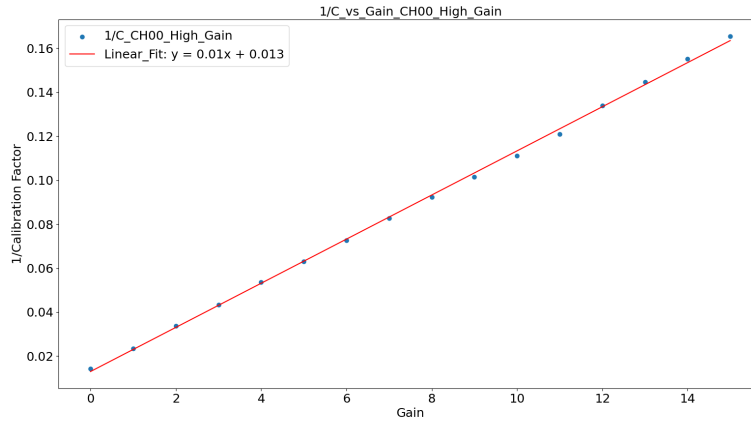


Figure 5.19: C_{inv} vs Gain_Ch00 for HG00 to HG15

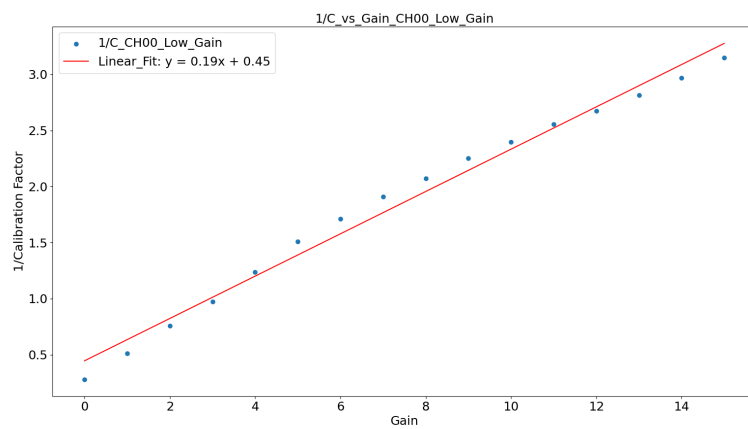


Figure 5.20: C_{inv} vs Gain_Ch00 for LG00 to LG15

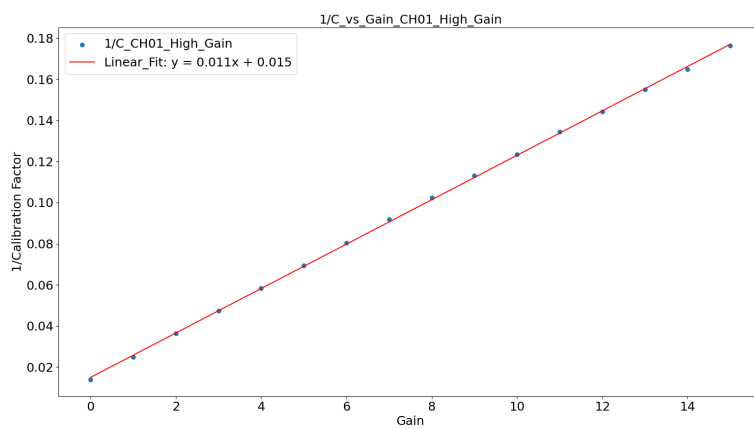


Figure 5.21: C_{inv} vs Gain_Ch01 for HG00 to HG15

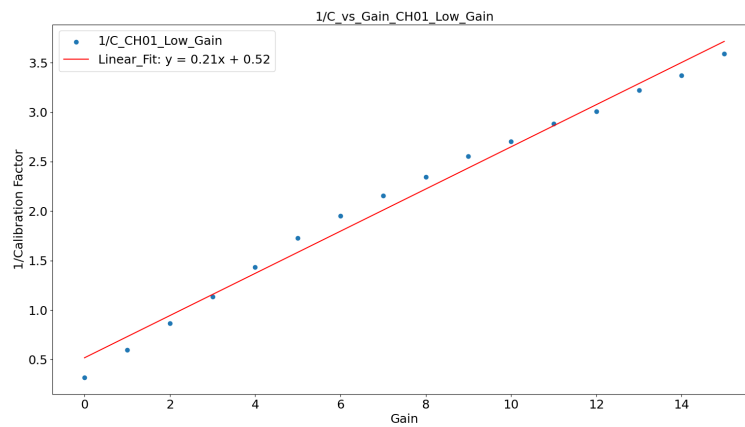


Figure 5.22: C_{inv} vs Gain_Ch01 for LG00 to LG15

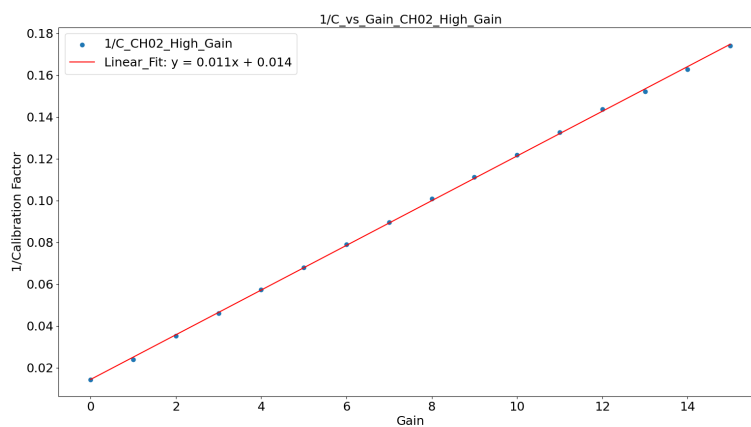


Figure 5.23: C_{inv} vs Gain_Ch02 for HG00 to HG15

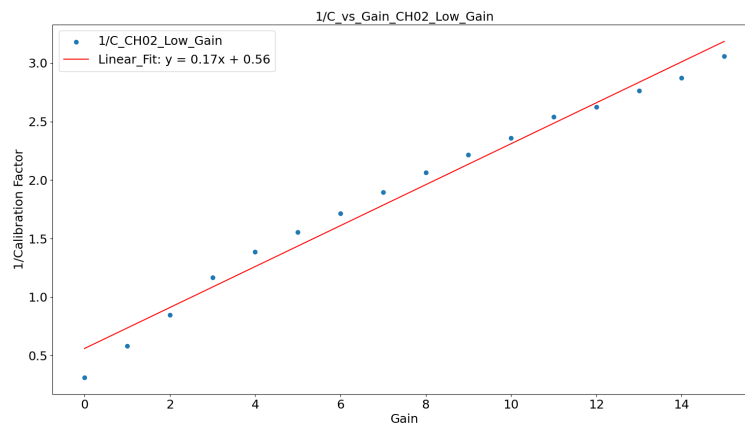


Figure 5.24: C_{inv} vs Gain_Ch02 for LG00 to LG15

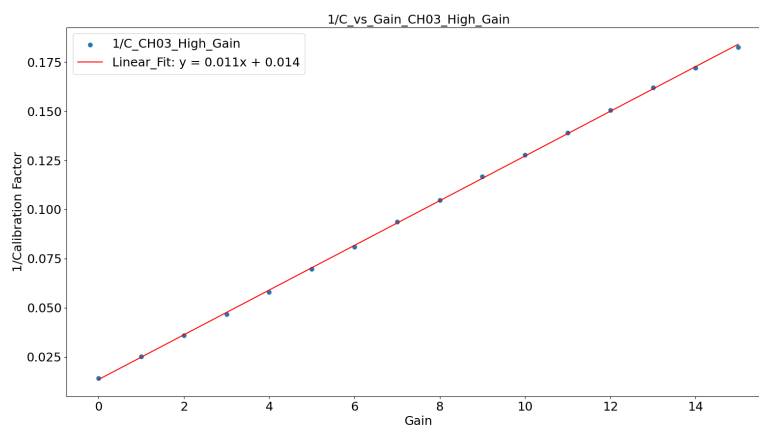


Figure 5.25: C_{inv} vs Gain_Ch03 for HG00 to HG15

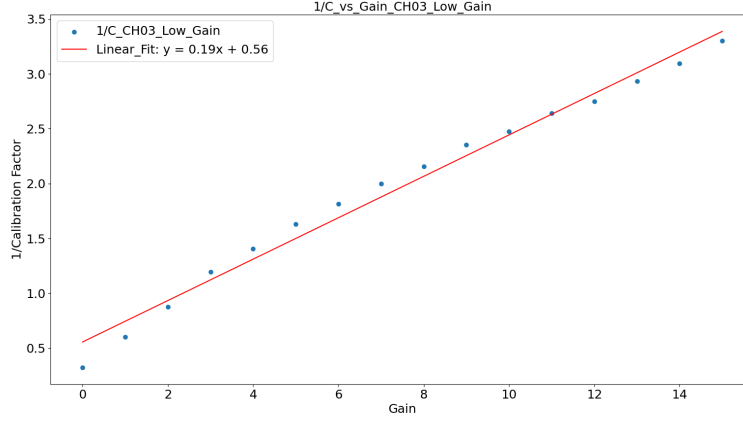


Figure 5.26: C_{inv} vs Gain_Ch03 for LG00 to LG15

The calibration factor is related to the feedback capacitance C_f inside the BETA-ASIC. Therefore, when the gain setting is changed from 00 to 15, it is actually the capacitance that is being modified. The relation between the calibration factor and capacitance C_f is:

$$CF \propto \frac{1}{C_f} \quad (5.10)$$

At HG00, the feedback capacitance is at its minimum. As the capacitor is small, a small amount of charge will create a large voltage:

$$V = \frac{Q}{C_f} \quad (5.11)$$

where V is the voltage, and Q is the charge. Therefore, the HG00 is the maximum gain. Consequently, when the gain setting changes from HG00 to HG15, more capacitance is added, reducing the gain.

Hence, the calibration factor across the different gain settings is directly related to the internal feedback capacitance of the BETA-ASIC. As the gain setting increases from 0 to 15, the ASIC increases the capacitance C_f , and the calibration factor decreases. The list of capacitance values against the different gain settings is shown in fig. 5.27 taken from the BETA-ASIC datasheet [93].

4-bit Dcap_CH (HG or LG)_Cf	Cf	HG preamplifier gain (linear)	Cf	LG preamplifier gain (linear)
0000 (default)	125 fF	40.00	200 fF	3.72
0001	250 fF	23.86	400 fF	1.97
0010	375 fF	16.95	600 fF	1.33
0011	500 fF	13.00	800 fF	1.00
0100	625 fF	10.64	1000 fF	0.81
0101	750 fF	8.95	1200 fF	0.67
0110	875 fF	7.73	1400 fF	0.58
0111	1000 fF	6.82	1600 fF	0.50
1000	1125 fF	6.05	1800 fF	0.45
1001	1250 fF	5.55	2000 fF	0.40
1010	1375 fF	5.00	2200 fF	0.36
1011	1500 fF	4.64	2400 fF	0.33
1100	1625 fF	4.27	2600 fF	0.30
1101	1750 fF	3.95	2800 fF	0.28
1110	1875 fF	3.73	3000 fF	0.26
1111	2000 fF	3.45	3200 fF	0.24

Figure 5.27: The preamplifier gain as a function of feedback capacitance resistors

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To check if the gain setting ratio scale as per capacitance ratios, the ratio between two calibration factors HG00 and HG01 and LG00 and LG01 were compared with the ratio of the capacitances at those respective gain settings. The results are as follows:

- **High-Gain Setting Validation:**

$$\begin{aligned} \text{Ratio}_{CF} &= \frac{70.20}{34.22} = 2.05 \\ \text{Ratio}_{C_f} &= \frac{250 \text{ fF}}{125 \text{ fF}} = 2.00 \end{aligned} \quad (5.12)$$

- **Low-Gain Setting Validation:**

$$\begin{aligned} \text{Ratio}_{CF} &= \frac{2.779}{1.501} = 1.85 \\ \text{Ratio}_{C_f} &= \frac{400 \text{ fF}}{200 \text{ fF}} = 2.00 \end{aligned} \quad (5.13)$$

5.2.1.5 Discussion from the betaPy measurement

The results shown above show that, although the ratios for the high-gain settings are in good agreement with each other, the low-gain settings show a slight deviation. This confirms the non-linear behaviour observed in all the plots, especially for the low-gain setting. It is an important reason why experimental validation is necessary, and the theoretical values obtained from the datasheet may not account for these variations. Therefore, betaPy is an important tool for calibration factor measurements across all gains, as this provides us with calibration factor measurements even when peaks cannot be resolved. Additionally,

it is an important check between the theoretical values and the experimental verification of the capacitance values and helps us determine the behaviour of the readout system. betaPy was tested only for the low-Z SiPM and could not be tested for high-Z due to time constraints.

