

Master thesis

Studies of readout electronics and optical elements for a gamma-ray telescope

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Abstract

All along the 20th century, astronomy has been extended to the whole electromagnetic wavelengths, allowing to discover new sources and new astrophysical phenomena. To detect the highest energy part of the electromagnetic spectrum, space-based instruments such as the instruments on board of the Fermi Gamma-ray Space Telescope are used. But above a few hundred GeV, the acceptance of space-based detectors is no more sufficient, forcing us to develop ground-based facilities. Since the atmosphere is opaque to γ -rays, indirect ways of detecting this radiation had to be developed. When entering the atmosphere, a high energy photon generates an electromagnetic shower. The charged particles, electrons and positrons, composing the showers, emit Cherenkov light which can be detected using Imaging Atmospheric Cherenkov Telescopes (IACTs). This technique was pioneered by Whipple since 1968. During the following decades, arrays of a few Cherenkov telescopes have been developed.

The first large scale Cherenkov observatory, that will be made of almost 150 telescopes distributed in the two hemispheres, is under development. In order to cover a wide range of energies, this observatory, called the Cherenkov Telescope Array (CTA), will employ three different sizes of telescopes. The smallest telescopes, with a diameter of about 4 meters, will be mainly sensitive to the highest energies that CTA will span, that is from a few TeV to a few hundreds of TeV. Three prototypes of telescopes have been developed for the small-sized telescopes (SST). Two of the prototypes are dual mirror telescopes, while the third, the SST-1M, is a single mirror telescope. The SST-1M telescope has been developed by a sub-consortium composed of institutes from Poland, Switzerland, and Czech Republic. The telescope structure and optical elements have been conceived in Poland and Czech Republic, respectively, while the SiPM-based digitizing camera has been designed at the University of Geneva.

A first prototype of telescope and camera has been built, and has been successfully operated to observe gamma events in 2017 and 2018. Nevertheless, the CTA requirement for the camera global detection efficiency (conversion efficiency from photons to photo-electrons, including the sensors, the light guides, and the entrance window) weighted by the Cherenkov spectrum in the range 300-550 nm has been set to 20%, which was not reached by the first prototype camera. This large value has challenged the SST-1M project and required dedicated studies of the possible solutions that can be adopted to achieve the required optical efficiency. A solution to achieve such optical efficiency for the whole camera is to upgrade the sensors by using SiPM that have a higher photo-detection efficiency (PDE) than the one currently used for the prototype. Another solution to improve the optical efficiency would be to improve the transmittance spectrum of the entrance

window of the camera (that protects the photo-detection plane from the dust and allows to filter the night sky background (NSB) above 550 nm) between 300 and 550 nm.

Two possible Hamamatsu SiPMs have been investigated to upgrade the camera photo-detection plane. The LCT5 sensor, based on the Low Cross Talk Hamamatsu technology, would bring the PDE to 48% at 8% optical cross talk. The current sensor used for the prototype (LCT2), based on the same technology, has a PDE of 34% at 8% crosstalk. Another solution would be to change the sensor for the LVR3, based on Hamamatsu Low Voltage Resistor technology, bringing the PDE to 52% at 8% crosstalk. The LVR3 sensor, having a large microcell capacitance compared to the LCT2 (128fF vs 85 fF), is expected to produce long pulses, that could not fit with the 30 ns integration window required by CTA. An electronic simulation of the LVR3 sensor using the Corsi model coupled to the preamplification front-end electronics has been performed, using the Cadence PSpice® simulation software. The elements of the circuitry have been fine-tuned to optimize the pulse shape to get a well-behaved exponentially decaying shape with the shortest achievable decay time. Even with the optimisation of the circuit, the best achievable pulse shape has a recovery time of about 170 ns, which does not fit with the integration window. The pulse shape has been measured to test the reliability of the model. The measured pulse shapes are even longer than the simulated one, this difference being due to the bad simulation of the OPA (Operational Pre-Amplifier) that consists of a black box made of transfer functions provided by the manufacturer (Texas Instrument).

Since the pulse of the LVR3 sensor is too long even after optimisation of the circuit, a solution to sharp the waveform has been considered. An ASIC called MUSIC (Multiple Use SiPM Integrated Circuit), developed at the University of Barcelona for SiPM readout, implements an option to reduce considerably the length of the pulse thanks to a shaper circuit. This ASIC has first been characterized coupled to a 3x3 mm² LVR3 SiPM. Satisfactory pulse shapes, with recovery time of less than 30 ns, can be easily achieved using the so-called Pole Zero Cancellation (PZC). When going to a 6x6 mm² LVR3 SiPM, the photon counting capability can only be achieved by considerably increasing the over-voltage and hence the crosstalk probability to more than 15%. This is not suitable for our application since the sensors in the camera are operated with a 8% crosstalk probability. The LCT5 sensor (microcell capacitance of 101fF) has therefore been tested with the MUSIC ASIC, since it also has a longer pulse shape than the LCT2 sensor. The application of the PZC on the LCT5 sensor allows to achieve easily pulses shorter than 30 ns, and single photon sensitivity is achieved without increasing the over-voltage. The linearity of the LCT5 sensor coupled to MUSIC has been measured. It appears to have a predictable behavior in saturation. The LCT5 sensor could therefore be a good solution to upgrade the photo-detection plane of the camera with the MUSIC ASIC as preamplification stage. Furthermore, the measured pulse shapes for different configurations of cancellation match very well with the simulation of the ASIC performed by the team of Barcelona.

A second solution to improve the overall optical efficiency has been investigated. A new entrance window has been produced and its transmittance spectrum and uniformity across its surface have been characterized. The transmissivity of this window compared to the first prototype has been improved, but not sufficiently to achieve the 20% camera efficiency just by changing the entrance window and without also upgrading the photo-sensors. Upgrading the sensor to LCT5 would, however, bring the optical efficiency to

about 25%. The uniformity of the new window is better than for the first one installed on the camera prototype. The impact of the non-uniformity of the window on image reconstruction has been studied. Even though the impact on the image reconstruction is negligible, a correction for this non-uniformity has been implemented in the camera pipeline that is used to process the data.

The first chapter of this thesis introduces the use of Cherenkov telescopes in gamma-ray astrophysics and describes the CTA project, especially the SST-1M telescope. The working principle of a silicon photo-multiplier (SiPM) is discussed in a second chapter. The third chapter describes the simulation work that has been performed to optimize the coupling between the camera front-end electronics and a new type of sensor with increased PDE. The characterization of the MUSIC ASIC is discussed in the fourth chapter. Finally, the measurement of the entrance window and the impact of non-uniformity on image reconstruction are discussed in a fifth chapter. Overall conclusions and outlooks are discussed at the end of this thesis.

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High Energy Astrophysics with the CTA Experiment

Throughout the ages, man has always been fascinated by the night sky. The existence of ancient buildings dating back nearly 5000 years, such as the Egyptian pyramids or megalithic stone alignments (e.g. that of Stonehenge, UK) edified according to some astronomical landmarks, is proof that astronomy is one of the oldest sciences. But it is from the end of the Renaissance that astronomy experienced a significant evolution, especially with the introduction of the heliocentric model by Copernicus or the laws governing the planetary motion by Kepler. It is during this same period that astronomers (Galileo Galilei among others) began to observe the sky with optical telescopes, marking the beginning of a new era for astronomy.

The use of optical instruments allows the observation of celestial objects invisible to the naked eye. It is first the planets of the solar system as well as some of the brightest nebulae that are studied by astronomers, who draw their observations by hand. Increasingly large and powerful telescopes are being built, giving access to more astronomical sources, but also to more distant sources. Space telescopes are also constructed (e.g. the Hubble Space Telescope) to avoid atmospheric turbulence. Data acquisition has also been improved through the development of photographic equipment at the end of the 19th century, and later through the design of digitizing detectors such as CCD cameras.

Visible light is the only source of information in astronomy until the beginning of the 20th century. It is mainly during the last century that the observations have been extended to the rest of the electromagnetic spectrum (Radio waves, InfraRed, UltraViolet, X-rays, γ -rays), thus allowing to gather more information about astronomical sources, including their composition and the different physical phenomena that govern these sources. This enlargement of the observational window led to the discovery of new extremely energetic sources such as radio galaxies, pulsars and quasars. Images of our galaxy at different wavelengths are shown in figure 1.

Nowadays, photons are not the only information carriers that can be used to study our universe. In 1912, Victor Hess figured out that the ionisation rate increases with the altitude, which is the evidence for a radiation of cosmic origin. This radiation, called cosmic rays, is a new way to see our universe. Cosmic rays are mainly composed of

protons, antiprotons, electrons, positrons, neutrons, and atomic nuclei. In 1987, the first neutrinos from a supernova have been detected by three neutrino experiments, including Kamiokande, giving birth to neutrino astronomy. More recently, the detection of gravitational waves from merging neutron stars opened a new field in astrophysics, offering a new approach to probe the cosmos. With all these different types of cosmic messengers, multi-messenger astronomy allows to study a wide range of aspects of astronomical sources.

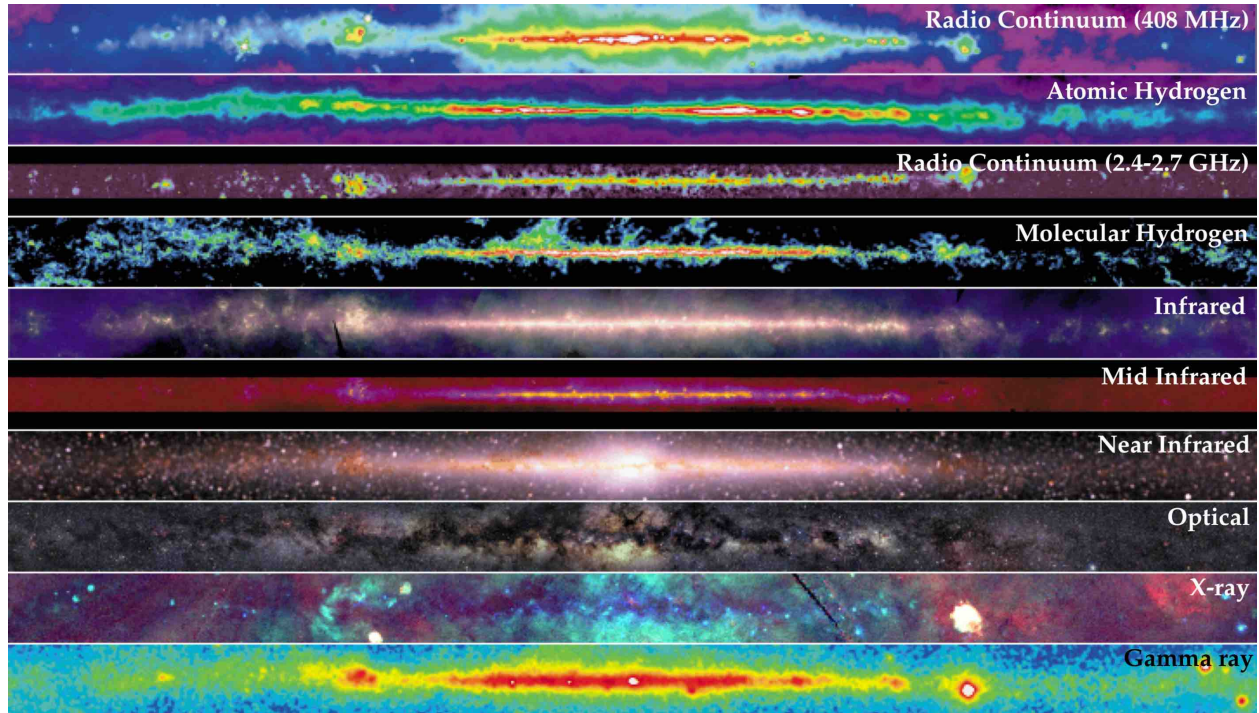


Figure 1. Multi-wavelength Milky Way Images (Credit: NASA)

As can be seen in figure 2, only visible light (including near IR and near UV) and radio waves can be detected on the ground using optical or radio telescopes. Indeed, other wavelengths are absorbed by the atmosphere, forcing us to send instruments into space to study the high energy part of the electromagnetic spectrum. Even if using space telescopes (e.g. the Fermi Gamma-ray Space Telescope) allows very low background noise, the effective area ($\sim 1 \text{ m}^2$) is limited by the mass that can be sent in space. But even if the atmosphere blocks gamma rays from reaching the ground, it can actually be used as a calorimeter. Gamma photons entering the atmosphere engender electromagnetic showers made of photons, electrons, and positrons. Incident gamma-ray photons being highly energetic, relativistic charged particles in the shower travel faster than light in the surrounding medium. This induces the emission of UV/blue light cones by the charged particles (the so-called Cherenkov effect) that can be detected from ground using telescopes. Gamma-rays can therefore be indirectly observed from ground using the Imaging Atmospheric Cherenkov Technique (IACT). Despite the enormous hadronic background noise of such detection, it has the advantage of having a huge effective area ($\sim 10^5 \text{ m}^2$), which allows to probe very high energies.

The current generation of IACT experiments, consisting of H.E.S.S., MAGIC, and VERITAS, has widened the field of investigation of the cosmos to extreme energies with the detection of more than 200 sources¹ and many new types of cosmic sources at TeV scale (SNR, PWN, ISM, galactic center, binary systems, star cluster, radiogalaxies, blazars, AGN, and new types of sources). The future Cherenkov Telescope Array (CTA) experiment, legacy of the experiments mentioned above, will allow to investigate in detail the TeV region thanks to its hundreds of telescopes. CTA will increase the sensitivity by one order of magnitude compared to the current observatories, while having a better angular resolution. Being spread over two sites (one per hemisphere), the CTA telescopes will be able to cover most of the sky. With its three different sizes of telescopes, the array will cover a wide range of energies, from 20 GeV, overlapping the energy range of Fermi, to the unexplored 300 TeV. The smaller telescopes, the SSTs, are covering the most energetic part of the CTA energy range. One of the three proposed designs for the Small-Sized Telescope of CTA is the single mirror SST-1M telescope, whose mechanical structure has been developed in Poland and optical systems in Czech Republic. The camera mechanics and photosensor plane has been designed and assembled by the University of Geneva, Switzerland.

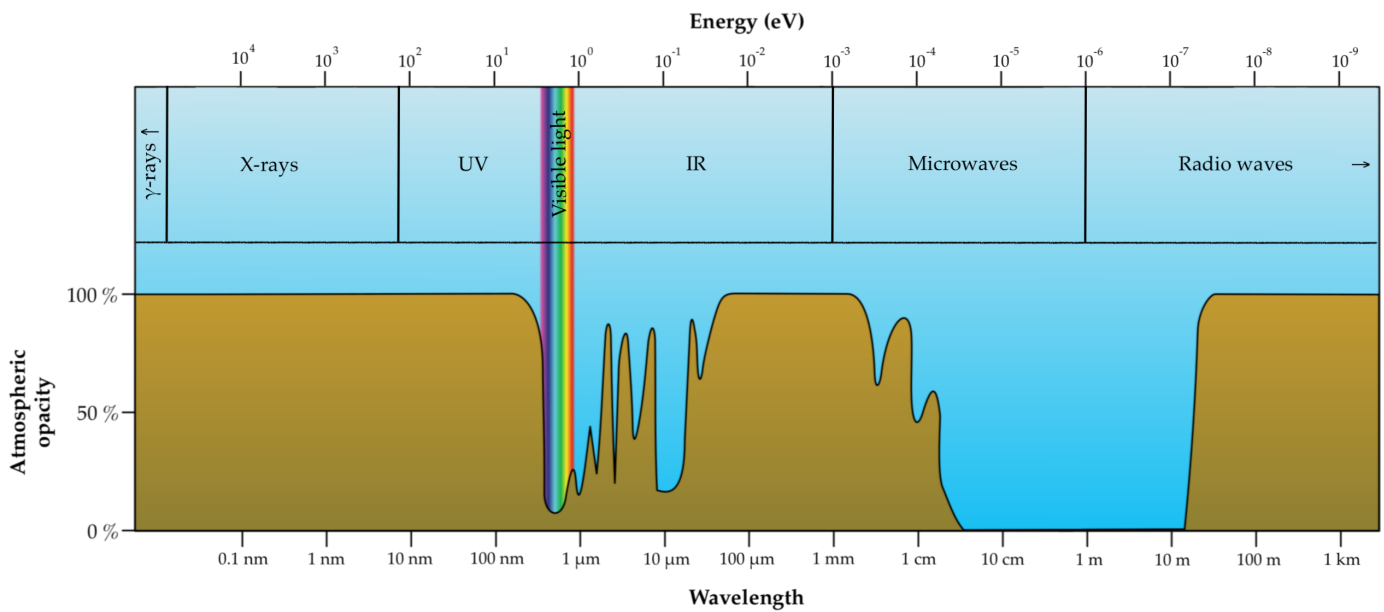


Figure 2. Atmospheric opacity to electromagnetic radiation
(Original picture credit: NASA)

In this chapter is first discussed the physics of gamma-rays, from their emission to their arrival on Earth. The Imaging Atmospheric Cherenkov Technique is then described so as the current IACT experiments. The future CTA experiment performances and its scientific goals are subsequently depicted. Finally, the working principle of the SiPM-based digitizing camera of the SST-1M telescope is detailed.

¹<http://tevcat.uchicago.edu>

1 Gamma-Ray Astrophysics

Gamma-rays form the most energetic part of the electromagnetic spectrum, with photon energies above 100 keV. Gamma-rays are detected up to hundreds of EeV ($\sim 10^{20}$ eV). Hence, it is useful to split this huge energy interval into energy sub-bands. Consequently, photons usually detected from space are divided into low/medium energy (from 100 keV to 30 MeV) and High Energy (from 30 MeV to 100 GeV) ranges. Gammas typically detected via ground-based experiments are conventionally distributed into two ranges: the Very High Energy (VHE) range from 100 GeV to 100 TeV and the Ultra High Energy (UHE) photons with energies above 100 TeV.

Observing simultaneously an astrophysical object over the whole electromagnetic spectrum, from radio to γ -rays, is very important to understand the physical processes involved within the source. Even though this implies to work with different observational techniques because of the wide range of energy, it is more suitable to represent the quantity of emitted energy by the source in a given range of the spectrum in a universal way. The emission of an object is therefore expressed by the Spectral Energy Distribution (SED), which is a plot of the flux density $\nu F(\nu)$ versus the frequency. $F(\nu)$, measured in units of $\text{erg cm}^{-2}\text{s}^{-1}\text{Hz}^{-1}$, is the energy received on a given surface per unit of time in a given frequency range $\Delta\nu$. Equivalently, with the spectrum $\frac{dN}{dE}$, the SED can be defined as the plot of $E^2 \frac{dN}{dE}$ ($= \nu F(\nu)$) as a function of energy, N being the photon number density

The underlying physical processes in gamma-ray sources and the possible high-energy astrophysical sources themselves are discussed in this section.

1.1 Gamma-Ray Production Processes

Interaction between high-energy charged particles (for instance, electrons accelerated by the shock waves of a supernova remnant) and magnetic fields or molecular clouds can produce highly energetic photons. But gamma-rays can also be generated by decaying heavy particles. Two classes of production mechanism are then notable: those purely leptonic, and models in which photons are produced via hadronic interactions. The latter allows to gather information about acceleration sites of cosmic rays, since these are deflected by galactic magnetic fields and thus do not directly pointing back to their source. Apart from leptonic and hadronic models of gamma-ray production, there exist some more exotic models such as nuclear transformations, matter-antimatter annihilation or dark matter annihilation.