5.2.2 Pipeline to study different parameters for the characterisation of SiPMs

Once the calibration factor was calculated using BetaPy, the same dataset – particularly the datasets for HG00 and HG01 for low-Z and HG00 for high-Z – was used to study the following:

1. Calibration factor.
2. Signal-to-Noise ratio (SNR).
3. Crosstalk.

Since there were no existing procedures to study the aforementioned properties for this dataset, an ad hoc pipeline was developed from scratch to establish a methodology for analysing the 136 data files. Each dataset is unique, and a set of parameters was tuned to optimise the data analysis procedure. Only a few datasets required individual tuning to achieve better results. The individual plots for the complete dataset can be found in ??.

5.2.2.1 Raw Histogram

First, histograms of the raw data for the dark count data and the light intensity data are plotted. The dark counts are referred to as "LEDOFF data" and the intensity data for each channel are referred to as "LEDOOn data". An example of this plot is seen in Figure [5.28](#). The setting for the maximum gain is referred to as HG00.

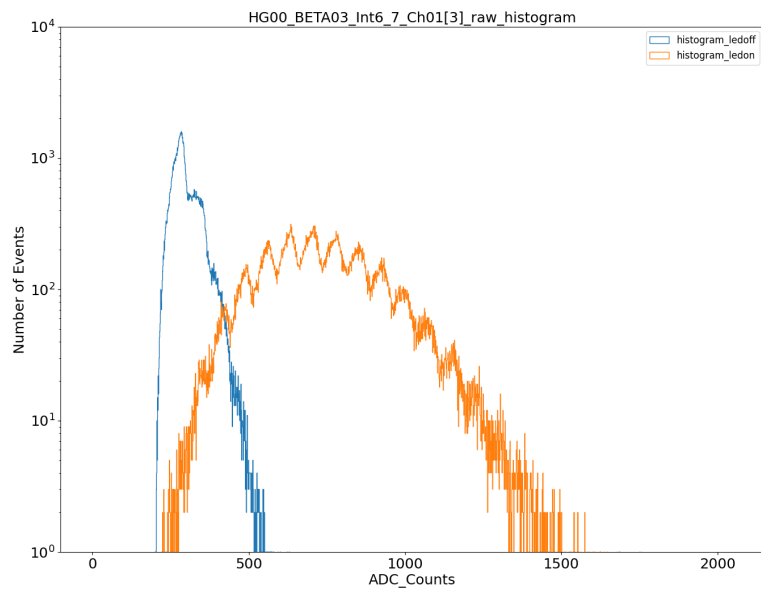


Figure 5.28: Raw histogram of the Ledoff and the Ledon data for 6.7V intensity for HG00 Ch01 of Low Z SiPM

5.2.2.2 Smoothed Histogram

The LEDOFF and the LEDOn data are smoothed using the Savitzky-Golay filter from the SciPy Python library ²⁶

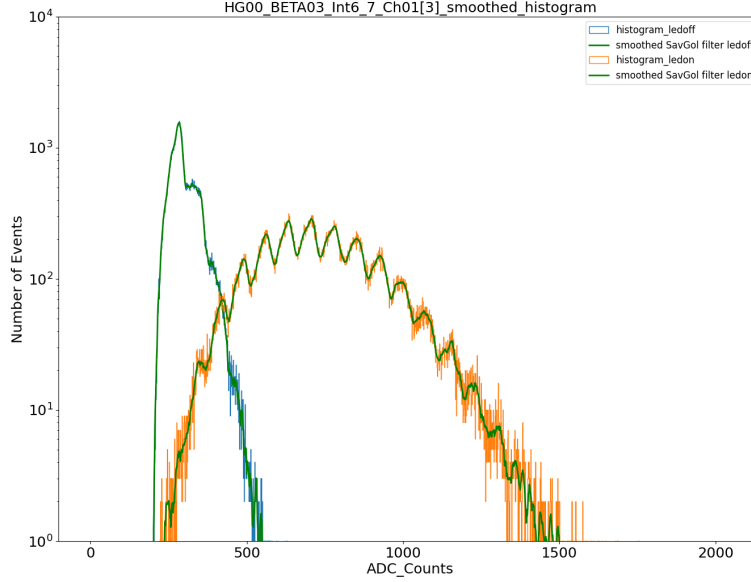


Figure 5.29: Smooth histogram of the Ledoff and the Ledon data for 6.7V intensity for HG00 Ch01 of Low Z SiPM

5.2.2.3 Peak-finding algorithm

A peak-finding algorithm is applied to the smoothed data to identify the peaks in the histogram. In this step, the algorithm filters out peaks aligning with the pedestal and identifies only subsequent peaks. This is important to obtain the correct number of photoelectron peaks. Using this method, the calibration factor for each dataset is calculated and printed on the plot. As seen in Figure ²⁶5.29, the data on the extreme right are noisy. To minimise the selection of these peaks, only 90% of the total range is selected. Therefore, only the peaks within this range are considered. In some cases, if the dataset is too noisy, the selection range was adjusted manually depending on the specific dataset. As the calibration factor is calculated directly from the peak-finding method, it

²⁶https://docs.scipy.org/doc/scipy/reference/generated/scipy.signal.savgol_filter.html

does not provide a direct error estimate. The calibration factor and its error are calculated as

$$\text{Peak distances: } \Delta P_i = \text{Peak}_{i+1} - \text{Peak}_i \quad (5.14)$$

$$\text{Calibration factor: } \bar{C} = \frac{1}{N} \sum_{i=1}^N \Delta P_i \quad (5.15)$$

$$\text{Standard deviation: } \sigma_C = \sqrt{\frac{1}{N-1} \sum_{i=1}^N (\Delta P_i - \bar{C})^2} \quad (5.16)$$

$$\text{Calibration factor error: } \text{Error}_C = \frac{\sigma_C}{\sqrt{N}} \quad (5.17)$$

where, N is the total number of peaks.

A plot of this step is seen in Figure [5.30](#)

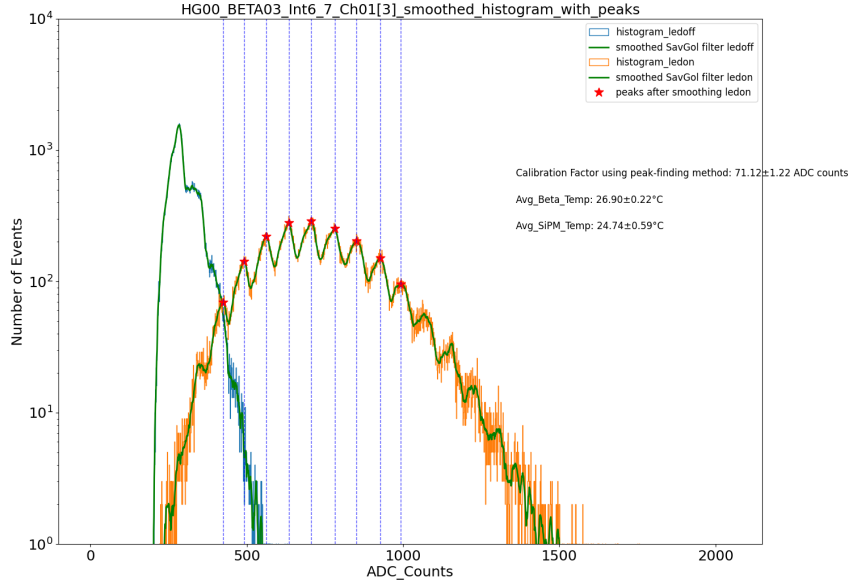


Figure 5.30: The detected peaks for the 6.7V intensity for HG00 Ch01 of Low Z SiPM

5.2.2.4 Normal Multi-Gaussian fit

A multi-Gaussian fit is then applied to these peaks. The sigma values obtained from this fit are used to calculate the weighted sigma and its corresponding

error. This weighted sigma is then used to perform a second multi-Gaussian fit, referred to as a "fixed multi-Gaussian fit". A plot for this step is shown in Figure 5.31.

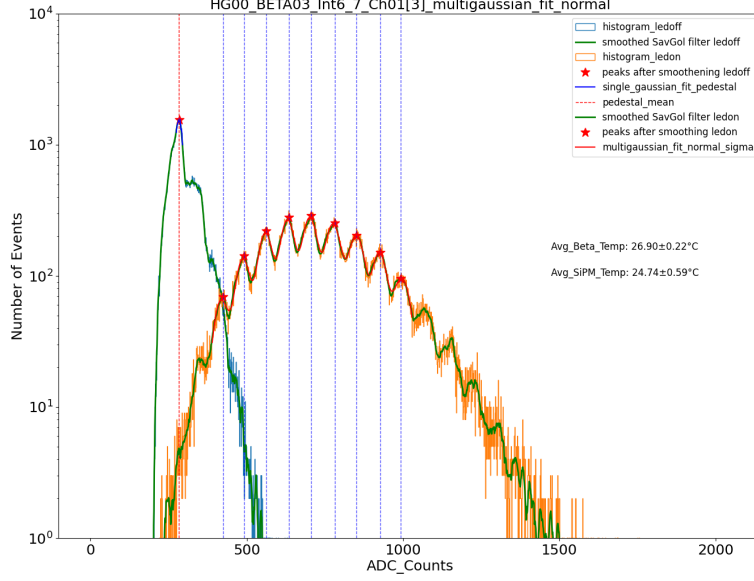


Figure 5.31: The normal gaussian fit for 6.7V intensity for HG00 Ch01 of Low Z SiPM

5.2.2.5 Fixed Multi-Gaussian fit

The sigma values obtained from Section 5.2.2.4 are used to calculate the weighted sigma of the fit and its corresponding error using this formula:

$$\text{Weights: } w_i = \frac{1}{\sigma_{\text{free},i}^2} \quad (5.18)$$

$$\text{Weighted mean: } \bar{\sigma}_w = \frac{\sum_{i=1}^N w_i \sigma_{\text{free},i}}{\sum_{i=1}^N w_i} \quad (5.19)$$

$$\text{Error on weighted mean: } \text{Error}_{\bar{\sigma}_w} = \frac{1}{\sqrt{\sum_{i=1}^N w_i}} \quad (5.20)$$

where, σ_{free} = sigma obtained from the Section 5.2.2.4. Performing this fit was essential to obtain reliable values for the SNR and crosstalk analysis.

Although the calibration factor was also determined using this method, it was not included in the calibration factor comparison analysis in Section 5.2.3. This was because the photoelectron peaks are not perfectly symmetric, so the centre of a symmetric Gaussian fit does not necessarily coincide with the "peaks" found using the peak-finding algorithm. An example of this method was tried, and the two plots are shown in Figure 5.32 and Figure 5.33.

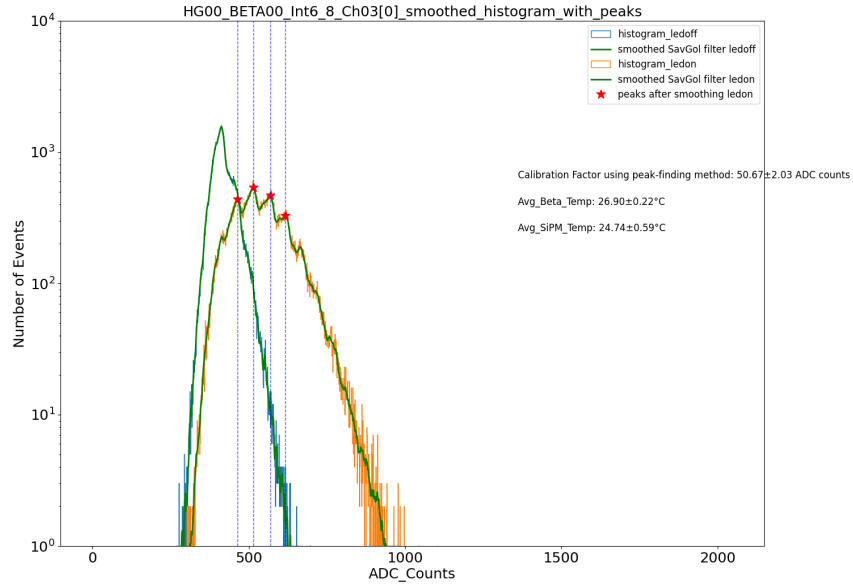


Figure 5.32: The calibration factor obtained for 6.8V intensity for HG00 Ch03 of high-Z SiPM using peak-finding method

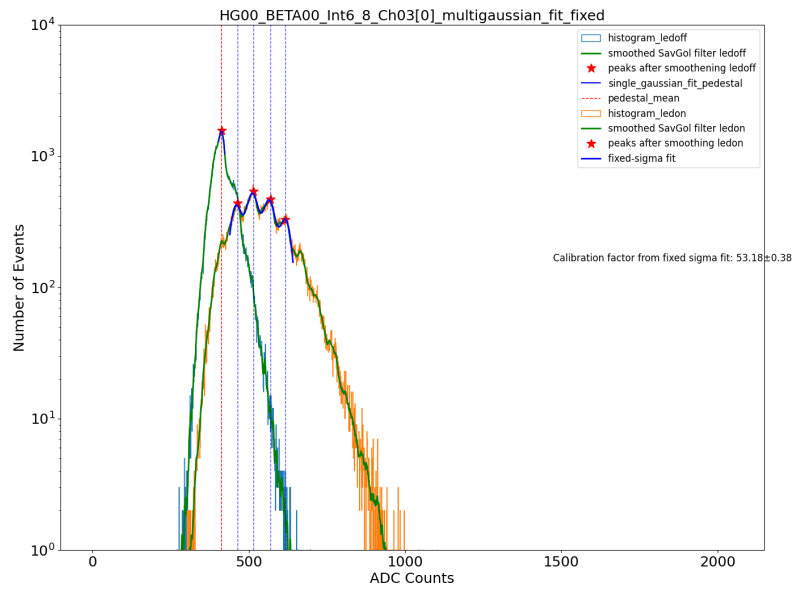


Figure 5.33: The calibration factor obtained for 6.8V intensity for HG00 Ch03 of high-Z SiPM using a fixed multi-gaussian fixed method

A single Gaussian fit is applied to the "LEDOFF" data to obtain the fitted parameters. These parameters were used to determine the SNR and crosstalk later on. A plot for this step is seen in Figure 5.34

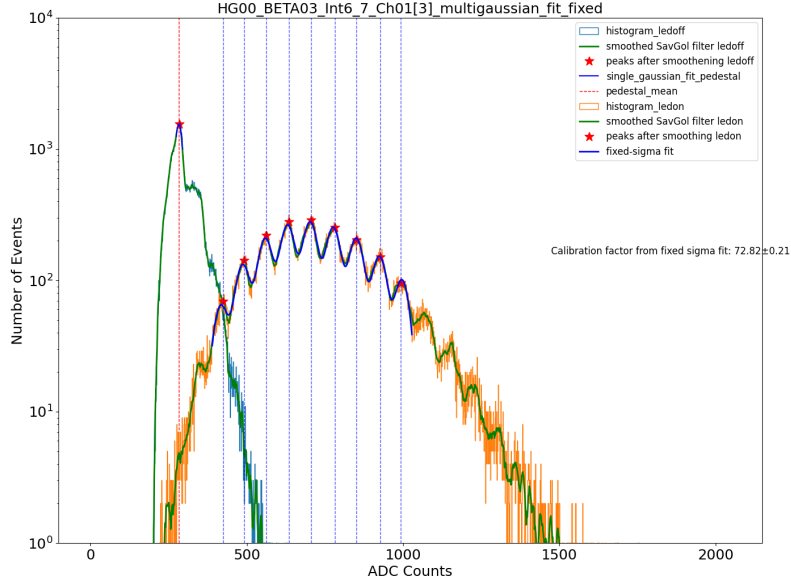


Figure 5.34: The gaussian fit with a fixed sigma for 6.7V intensity for HG00 Ch01 of Low Z SiPM

5.2.2.6 Signal-to-Noise Ratio (SNR)

The parameters obtained from Section 5.2.2.5 the SNR for the peaks was calculated. The formula used to calculate SNR is:

$$\text{Signal: } S_i = \text{Mean}_i - \text{Mean}_{\text{pedestal}} \quad (5.21)$$

$$\text{Signal error: } \sigma_{S_i} = \sqrt{\sigma_{\text{Mean}_i}^2 + \sigma_{\text{Mean}_{\text{pedestal}}}^2} \quad (5.22)$$

$$\text{Noise: } N = \sigma_{\text{fixed}} \quad (5.23)$$

$$\text{Noise error: } \sigma_N = \sigma_{\sigma_{\text{fixed}}} \quad (5.24)$$

$$\text{Signal-to-noise ratio: } \text{SNR}_i = \frac{S_i}{N_i} \quad (5.25)$$

$$\text{SNR error: } \sigma_{\text{SNR}_i} = \text{SNR}_i \sqrt{\left(\frac{\sigma_{S_i}}{S_i}\right)^2 + \left(\frac{\sigma_{N_i}}{N_i}\right)^2} \quad (5.26)$$

where, N and σ_N are the values obtained from eq. (5.19) and eq. (5.20) respectively.

Finally, a linear fit is applied to the SNR values. A plot of this step is shown in Figure 5.35

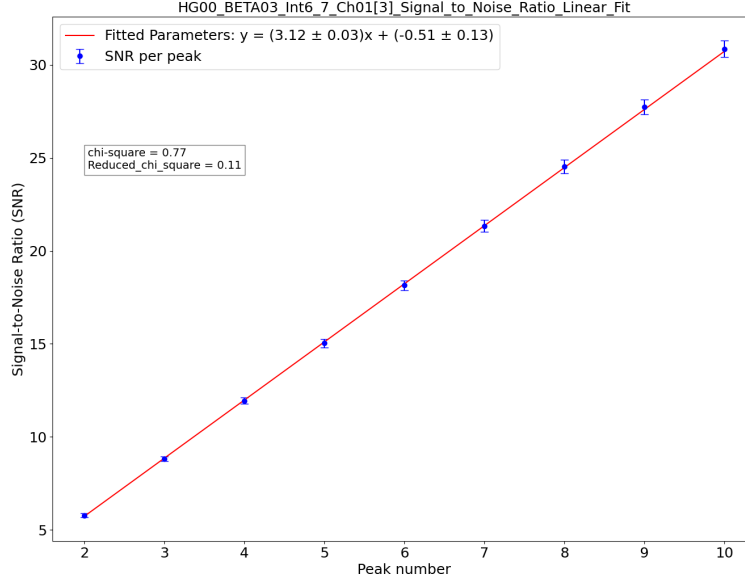


Figure 5.35: The linear fit on the SNR values for 6.7V intensity for HG00 Ch01 of Low Z SiPM

5.2.2.7 Crosstalk

Lastly, the crosstalk was calculated. To calculate the crosstalk, the area under each peak was calculated using the formula:

$$\text{Peak area: } A_i = \text{amp}_i \cdot \sigma_{\text{fixed}_i} \cdot \sqrt{2\pi} \quad (5.27)$$

$$\text{Error on peak area: } \sigma_{A_i} = \sqrt{\left(\sigma_{\text{amp}_i} \cdot \sigma_{\text{fixed}_i} \cdot \sqrt{2\pi}\right)^2 + \left(\text{amp}_i \cdot \sigma_{\sigma_{\text{fixed}_i}} \cdot \sqrt{2\pi}\right)^2} \quad (5.28)$$

Where, amp_i is the amplitude of each peak obtained from Section 5.2.2.5 and σ_{fixed_i} obtained from eq. (5.19), respectively.

Eventually, these peaks were fitted with the crosstalk model given by Vinogradov in [95]. The model is defined as:

$$f_i = \frac{A_i}{A_{\text{tot}}} \quad (5.29)$$

$$\sigma_{f_i} = f_i \sqrt{\left(\frac{\sigma_{A_i}}{A_i}\right)^2 + \left(\frac{\sigma_{A_{\text{tot}}}}{A_{\text{tot}}}\right)^2} \quad (5.30)$$

Where A_{tot} is the total area of the "LEDOn" histogram.

Finally, the percentage of the area of each peak is plotted against its respective peak number. The fitting model used to study crosstalk is:

$$f_k(p, L) = \sum_{i=0}^k \frac{e^{-L} B_{i,k} [L(1-p)]^i p^{k-i}}{k!}, \quad (5.31)$$

where,

$$B_{i,k} = \begin{cases} 1 & \text{if } i = 0 \text{ and } k = 0, \\ 0 & \text{if } i = 0 \text{ and } k > 0, \\ \frac{k! (k-1)!}{i! (i-1)! (k-i)!} & \text{otherwise.} \end{cases}$$

where, L is the mean number of photoelectrons, p is the crosstalk probability, and $B_{i,k}$ is the probability that i primary photoelectrons will result in k number of detected photoelectrons as a result of the crosstalk branching process.

A plot of the crosstalk is seen in Figure 5.36.

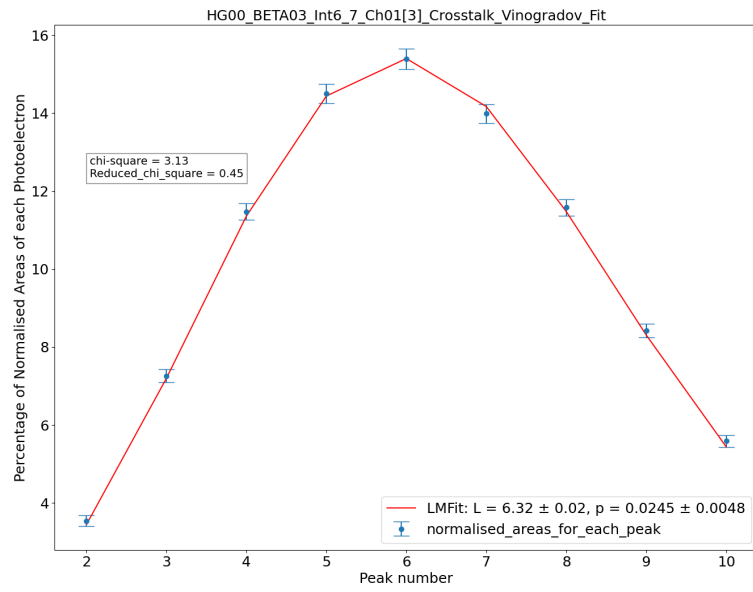


Figure 5.36: The Vinogradov fit on the crosstalk values for 6.7V intensity for HG00 Ch01 for low-Z SiPM

The complete set of plots generated from this pipeline are listed below:

1. Raw histogram
2. Smooth histogram
3. Histogram with identified peaks
4. Normal multi-Gaussian fit
5. Fixed multi-Gaussian fit
6. Signal-to-Noise Ratio
7. Crosstalk

For this analysis, only channels Ch00, Ch01 and Ch03 for the HG00 configuration were considered for the low-Z SiPMs. The peaks for HG00 Ch02 could not be easily resolved; consequently, this channel was excluded from the analysis. A plot of the Ch02 spectrum is shown in Figure 5.37. For the high-Z SiPMs, all four channels – Ch00, Ch01, Ch02 and Ch03 for HG00 – were included in the analysis.