1.1.1 Leptonic Gamma-Ray Production

The elementary astrophysical leptonic model is the so-called Synchrotron Self-Compton (SSC) mechanism. Ultra-relativistic electrons accelerated in a magnetic field within the source emit Synchrotron Radiation (SR), also known as magnetobremsstrahlung, creating a peak in the energy spectrum from the infrared to X-rays. These soft photons produced by SR subsequently interact with their parent electrons via Inverse Compton scattering (IC). Inverse Compton scattering is the scattering of a low-energy photon with a high-energy electron, that transfer part of its kinetic energy to the former. This second process

is responsible for a second peak in the GeV-TeV region of the energy spectrum. Both mechanism are illustrated in figure 3.

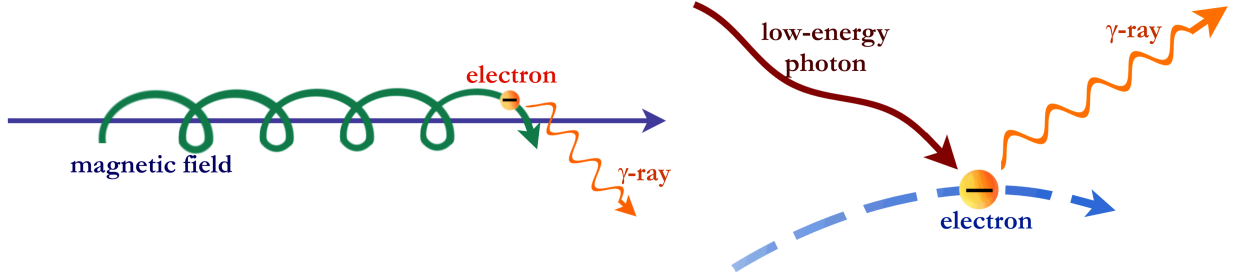


Figure 3. Synchrotron radiation and Inverse Compton scattering (Credits: CXC, S.Lee)

To understand the shape of the spectrum corresponding to SR and IC mechanism, we first assume the energy spectrum of the parent electrons to follow a power law of spectral index γ_e : $\frac{dN}{dE} \propto E^{-\gamma_e}$. To better describe its behavior, the spectrum generated by leptonic model, sketched in figure 4, is separated in four regions designated by I, II, III, and IV.

The synchrotron part of the spectrum is describe by a power law:

$$E^2 \frac{dN}{dE} \propto E^{(-\gamma_e+1)/2} \quad (1)$$

This expression is diverging at small energies. Actually, it describes the falling part of the synchrotron peak (II), which also exhibit a dependency on the magnetic field: $E^2 \frac{dN}{dE} \propto B^{(\gamma_e+1)/2}$. This infrared divergence can be revised by thermodynamical considerations. Since the brightness temperature of a source cannot exceed the kinetic temperature of the emitting electrons, part of the synchrotron radiation is absorbed via synchrotron self-absorption by the surrounding matter. In the low-energy Rayleigh-Jeans limit, this leads to the following behavior for branch I:

$$E^2 \frac{dN}{dE} \propto E^{5/2} \quad (2)$$

To be noted that in this region the magnetic field dependency of the flux density is also different: $E^2 \frac{dN}{dE} \propto B^{1/2}$.

At low energy, the Inverse Compton scattered photons have a spectrum of the form (region III):

$$E^2 \frac{dN}{dE} \propto E \quad (3)$$

For the highest energy part, the ultra-relativistic Klein-Nishina limit has to be considered, leading to a distribution of the form:

$$E^2 \frac{dN}{dE} \propto E^{-\gamma_e} \ln(E) \quad (4)$$

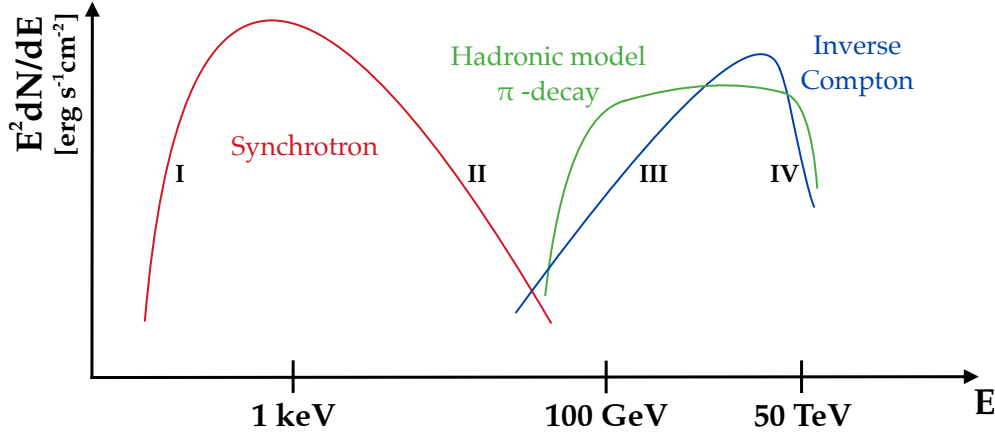


Figure 4. Spectral Energy Distribution of high-energy photons produced in leptonic/hadronic models (Adapted from [4])

An important feature of the SSC model is the correlation between synchrotron radiation and inverse Compton processes. This interplay between those two processes determines the position and amplitude of the corresponding peaks in the SED. Magnetic field strength plays an important role in this connection between SR and IC mechanisms. Indeed, emission of synchrotron photons leads to inverse Compton scattering but reduces in the meantime the energy of the parent electrons available for this same inverse Compton scattering. In turn, up-scattered photons reduces the amount of energy available for the electrons to emit synchrotron radiation. A faithful model of the physical processes governing the sources allows to access object parameters such as the amount of electrons, the strength of the magnetic field, and the spectral index of the electron.

The power loss for synchrotron radiation and inverse Compton mechanisms are given by, respectively:

$$P_{\text{synch}} = -\left(\frac{dE}{dt}\right)_{\text{synch}} = \frac{4}{3}\sigma_T c \gamma^2 \beta^2 u_B \quad (5)$$

and:

$$P_{\text{IC}} = -\left(\frac{dE}{dt}\right)_{\text{IC}} = \frac{4}{3}\sigma_T c \gamma^2 \beta^2 u_{\text{rad}} \quad (6)$$

where $\sigma_T = \frac{8\pi e^4}{3m_e^2 c^4}$ is the Thomson cross section, $u_B = \frac{B^2}{8\pi}$ is the energy density of the magnetic field, and $u_{\text{rad}} = Nh\nu$ is the photon energy density.

1.1.2 Hadronic Gamma-Ray Production

High energy photons can also be generated via pion decay in hadronic showers induced by accelerated protons or nuclei. The neutral pion can be produced via two main processes. On one hand, pion can be generated in proton-proton collisions:

$$p + p \rightarrow \pi^\pm, \pi^0, K^\pm, K^0, p, n, \dots \quad (7)$$

This kind of interaction happens when accelerated hadrons collide with target nucleons, e.g. molecular clouds. Such mechanism is known as the astrophysical beam dump. On the other hand, beam of high energy hadrons can interact with a sea of soft photons, referred as hadronic photo-production. This mechanism takes place through the Δ^+ resonance:

$$p + \gamma \rightarrow \Delta^+ \rightarrow \pi^0 + p \quad (8)$$

Neutral π^0 mesons decay into a pair of gamma photons:

$$\pi^0 \rightarrow \gamma\gamma \quad (9)$$

High energy neutrinos can also be produced by similar processes: the interaction between hadrons and low-energy photons (8) can produce charged pions along with neutrons. Charged pions generated by (7) or (8) undergo a decay chain made of charged leptons and neutrinos.

In the case of a source smaller than the meson interaction length but larger than the proton mean free path, high energy neutrinos and photons are produced via the same mechanism. Hence, there is a strong relationship between energy spectrum of primary cosmic rays, neutrinos, and photons (in terms of spectral indices: $\gamma_{CR} \sim \gamma_\nu \sim \gamma_\gamma$ if we neglect the absorption of photons). Thus, measuring gamma-ray SED provides important constrain on the expected neutrino flux and is a valuable source of information on cosmic rays.

In the rest frame of the neutral pion, the two gammas produced in (9) share the 135 MeV mass of the pion. Considering isotropic angular distribution of the emitted photons (since π^0 has spin 0), one finds the photon spectrum ([4]):

$$\frac{dN}{dE} = \frac{1}{2\beta\gamma p_\gamma^*} \quad (10)$$

where p_γ^* is the momentum of one of the photons in the pion frame.

The formula (10) being constant for a given pion energy, the distribution of the number of photons is constant over the energy range $[E_{\min}, E_{\max}]$, as depicted in figure 4. This feature of the SED is called pion-decay bump.

By kinematic considerations, the energy range of the photon in the laboratory frame is found to be constrained by $E_{\min}^{\max} = \frac{E_\pi}{2}(1 \pm \beta)$.

Another possible way to hadronically originate photons is via synchrotron radiation of the proton. Since the proton is ~ 1836 times heavier than the electron, it is obvious from (5) that the power loss via proton synchrotron radiation has a fainter contribution to the spectrum due to the m^{-2} behavior of the Thomson cross section.

1.2 Possible Gamma-Ray Sources

The biggest amount of gamma-rays come from the galactic plane, whose center is especially luminous at very high energies. More than two hundred sources have been measured at TeV energies until now. As shown in figure 5, a significative fraction of these VHE sources are located in the galactic plane, with the super massive black hole Sgr A* in the center. In addition to the galactic gamma-rays, TeV emissions are also detected from extragalactic sources.

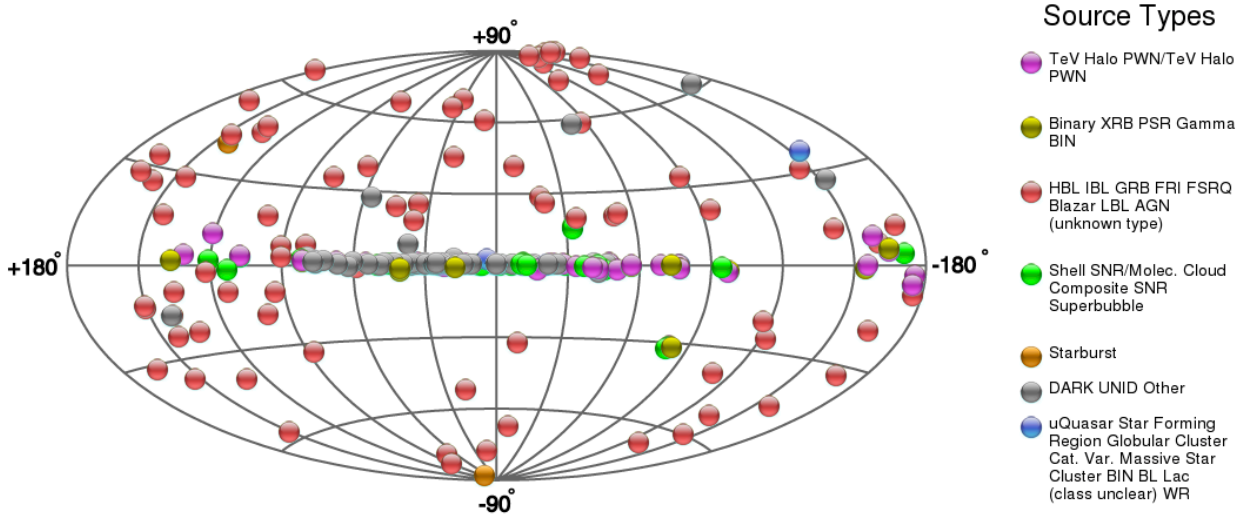


Figure 5. Sky map of the discovered VHE gamma sources
(Credit: [TeVCat catalog](#))

The principal classes of galactic and extragalactic VHE sources are discussed here.

1.2.1 Galactic sources

The advantage of studying galactic sources is that their detailed morphology can be studied due to their proximity. The most common sources in the galaxy are the supernova remnants (SNRs). They constitute the structure left by the explosion of massive stars. Two types of SNRs can be distinguished: the shell-type SNRs, consisting of a nebula without core, and the pulsar wind nebulae (PWN), where a rotating magnetized neutron star (pulsar) constitute the core of the surrounding shell. A neutron star is a very dense object with a mass comparable to that of our Sun for a diameter of about 10 km.

The best know VHE galactic source is a PWN called the Crab source. It consists of a pulsar, observable in the X-ray band, surrounded by a shell nebula visible via optical instruments (see figure 6). The Crab nebula, discovered in 1054 by a Chinese astronomer and located at less than 2 kpc in the Taurus constellation, is a very bright and steady source, emitting photons in all wavelengths from radio to gamma. This is the reason why it is used as a "cosmic candle" to calibrate ground-based and spatial instruments. The SSC behavior can be recognized on the spectrum of the Crab source, shown in figure 6.

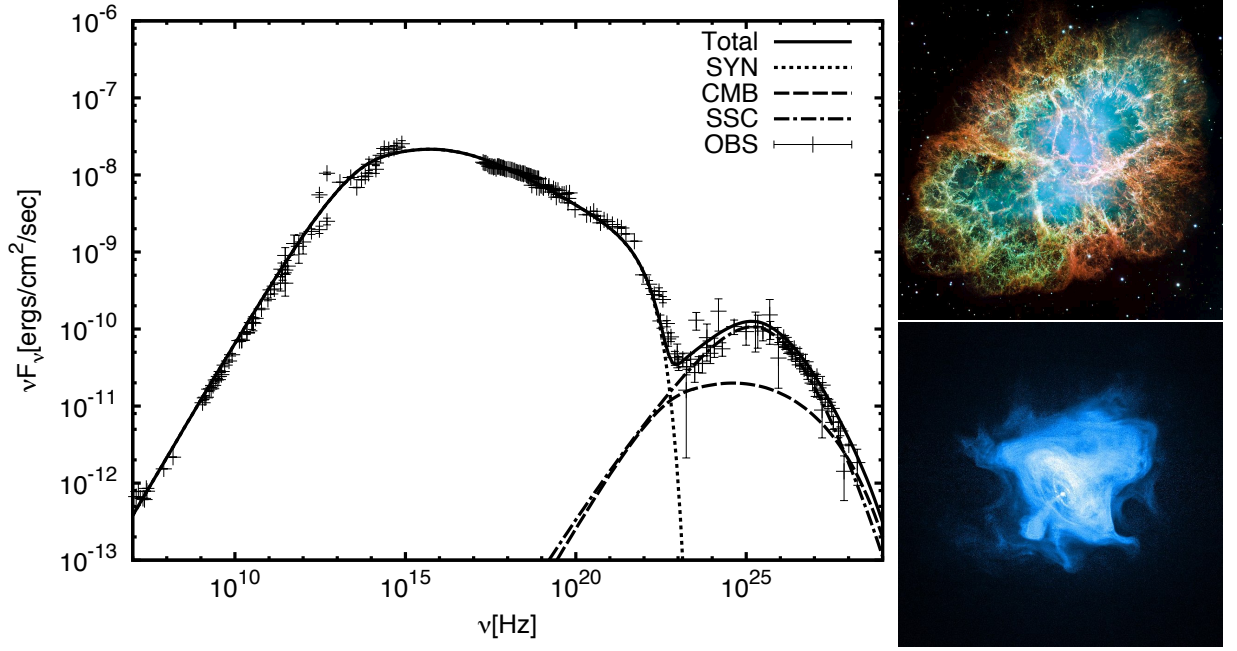


Figure 6. Spectrum of the Crab source (left, Credit: [arXiv:1004.3098](https://arxiv.org/abs/1004.3098)), Crab nebula (upper right, Credits: NASA/ESA/J. Hester and A. Loll), and Crab pulsar (lower right, Credits: NASA/CXC/SAO/F.Seward et al.)

Another common type of galactic sources emitting gamma-rays is the binary systems, where a normal star (usually a white dwarf or a blue giant) is accompanied by a compact object such as a neutron star or a black hole. The star transfers part of its mass to the compact object, producing an accretion disk around it or emitting directly X-ray photons. The accreted matter releases gravitational potential energy and is heated up, forming a hot plasma that generates strong magnetic fields. Thereafter, this magnetic field accelerates particles, emitting relativistic jets of particles. When the compact object is a black hole, the binary system is called microquasar.

1.2.2 Extragalactic sources

The active galactic nuclei (AGN) are the most typical extragalactic sources. An AGN is a galaxy whose core is a supermassive black hole (SMBH) of mass ranging from a million to a billion times the solar mass. The flux of such sources span the whole electromagnetic spectrum, and is very variable, especially when the source is flaring, where the flux can increase of a few orders of magnitude during small periods.

Different kinds of AGN with various observed properties have been observed (e.g. blazars, quasars, Seyfert galaxies, radio galaxies). A unified model of AGNs, illustrated in figure 7, describes the different types of observed sources as being the same kind of source observed with a different inclination. In this model, a central rotating SMBH generates an accretion disk that emits photons from optical to X-ray bands. The outer part of the disk is a torus made of dust that absorbs the photons from the inner disk and emits infrared photons. Tight jets of a few kpc long are emitted perpendicularly to the disk. An AGN

whose jets are aligned with our line of sight is called a blazar, while an AGN seen from the side is a radiogalaxy.

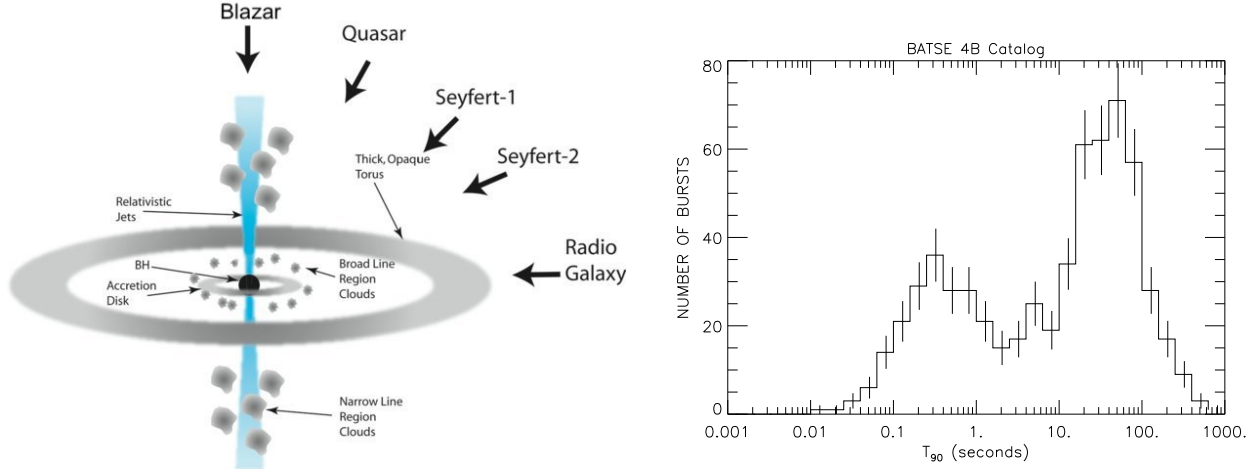


Figure 7. Classification of the AGNs (left, Credit: Biplob Sarkar) and time duration of GRBs from BATSE catalog (right, Credit: Robert S. Mallozzi)

Another violent phenomenon, this time relatively concentrated in time, are flashes of gamma-rays coming from random places in the sky, called gamma-ray bursts (GRBs). The duration of these bursts varies from milliseconds to minutes. Figure 7 shows a histogram of the time duration of the GRBs measured until now. From this plot, two types of GRBs can be distinguished, the short bursts, whose duration does not exceed 2 seconds, and the long bursts, which can last up to a few minutes. The long GRBs are thought to be originated by hypernovae, explosion of supermassive stars, while the short GRBs are probably connected to neutrons star mergers.

1.3 Propagation of Gamma-Rays

Very high energy photons from the source must reach the observer on Earth to be detected. In the high energy regime, the dominant interaction mode of the photons is pair production (see figure 9). Interaction with the extragalactic background light (EBL) is a source of opacity for VHE photons:

$$\gamma + \gamma_{\text{EBL}} \rightarrow e^+ + e^- \quad (11)$$

Extragalactic background photons span a wide range of frequencies from CMB photons to near UV energies. The cross section of this process is given by the Bethe-Heitler formula [4]:

$$\sigma(E_\gamma, E_{\text{EBL}}) \approx 1.25 \times 10^{-25} \frac{m_e^2 c^4}{E_\gamma E_{\text{EBL}}} \text{ cm}^2 \quad (12)$$

In the case of an isotropic distribution of background photons, the cross section above is maximised for:

$$E_{\text{EBL}}(E_\gamma) = 2 \frac{(m_e c^2)^2}{E} \approx \left(\frac{520 \text{ GeV}}{E_\gamma} \right) \text{ eV} \quad (13)$$

This effect is therefore energy dependent. Around a few tens of GeV, the absorption is dominated by UV photons, while for 100 TeV gammas it is dominated by IR photons. In the PeV-EeV region, the main source of opacity is the interaction with CMB photons. Above tens of EeV, the attenuation is led by the radio background.

The interaction of gamma-rays with the EBL is similar to the GZK cutoff for cosmic rays, implying a maximum travelling distance for high energy photons. As can be seen in figure 8, the highest energy photons that will be detected with the CTA experiment (300 TeV) will come from ~ 1 Mpc at maximum.

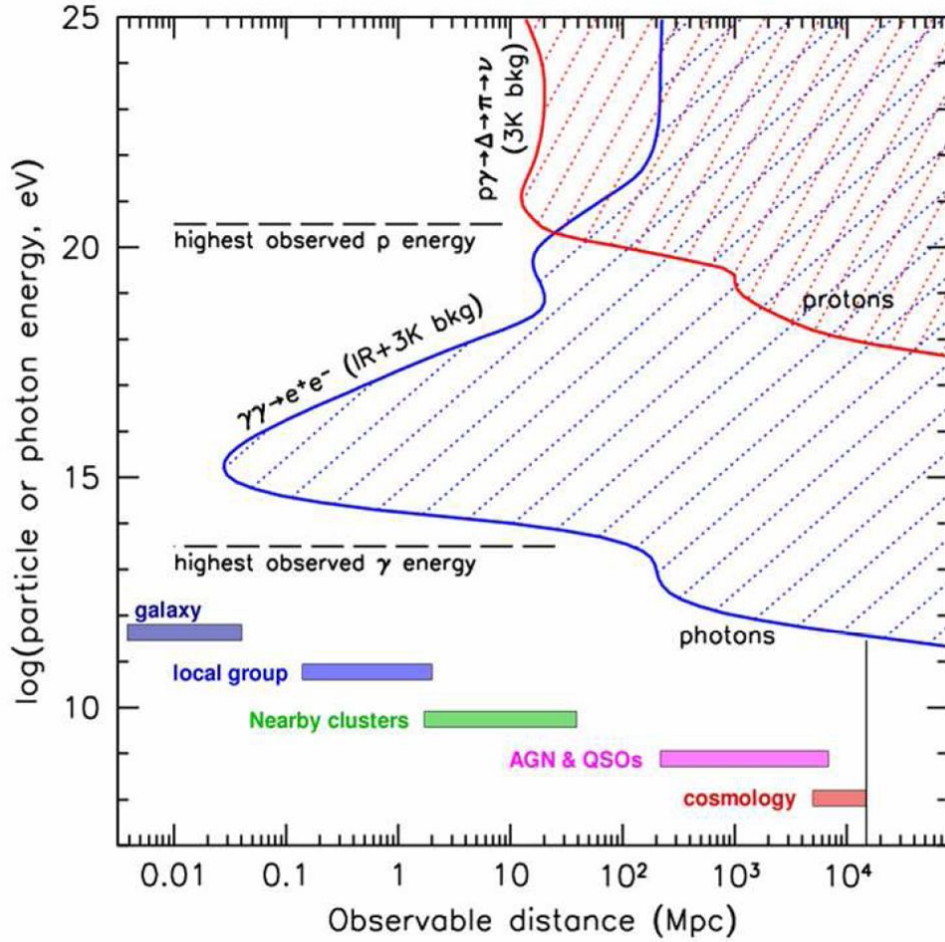


Figure 8. Mean free path of photons and protons as a function of their energy
(Credit: [arXiv:0902.3288](https://arxiv.org/abs/0902.3288))

2 The Cherenkov Telescope Array Observatory

A way to detect gamma-rays of cosmic origin is to detect the Cherenkov light produced by the charged particles generated in atmospheric showers using optical telescopes equipped with pixelated cameras. Current experiments using Cherenkov telescopes are made of a few telescopes. The astroparticle community has the project to build an array of more than hundred telescopes with improved capacities. This project, known as the Cherenkov Telescope Array (CTA), is part of the future generation of large-scale experiments in high energy astrophysics. To cover a wider range of the electromagnetic spectrum with an optimized sensitivity, different types of telescopes have been developed. Large telescopes (LSTs) are used to lower the energy threshold, medium telescopes (MSTs) have an improved sensitivity to intermediate energies, and small telescopes (SSTs) are sensitive to the highest energies. One of the proposed designed for the SSTs, the small size telescope SST-1M, was designed and developed partly by the University of Geneva.

Firstly, the arrival of gamma-rays on Earth and their detection via Cherenkov telescopes are described. The current Cherenkov telescope experiments are then depicted. Finally, the CTA project so as its expected performances and its science questions are discussed.

2.1 Detection of gamma-rays with Cherenkov telescopes

2.1.1 Gamma-rays arrival on Earth and the ways to detect them

Once they traveled over large distances, gamma-ray photons enter the atmosphere and interact with nuclei producing electron-positron pairs, which is the dominant interaction process for photons above GeV (see figure 9). These charged leptons will in turn interact via bremsstrahlung producing other photons. This chain reaction generates an electromagnetic shower, as illustrated in figure 10.

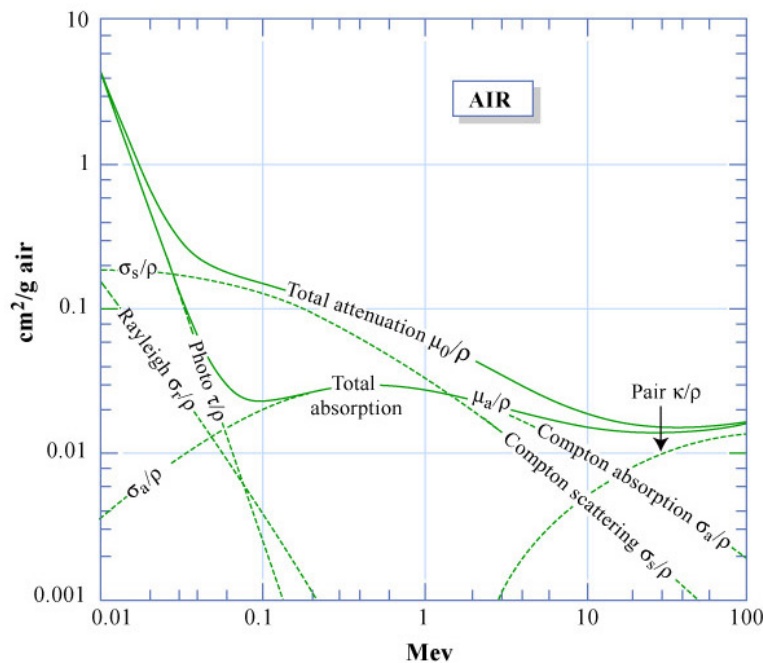


Figure 9. Mass attenuation coefficient for photons in air (Source: [MIT OpenCourseWare](#))

Detection of astrophysical gamma-rays can be performed either from space, directly detecting the high-energy photons, or from the ground, using the atmosphere as a calorimeter and detecting secondary products of the interaction between primary gammas and nucleus in the atmosphere. Sending detectors into space allows a low background, but the detectors are size-limited since it is very expensive to send heavy instruments in orbit. The effective area of space detectors is therefore of the order of a few squared meters at maximum. Since the flux of gamma photons decreases with energy, the effective area limitation of space detectors restraints the maximum detectable energy. Hence, to detect photons with energy greater than a few hundreds of GeV, ground facilities with higher effective area (up to squared kilometers) have to be developed. The main drawback of ground detectors is the huge hadronic background due to extensive air showers generated by cosmic rays compared to low-noise space instruments.

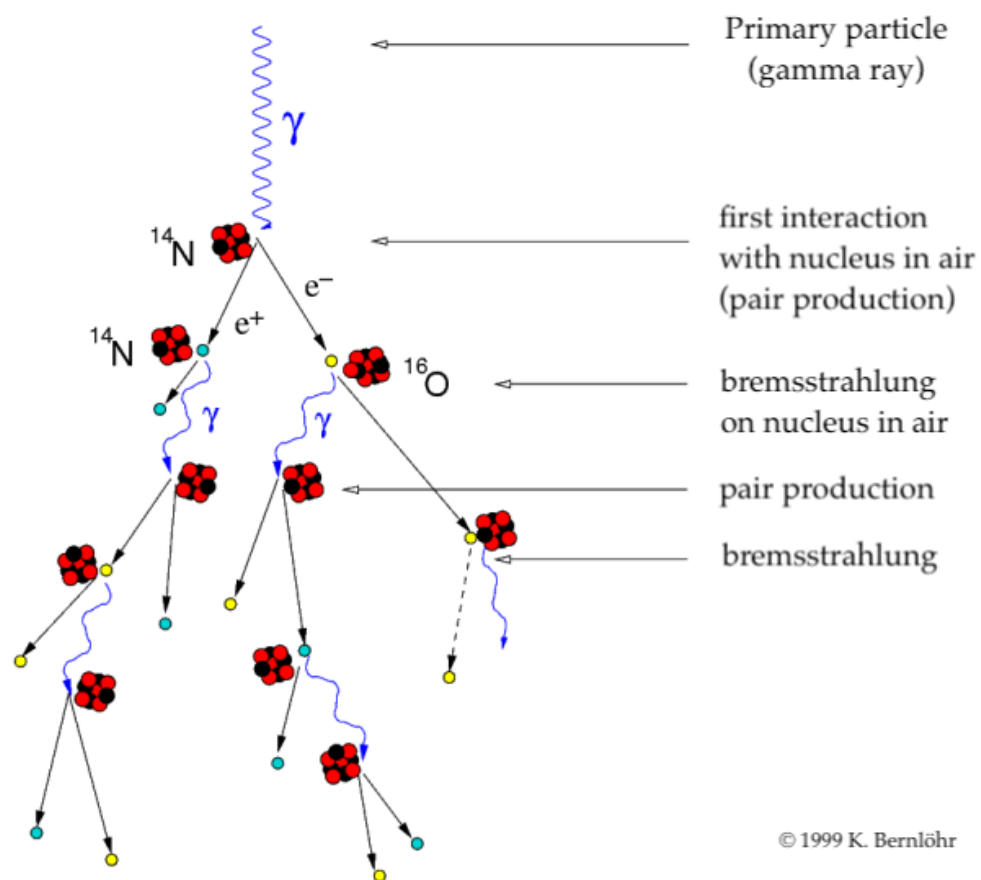


Figure 10. Electromagnetic air shower induced by a gamma-ray photon entering the atmosphere (Modified picture. Source: [Konrad Bernlöhr, 1999 - Max Planck Institute](#))

From the ground, the charged particles that compose the electromagnetic showers can be detected by the light they emit. Indeed, being very energetic, electrons and positrons travel faster than the speed of light in the air. This implies the emission of blue light via the so-called Cherenkov effect. This radiated visible light can afterwards be detected using photo-detectors.

2.1.2 Cherenkov effect

When a charged particle of velocity v travels in a transparent medium, the atoms along its path are polarized, becoming electrical dipoles which emit electromagnetic radiation. When the velocity of the charged particle is smaller than that of the light in the medium (c/n), the radiation on both sides of the trajectory cancel each other. But if the charged particle moves faster than light in the medium, the downstream material cannot be polarized. The electromagnetic radiation generated by the charged particle spreads slower than the particle itself, and a net radiation results.

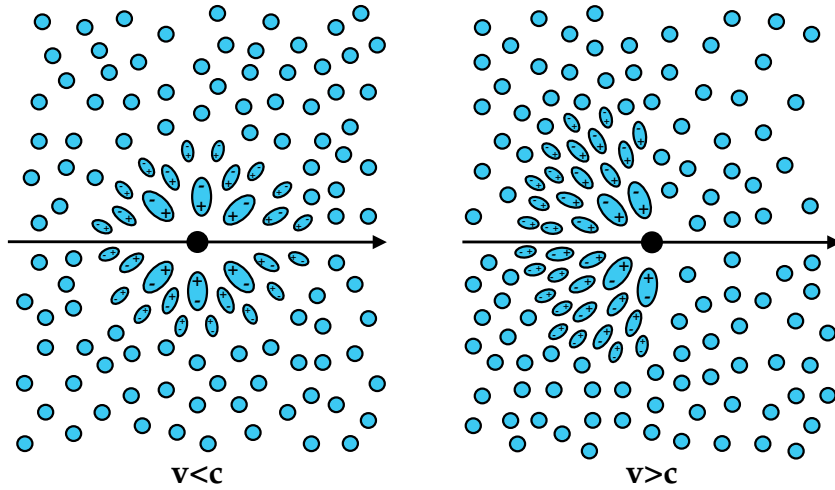


Figure 11. Polarization of a medium crossed by a charged particle faster (left) and slower (right) than light in the medium

Polarization of the surrounding medium is shown in figure 11 for $v < c$ and $v > c$. The wavelets generated by the charged particles for both cases are shown in figure 12. The cone of emitted Cherenkov light is depicted for the case $v > c$.

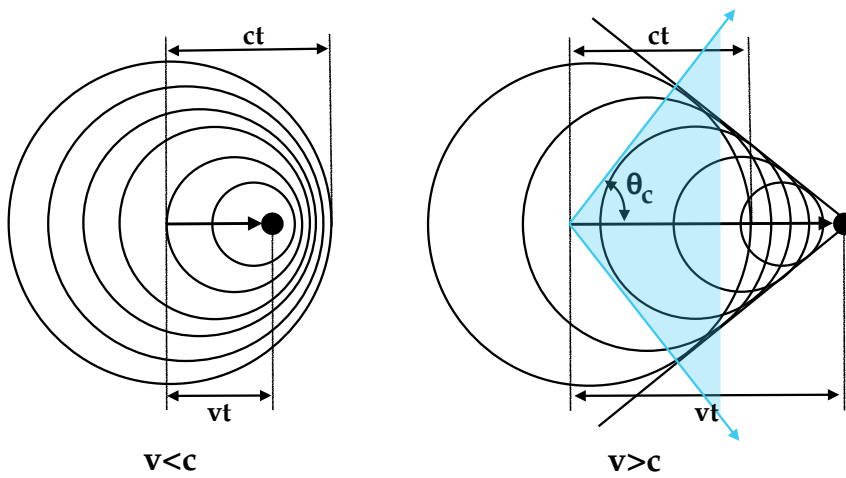


Figure 12. Emission of Cherenkov radiation by a relativistic particle

The aperture angle of the Cherenkov cone is given by the relation:

$$\cos \theta_c = \frac{1}{\beta n} + \frac{\hbar k}{2p} \left(1 - \frac{1}{n^2} \right) \quad (14)$$

where p is the momentum of the charged particle and $\hbar k$ is the momentum of the photons.

Usually, since $\hbar k \ll p$, the recoil of the charged particle is neglected, leading to the relation:

$$\cos \theta_c = \frac{1}{\beta n} \quad (15)$$

When a gamma-ray photon enters the atmosphere, it generates an electromagnetic air shower made of very energetic charged particles, which emits Cherenkov photons. This effect can be used to indirectly detect these air showers.

altitude (km)	vertical depth (g/cm ²)	local density (10 ⁻³ g/cm ³)	Cherenkov threshold (MeV)	Cherenkov angle (°)
40	3	3.8 · 10 ⁻³	386	0.076
30	11.8	1.8 · 10 ⁻²	176	0.17
20	55.8	8.8 · 10 ⁻²	80	0.36
15	123	0.19	54	0.54
10	269	0.42	37	0.79
5	550	0.74	28	1.05
3	715	0.91	25	1.17
1.5	862	1.06	23	1.26
0.5	974	1.17	22	1.33
0	1032	1.23	21	1.36

Table 1. Relevant parameters for production of Cherenkov light in the atmosphere by an electron [2]

The intensity of the Cherenkov light can be estimated starting with the expression of the number of emitted photons per unit of wavelengths and travelled distance:

$$\frac{dN}{d\lambda dx} \approx \frac{2\pi\alpha Z^2}{\lambda^2} \sin^2 \theta_c \quad (16)$$

where Z is the charge of the particle emitting the Cherenkov light and $\alpha \approx \frac{1}{137}$ is the fine-structure constant.

Integrating over wavelengths and using (15) leads to the Franck-Tamm formula:

$$\frac{dN}{dx} = 2\pi\alpha Z^2 \int \left(1 - \frac{1}{\beta^2 n^2} \right) \frac{d\lambda}{\lambda^2} \quad (17)$$

It is clear from the λ^{-2} dependency of (17) that the main contribution of Cherenkov light is due to the lower wavelength photons, or equivalently to the most energetic photons. Since the light above UV is absorbed in the air, the Cherenkov light is mainly made of blue and near-ultraviolet photons. The formula (17) gives the amount of Cherenkov photons emitted per unit of distance for a given initial charged particle. For instance, considering the wavelength window 300–700 nm, a 1 GeV electron emits about 50 Cherenkov photons per meter.

We see from (15) that the threshold for Cherenkov emission is the defined by the condition $\beta > 1/n$. Accounting for the relations $E^2 = p^2 + m^2$ and $p = E\beta$ leads to an energy threshold:

$$\beta = \sqrt{1 - \frac{m^2}{E^2}} \Rightarrow E_{\text{thr}} = \frac{m}{\sqrt{1 - \frac{1}{n^2}}} \quad (18)$$

Consequently, a particle of mass m can emit Cherenkov light only if its energy is bigger than E_{thr} .

Since the density of the air, and so its refractive index, varies with the altitude, the Cherenkov energy threshold and the cone aperture angle depends on the altitude. The table 1 gives theses two quantities for different altitudes in the case of the electron. Figure 13 shows the evolution of the cone aperture as the shower penetrates deeper into the atmosphere. The refractive index can be linked to the pressure or to the density of the air by empirical relations [37].

The Cherenkov effect is very useful in multi-messenger astronomy and particle physics. It is used for instance to indirectly detect neutrinos with experiments such as IceCube, or to detect air showers generated by charged cosmic rays or gamma rays. Extensive air showers can be detected via Cherenkov effect either using water tanks equipped with photo-sensors to detect charged particles that cross the water, or by using telescopes equipped of pixelated cameras to detect the Cherenkov light produced in the atmosphere. Unlike the former method, the latter one needs cloudless and clear nights to be operated.