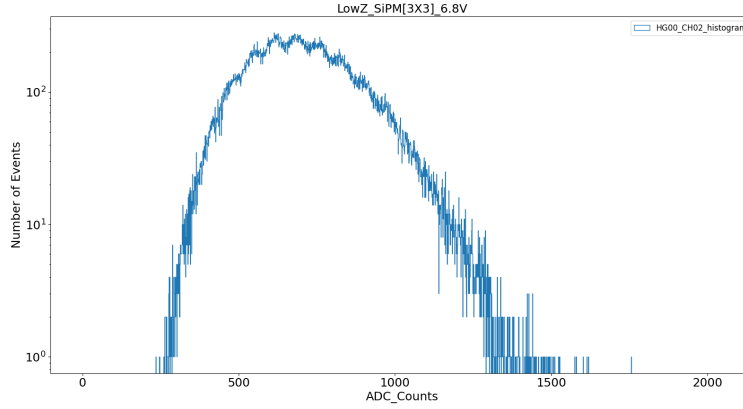


Figure 5.37: Raw histogram of the Ledon data for 6.8V intensity for Ch02 of Low Z SiPM

To explain all the steps of this ad hoc pipeline, each procedure is explained in Section 5.2.2.1, Section 5.2.2.2, Section 5.2.2.4, Section 5.2.2.5, Section 5.2.2.6 and Section 5.2.2.7. Only the results for HG00 Ch01 for 6.8V light intensity are shown in these sections as a representative example. The plots for the entire dataset can be found in ???. The nomenclature used for all the plots is as follows:

1. high-z_hg00_Ch00 = HighZ for gain setting HG00 for Channel00

2. high-z_hg00_Ch01 = HighZ for gain setting HG00 for Channel01
3. high-z_hg00_Ch02 = HighZ for gain setting HG00 for Channel02
4. high-z_hg00_Ch03 = HighZ for gain setting HG00 for Channel03
5. low-z_hg00_Ch00 = LowZ for gain setting HG00 for Channel00
6. low-z_hg00_Ch01 = LowZ for gain setting HG00 for Channel01
7. low-z_hg00_Ch03 = LowZ for gain setting HG00 for Channel03
8. low-z_hg01_Ch00 = LowZ for gain setting HG01 for Channel00
9. low-z_hg01_Ch01 = LowZ for gain setting HG01 for Channel01
10. low-z_hg01_Ch03 = LowZ for gain setting HG01 for Channel03

5.2.3 Results from calibration factor using peak-finding method

The calibration factor was calculated again using this ad hoc method and compared to betaPy. This is because betaPy calculates this for the overall gain, whereas the ad hoc procedure calculates the calibration factor for individual intensities. Ideally, both procedures should yield the same result. However, it has been found that the calibration factor is highly sensitive to the selection of peaks and intensities. The calibration factor for all the channels for low-Z HG00 is shown in Figure 5.38, low-Z HG01 in Figure 5.39 and high-Z HG00 in Figure 5.40.

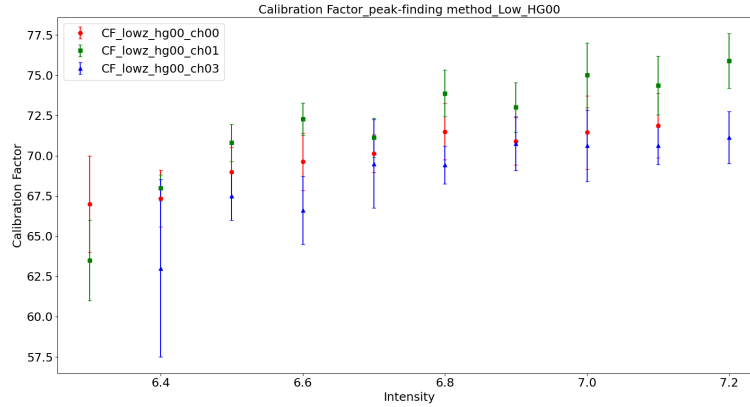


Figure 5.38: Calibration factor for all the intensities for HG00 low-Z of all channels

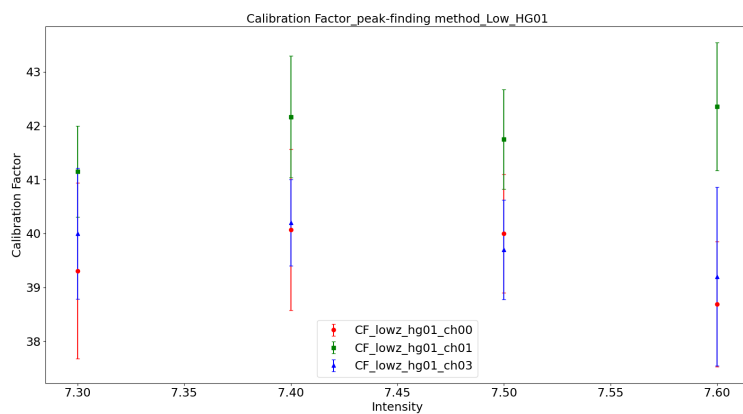


Figure 5.39: Calibration factor for all the intensities for HG01 low-Z of all channels

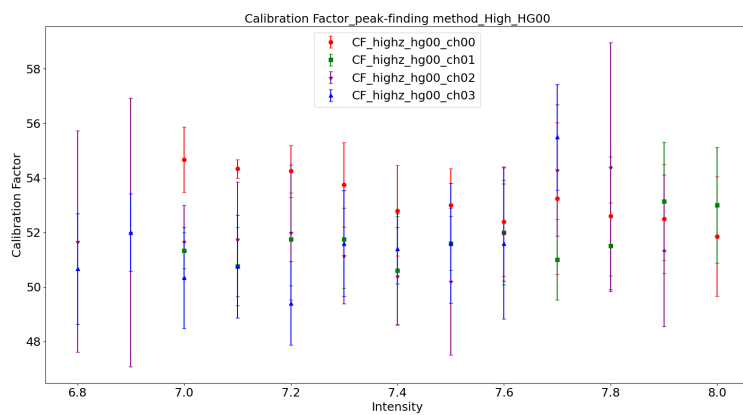


Figure 5.40: Calibration factor for all the intensities for HG00 high-Z of all channels

The calibration factor shows an increasing trend for the low-Z HG00 configuration as the intensity increases from 6.3V to 7.2V. For low-Z HG01, it remains fairly constant, but the sample size is much smaller than that of HG00. For high-Z HG00, the calibration factor also fluctuates slightly across the intensities 6.8V to 8.0V

5.2.4 Calibration factor: Betapy software vs Peak-detection code

The calibration factors for the two gain settings, HG00 and HG01, were compared between betaPy and this ad hoc procedure. One important observation is that the calibration factor is highly sensitive to the peak selection. The result can change drastically depending on the total number of peaks selected for this calculation. Since Ch02 (Figure 5.37) was excluded from the analysis using the ad hoc procedure, the results obtained for Ch02 from betaPy were also excluded from the comparison plot as seen in Figure 5.41 and Figure 5.42

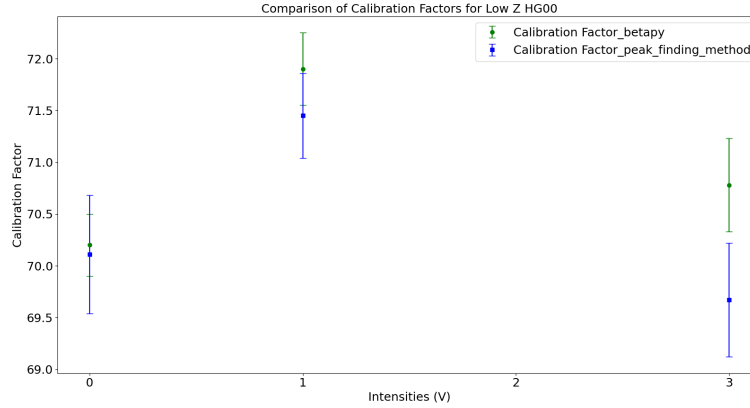


Figure 5.41: Calibration factors for HG00 low-Z are compared between betaPy and the peak-detection method.

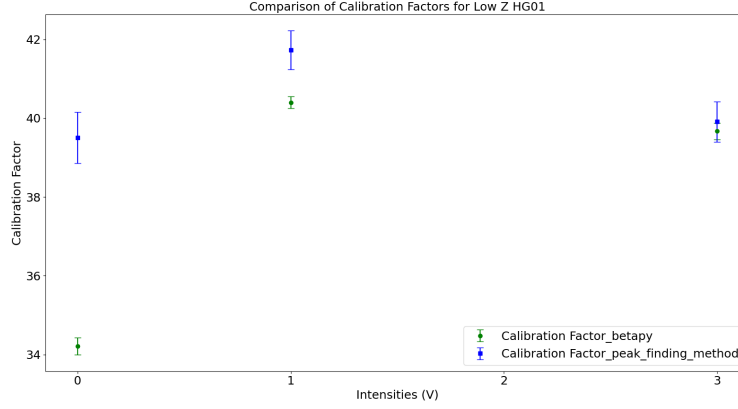


Figure 5.42: Calibration factors for HG01 low-Z compared between betaPy and the peak-detection method.

The calibration factor shows a good agreement for HG00 for all channels. For Ch00 for HG01, the calibration factor from betaPy is much lower than that of Ch01 and Ch03.

5.2.5 SNR results and discussion

The SNR for each photoelectron detected at each intensity was plotted for the channels Ch00, Ch01 and Ch03 for HG00 for low-Z SiPMs and for Ch00, Ch01, Ch02 and Ch03 for HG00 for high-Z SiPMs. The extracted parameters slope and intercept were plotted for all the intensities listed channel-wise in Table 5.3, Table 5.4 and Table 5.5 for low-Z and Table 5.6, Table 5.7, Table 5.8 and Table 5.9 for high-Z. For low-Z, the slopes for all channels are shown in Figure 5.43 and the intercepts in Figure 5.44. The slopes and intercepts of all the channels for high-Z are shown in Figure 5.45 and Figure 5.46, respectively.