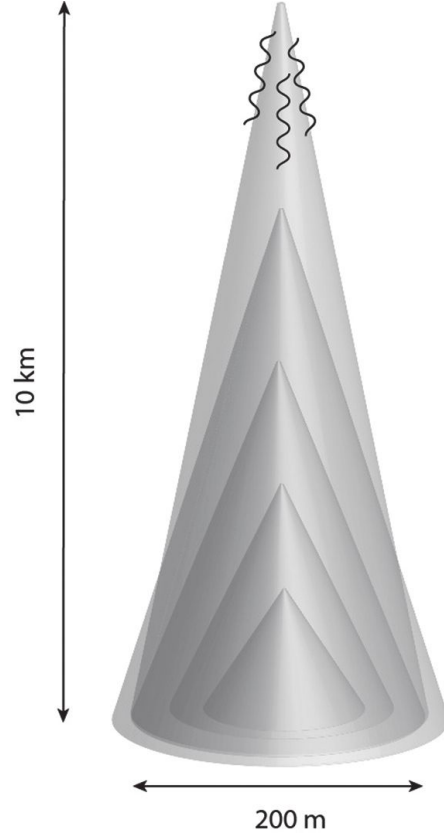


Figure 13. Evolution of the aperture of the Cherenkov light cone with the altitude [2]

2.1.3 Imaging Atmospheric Cherenkov Technique

Since the primary photons are very energetic, the charged leptons generated in the electromagnetic air showers described earlier are moving very fast. They are so energetic that they travel faster than light in the atmosphere, whose velocity is given by c/n with $n \approx 1.0003$ the refractive index of the air. The resulting Cherenkov light forms a light pool of about 200-300m diameter depending on the primary photon energy. This light pool is an ellipse whose eccentricity increases with the angle between shower incoming direction and zenith.

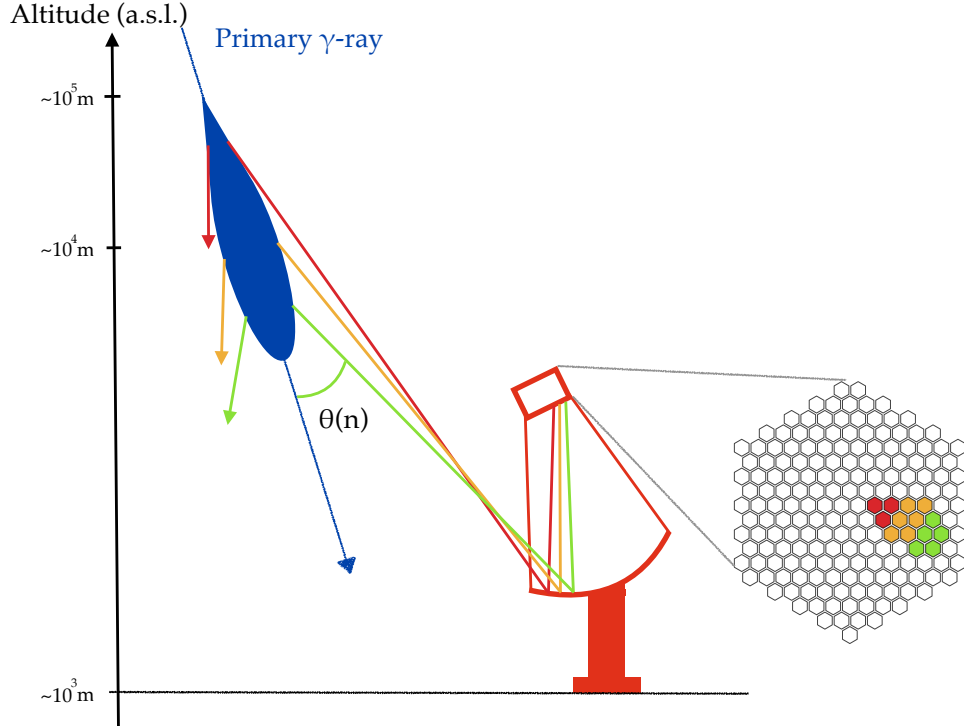


Figure 14. Operating principle of an Imaging Atmospheric Cherenkov Telescope

The working principle of an Imaging Atmospheric Cherenkov Telescope is shown in figure 14. The telescope has large mirrors that reflect Cherenkov light from the showers into pixelated cameras made of fast response photo-sensors. These photo-sensors are usually photo-multiplier tubes (PMT) or silicon photo-multipliers (SiPM). The fast response of the sensitive pixels allows to observe the evolution of the shower in time. The obtained image is an ellipse (a circle for on-axis showers) which is described by a set of parameters.

To obtain a readable image, a cleaning mask has to be applied to avoid some of the pixels that are enlightened by night sky background (NSB) photons. The NSB is a background light mainly composed of light pollution from artificial infrastructures (e.g. cities) reflected on the atmosphere, of moonlight (either directly or scattered by the floor), of light from stars, and of light reflected on the ground.

Even once the image has been cleaned, a lot of hadron events are still triggered (about 1000 hadron events for a single γ like event). To perform a γ /hadron separation, the image has to be parametrized. An ellipse can be fitted to the remaining pixels. The resulting ellipse is parameterised by the Hillas' parameters and additional parameters:

Size: The size gives an idea of the intensity of the event and is defined by the number of photo-electrons (p.e.) in the image.

Length: The length is the major axis of the ellipse and is a measurement of the longitudinal development of the shower.

Width: The width is the minor axis of the ellipse and is a measurement of the lateral development of the shower.

Center of Gravity (CoG): Coordinates (x,y) or (r, ϕ) of the center of gravity of the ellipse. The origin is defined as the center of the field of view (FoV) of the camera.

Dist: The distance between the CoG of the ellipse and the position of the source on the camera.

Alpha: Alpha is the angle between the major axis of the ellipse and the line linking the centroid to the expected source position on the camera.

Miss: Distance between the main axis of the shower and the source position.

Skewness: Distance between the highest pixel and the center of gravity. It characterises the longitudinal asymmetry of intensity within the ellipse.

Kurtosis: The kurtosis is a dimensionless quantity that determines how much the distribution of intensities over the ellipse is flat.

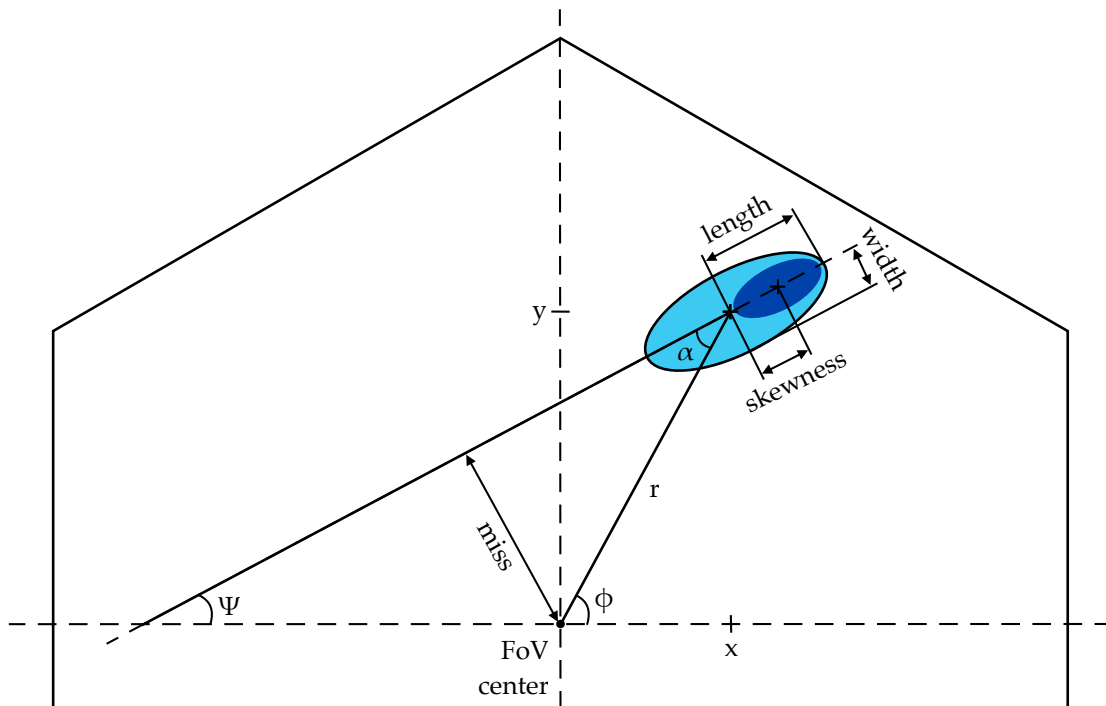


Figure 15. Definition of the main image parameters

These parameters are depicted in figure 15, where the source is in the center of the field of view. Other image quality parameters can be used to describe the events:

Number of islands: The number of islands is the number of separated groups of pixels in an event. It allows to characterize the quality of the cleaning.

Leakage: The leakage is defined as the fraction of the signal in the outermost ring of pixels. It allows to know which fraction of the signal is outside the camera.

The reconstruction of the incoming direction of the primary gamma is quite ambiguous using the Hillas parameterisation. A proper reconstruction of the incoming direction of the shower can be obtained by using stereoscopic measurements. It consists of using an array of Cherenkov telescopes to observe the showers from different perspectives. The combination of the images acquired by the telescopes allow to determine the source position as the crossing of the ellipses axes. This is illustrated in figure 16.

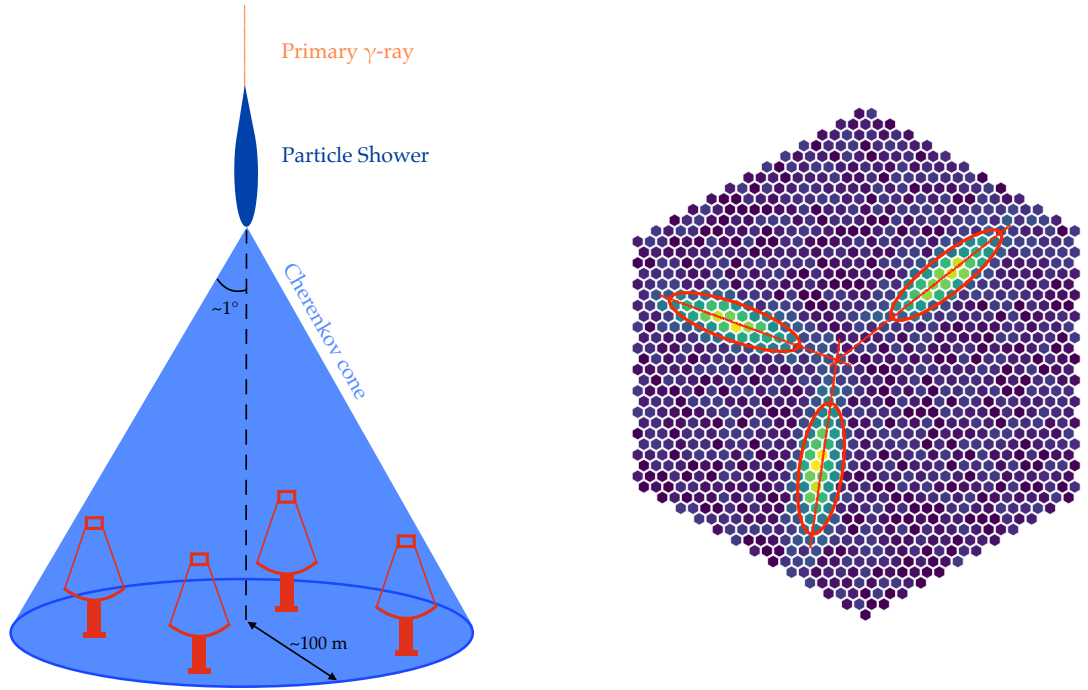


Figure 16. Stereoscopic observations with Cherenkov telescopes (left) and superposition of three camera images for reliable reconstruction of shower direction (right)

With a single IACT telescope, stereoscopy cannot be used to determine the direction of the shower and the position of the source. The distance between the source position and the centroid of the ellipse along its major axis is then estimated by using the displacement method [9]. A possible parameterisation of the displacement, that depends on the width over length ratio, is given by:

$$\text{disp} = \text{sign}(\text{skewness}) \cdot \xi \cdot \left(1 - \frac{\text{width}}{\text{length}}\right) \quad (19)$$

where ξ is a scaling parameter.

This method provides a good estimate of the source position. It is also used for stereo reconstruction since it improves the determination of the source location. Figure 17 illustrates the determination of source position via stereoscopy and via the displacement method. The real source position is marked with a dark blue star. The cyan triangular marker represents the reconstructed source position from stereoscopy and the yellow square is the location determined by combining the disp of the two events. The final outcome of the data analysis is the primary incoming direction (source position) and its energy.

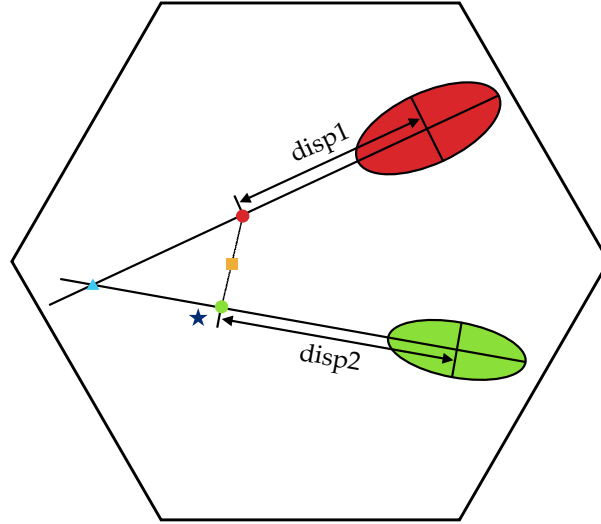


Figure 17. Illustration of the displacement method

2.2 The current generation of Cherenkov observatories

The current generation of IACT experiments is mainly represented by MAGIC (Major Atmospheric Gamma Imaging Cherenkov telescopes), H.E.S.S. (High Energy Stereoscopic System), and VERITAS (Very Energetic Radiation Imaging Telescope Array System). These observatories compose the third generation of imaging Cherenkov telescopes. The pioneer IACT experiment, called Whipple, was made of a single 10 m diameter telescope. It allowed to discover the first TeV emission from extragalactic sources. The first Cherenkov telescope array that used stereoscopy was the HEGRA experiment.

MAGIC, H.E.S.S., and VERITAS are Cherenkov observatories composed of a few telescopes each and exploring the electromagnetic spectrum from a few tens of GeV to a hundred TeV. These telescopes discovered a few tens of VHE sources. The table 2 gives the location, energy range, and number of telescopes of H.E.S.S., VERITAS and MAGIC.

	H.E.S.S.	VERITAS	MAGIC
Location	Namibia	Arizona, USA	La Palma, Spain
Hemisphere	South	North	North
Number of telescopes	5	4	2
Field of View	5°	3.5°	3.5°
Energy range	30 GeV - 100 TeV	50 GeV - 50 TeV	30 GeV - 100 TeV
Telescope diameter	4 × 12 m + 1 × 18 m	4 × 12 m	2 × 17 m

Table 2. Principal features of the current generation IACT experiments ²

The first telescope of MAGIC has started to observe the VHE sky in 2004. With his single telescope, the MAGIC collaboration developed the displacement method to determine the source position [10]. To take advantage of stereoscopic measurements, a second telescope, MAGIC-II, was built in 2009. The better precision of three-dimensional shower reconstruction allowed to improve angular and energy resolutions. By adding a second telescope, the background rejection became stronger, improving the sensitivity. The MAGIC telescopes have discovered 44 sources until February 2019.

The H.E.S.S. experiment started the observations in 2003 with four telescopes. In 2012, a fifth telescope, much larger, has been built in the center of the existing telescopes to improve the sensitivity and extend energy range to lower energies. The H.E.S.S. telescopes have discovered 111 very high energy sources.

The VERITAS observatory is composed of four 12m diameter telescopes. It is operated since 2004 and has discovered 24 very high energy sources. The design of the telescopes is based on the previous generation 10 m diameter Whipple telescope. The experiment is using stereoscopy, but also the displacement method developed for MAGIC since it was proven to improve the determination of the source location.

²H.E.S.S.: <https://www.mpi-hd.mpg.de/hfm/HESS/>
 VERITAS: <https://veritas.sao.arizona.edu>
 MAGIC: <https://magic.mpp.mpg.de>



Figure 18. H.E.S.S. (upper left), VERITAS (lower left), and MAGIC (right) experiments
(Source: @Wikimedia Commons)

As for the previous generation of IACT, the three observatories shown in figure 18 use pixelated cameras made of photomultiplier tubes. A new emerging photo-detector, used by the First G-APD Cherenkov Telescope (FACT), is the silicon photomultiplier (SiPM). The advantages of this kind of detector are the low power consumption and the high quantum efficiency. This is why it will be used in most of the telescopes of the next IACT generation. This next generation array, called Cherenkov Telescope Array (CTA), is the legacy of the experiments described above.

2.3 The Cherenkov Telescope Array and its performance

2.3.1 The array of Cherenkov telescopes

The next generation IACT experiment is the Cherenkov Telescope Array (CTA). Thanks to three different sizes of telescope, CTA will cover a wide energy range from 20 GeV to 300 TeV. The large-sized telescopes (LST) will be sensitive to the lowest energies, the medium-sized telescopes (MST) will measure gamma-rays from 150 GeV to 5 TeV, and the smaller telescopes (SST) will extend the energy range up to the unexplored 300 TeV energy. The effective area is linked to the size of the array (number of telescopes and distance between them), while the size of the mirrors is related to the energy threshold. This is why large telescopes are used to lower the energy threshold while a lot of small telescopes distributed on large surfaces are used for the more energetic part in order to compensate for the low γ -ray flux at high energy. Figure 19 shows the proposed designs for each three sizes of telescopes. The highest energies will be useful to study the extreme objects that accelerates cosmic-rays in our galaxy, and the lowest energies will provide the possibility to measure sources far into the universe (since at ~ 10 -100 GeV the gammas are not absorbed by EBL, see figure 8).

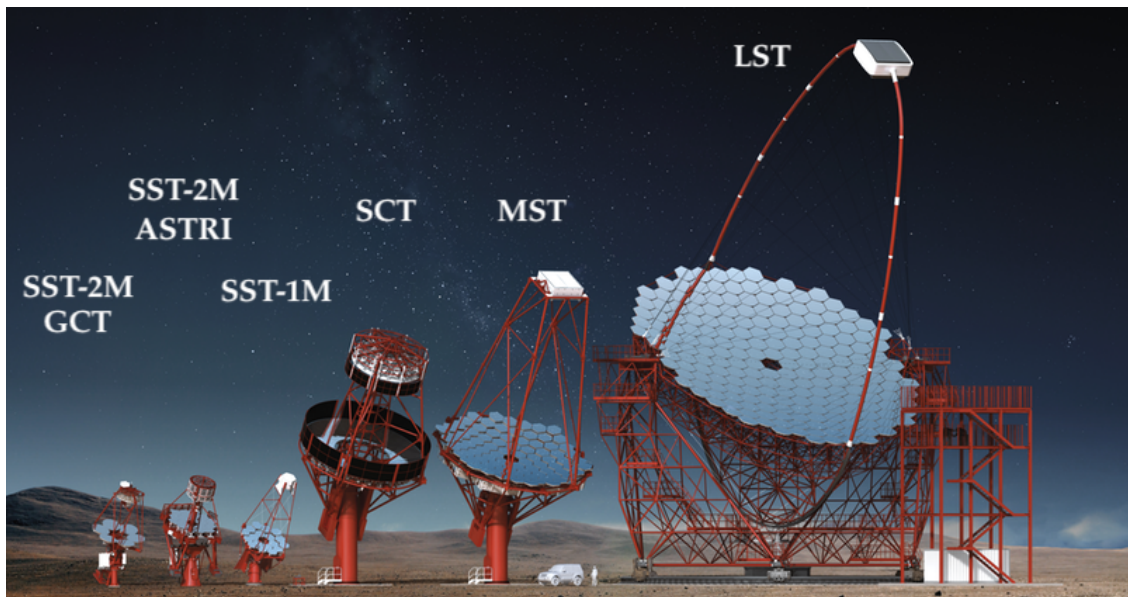


Figure 19. Prototype designs of the CTA telescopes.
(Credit: Gabriel Pérez Diaz, IAC.)