Low Z HG00 CHANNEL 00			
Signal-to-Noise Parameters			
Intensity (V)	Slope	Intercept	Degree of Freedom
6.3	3.202 $\pm$ 0.083	-0.404 $\pm$ 0.121	1
6.4	3.207 $\pm$ 0.059	-0.256 $\pm$ 0.099	2
6.5	3.183 $\pm$ 0.036	-0.201 $\pm$ 0.076	4
6.6	3.147 $\pm$ 0.027	-0.335 $\pm$ 0.084	7
6.7	3.091 $\pm$ 0.035	-0.524 $\pm$ 0.152	7
6.8	3.075 $\pm$ 0.050	-0.782 $\pm$ 0.330	7
6.9	3.019 $\pm$ 0.055	-0.719 $\pm$ 0.527	9
7.0	3.028 $\pm$ 0.083	-0.725 $\pm$ 0.952	8
7.1	2.947 $\pm$ 0.122	-3.594 $\pm$ 1.871	7

Table 5.3: Comparison of SNR parameters for HG00 different intensities_Ch00

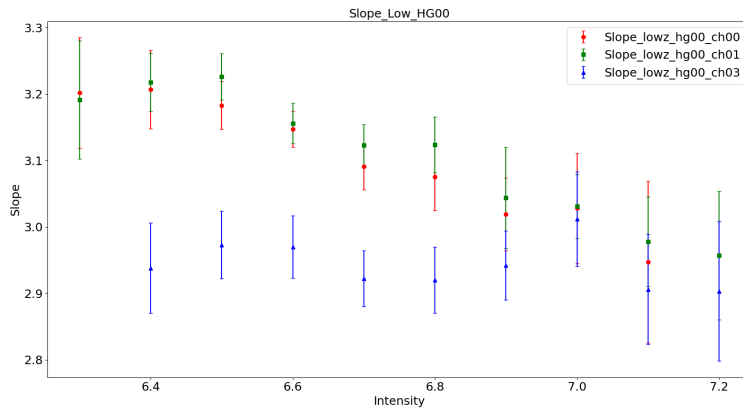


Figure 5.43: Slope values for HG00 low-Z for all channels

Low Z HG00 CHANNEL 01			
Signal-to-Noise Parameters			
Intensity (V)	Slope	Intercept	Freedom
6.3	3.191 $\pm$ 0.089	-0.368 $\pm$ 0.129	1
6.4	3.218 $\pm$ 0.044	-0.307 $\pm$ 0.080	3
6.5	3.226 $\pm$ 0.035	-0.282 $\pm$ 0.073	4
6.6	3.156 $\pm$ 0.030	-0.277 $\pm$ 0.083	6
6.7	3.123 $\pm$ 0.031	-0.511 $\pm$ 0.131	7
6.8	3.124 $\pm$ 0.042	-0.786 $\pm$ 0.279	7
6.9	3.044 $\pm$ 0.076	-0.974 $\pm$ 0.550	5
7.0	3.031 $\pm$ 0.048	-4.193 $\pm$ 0.513	10
7.1	2.978 $\pm$ 0.067	-4.310 $\pm$ 0.943	10
7.2	2.957 $\pm$ 0.097	-4.778 $\pm$ 1.41	8

Table 5.4: Comparison of SNR parameters for HG00 different intensities_Ch01

Low Z HG00 CHANNEL 03			
Signal-to-Noise Parameters			
Intensity (V)	Slope	Intercept	Freedom
6.4	2.938 $\pm$ 0.068	-0.099 $\pm$ 0.114	2
6.5	2.973 $\pm$ 0.051	0.007 $\pm$ 0.096	3
6.6	2.970 $\pm$ 0.047	0.36 $\pm$ 0.099	4
6.7	2.922 $\pm$ 0.042	-0.018 $\pm$ 0.104	5
6.8	2.920 $\pm$ 0.050	-0.170 $\pm$ 0.196	6
6.9	2.942 $\pm$ 0.052	-0.332 $\pm$ 0.283	7
7.0	3.012 $\pm$ 0.071	-3.555 $\pm$ 0.621	7
7.1	2.906 $\pm$ 0.083	-3.473 $\pm$ 0.824	7
7.2	2.903 $\pm$ 0.105	-3.374 $\pm$ 1.155	7

Table 5.5: Comparison of SNR parameters for HG00 different intensities_Ch03

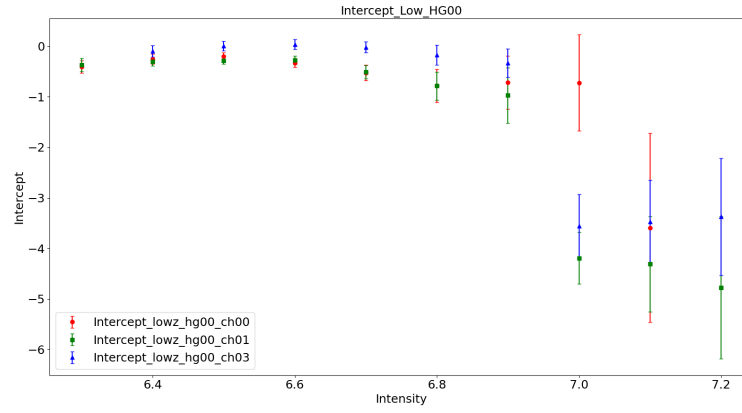


Figure 5.44: Intercept values for HG00 low-Z for all channels

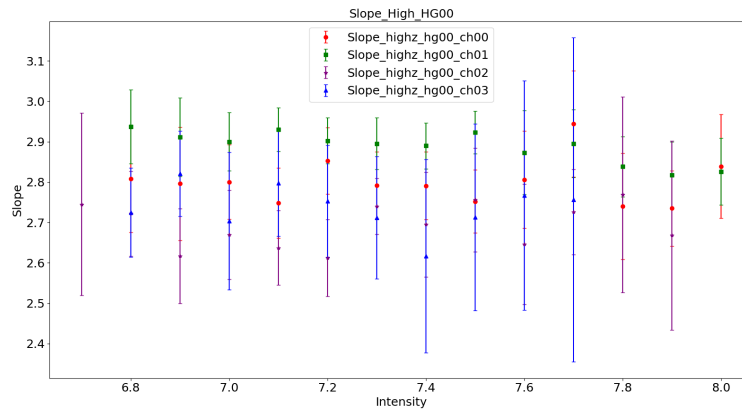


Figure 5.45: Slope values for HG00 high-Z for all channels

High Z HG00 CHANNEL 00			
Signal-to-Noise Parameters			
Intensity (V)	Slope	Intercept	Freedom
7.0	2.800 $\pm$ 0.092	-0.574 $\pm$ 0.146	2
7.1	2.748 $\pm$ 0.087	-0.508 $\pm$ 0.141	2
7.2	2.853 $\pm$ 0.082	-0.425 $\pm$ 0.146	3
7.3	2.792 $\pm$ 0.083	-0.415 $\pm$ 0.150	3
7.4	2.791 $\pm$ 0.084	-0.321 $\pm$ 0.166	4
7.5	2.752 $\pm$ 0.078	-0.397 $\pm$ 0.157	4
7.6	2.806 $\pm$ 0.120	-0.285 $\pm$ 0.407	4
7.7	2.944 $\pm$ 0.131	-0.351 $\pm$ 0.417	3
7.8	2.740 $\pm$ 0.131	-0.131 $\pm$ 0.444	4
7.9	2.735 $\pm$ 0.093	-0.079 $\pm$ 0.379	7
8.0	2.839 $\pm$ 0.128	0.178 $\pm$ 0.668	6

Table 5.6: Comparison of SNR parameters for HG00 different intensities_CH00

High Z HG00 CHANNEL 01			
Signal-to-Noise Parameters			
Intensity (V)	Slope	Intercept	Freedom
7.0	2.900 $\pm$ 0.072	-0.54 $\pm$ 0.12	2
7.1	2.93 $\pm$ 0.054	-0.44 $\pm$ 0.09	3
7.2	2.9 $\pm$ 0.057	-0.47 $\pm$ 0.1	3
7.3	2.89 $\pm$ 0.064	-0.411 $\pm$ 0.12	3
7.4	2.89 $\pm$ 0.057	-0.39 $\pm$ 0.11	4
7.5	2.92 $\pm$ 0.053	-0.36 $\pm$ 0.11	4
7.6	2.87 $\pm$ 0.10	-0.55 $\pm$ 0.33	3
7.7	2.90 $\pm$ 0.08	-0.36 $\pm$ 0.29	4
7.8	2.84 $\pm$ 0.08	-0.275 $\pm$ 0.272	5
7.9	2.82 $\pm$ 0.083	-0.193 $\pm$ 0.429	6
8.0	2.826 $\pm$ 0.083	-0.124 $\pm$ 0.430	6

Table 5.7: Comparison of SNR parameters for HG00 different intensities_Ch01

High Z HG00 CHANNEL 02					
Signal-to-Noise Parameters					
Intensity (V)	Slope		Intercept		Freedom
6.8	2.72	± 0.12	-0.20	± 0.17	2
6.9	2.62	± 0.12	-0.2 ± 0.2		2
7.0	2.67	± 0.11	-0.12	± 0.19	2
7.1	2.64	± 0.09	0.006	± 0.17	2
7.2	2.61	± 0.1	-0.04	± 0.18	3
7.3	2.74	± 0.7	0.3	± 0.17	6
7.4	2.70	± 0.13	0.22	± 0.45	4
7.5	2.76	± 0.13	0.2	± 0.45	4
7.6	2.65	± 0.15	-0.07	± 0.69	4
7.7	2.73	± 0.11	-0.17	± 0.54	6
7.8	2.77	± 0.24	-0.39	± 1.67	4
7.9	2.67	± 0.23	-0.2	± 1.69	5

Table 5.8: Comparison of SNR parameters for HG00 different intensities_Ch02

High Z HG00 CHANNEL 03					
Signal-to-Noise Parameters					
Intensity (V)	Slope		Intercept		Freedom
6.8	2.73	± 0.11	-0.34	± 0.18	2
6.9	2.82	± 0.11	-0.29	± 0.2	3
7.0	2.70	± 0.17	-0.43	± 0.5	2
7.1	2.8	± 0.12	2.58	± 0.3	3
7.2	2.75	± 0.14	2.76	± 0.35	4
7.3	2.71	± 0.15	2.62	± 0.56	4
7.4	2.62	± 0.24	2.32	± 1.15	4
7.5	2.71	± 0.23	2.5	± 1.11	4
7.6	2.77	± 0.28	2.22	± 1.68	4
7.7	2.76	± 0.4	1.02	± 2.64	3

Table 5.9: Comparison of SNR parameters for HG00 different intensities_Ch03

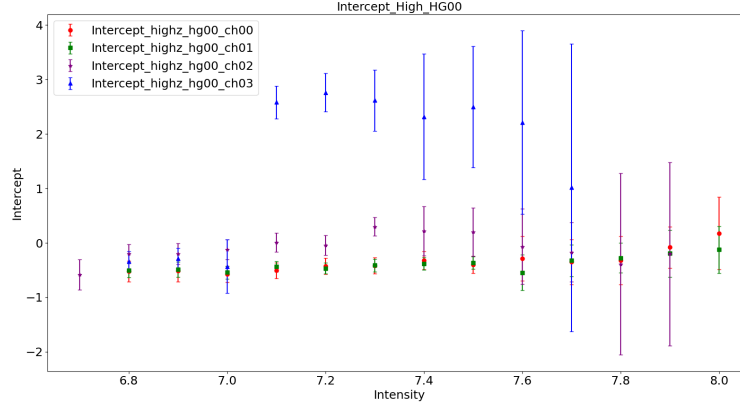


Figure 5.46: Intercept values for HG00 high-Z for all channels

The slope values range between 2.7 and 2.8. The intercept is between 0 and -1 for lower peak numbers. As the light intensity increases, the intercept becomes more negative. Although the intercept for Ch03 for high Z exhibits an unusual trend as compared to the other channels. The results shown in Figure 5.43, Figure 5.45, Figure 5.44 and Figure 5.46 show that the SNR scales consistently across all channels and that the detector has a linearly growing SNR across all channels. The degrees of freedom reflect the number of data points used to obtain these parameters. Overall, the results demonstrate uniform SNR behaviour. This provides a good starting point for calibrating the system response. Several studies have reported the SNR of an SiPM, such as [96] [97] [98] [99] [100] [101] [102] [103] [104] and [105]. However, to my knowledge, no studies were found reporting the SNR for individual photoelectron peak as a function of varying intensities.

5.2.6 Crosstalk results and discussion

The extracted parameters from the crosstalk fitting are L and p . L represents the mean number of photoelectrons detected and p represents the crosstalk probability. These parameters for the entire data set are listed in tables channel-wise in Table 5.10, Table 5.11 and Table 5.12 for HG00 low-Z and Table 5.13, Table 5.14, Table 5.15 and Table 5.16 for HG00 high-Z SiPM. The plots of L and p for all channels are shown in Figure 5.47 and Figure 5.48 for low-Z Figure 5.50 and Figure 5.51 high-Z.

Low Z HG00 CHANNEL 00				
Crosstalk Parameters				
Intensity (V)	L		p	Freedom
6.3	1.43	± 0.04	0.00 ± 0.02	1
6.4	2.33	± 0.04	0.03 ± 0.02	2
6.5	3.51	± 0.03	0.04 ± 0.01	4
6.6	4.98	± 0.02	0.03 ± 0.005	7
6.7	6.74	± 0.03	0.02 ± 0.005	7
6.8	8.73	± 0.07	0.02 ± 0.01	7
6.9	10.82	± 0.06	0.01 ± 0.007	9
7.0	13.07	± 0.05	0.01 ± 0.005	8
7.1	16.78	± 0.53	-0.004 ± 0.032	7

Table 5.10: Comparison of crosstalk parameters for HG00 different intensities_Ch00

Low Z HG00 CHANNEL 01					
Crosstalk Parameters					
Intensity (V)	L		p		Freedom
6.3	1.34	± 0.03	0.014	± 0.02	1
6.4	2.61	± 0.02	0.04	± 0.009	3
6.5	3.30	± 0.01	0.032	± 0.004	4
6.6	4.68	± 0.03	0.03	± 0.009	6
6.7	6.32	± 0.02	0.03	± 0.005	7
6.8	8.16	± 0.06	0.02	± 0.009	7
6.9	10.1	± 0.1	0.016	± 0.01	5
7.0	13.56	± 0.09	-0.008	± 0.006	10
7.1	15.71	± 0.22	0.0003	± 0.01	10
7.2	18.05	± 0.4	-0.003	± 0.03	8

Table 5.11: Comparison of crosstalk parameters for HG00 different intensities.Ch01

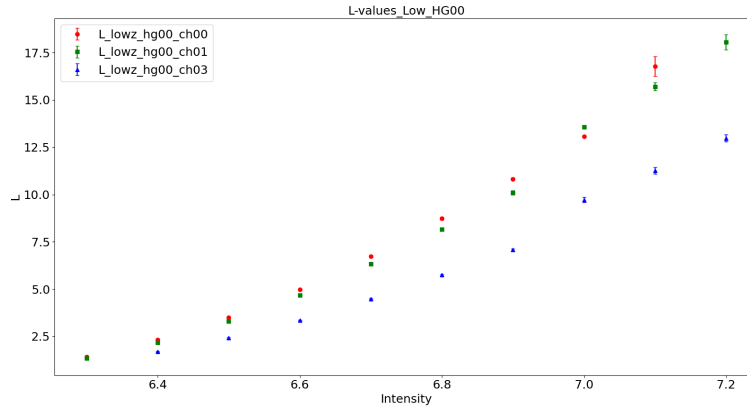


Figure 5.47: L values for HG00 low-Z fo all channels

Low Z HG00 CHANNEL 03				
Crosstalk Parameters				
Intensity (V)	L		p	Freedom
6.4	1.69	$\pm$	0.02	$\pm$ 2
	0.03		0.01	
6.5	2.42	$\pm$	0.04	$\pm$ 3
	0.03		0.02	
6.6	3.35	$\pm$	0.04	$\pm$ 4
	0.02		0.006	
6.7	4.49	$\pm$	0.03	$\pm$ 5
	0.04		0.012	
6.8	5.75	$\pm$	0.03	$\pm$ 6
	0.04		0.008	
6.9	7.08	$\pm$	0.02	$\pm$ 7
	0.06		0.01	
7.0	9.72	$\pm$	-0.006	$\pm$ 7
	0.14		0.01	
7.1	11.27	$\pm$	-0.007	$\pm$ 7
	0.19		0.02	
7.2	12.98	$\pm$	-0.007	$\pm$ 7
	0.19		0.015	

Table 5.12: Comparison of crosstalk parameters for HG00 different intensities_Ch03

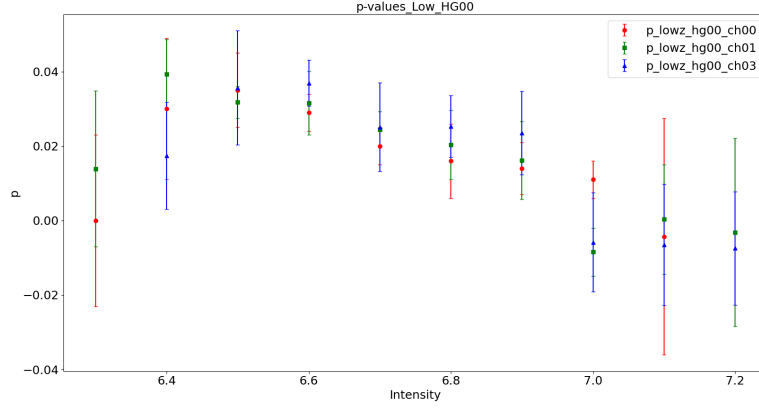


Figure 5.48: p-values for HG00 low-Z

Electrical and optical characteristics (Typ. Ta=25 °C, Vover=2.7 V, unless otherwise noted)

Parameter	Symbol	S14160/S14161 -3050HS-04, -08	S14160/S14161 -4050HS-06	S14160/S14161 -6050HS-04	unit
Spectral response range	λ	270 to 900			nm
Peak sensitivity wavelength	λ_p	450			nm
Photon detection efficiency at λ_p ^{*3}	PDE	50			%
Breakdown voltage	VBR	38			V
Recommended operating voltage ^{*4}	Vop	VBR + 2.7			V
Vop variation between channels in one product ^{*5}	Typ.	0.1			V
	Max.	0.2			
Dark current	Typ.	0.6	1.1	2.5	μ A
	Max.	1.8	3.3	7.5	
Crosstalk probability	-	7			%
Terminal capacitance	Ct	500	900	2000	pF
Gain	M	2.5×10^6			-
Temperature coefficient of recommended reverse voltage	Δ TVop	34			mV/°C

*3: Photon detection efficiency does not include crosstalk and afterpulses.

*4: Refer to the data attached for each product.

*5: The parameter is for the S14161 series (multichannel type)

Figure 5.49: Crosstalk value for low-Z 78

The p_value obtained is shown in Figure 5.48. Since the crosstalk is plotted as a function of overvoltage, the overvoltage is calculated as:

$$V_{\text{overvoltage}} = V_{\text{bias}} - V_{\text{breakdown}} \quad (5.32)$$

The breakdown voltage is 38V, and the bias voltage that we set was 39.5V. Therefore, the overvoltage is $V_{\text{overvoltage}} = 1.5\text{V}$ for low-Z SiPMs. The crosstalk value given in the datasheet 78 is 7% or 0.07 at $V_{\text{overvoltage}} = 2.7\text{ V}$. The p_value at 1.5 V can be calculated as

$$p_{\text{expected}} \approx 7\% \times \frac{1.5\text{ V}}{2.7\text{ V}} \approx 3.9\% \quad (5.33)$$

The average of the measured crosstalk for Ch00 is 0.017 ± 0.005 , 0.017 ± 0.004 for Ch01, and 0.018 ± 0.004 for Ch03 at $V_{\text{overvoltage}} = 1.5\text{ V}$. In terms of

percentage, the crosstalk for Ch00 is approximately $1.7\% \pm 0.05\%$, Ch01 is $1.7\% \pm 0.04\%$, and $1.8\% \pm 0.4\%$ for Ch03, which is less than the expected crosstalk estimated to be 3.9% approximately.

The value for p_expected calculated here is true only if the decrease is linear.

High Z HG00 CHANNEL 00			
Crosstalk Parameters			
Intensity (V)	L	p	Freedom
7.0	2.303 $\pm$ 0.088	0.06 $\pm$ 0.04	2
7.1	2.666 $\pm$ 0.118	0.052 $\pm$ 0.0467	2
7.2	3.087 $\pm$ 0.093	0.066 $\pm$ 0.04	3
7.3	3.455 $\pm$ 0.117	0.056 $\pm$ 0.04	3
7.4	3.870 $\pm$ 0.10	0.064 $\pm$ 0.034	4
7.5	4.271 $\pm$ 0.126	0.06 $\pm$ 0.034	4
7.6	4.856 $\pm$ 0.066	0.045 $\pm$ 0.016	4
7.7	5.327 $\pm$ 0.094	0.032 $\pm$ 0.02	3
7.8	5.81 $\pm$ 0.10	0.034 $\pm$ 0.021	4
7.9	6.3 $\pm$ 0.1	0.048 $\pm$ 0.02	7
8.0	6.84 $\pm$ 0.083	0.047 $\pm$ 0.015	6

Table 5.13: Comparison of crosstalk parameters for HG00 different intensities_Ch00

High Z HG00 CHANNEL 01				
Crosstalk Parameters				
Intensity (V)	L		p	
		Freedom		
7.0	2.25 ± 0.06	2	0.05 ± 0.03	
7.1	2.6 ± 0.06	3	0.07 ± 0.03	
7.2	2.99 ± 0.09	3	0.06 ± 0.03	
7.3	3.37 ± 0.11	3	0.06 ± 0.04	
7.4	3.78 ± 0.09	4	0.05 ± 0.03	
7.5	4.22 ± 0.10	4	0.05 ± 0.03	
7.6	4.84 ± 0.11	3	0.014 ± 0.024	
7.7	5.26 ± 0.09	4	0.034 ± 0.02	
7.8	5.68 ± 0.05	5	0.04 ± 0.01	
7.9	6.32 ± 0.085	6	0.03 ± 0.02	
8.0	6.83 ± 0.084	6	0.028 ± 0.015	

Table 5.14: Comparison of crosstalk parameters for HG00 different intensities_Ch01

High Z HG00 CHANNEL 02					
Crosstalk Parameters					
Intensity (V)	L		p		Freedom
6.8	1.98	±	0.07	±	2
	0.063		0.03		
6.9	2.41	±	0.05	±	2
	0.07		0.03		
7.2	3.86	±	0.04	±	3
	0.11		0.04		
7.3	4.36	±	0.06	±	6
	0.06		0.02		
7.4	4.96	±	0.044	±	4
	0.10		0.024		
7.5	5.52	±	0.04	±	4
	0.07		0.01		
7.6	6.11	±	0.03	±	4
	0.07		0.011		
7.7	6.81	±	0.03	±	6
	0.09		0.02		

Table 5.15: Comparison of crosstalk parameters for HG00 different intensities_Ch02

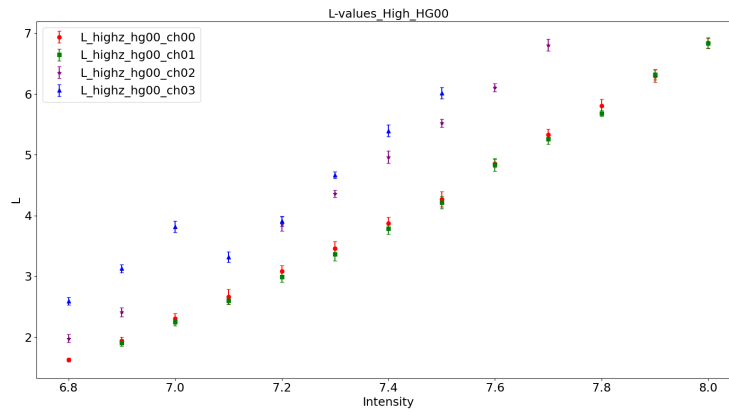


Figure 5.50: L values for high-Z HG00 fo all channels

High Z HG00 CHANNEL 03				
Crosstalk Parameters				
Intensity (V)	L		p	
6.8	2.5	$\pm$	0.044	$\pm$
	0.062		0.02	
6.9	3.13	$\pm$	0.05	$\pm$
	0.07		0.03	
7.0	3.82	$\pm$	0.02	$\pm$
	0.09		0.02	
7.1	3.32	$\pm$	0.13	$\pm$
	0.08		0.03	
7.2	3.90	$\pm$	0.11	$\pm$
	0.08		0.02	
7.3	4.67	$\pm$	0.08	$\pm$
	0.06		0.01	
7.4	5.40	$\pm$	0.07	$\pm$
	0.10		0.02	
7.5	6.02	$\pm$	0.08	$\pm$
	0.1		0.01	