The array will be split on two sites, one on each hemisphere, to cover most of the sky. The northern site, located at La Palma, Spain, on the same site of the MAGIC telescopes, will host 4 large telescopes and 15 medium telescopes. The southern site, located at the ESO site of Paranal, Chile, will host 4 LSTs, 25 MSTs, and up to 70 SSTs, and will be able to measure gammas up to 300 TeV with an improved sensitivity. Figure 20 shows the location of the two sites, and the sky coverage with the combination of both sites. The northern sky will be mainly focused on observations of extragalactic targets since the galactic center is part of the southern sky, which explains the absence of SSTs in the northern hemisphere.

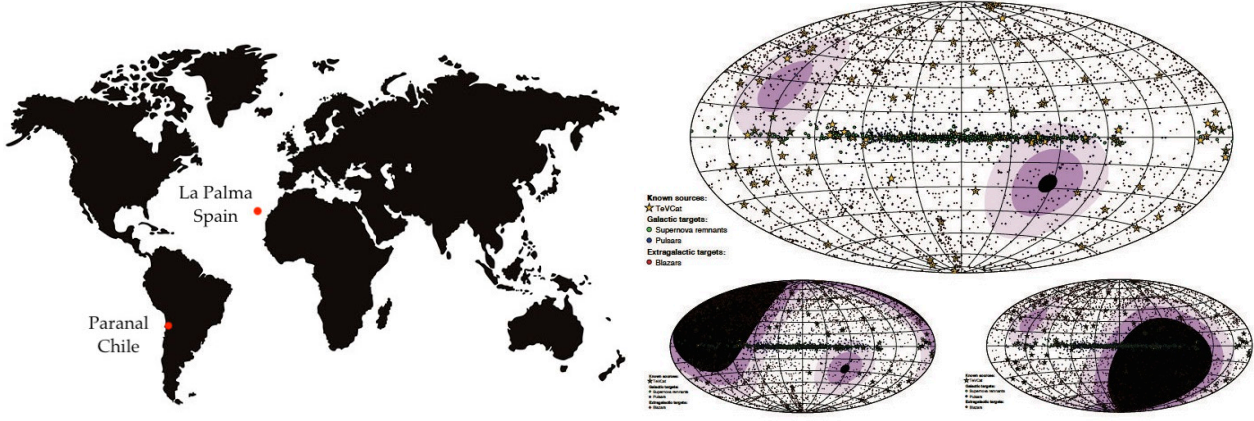


Figure 20. CTA sites locations (left) and sky coverage obtained with both sites (right, Credit: [doi:10.1063/1.4968902](https://doi.org/10.1063/1.4968902))

The distribution of the telescopes on both sites are shown in figure 21. The northern array is spread over 0.6 squared kilometers, and the southern sky is spread over four squared kilometers.

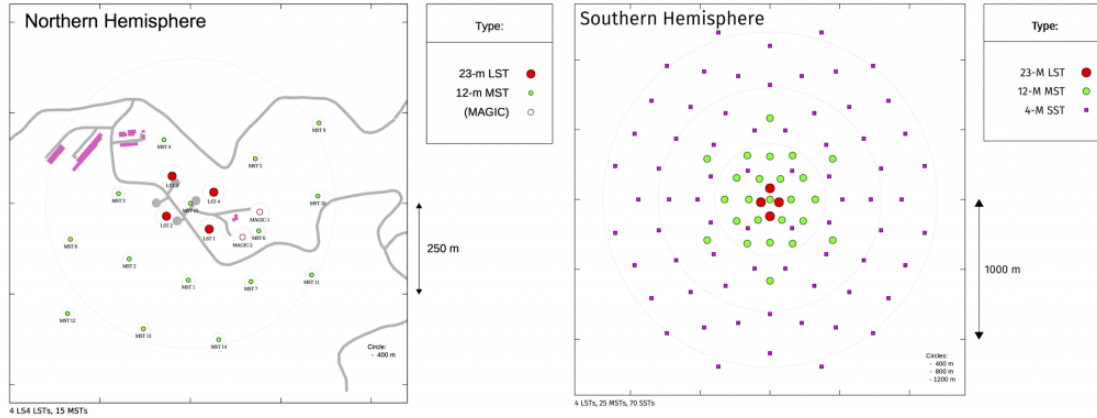


Figure 21. Proposed layout for the CTA telescopes on both sites [11]

The CTA consortium is composed of about 200 institutes in 31 countries. The Cherenkov Telescope Array will be the first IACT observatory operated as optical observatories: the whole astrophysics community will be able to submit observation proposals, boosting the scientific output of the experiment. 40% of the observing time will, however, be dedicated to multipurpose observations prepared by the CTA consortium to answer predefined science questions [12]. Few designs are proposed for MSTs and SSTs. For the small-sized telescopes, two of the three designed are dual mirror telescopes, while the SST-1M is a single mirror telescope. Table 3 details the features of each type of telescopes.

	Large-Sized Telescope (LST)	Medium-Sized Telescope (MST)			Small-Sized Telescope (SST)		
		FlashCam	NectarCam	SCT	ASTRI	GCT	SST-1M
Energy range (full sensitivity)	20 GeV - 150 GeV	150 GeV - 5 TeV			5 TeV - 300 TeV		
Number of telescopes	4 (South) 4 (North)	25 (South) 15 (North)			70 (South) 0 (North)		
Optical design	Parabolic	Modified Davis-Cotton			Schwarzschild- Couder		
Primary reflector diameter	23.0 m	11.5 m			4.3 m		
Secondary reflector diameter	–	–			1.8 m		
Effective mirror area	370 m ²	88 m ²			8 m ²		
Focal length	28 m	16 m			2.15 m		
Total weight	103 t	82 t			19 t		
Field of view	4.3 deg	7.5 deg			10.5 deg		
Number of pixels in Cherenkov camera	1855	1764			2368		
Pixel size (imaging)	0.1 deg	0.17 deg			0.19 deg		
Photodetector type	PMT	PMT			SiPM		

Table 3. Comparison chart of the CTA telescopes features [11]

2.3.2 CTA performance

The wide field of view of the individual telescopes allows to contain entire shower images and increases the field of view of the whole array. The large number of telescopes combined with wide individual field of view provide a collection area of more than one order of magnitude bigger compared to previous IACTs. This increase of collection area improves the detected photon rate and therefore gives access to short time scale phenomena.

The large number of recorded images for a single shower by different telescopes (>10) provides excellent angular and energy resolution. The angular resolution for CTA as a function of reconstructed energy is shown in figure 22 and is defined as the angle containing 68% of the reconstructed gamma-rays. The large field of view and the improvement of angular resolution make possible for CTA to observe extended sources.

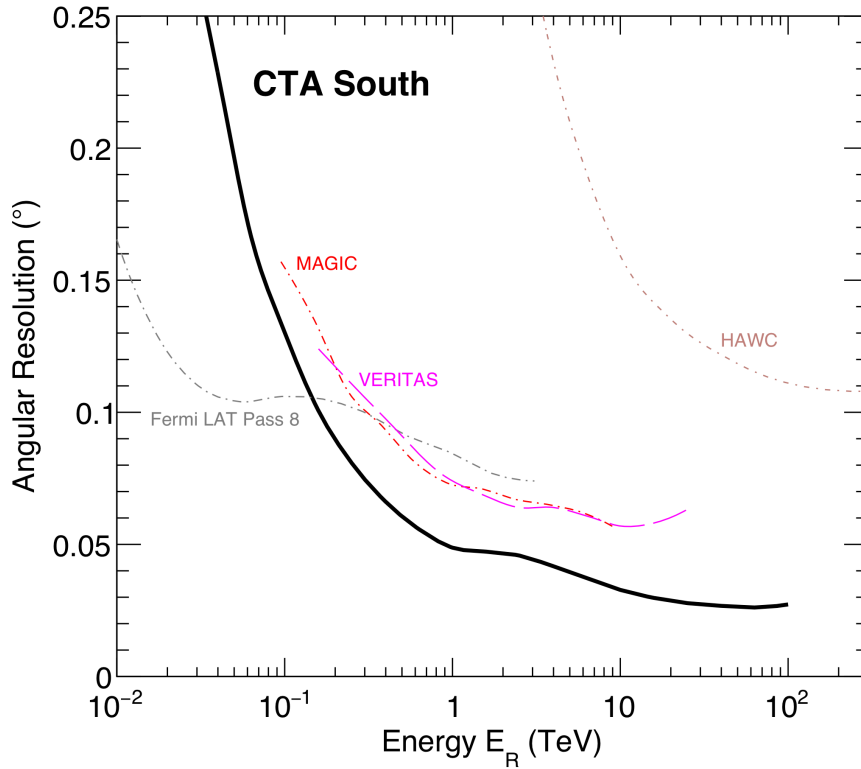


Figure 22. Angular resolution as a function of reconstructed energy for CTA South and other instruments [11]

The high image multiplicity also improves the background rejection, which, combined with the good angular resolution and the increased collection area, improves the point-source sensitivity of the array. The differential energy flux sensitivity for 5σ detections, improved by one order of magnitude at 1 TeV, is plotted as a function of the energy and compared to that of other experiments in figure 23. The sensitivity for CTA is plotted for at least 10 detected primary gammas per energy bin and for 50 hours of observation time.

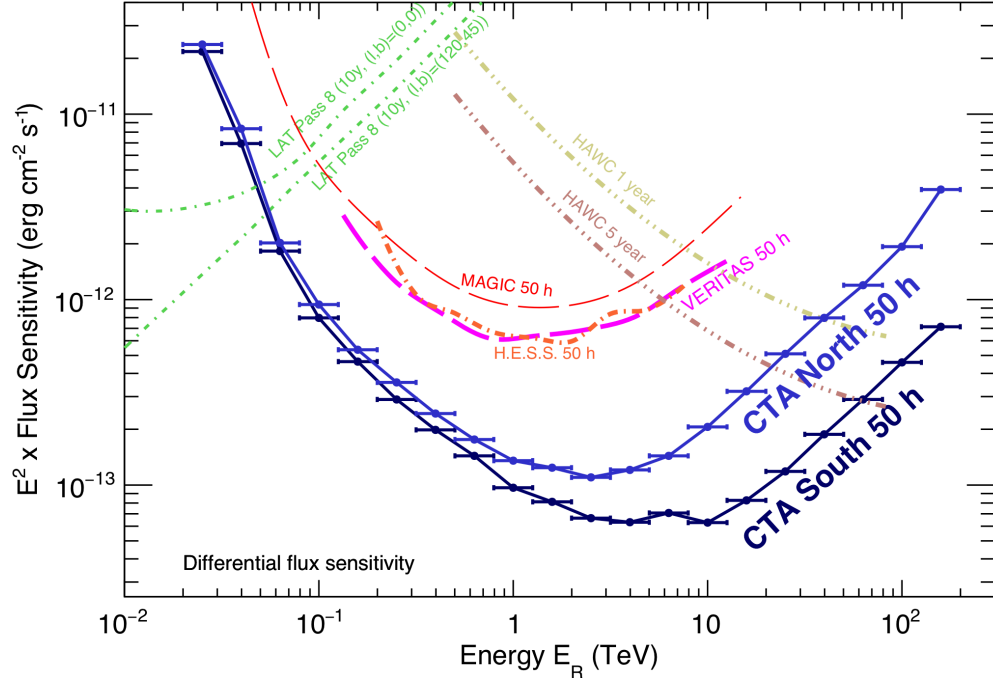


Figure 23. Differential energy flux sensitivity for CTA South and North compared to other experiments [11]

The overall improvement of performances of CTA compared to current Cherenkov arrays is illustrated with the figure 24, which shows the H.E.S.S. galactic plane survey compared to the simulated one for CTA.

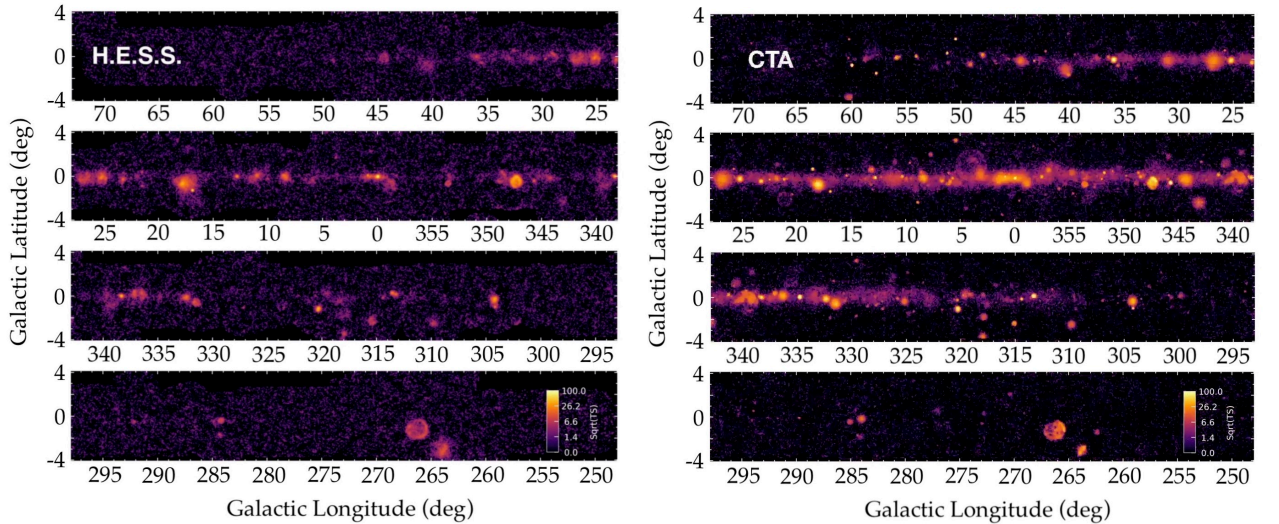


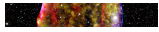
Figure 24. H.E.S.S. Galactic Plane Survey (left) and CTA Galactic Plane Simulation (right) (Plot credits: Christoph Deil, Roberta Zanin)

In addition to sensitivity and resolution improvements, CTA will be able to operate multiple sub-arrays pointing different directions in the sky. This operation flexibility and the possibility of responding to external alerts rapidly and point the telescopes anywhere in the sky in less than a minute make CTA a very effective array.

2.4 Science with the CTA experiment

2.4.1 Science themes

The science goals of CTA can be classified in three themes [12]. These opened questions in astrophysics are discussed here. The observation program planned to answer these questions is discussed in the next section.



Theme 1: Understanding the Origin and Role of Relativistic Cosmic Particles

Highly energetic particles are known to play an important role in many astrophysical systems such as supernova remnants, galaxy clusters, or active galactic nuclei. But the relationship between relativistic cosmic rays and the evolution of stars and galaxies has still not been figured out. With its high angular resolution measurements, CTA will provide a better understanding of the acceleration and transport processes responsible for the evolution of galaxies.

Cosmic Accelerators: Understanding where particle acceleration takes place is a major goal in gamma-ray astrophysics. Galactic and extragalactic surveys will allow to identify particle acceleration sites in the universe. CTA will also provide an insight in acceleration processes establishing resolved spectroscopy and very high statistics light curves of bright nearby sources. These approaches are meant to answer key questions: Are supernova remnants the only major contributor to the galactic cosmic rays? Where in our galaxy are particles accelerated up to PeV energies? What are the sources of high-energy cosmic electrons? What are the sources of the ultra-high energy cosmic rays (UHECRs)?

Propagation and influence of Accelerated Particles: Apart from acceleration sites and processes, another important point to be solved is the role of the accelerated particles in the evolution of their surrounding objects. Thanks to its powerful background rejection and to its unrivalled angular and energy resolutions, CTA will study the extended emissions around gamma sources and disentangle emissions associated with cooling (electrons) and diffusion (hadrons).



Theme 2: Probing Extreme Environments

Extreme environments such as neutron stars and black holes are believed to be responsible for the emission of very high energy particles. CTA therefore constitute a way to probe these compact objects.

Black Holes and Jets: Both supermassive and stellar mass black holes are known to produce jets of relativistic particles. But the process by which these jets are produced is still an open question, so as the region of the black holes responsible for particle acceleration. CTA will provide access to the composition of these jets at VHE and to the inner regions of the jets.

Neutron Stars and Relativistic Outflows: The ultra-relativistic outflows and the gamma emission from magnetosphere of pulsars will give to CTA a probe to study neutron stars and their environment. CTA will also be able to observe merging neutron stars in parallel to GRB (gamma-ray burst) and GW (gravitational waves) detections.

Cosmic Voids: By studying the universe at large scales, it turns out that its structure is composed of filaments of galaxy clusters separated by enormous cosmic voids (typical diameter of $\sim 10\text{-}100$ Mpc). CTA will allow to study the weak radiation and magnetic fields contained in cosmic voids via the detection of VHE photons that interacts in these voids.



Theme 3: Exploring Frontiers in Physics

In addition to the study of high energy sources and acceleration mechanisms, CTA will also bring major breakthroughs in fundamental physics for instance by covering a wide range of masses for self-annihilating dark matter particles or by studying the variation of the speed of light due to quantum fluctuations of the metric.

Dark Matter: It has been learned from the measurement of the CMB (cosmic microwave background) acoustic oscillations that about 27% of the energy content of the universe is made of an unknown form of massive matter that does not interact via electromagnetic interactions and that is not part of the standard model of particle physics. The long distances traveled by gamma-rays combined with their low wavelengths will allow CTA to study this so-called dark matter by measuring quantum-gravity effects on the speed of light.

Quantum Gravity and Axion-Like Particles: Apart from the quantum-gravity effect just mentioned, CTA could also detect axion-like particles (ALPs) and study a possible Lorentz Invariance Violation induced by quantum effects on space-time. ALPs are a candidate for cold dark matter and are supposed to couple to gamma-rays. This coupling would result in an increase of photons flux at TeV energies, hence detectable by CTA.

2.4.2 Key targets

Trying to address the science questions discussed above, a core program has been proposed by the CTA consortium [12]. The key targets of this observation program are described here.

The Galactic Center: The Galactic Center is the richest region of the sky in terms of variety and number of sources, especially at high energies. In this part of the sky can be found supermassive black holes (SMBH), supernova remnants (SNR) and pulsar wind nebulae (PWN), stellar nurseries, dense molecular clouds, and many other classes of sources. This is why the galactic center is the most observed region in any part of the electromagnetic spectrum. CTA will investigate particle accelerators in the region and characterize the central source: Sgr A*. In addition to the apparent scientific output, the study of the galactic center will also allow to look for signatures of dark matter self-annihilation.

Large Magellanic Cloud: The Large Magellanic Cloud (LMC) is a satellite galaxy of the milky way that hosts the famous SN1987A supernova remnant. As one of the nearest galaxies and being very active, the LMC is a perfect target for CTA to study the high energy population of an entire galaxy. This source will also be used to study individual sources like SNR and PWN, but also to investigate the transport of cosmic rays on long distances and to search for dark matter signatures.

The Galactic Plane: The whole galactic plane will be surveyed by CTA to address a few important scientific goals among which the galactic PeVatrons, the discovery of new physical phenomena and new classes of energetic sources, but also to improve the statistic on the already known classes. This higher statistic is useful for population and distribution study of energetic sources.