Table 5.16: Comparison of crosstalk parameters for HG00 different intensities_Ch03

The overvoltage for high-Z SiPM is the following:
the $V_{breakdown}$ reported in [77] is $(38 \pm 3)V$ and the bias voltage that we set was $42.5V$.

$$V_{overvoltage} = 3V \quad (5.34)$$

for high-Z SiPMs

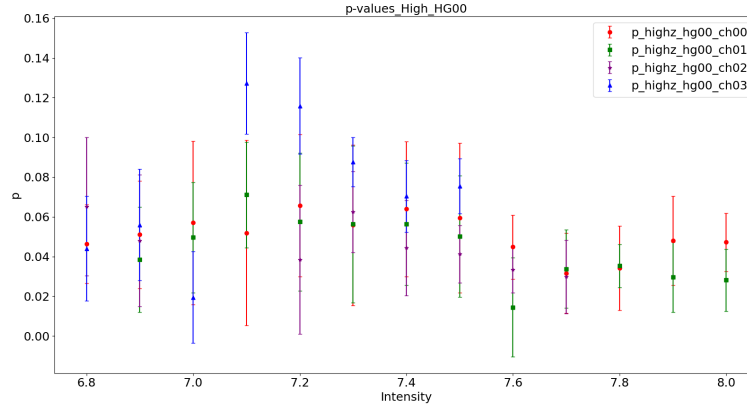


Figure 5.51: p-values for High Z

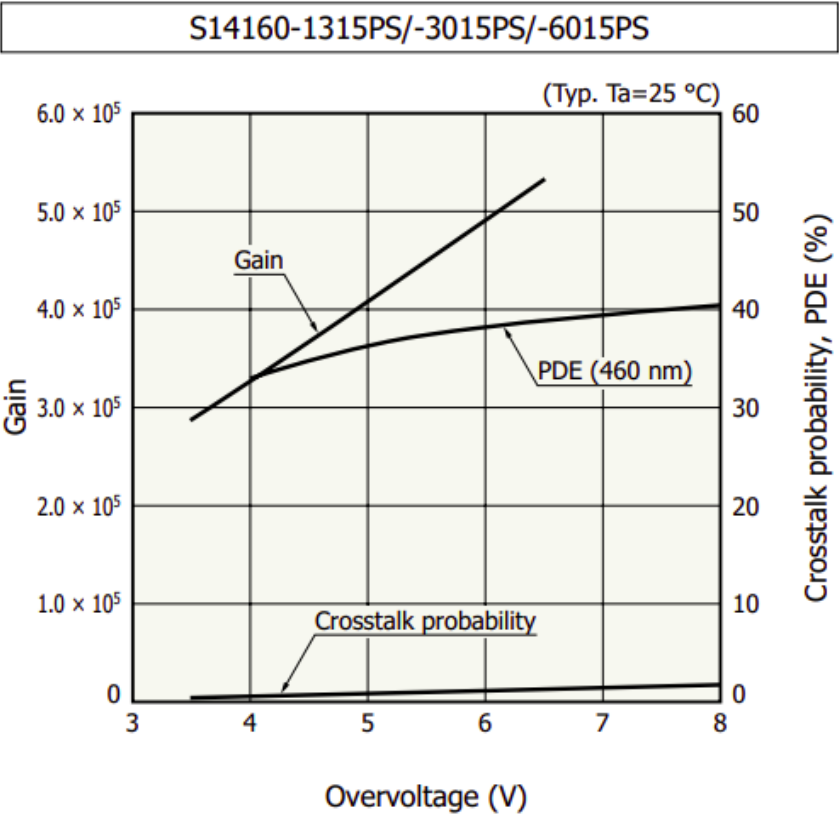


Figure 5.52: Crosstalk value for high-Z [77]

For the high-Z SiPM, the average crosstalk is 0.048 ± 0.009 for Ch00, 0.044 ± 0.008 for Ch01, 0.046 ± 0.008 for Ch02, and 0.073 ± 0.007 for Ch03. The two outliers are 0.11 and 0.13 for 7.1 V and 7.2 V for Ch03, which is an unusual behaviour compared to the rest of the intensities for the rest of the channels. From Figure 5.52, the crosstalk is around 0, which is in good agreement with the experimental results.

To summarise, L increases with the intensity of light, which is consistent with the fact that the number of photoelectrons increases with increasing intensity of light. This trend is observed for both kinds of SiPMs. Channel 03 of the high-Z SiPM shows a strange behaviour for L as well as for the intercept. Although L is higher for higher intensities for low-Z SiPM as compared to high-Z SiPM.

The crosstalk parameter p remains low across all intensities for both kinds of SiPMs. The increase in degrees of freedom with increasing intensity corresponds to the detection of more peaks.

Therefore, this indicates that the detector response is uniform for both SiPMs. Several studies have reported crosstalk studies, including [106] [107] [108] [109] [110] [111] and [112] to my knowledge. However, no existing studies were found that characterised crosstalk using the Vinogradov model for different intensities of light. Some publications reported crosstalk results for different SiPMs from Hamamatsu. In [113], the crosstalk for Hamamatsu-S14466 is taken as a reference with a crosstalk of 5%, [114] has reported a crosstalk of 4% for S14160-3050HS MPPC and [115] has shown crosstalk of Hamamatsu at 20°C, which is around 4%.

5.2.7 Threshold calibration

The threshold calibration was performed to determine the discrete photoelectron levels of the low-Z SiPMs using the BETA-ASIC readout. By scanning through the trigger values, the response increases in steps that correspond to integer multiples of photoelectrons. This parameter could not be calibrated for the high-Z configuration because the pre-amplifier offset could not be characterised Section 5.1.5. Dark count data were taken by changing the self trigger values from 0 to 90 in steps of 1 as shown in Figure 5.53. By doing a scan of the self trigger values, we can see at which threshold value the first photoelectron can be detected. This can be seen very clearly in Figure 5.53 for all the four channels. To obtain the trigger counts, the log scale of the self-trigger values are plotted as shown in Figure 5.54.

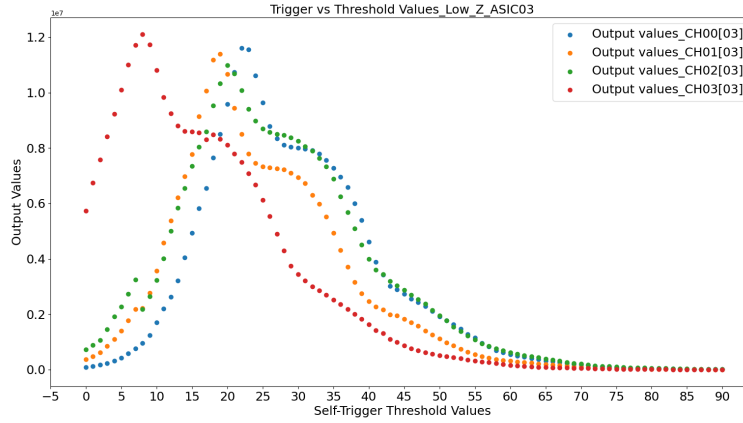


Figure 5.53: Self-trigger threshold values

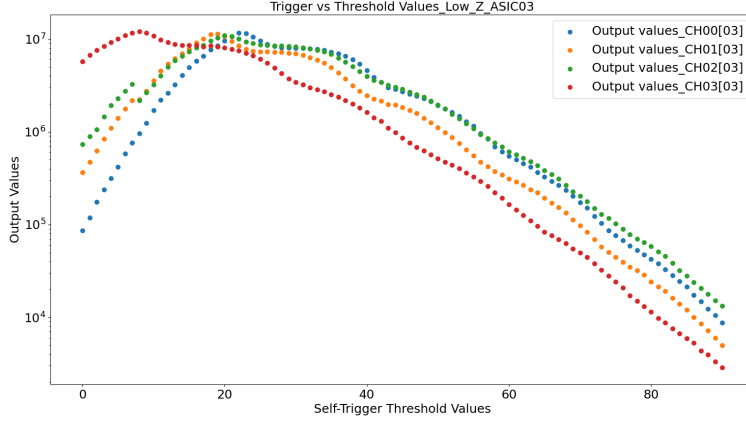


Figure 5.54: Self-trigger threshold values.logscale

In Figure 5.54, the idea is to see a step-function behaviour every time a multiple of one photoelectron is reached [116]. Ideally, the response would exhibit a staircase pattern, but all the channels show a smeared transition due to the noise in the dataset.

The second derivative on the trigger counts allows us to observe where the rate of change in events occurs most rapidly. This corresponds to the transition between the successive photoelectron levels. It is calculated using a Taylor expansion, and the Equation (5.35) is:

$$D_i \equiv \frac{d^2 N}{dx^2} \Big|_i \approx N_{i+1} - 2N_i + N_{i-1} \quad (5.35)$$

and the uncertainty is calculated using Equation (5.36):

$$\sigma_{D_i} = \sqrt{N_{i+1} + 4N_i + N_{i-1}} \quad (5.36)$$

To identify the threshold positions more precisely, the ratio between the second derivative and its corresponding error was calculated using Equation (5.37). This points out where this distribution changes sign from negative to positive, known as a 'zero crossing'.

$$R_i = \frac{D_i}{\sigma_{D_i}} \quad (5.37)$$

Only the peaks around where the $R_i \gg 0$ is selected for finding peaks. This ensures that the identified feature stands out against the background noise. Then the code performs a backward search (moving from right to left) to locate the first negative value where $R_i < 0$. This is the "crossed" zero-point. Once the two points are found where R_i is slightly negative and one where R_i is slightly

positive, a linear intercept is used to calculate the decimal value and find the exact value of R_i . The zero-crossing point x_{cross} , represents the centre of the photoelectron transition. It is calculated using Equation (5.38):

$$x_{cross} = x_i - R_i \left(\frac{x_{i+1} - x_i}{R_{i+1} - R_i} \right) \quad (5.38)$$

The trigger counts and their corresponding zero-crossings for all four channels are shown in fig. 5.55, fig. 5.56, fig. 5.57, and fig. 5.58.