Galaxy Clusters: Galaxies and AGN within clusters and formation processes of these clusters are thought to be responsible for the acceleration of a consequent population of charged cosmic rays. These cosmic rays are expected from some models to play a valuable role in cooling flows on galaxy clusters. Galaxies could also be detected individually due to high activity (star formation or AGN). Due to their large size, galaxy clusters are also suitable for dark matter study.

Cosmic Ray PeVatrons: The spectral index of cosmic ray spectrum changes around a few PeV, at the knee. This implies that some galactic sources, called PeVatrons, can accelerate particles up to PeV. But most of the PeVatrons in the milky way are to be discovered, since the only known PeVatron in our galaxy, Sgr A*, is not powerful enough to explain the measured flux at such energies. The interaction of PeV CR with interstellar medium (ISM) produces gamma-rays beyond tens of TeV. CTA is thus suitable for the indirect study of galactic PeVatrons.

Star Forming Systems: CTA will be able to study the role of high energy cosmic rays in the regulation of the star-formation process by observing star-forming systems over six orders of magnitude in star-formation rate. By measuring the gamma-ray flux for different formation rates both in small formation regions and in entire galaxies, CTA will be able to disentangle between global properties and source-specific properties and to study the equipartition between CR, magnetic and radiation fields.

Active Galactic Nuclei: Active Galactic nuclei are galaxies with a SMBH in their core. These objects emit very luminous radiation over the whole electromagnetic spectrum, and could influence the evolution of the whole host cluster of galaxies. The signals from AGN vary in time, especially at TeV energies, that give access to the core of AGN. CTA observations of such objects will be linked to AGN physics but also to CR and fundamental physics.

Transient Phenomena: Extreme objects in the universe happen to flare or explode unpredictably emitting radiation over the full EM spectrum but also via multi-messengers (neutrinos, GW, CR). The time scale of such events varies from milliseconds to years. Thanks to its sensitivity and ability to study short time-scale events, CTA will be able to study the physics of these variable objects in parallel to other instruments such as GW interferometers or neutrino observatories.

3 The SST-1M telescope and its digitizing camera

For the small-sized telescopes, that will be sensitive to highest CTA energies, three designs have been proposed. One of them is the single mirror SST-1M telescope. The general idea of the SST-1M telescope is first discussed, followed by the working principle of its digitizing camera.

3.1 The telescope structure and optics

The SST-1M telescope has a dish diameter of 4m and a focal length of 5.6m. It is based on the Davies-Cotton geometry [13] (see figure 26), which provides a good imaging quality for large field of view telescopes. The FoV of the SST-1M is of almost 9° , with an angular pixel size of 0.24° . The point spread function (PSF) is 0.07° on axis and 0.22° at 4° off-axis, which fits the CTA requirement of 0.25° at 4° off-axis. The entire telescope weighs 8.6 tons accounting for the 200 kg digitizing camera. The telescope structure is made of steel, and is industrially buildable. Moreover, it is compact, stiff, and has a low production cost compared to the other Schwarzschild-Couder dual mirror SST telescopes. The SST-1M is therefore suitable to be produced in series and transported and installed to high-altitude sites.



Figure 25. Picture and CAD view of the SST-1M first prototype [19]

As can be seen in figure 25, the mirror is made of 18 hexagonal facets distributed on two concentric rings. The mirrors are coated with AlSiO_2 to achieve a reflectance of roughly 90% between 300 and 600 nm. A mirror prototype is shown in figure 26. The size of a mirror is 780 mm flat-to-flat. Each mirror is fixed on 3 points for a secure fixation and can be orientated individually using actuators. The total reflection area is 9.42 m^2 . By accounting the shadow of the camera and the mast on the mirrors, the effective collection area of the reflectors reduces to 6.47 m^2 .

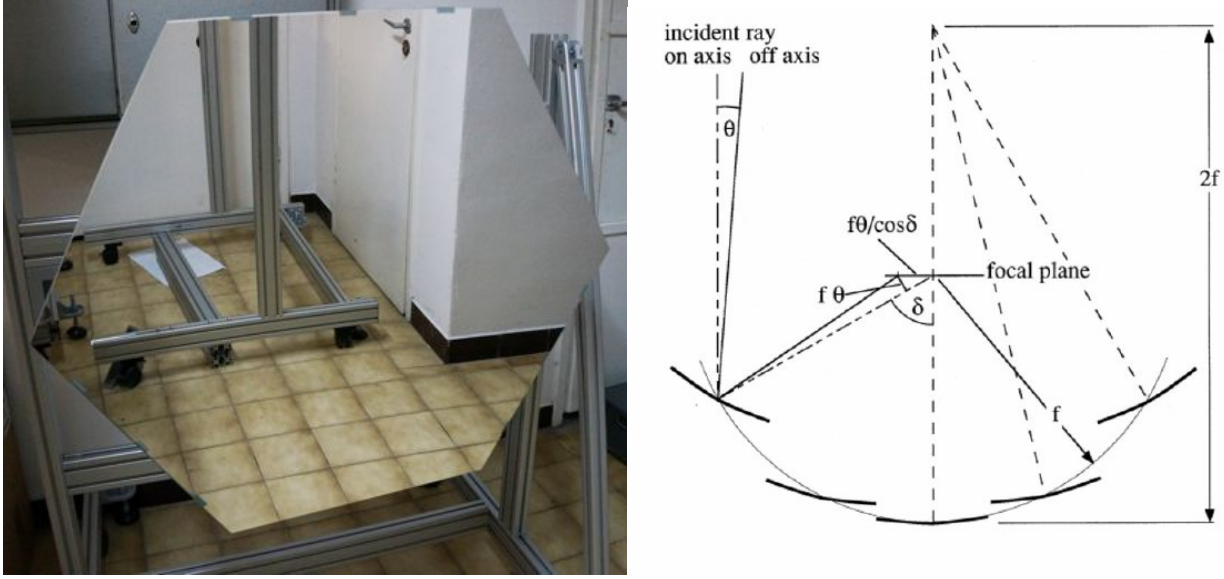


Figure 26. Picture of an SST-1M mirror [19] and schematic of the Davies-Cotton design (Credit: [arXiv:1610.00723](https://arxiv.org/abs/1610.00723))

3.2 The camera working principle and design

The SST-1M camera is composed of a detection part, the photo-detection plane (PDP), and a trigger/readout part, called DigiCam (see figure 27). Its dimensions are restricted by the telescope geometry. It has a hexagonal shape with a vertex-to-vertex size of 112cm and a height of 73.5cm.

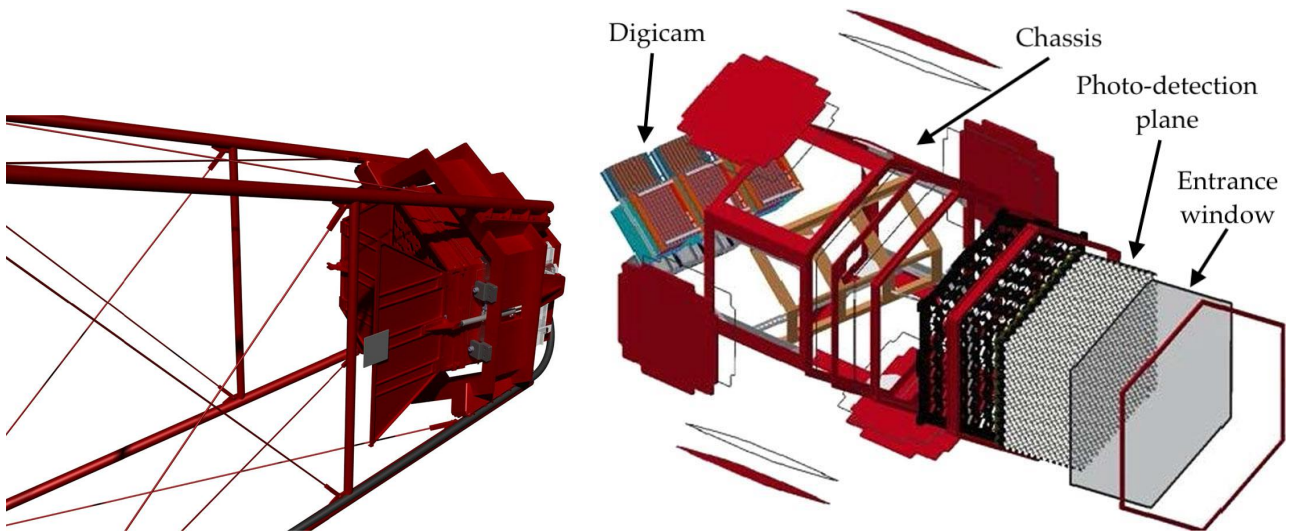


Figure 27. CAD view of the camera housing and shutter and split view of the camera [14]

When the telescope is not being operated, the camera entrance is protected by a shutter from environmental conditions and surrounding light (see figure 27). During operations, when the shutter is opened, the PDP is protected from dust and water by a 3.3 mm thick entrance window made of Borofloat (see figure 28). The use of this material allows mechanical rigidity. The coating applied on the window allows to filter wavelengths above 540 nm, where the Cherenkov contribution is negligible. The window has a satisfying transmittance down to 310 nm (see figure 28). Cutting off the high wavelengths allows to avoid most of the night sky background (NSB) since it is peaked in the red, and is especially important for a SiPM-based camera since silicon photomultipliers are sensitive up to near-infrared wavelengths. It can be seen from the plot in figure 28 that the optical efficiency of the camera (conversion factor from photons to photoelectrons) between 300 nm and 550 nm is 16.6%. The required optical efficiency has been increased to 20% by CTA, which is not reached by the camera prototype. The optical efficiency is computed as the transmittance spectrum of the entrance window weighted by the Cherenkov spectrum and convolved with the sensor PhotoDetection Efficiency (PDE), the fill factor of the PDP (to account for dead spaces between pixels), and the collection efficiency of the light guides. The requirement can therefore be reached either by improving the entrance window spectrum or by upgrading the sensors to achieve a better PDE.

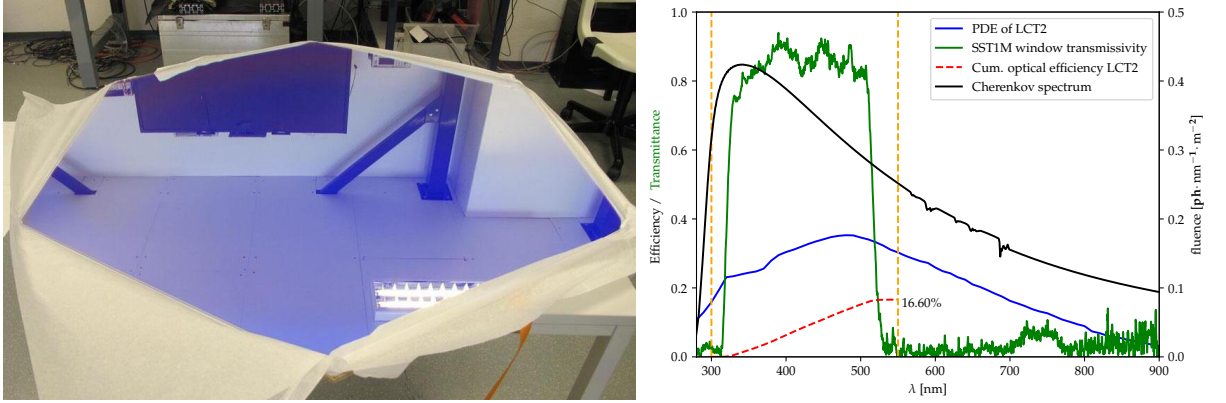


Figure 28. Picture of the camera entrance window (left, [14]) and its transmittance spectrum (right)

The PDP is made of 1296 pixels distributed in 108 modules of 12 pixels each and weighs 35 kg. Each pixel is made of a hexagonal hollow-light concentrator (see figure 30) coupled to a hexagonal SiPM sensor (see figure 31). A hexagonal shape is used for the pixels to have fully symmetrical conditions (equal distance between any pixels), important for pattern recognition, and to minimize the dead space between pixels. In each module, twelve pixels are mounted on the front-end electronics, composed of a preamplifier board that handles the signal from the sensors, and a slow control board (SCB), whose main purposes are to stabilize the operational point of the sensors and to route the signal from the preamplifier board to DigiCam. The 108 modules are screwed together on an aluminium backplate, which ensures the mechanical stability of the PDP. The temperature of the whole PDP is stabilised by water cooling (air cooling being incompatible with the IP65 insulation requirement for the camera). The full PDP and a single module are shown in figure 29. The different elements composing the PDP are described thereafter.

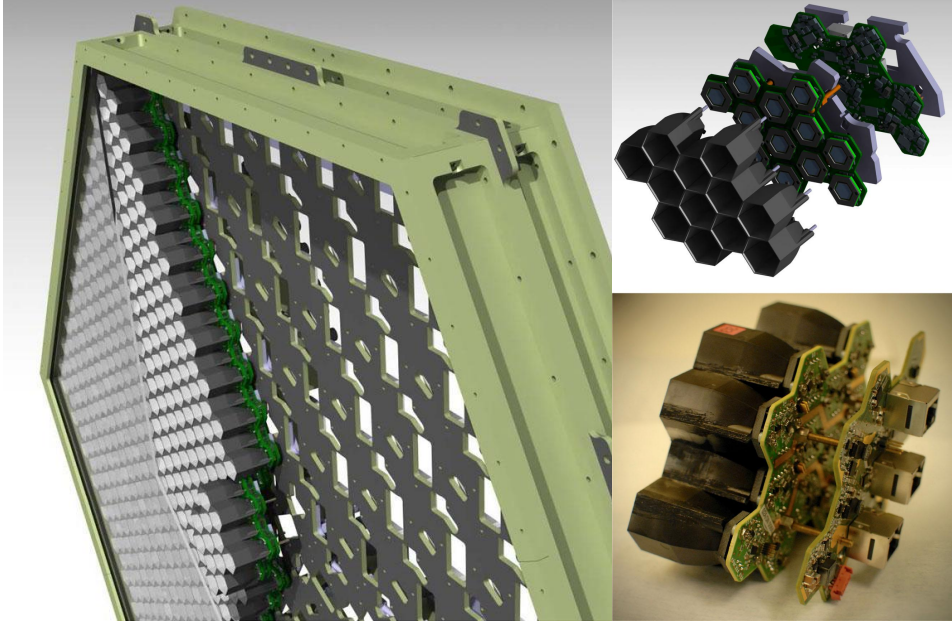


Figure 29. CAD view of the photo-detection plane (left), CAD view and picture of a 12 pixels module (right) [14]

The hollow light guides, whose dimensions are shown in figure 30, are used to focus the light from the pixel entrance surface to the sensor surface with a compression factor of about 6. The design of the light funnels is based on the Winston cone shape and the inner surface of the cone has been optimized by a Bézier curve, which, together with the coating applied on the inner surface, allows to reach an 88-90% collection efficiency (see figure 30). The angular size of a single pixel is 0.24° . The PSF being fixed by the optics of the telescope, smaller pixels would not improve the image resolution. Another purpose of the cones is to reduce the amount of stray light entering the sensors mainly coming from reflections on the ground. The geometry of the cones has been studied to reject the light coming from incident angles greater than the cut-off angle of 24° . The cones are produced in two halves to improve the uniformity of the deposited coating (whose goal is to enhance the reflectivity of the inner surface of the cone), which are glued together after the coating process.

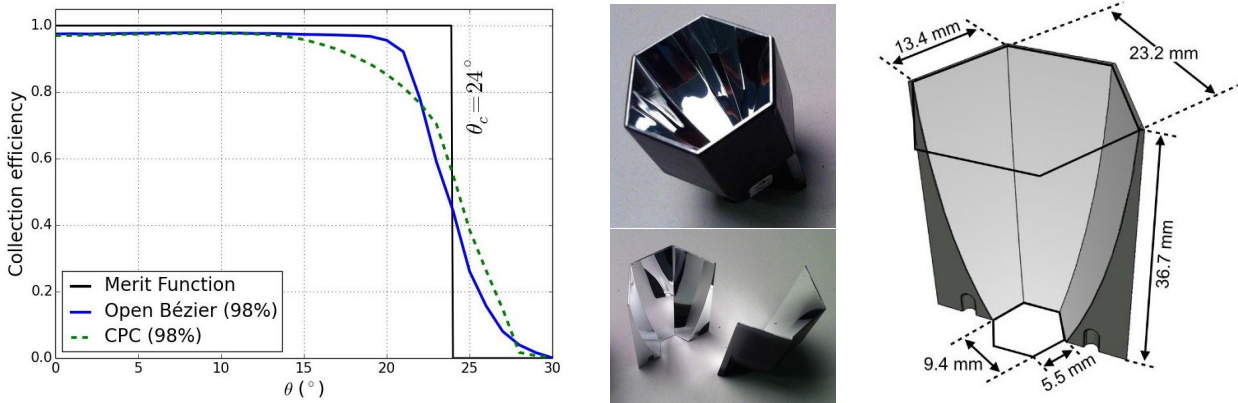


Figure 30. Collection efficiency as a function of the incidence angle [17] (left), picture of a cone before and after being assembled [14] (middle), and dimensions of the cone (right) [14]

The SiPM sensors (see [chapter II](#)) are based on the low cross-talk technology developed by Hamamatsu, where the microcells are separated by trenches that limits the optical cross-talk between the cells without reducing much the fill factor. The so-called S10943-3739(X) sensor (LCT2) is used for the PDP. The hexagonal sensor has a large sensitive surface of 95.56 mm^2 and is composed of 36840 square $50 \text{ }\mu\text{m}$ microcells (see [figure 31](#)). Such large sensitive area implies a relatively large capacitance (3.4 nF) which induces long signals that are incompatible with the 30 ns integration window requirement. To deal with such large surface, the sensors are divided in 4 channels of 9210 cells each (see [figure 31](#)), reducing the capacitance to 850 pF per channel. The high number of cells allows a high dynamic range up to thousands of collected photons. The sensors are DC coupled to the front-end electronics, which allows to monitor the baseline shift due to changes of intensity of the NSB and to correct for it. The break-down voltage of the SiPMs depends on temperature with a coefficient of $54 \text{ mV}/^\circ\text{C}$. Since the gain of the sensors is proportional to the over-voltage, defined as the difference between bias and break-down voltages ($\Delta V = V_{\text{bias}} - V_{\text{BD}} = 2.8 \text{ V}$), the sensors undergo a gain variation of $2\%/^\circ\text{C}$. This is the reason why each pixel is equipped with a NTC (negative temperature coefficient) probe to monitor the temperature of the device. This temperature is then readout by the front-end electronics to stabilize the working point of each sensor, as explained later.

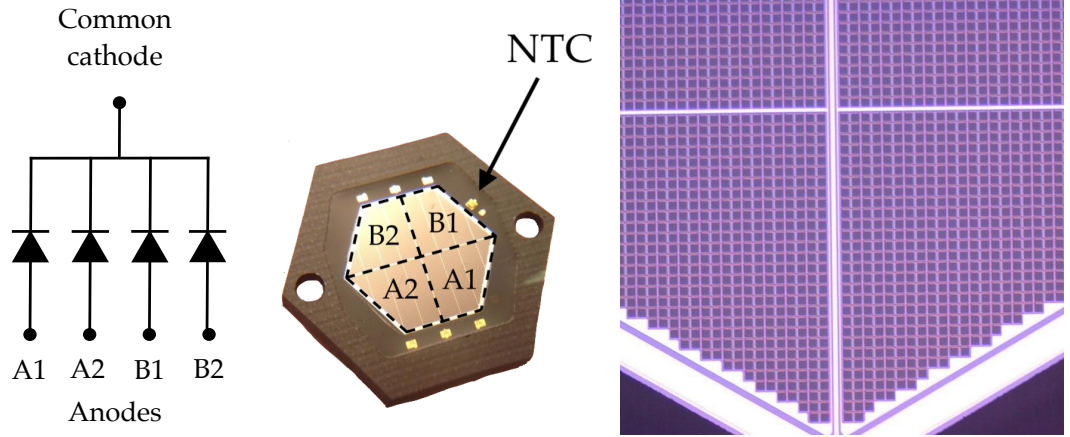


Figure 31. Picture of a sensor and its electric equivalent circuit (left, [16]) and microscope picture of the sensor showing the microcells matrix (right, [14])

The front-end electronics is divided into two printed circuit boards (PCBs) because of space constraints (see [figure 29](#)): the preamplifier board, whose purpose is to hold the twelve pixels together and to amplify the signal of the sensors, and the slow control board (SCB), whose goals are to route the signal from the preamplification stage to DigiCam, to read the bias voltage and temperature of each sensor, and to stabilize the working point of the pixels. Because of power and cost constraints, the four channels of each pixel are summed together in pairs via two low-noise transimpedance amplifiers, whose outputs are combined by a differential output stage. This electrical topology is shown in [figure 32](#). The parameters of the electrical circuit have been fine-tuned to get well-behaved waveforms over the whole dynamic range, implying that even if the response is linear only up to 750 photons, the signal above saturation can be reconstructed up to thousands of photons with a satisfying resolution. As mentioned above, temperature has an effect on the over-voltage of the sensors (but also on PDE, optical cross talk, and after pulse probability), implying that temperature variations across the PDP and even in time would

affect the uniformity of the gain and thus of the reconstructed image and the reliability of the trigger. The working point of the sensor (over-voltage) has therefore to be tuned in time for each pixel according to temperature variations. A water-based cooling system is responsible for keeping the PDP temperature between -15°C and $+25^{\circ}\text{C}$ during operations. The working point of each sensor is then stabilised by a correction loop implemented in the SCB that reads the temperature from the NTC probes to keep constant the over-voltage of each sensor.

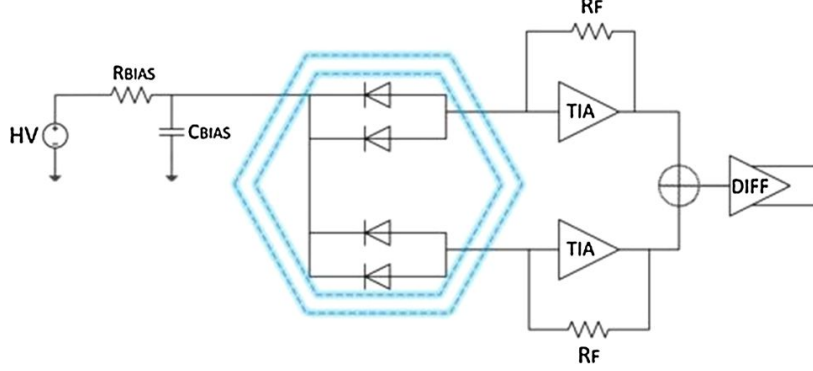


Figure 32. Electronic topology of the preamplification stage [14]

Once the signals from all pixels are amplified and received by the SCB, they are sent to DigiCam and stored in ring buffers. A low resolution copy of the data is used to apply the pattern matching trigger logic. If an event passes the trigger, the original data set is sent to the camera server. This allows to keep data taking while applying trigger selection to previous events. The fully digital system that digitizes the data, applies trigger selection, and sends data to the camera server, is called DigiCam and is based on field programmable gate arrays (FPGAs). DigiCam is composed of 27 digitizer boards and 3 trigger boards equally distributed in 3 micro-crates (see figure 33), each micro-crate being connected to one third of the PDP (36 modules). Each digitizer board receives analog signals from 4 modules, and digitizes the signals at a rate of 250 MHz by 12-bit fast analog to digital converters (FADCs). The trigger boards of the three micro-crates are connected together to allow data processing of images that are spread on two or the three sectors. DigiCam has its own cooling system based on heat pipes.

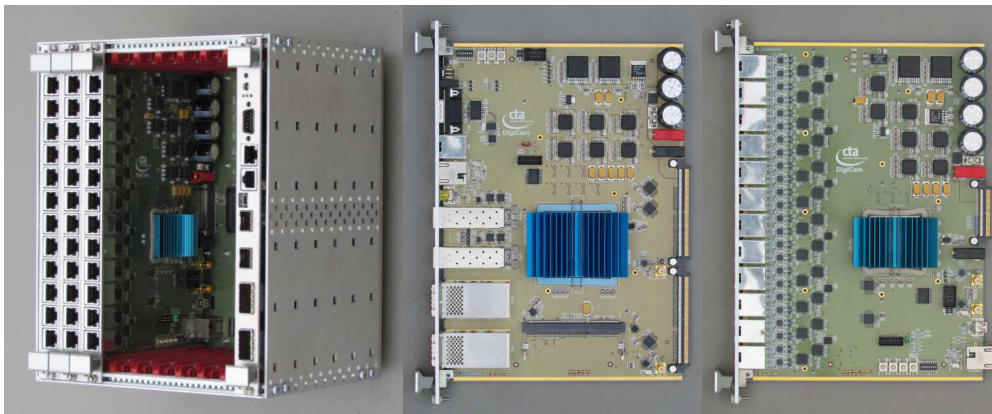


Figure 33. A digicam micro-crate (left), one digicam trigger board (middle), and one digicam digitizer board (right) [14]

Chapter II

Silicon Photomultipliers (SiPM)

During the last decades, silicon photomultipliers (SiPMs) have begun to replace photomultiplier tubes (PMTs) in many applications, especially in high-energy physics. The reason for this change in terms of technology is that SiPMs have a lot of advantages compared to PMTs. For instance, they are very compact devices with high quantum efficiency over a wide range of wavelengths. They are also more robust against intense light, insensitive to magnetic fields, and cheaper to manufacture. The fact that SiPMs have negligible ageing effects make them suitable for long period experiments such as CTA. The low power consumption of such devices is perfect for big-scale experiments. The table 4 summarizes the benefits of SiPMs compared to PMTs.

	PMT	APD	SiPM
Quantum Efficiency	25% to 40%	up to 80%	up to 80%
Single photon resolution	✓	-	✓
Operation voltage	1-3 kV	100-500V	20-40 V
Gain	10^4 - 10^9	30-300	10^5 - 10^7
Temperature dependence	Low	High	Low
Robustness	-	✓	✓
No damage in bright light	-	✓	✓
Insensitivity to magnetic fields	-	✓	✓
Miniaturisation	-	✓	✓
Production costs	Medium	Low	Low

Table 4. Comparison chart of PMT, APD, and SiPM [27]

A reminder of semiconductor physics is first proposed. The photo-detection mechanism and the working principle of photodiodes are then discussed. Subsequently, the concept of the silicon photomultiplier is described so as its main characteristics. Finally, the so-called Corsi model, that describes the SiPMs behavior via electronic circuits, is detailed.

1 Semiconductor physics

1.1 Basics of semiconductor physics

In the case of an isolated atom, its electrons can only occupy given discrete energy levels. When atoms are combined into molecules, their respective orbitals overlap. When growing the number of atoms to reach macroscopic crystal lattice, the allowed energy levels for the electrons form continuous bands of energy, separated by forbidden energy bands. The electrons fill the bands starting from the less energetic. The last (more energetic) filled band is called the Valence band, while the next one, that can be either empty or partially filled, is called the conduction band. This is what is called electronic band structure of a solid. From this band structure we differentiate three types of solids.

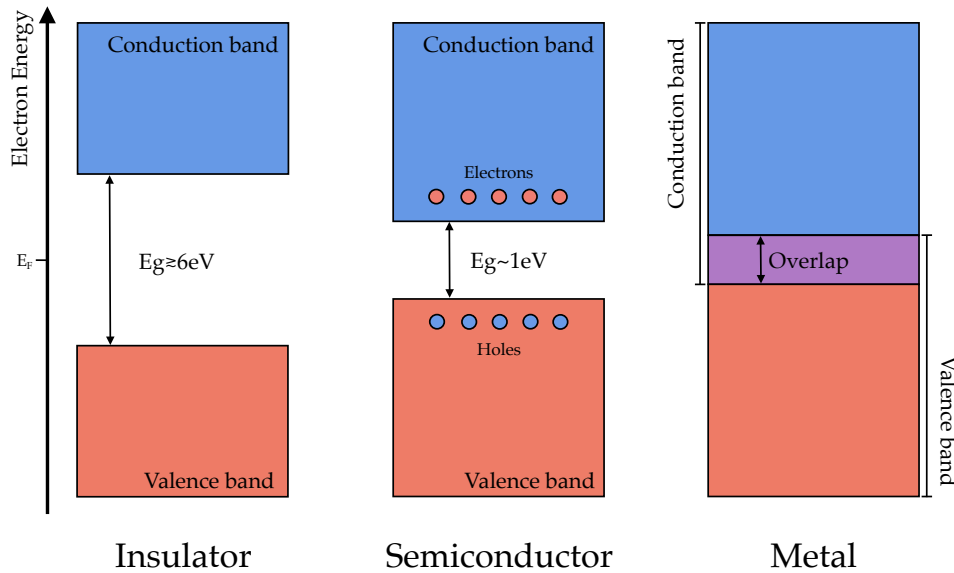


Figure 34. Valence and Conduction bands in solids

The figure 34 depicts the band structure of these three families of solids. We distinguish the electrical insulators, which have a forbidden gap of energy E_g between their valence and conduction bands, from the metals (electrical conductors), where valence and conduction bands overlap. The last energy band of a metal is thus partially filled. The insulators have their valence band completely filled and their conduction band empty. But when the energy gap that separates valence band from conduction band is small enough (of the order of eV), electrons can be thermally excited to the conduction band by a photon (whose energy is bigger than the gap). This is what defines the semiconductors.

Material	Electrical resistivity ρ
Insulators	$10^{14} - 10^{22} \Omega \cdot \text{cm}$
Semiconductors	$10^{-2} - 10^9 \Omega \cdot \text{cm}$
Conductors (Metals)	$10^{-6} \Omega \cdot \text{cm}$

Table 5. Resistivity range of insulators, semiconductor, and metals

The fraction of thermally excited electrons in an insulator is given by $\exp\left(-\frac{E_g}{2k_b T}\right)$ with E_g the size of the forbidden gap at 0 K (1.1 eV for Silicon). The electrical resistivity ρ , inversely proportional to the fraction of excited electrons, decreases therefore with temperature. Despite this behavior, opposite to that of metals, the electrical conductivity ($\sigma \equiv 1/\rho$) of a semiconductor is still smaller than that of a metal, even at high temperatures. The typical values of electrical resistivity for these three types of solids are shown in the table 5.

Electron-hole pairs are continually produced by thermal excitation in a semiconductor. Considering the probability that a state of energy E is occupied by an electron, given by the Fermi-Dirac distribution $F_{FD}(E) = \frac{1}{e^{(E-E_F)/k_B T} + 1}$, the concentration of electrons n (equivalently, the concentration of holes p) under stable conditions is found to be:

$$n = p = \sqrt{N_C N_V} \exp\left(\frac{-E_g}{2k_B T}\right) \propto T^{3/2} \exp\left(\frac{-E_g}{2k_B T}\right) \quad (20)$$

where $k_B = 8.62 \cdot 10^{-5} \text{ eV} \cdot \text{K}^{-1}$ is the Boltzmann constant, and N_V and N_C are the number of states in the valence and conduction bands, respectively. For intrinsic (pure) semiconductor crystals, the Fermi energy level is E_F .

1.2 Doped semiconductors

The number of electrons equals the number of holes in a pure semiconductor crystal. By introducing impurity atoms with one more/less valence electron in the lattice, this equilibrium can be broken. This process, called doping, gives birth to an extrinsic semiconductor. The additional electron/hole brought by the impurity comes apart from the remaining ion impurity, contributing to the overall conduction of the material. Therefore, doping can be used to boost the electrical conductivity of the semiconductor. As an example, introducing a fraction of 10^{-5} Boron atoms in a Silicon lattice would boost the electrical conductivity of the material by a factor 10^3 .

Two types of impurities are distinguished. The donor impurities, which releases electrons in the lattice and create a donor bound level just below the conduction band, in the gap, give rise to n-type semiconductors. The acceptor impurities, which releases holes in the lattice and create an acceptor bound level just above the valence band, in the gap, give rise to p-type semiconductors. These two types of semiconductor impurities are illustrated in figures 35 and 36.

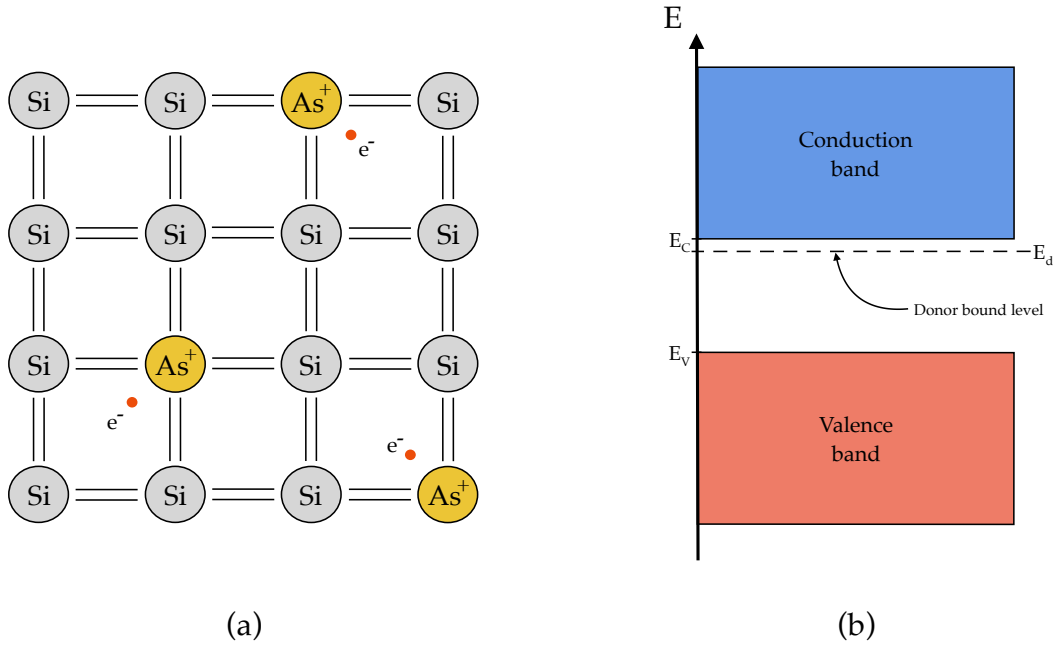


Figure 35. (a) Introduction of an impurity in a Silicon crystal structure to get a n-doped semiconductor with an excess of negative charge (electrons).
(b) Donor energy level induced by the Arsenic impurity.

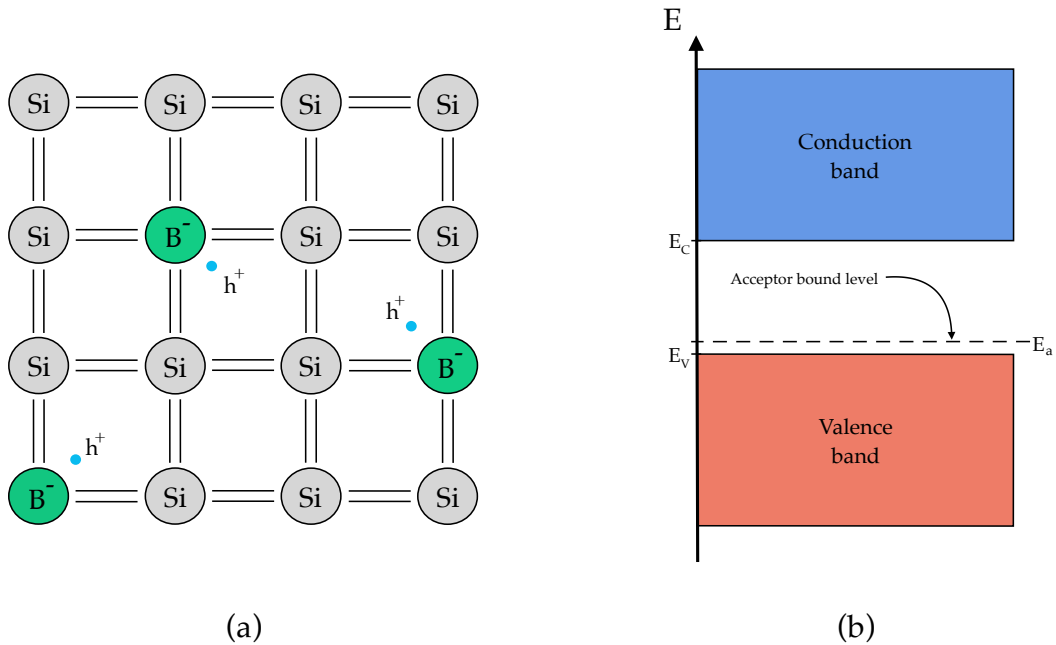


Figure 36. (a) Introduction of an impurity in a Silicon crystal structure to get a p-doped semiconductor with an excess of positive charge (holes).
(b) Acceptor energy level induced by the Boron impurity.

2 Detection mechanism of Avalanche PhotoDiodes (APDs)

A boundary between a p-type and an n-type semiconductors in a crystal is called a pn junction. When such a junction is created, the two Fermi levels of the n and p semiconductors are matching and a transition region with an electric field, called the depletion region, is formed between the n and the p sides. An equilibrium state is reached where some electrons are drifting from the p to the n side due to the electric field, compensating the diffusion of electrons from the n side to the p side. An external bias voltage can be applied to the pn junction. The junction can either be forward biased or reversely biased. In the case of a forward bias, the p side is made more positive and the depletion region becomes smaller, while in the case of a reverse bias, the p side is made more negative and the depletion zone is wider. The three biasing modes of a pn junction so as its I-V characteristics are depicted in figure 37. Forward bias cannot be used to detect photons since current is growing exponentially with voltage and is already very important at low voltage. Moreover, the depletion zone, which is the zone used to detect the photons, is very small. Detectors using pn junction, such as for instance diodes, are therefore reversely biased.