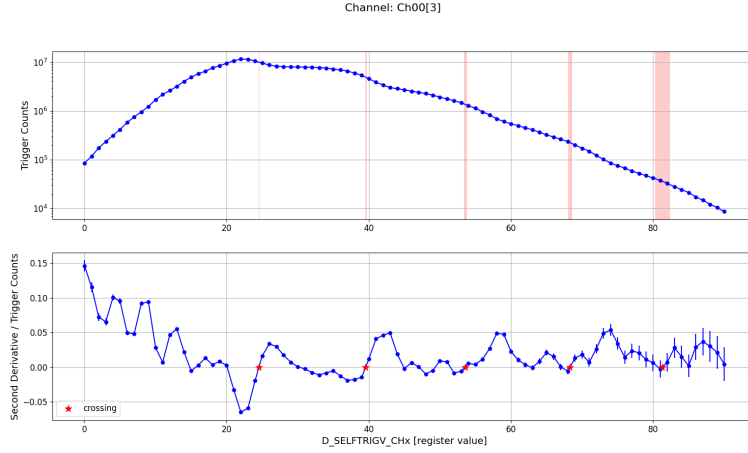


Figure 5.55: The zero-crossing and the corresponding self-trigger values for Channel 00

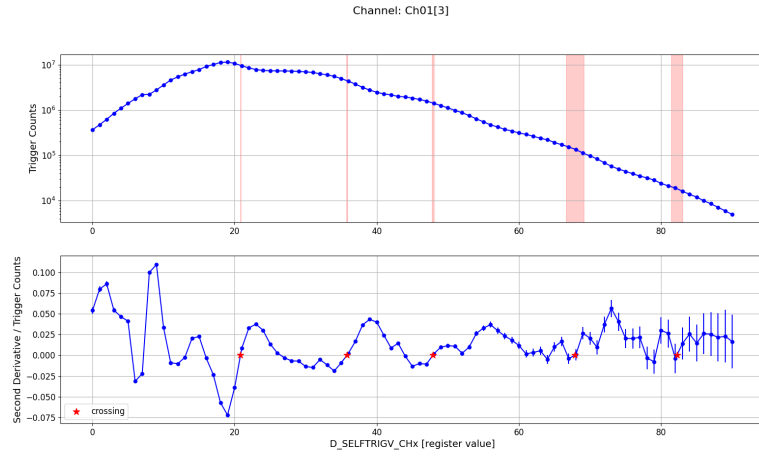


Figure 5.56: The zero-crossing and the corresponding self-trigger values for Channel 01

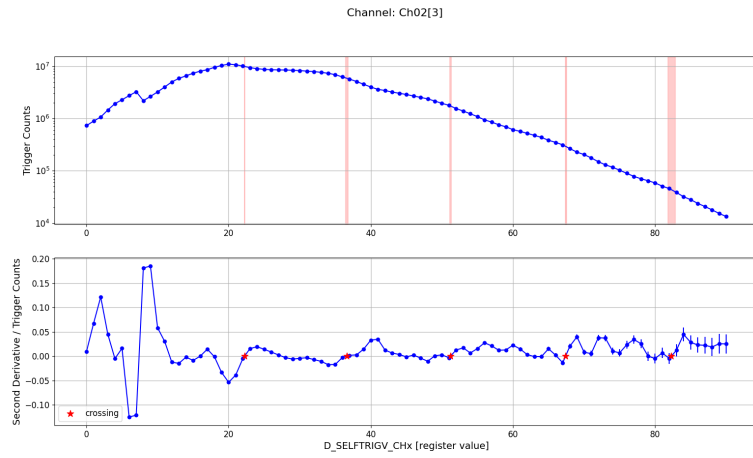


Figure 5.57: The zero-crossing and the corresponding self-trigger values for Channel 02

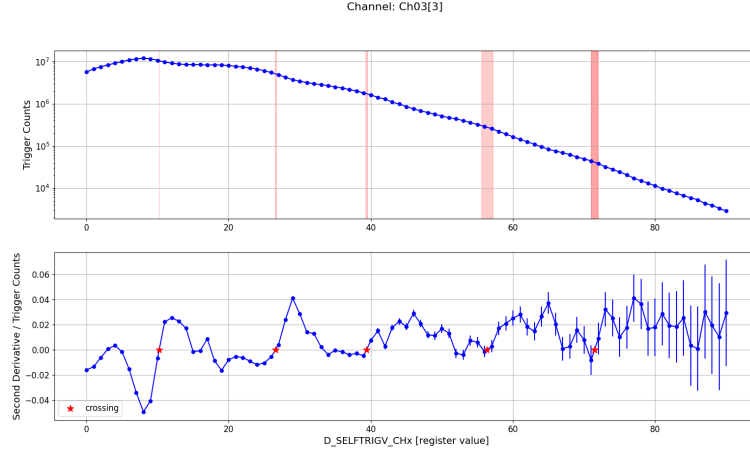


Figure 5.58: The zero-crossing and the corresponding self-trigger values for Channel 03

5.2.8 Threshold calibration results and discussion

Overall, this study demonstrates the identification of a very low number of photoelectrons as a function of the internal trigger of the system. It provides a direct correlation between the trigger values and the number of detected photoelectrons. Setting an appropriate trigger threshold is crucial for the detection of low-energy events, which is one of the objectives of the PSD for HERD Section 3.1.3. A similar study of the threshold calibration was performed for the S13360-3050CS MPPC using the 32-channel Citiroc 1A front-end evaluation system and was reported in this work [36]. Another paper in which threshold calibration was performed and reported is [117], where the photoelectron threshold was measured in millivolts and plotted as a function of frequency. Therefore, a direct comparison of results could not be made.

5.2.9 Overall results of this work

The scope of this work was to have a first assessment of the performance of the readout of the architecture. The first results from this work shows promising results and it can be used for further tests. The calibration factor was validated using two different methods, low values of SNR are promising, crosstalk results are in good agreement with the values stated in the datasheet and the threshold could be calibrated for the low Z SiPMs. The work was performed using only one configuration. In the near future, more tests with different configurations can be done and the results of a different configuration can be compared to the results obtained from this work. For future calibration activities, we can observe the performance of the optimised parameters under different circumstances like

testing the setup at a test-beam or with a radioactive source that will further enable us to quantify the parameters of the system. Furthermore, the operational implication of this work will be decided once the SiPMs are equipped to the scintillators and tested further. Apart from that, SNR and crosstalk will help us differentiate between the detected signal and noise. The measured SNR and crosstalk will have direct implications on the data processing framework of HERD. Lastly, some of the uncertainties that affected the measurements was temperature. Temperature was the biggest source of uncertainty affecting the calibration constants. In addition to temperature, any loose connection in the setup also affected the results. Therefore, it was important to check the complete setup everytime before taking new data. Another factor that can affect the calibration constant is the background light. Although the SiPMs were inside the black box, there were some openings for the cable connections. These openings were covered with a black cloth. However, it can be a source of uncertainty if not taken care of.

"It's very rare that things work the first time"

***Pierre Agostini
Nobel Prize in Physics 2023***

Conclusions & Future work

This thesis reports the configuration of the BETA-ASIC readout for low-Z and high-Z SiPMs in the context of charge particle detection using the plastic scintillator detector for HERD. The steps of configuration were followed chronologically to achieve optimised results. The goal of the optimisation was to set a good bias voltage where the peaks can be resolved and have a good ADC range. Although the configuration of the low-Z SiPMs was completed successfully, the configuration for the preamplifier offset for high-Z could not be completed due to data mixing between channels. This problem could not be resolved within the given timeline of this PhD. Consequently, the threshold could not be calibrated for the high-Z SiPM. The other three parameters, calibration factor, signal-to-noise ratio, and crosstalk - were calibrated for high-Z SiPMs. After the configuration was completed, the next step was to characterise the SiPMs. Data were acquired for different intensities to study a set of parameters. A total of four parameters were characterised for low-Z and three for high-Z SiPMs. Firstly, the data for different gain settings were used to study the calibration factor across low-gain setting and high-gain setting using betaPy. The calibration factor for the high-Z using this method could not be determined due to time constraints. betaPy is a powerful tool for determining calibration factors even when the peaks cannot be resolved. Finally, linearity plots for all channels were generated, showing the system response with respect to the capacitance change.

Next, a dedicated pipeline was built to study three parameters using the peak-detection method. They are the calibration factor, signal-to-noise ratio and crosstalk. The calibration factor obtained from betaPy and the calibration factor from this pipeline were compared for HG00 and HG01 for low-Z. The results for HG00 are in good agreement with each other, whereas for channel 00 for HG01, the results were inconsistent. An important factor to note is that the calibration factor is highly sensitive to peak selection. This can be noted in the plots in the appendix. For lower intensities, the calibration factor is smaller at low intensities because the peak close to the pedestal are close to each other. This is the characteristics of the detector and amplifier. This is also seen in the calibration factor plots as a function of the intensity.

The second parameter that was studied was the SNR. The SNR was studied for HG00 for both low-Z and high-Z SiPMs. A linear fit was applied to the SNR values and the extracted parameters, slope and intercept, were plotted for all

intensities. Slopes show a consistent value across the entire dataset. The intercepts are consistent between zero and -1 when the peak numbers are low. As the peak number increases, the intercept becomes more negative. Here, channel 03 does not show a consistent behaviour as compared to the rest of the dataset. Further analysis is needed to understand this discrepancy. Although many publications have reported SNR values, none have provided results that are suitable for a direct comparison with the results obtained here.

The last parameter studied using this pipeline is the crosstalk. A Vinogradov model was fitted to the data, and the crosstalk values obtained are in good agreement with the datasheet specifications as well as some of the publications cited. Although none of the publications has reported using the Vinogradov model to study the crosstalk. A limitation of this pipeline is that it cannot be used where peaks cannot be resolved.

Once this entire analysis was completed, the last calibration performed was the threshold calibration for low-Z SiPMs. It identifies the transition points between consecutive photoelectrons. Some publications have reported this calibration. However, the results could not be compared, as the threshold was calibrated as a function of different parameters in different publications.

To summarise the key takeaways, selecting a good bias voltage provided a good dynamic range to characterise the SiPMs. The calibration factor was determined using betaPy in the entire low-gain and high-gain setting. The study of signal-to-noise ratio shows a consistent behaviour across varying light intensity for both kinds of SiPMs, and the crosstalk measurements are in good agreement with the datasheet specifications. Threshold calibration for low-Z SiPMs enabled the identification of the internal trigger counts corresponding to the transition points for the low photoelectrons detected. Overall, this work establishes a solid groundwork for the characterisation of SiPMs, laying the foundation for further work. This work contributes to the Technological Readiness Level (TRL 4) of the HERD detector. TRL, as defined by NASA, refers to the 'component or basic technology validated in a laboratory environment'. The other potential applications where this readout architecture can be useful are the future space detectors. The future space-based architecture can adapt our readout architecture to their setup. Apart from space-based detectors, this readout architecture can find applications in medical imaging, drones and tomography. The calibration procedures for SiPMs are standardised, and this work can be reproduced by the scientific communities and industries alike.

An initial roadmap for the configuration of the readout and the calibration of the SiPMs has been drawn. There is scope for further tests and improvements in the near future.

To start with, the remaining tests for setting the preamplifier offset and the low-pass filter need to be done. This will enable the threshold calibration to be performed for the high-Z SiPMs. The calibration factor can be studied using betaPy for the high-Z SiPM and can be compared to the results obtained here. Only the calibration factor for HG01 for Low Z has been reported here, and their SNR and crosstalk can also be studied by taking data at lower intensities and identifying the first photoelectron.

All the results reported here have been performed at room temperature. The entire characterisation process can be performed in a temperature-controlled environment. A range of temperatures can be selected to study the same parameters mentioned above. Since temperature is one of the most important parameters for spaceborne detectors, the dynamic range, linearity of the system, calibration factor, signal-to-noise ratio and crosstalk can be studied across the different temperatures, and observe the performance of the SiPM and its readout and study its systematic uncertainties. Once the laboratory parameters have been characterised, the SiPMs can be further equipped to the PSD bar and examined at the test beam facilities at CERN, Switzerland. This will give a good estimation of their performance when exposed to a high radiation environment.

This is a first-of-its-kind study (the combination of a BETA-ASIC readout board with two different Hamamatsu models - S14160-3050HS and S14160-1315 for low Z and high Z, respectively) that shows promising results. Although this work was performed in the context of HERD, it can find application where high photon detection efficiency, volume, cost and power are the deciding parameters. Taking into account that various new technologies are being tested around the world for different projects, BETA-ASIC and Hamamatsu SiPMs have the potential to be a strong contender for future space-based astroparticle detectors.

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