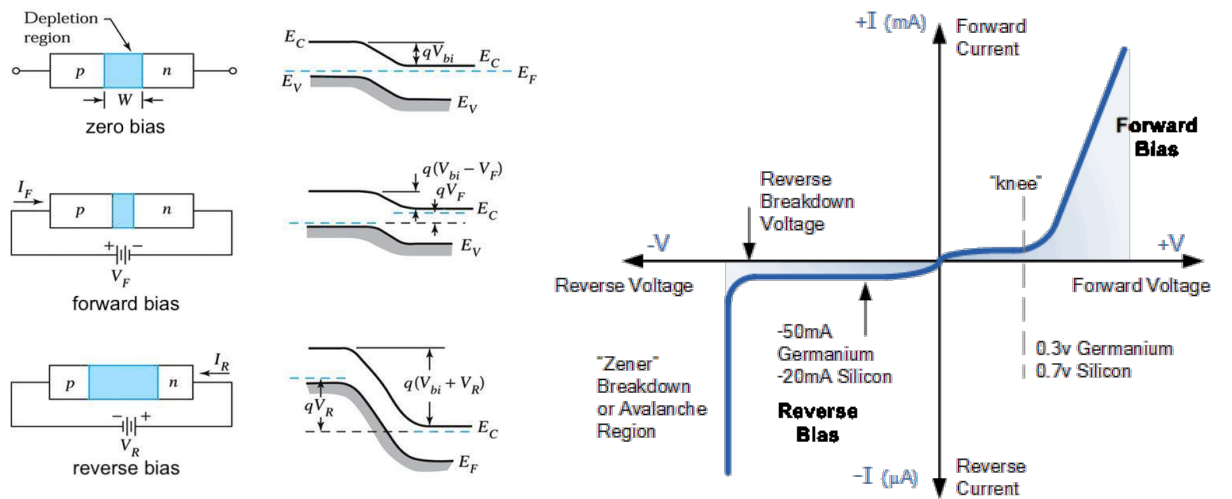


Figure 37. Biasing modes of a pn junction (left, from A. Bravar PhD lectures) and I-V characteristics of a pn junction (right, Credit: Nikhil.M.R)

The working principle of an Avalanche PhotoDiode (APD) is illustrated in figure 38. An incoming photon with a minimal energy of 1.1 eV, corresponding to the gap of Silicon, is absorbed by the intrinsic region "i". The absorbed photon generates an electron-hole pair. The electron drifts to the n^+ side and the hole drifts towards the p^+ side. The electron can gain enough energy thanks to the electric field and then scatters on the lattice and create a new electron/hole pair. This pair is accelerated in turn, creating more pairs. This process is known as an *avalanche* and allows to convert a photon to an electric signal. The number of electrons produced by the avalanche is known as the gain. Layers with different doping are used to enhance the electric field near the avalanche region, increasing the acceleration power and therefore the gain of the APD. A standard APD is operated in a

linear mode, for which the charge generated is proportional to the energy of the absorbed photon. The typical gain of an APD is of the order of a few hundred.

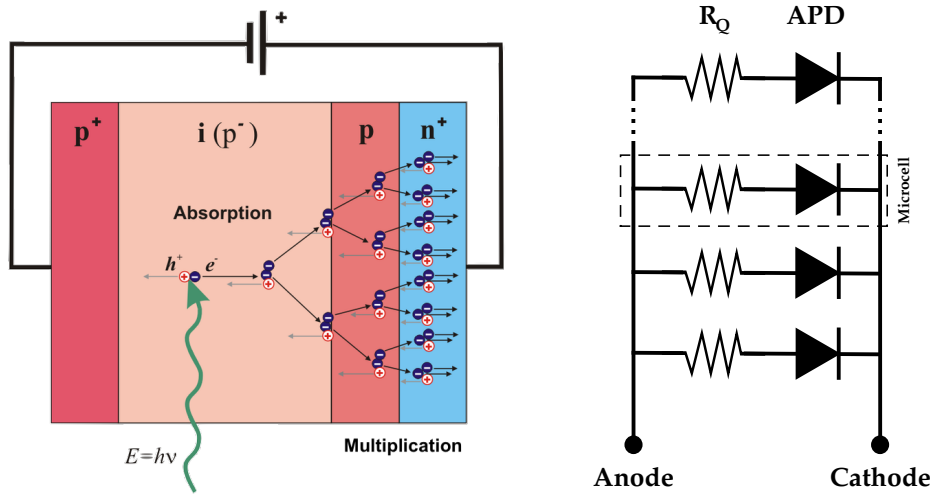


Figure 38. Working principle of an APD (left, from Wikipedia) and SiPM circuit schematic showing the APD microcells (right)

3 Characteristics of a Silicon PhotoMultiplier

The gain of an APD can be increased by increasing the magnitude of the electric field, or equivalently, by biasing the diode above breakdown voltage. For high enough electric fields, the avalanche is saturating, and the amount of deposited charge is no more related to the energy of the incoming photon. Such device is called a Geiger-mode APD (G-APD) and has a binary response. An array of G-APD can therefore be used to detect the amount of incoming photon. This is the principle of a Silicon PhotoMultiplier (SiPM). An SiPM consists of a matrix of microcells connected in parallel. Each pixel is composed of a G-APD and a quenching resistor R_Q (see figure 38). When a photon induces an avalanche in a microcell, the silicon breaks down and become conductive, amplifying the primary electron in a detectable current. Once a current flows into the microcell, it is quenched by the quenching resistor, limiting the current flowing into the diode. Once the avalanche is stopped due to quenching, the diode recharges to the bias

voltage, and becomes operational again after the recovery of the microcell. This cycle is depicted in figure 39. The main performance parameters of an SiPM are now described.

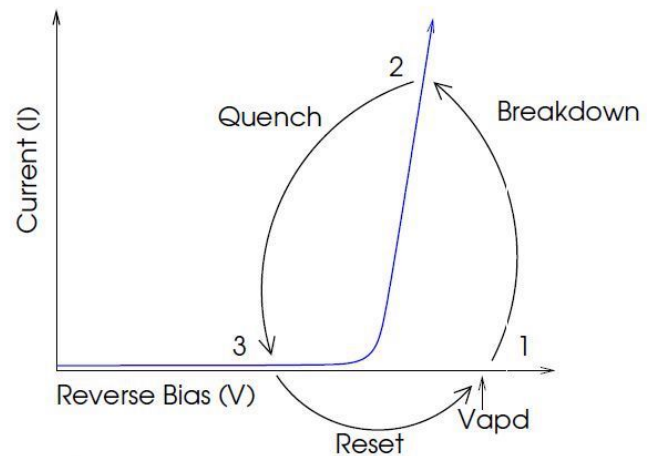


Figure 39. Breakdown, quench and reset cycle of a G-APD [26]

Break-down voltage: The breakdown voltage V_{BD} is the bias voltage above which the electric field in the depletion zone is strong enough to create a Geiger discharge. It can be determined by measuring the dark current as a function of the bias voltage. The break down is then corresponding to the bias point where the dark current begins to exponentially increase. Usually, SiPMs are operated a few volts above the breakdown. The bias voltage of a SiPM can therefore be expressed as:

$$V_{bias} = V_{BD} + \Delta V \quad (21)$$

Gain: The gain of an SiPM is defined as the amount of charge induced by a single photoelectron (i.e. detected photon) and can be expressed as:

$$\text{Gain} = \frac{Q}{e} = \frac{C_{\mu\text{cell}} \cdot \Delta V}{e} \quad (22)$$

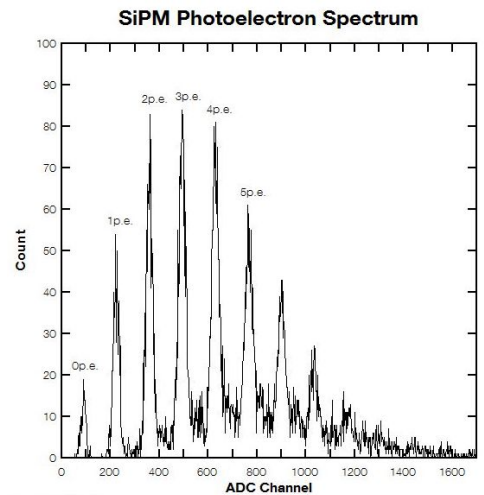
where e is the charge of an electron, Q is the charge released in the avalanche, and $C_{\mu\text{cell}}$ is the microcell capacitance. The typical gain of an SiPM is of the order of 10^5 - 10^6 .

Photo Detection Efficiency (PDE): The PDE is the ratio between the number of fired cells (number of photoelectrons) and the number of incident photons. The PDE is different from the Quantum Efficiency (QE) that is usually used to characterised PMTs or APDs due to the microcell structure of the SiPM. Indeed, it is expressed as the product of the QE with the avalanche probability ϵ (also called Geiger efficiency, which correspond to the number of excited pixels divided by the number of pixels hit by a photon) and the geometrical fill factor F (the fraction of the overall SiPM surface covered by the sensitive microcells, usually about 60%):

$$\text{PDE}(\lambda, V) = \text{QE}(\lambda) \cdot \epsilon(V) \cdot F \quad (23)$$

Note that the QE depends on the wavelength of the incoming photon and that the Geiger efficiency depends on the bias voltage.

Photon counting ability: Each microcell being a G-APD, it has a binary response and can detect a photon independently. The resulting signal of an SiPM being the sum of the photocurrents of each cells, it is thus providing information on the number of measured photons. Making a photoelectron spectrum of an SiPM, like the one shown on the right [26], allows therefore to count the number of detected photons as a function of the amplitude or the charge of the signal.



Dark Count Rate (DCR): The DCR is the main source of noise of an SiPM. It correspond to the rate of dark pulses generated by thermally excited electrons. The DCR increases with the overvoltage and temperature. It is usually of the order of MHz for a few mm^2 detection surface.

Optical crosstalk: Another source of noise is the optical crosstalk between the microcells.

In the avalanche, accelerated electrons within the high field region can emit photons, that can cause an avalanche in a second microcell. The secondary photon can either directly travel to a neighbor cell (direct crosstalk), generate an electron/hole pair near a neighbor cell that can diffuse to the microcell and cause a discharge (delayed crosstalk), or even being reflected on one of the layer interfaces and reach a neighbor cell indirectly (indirect crosstalk). The crosstalk probability increases with the overvoltage, and can be limited by trenches or guard rings around the microcells. Nevertheless, such technologies affects the fill factor of the sensor (fraction of sensitive surface).

After pulsing: During the avalanche multiplication, charge carriers can be trapped in defects in the silicon, and released a few ns later, inducing a second avalanche and therefore an afterpulse in the same microcell.

Dynamic range and Linearity: The dynamic range is the optical range over which the SiPM provides a signal from which we can extract the light level with a satisfactory resolution. The response of the sensor is first linear up to a certain point, above which a saturation occurs. This saturation is due to the recovery time of the microcells and to the limited number of microcells. Two photons hitting the same microcell one after the other (within a time shorter than the recovery time of the sensor) will count for a single photon. The dynamic range depends therefore on the number of cells and the geometrical saturation of the sensor can be expressed as:

$$N_{\text{firedcells}} = N_{\text{cells}} \left(1 - \exp \left(- \frac{N_{\gamma} \cdot \text{PDE} \cdot (1 + P_{\text{XT}})}{N_{\text{cells}}} \right) \right) \quad (24)$$

where N_{cells} is the total number of cells, N_{γ} is the number of incident photons, PDE is the photodetection efficiency of the sensor, and P_{XT} is the optical crosstalk probability. Note that the afterpulses probability is neglected since afterpulsing occurs after the initial detected pulse.

Temperature coefficient: Temperature as an effect on the breakdown voltage of an APD and therefore has a direct effect on the gain and on the applied overvoltage:

$$\frac{1}{G} \cdot \frac{\partial G}{\partial T} = - \frac{1}{\Delta V} \cdot \frac{\partial V_{\text{BD}}}{\partial T} \quad (25)$$

Typical temperature coefficients are of the order of a few tens of mV/K.

4 Modelling the pulse shape of an SiPM

An electrical model of an SiPM has been proposed by Corsi et al. [31] in order to describe the output pulse shape of such detector. This model is shown in figure 40.

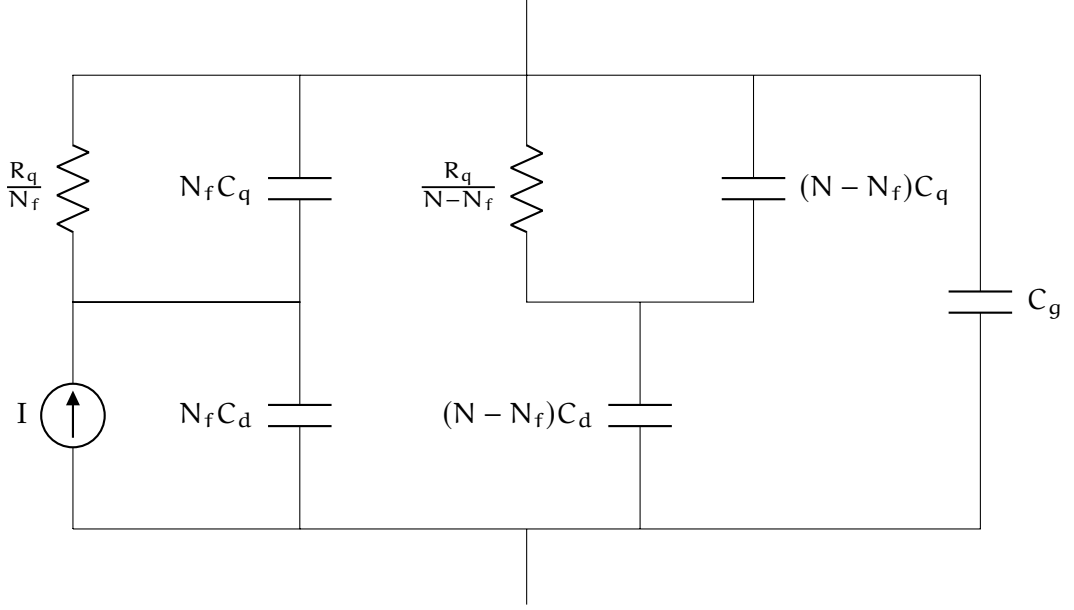


Figure 40. Equivalent circuit of the SiPM according to the Corsi model [31]

The model of a single cell is composed of a diode capacitance C_d coupled in series with the quenching resistor R_q . A small parasitic capacitance C_q is placed in parallel to the quenching resistor. In order to simulate a fired cell, a current source can be added parallel to the diode capacitance to model the charge released in the microcell during a Geiger discharge. The whole matrix of microcells (SiPM) can then be simulated using the circuit shown in figure 40. It can be described in three parts. The first part of the circuit represents the N_f fired cells with the current source simulating the avalanche. The second part of the model is made of the same circuit but without current source, and corresponds to the remaining $N - N_f$ non-fired microcells. Finally, a grid capacitance C_g , parallel to the fired and unfired cells, accounts for the presence of a parasitic component due to the metal grid spanning the surface of the sensor that connects the microcells all together. An SiPM can therefore be characterised by the Corsi parameters C_d , C_q , C_g , and R_q .

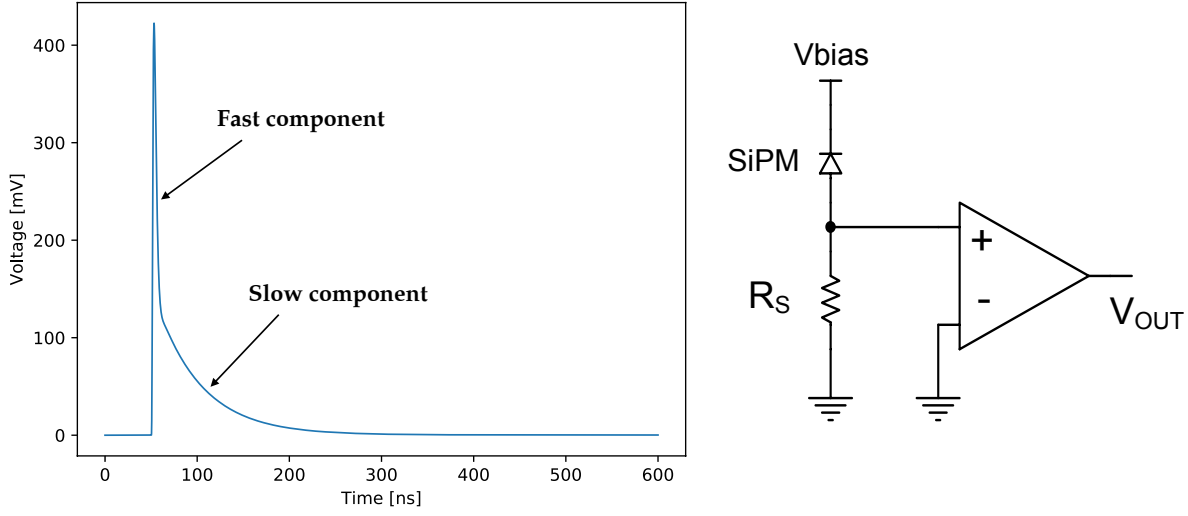


Figure 41. Example of SiPM pulse shape (left) and typical readout schematic of a SiPM (right, [30])

A typical readout electronic circuit for SiPMs is shown in figure 41, so as the usual shape of the output signal. The characteristic time of the rising edge of the pulse is given by the product of the output resistor of the sensor R_s and the diode capacitance:

$$\tau_{\text{rise}} = R_s \cdot C_d \quad (26)$$

The tail of the pulse is composed of a fast exponentially decaying part, whose characteristic time is:

$$\tau_{\text{fall,fast}} = R_s \cdot (C_q + C_g) \quad (27)$$

and of a slow exponentially decaying component, whose decay time is given by:

$$\tau_{\text{fall,slow}} = R_q \cdot (C_q + C_d) \quad (28)$$

The recovery time of the whole pulse, which correspond to the time for the microcell to be recharged, is given by:

$$\tau_{\text{RC}} = C_d(R_q + R_s \cdot N) \quad (29)$$

where N is the number of microcells.

Pulse shape simulation of SiPM with PSpice®

Since the requirement for overall camera optical efficiency (B-TEL-1170) has been increased to 20% (that includes the PDE of the sensors but also the entrance window transmittance, the cone efficiency, and the dead spaces between pixels), the sensors have to be upgraded to a greater photo detection efficiency technology in order to meet this requirement. Two sensors with increased PDE, the Hamamatsu LCT5 (S13360) and LVR3 (S14520) SiPMs, are good candidates for this upgrade. At the working point of 8% crosstalk probability, the use of LCT5 or LVR3 sensors would increase the PDE from 34% to 48% or 52%, respectively (see figure 42).

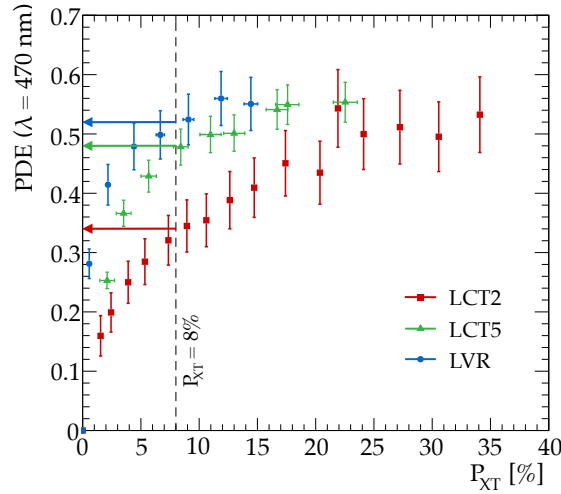


Figure 42. Photo-detection efficiency versus crosstalk probability for LCT2, LCT5, and LVR3 SiPMs (Measurements from A. Nagai)

The microcell capacitance and quenching resistor of the LCT5 and LVR3 sensors being bigger than that of LCT2 sensor (85 fF and 190 kΩ for LCT2, 101 fF and 300 kΩ for LCT5, and 128 fF and 430 kΩ for LVR3), the signal induced is expected to be longer (see chapter II). A study has already been performed for the LCT5 sensor. The LVR3 sensor has to be considered not only for its bigger PDE but also for questions of technology harmonisation between the different SST projects. The idea of the work presented here is therefore to use the Corsi model parameters corresponding to the LVR3 sensor as an input to the front-end electronics PSpice model, and to fine-tune electronic components to have an optimized short and well-behaved pulse with the LVR3 sensor while keeping a good photon counting ability and a wide dynamic range.

1 Electronic model of the camera front-end electronics

The electronic PSpice model of a four-channels hexagonal sensor coupled to the pre-amplification stage is shown in figure 43. It consists of four parallel Corsi circuits, each one modelling a channel of the hexagonal sensor, summed by pairs via two low-noise transimpedance amplifiers. The outputs of the two operational preamplifiers (OPA846 from Texas Instruments) are then combined via a differential amplifier (LMH6551 from Texas Instruments). The pulse is measured as the voltage difference between the positive and negative outputs of the differential amplifier.

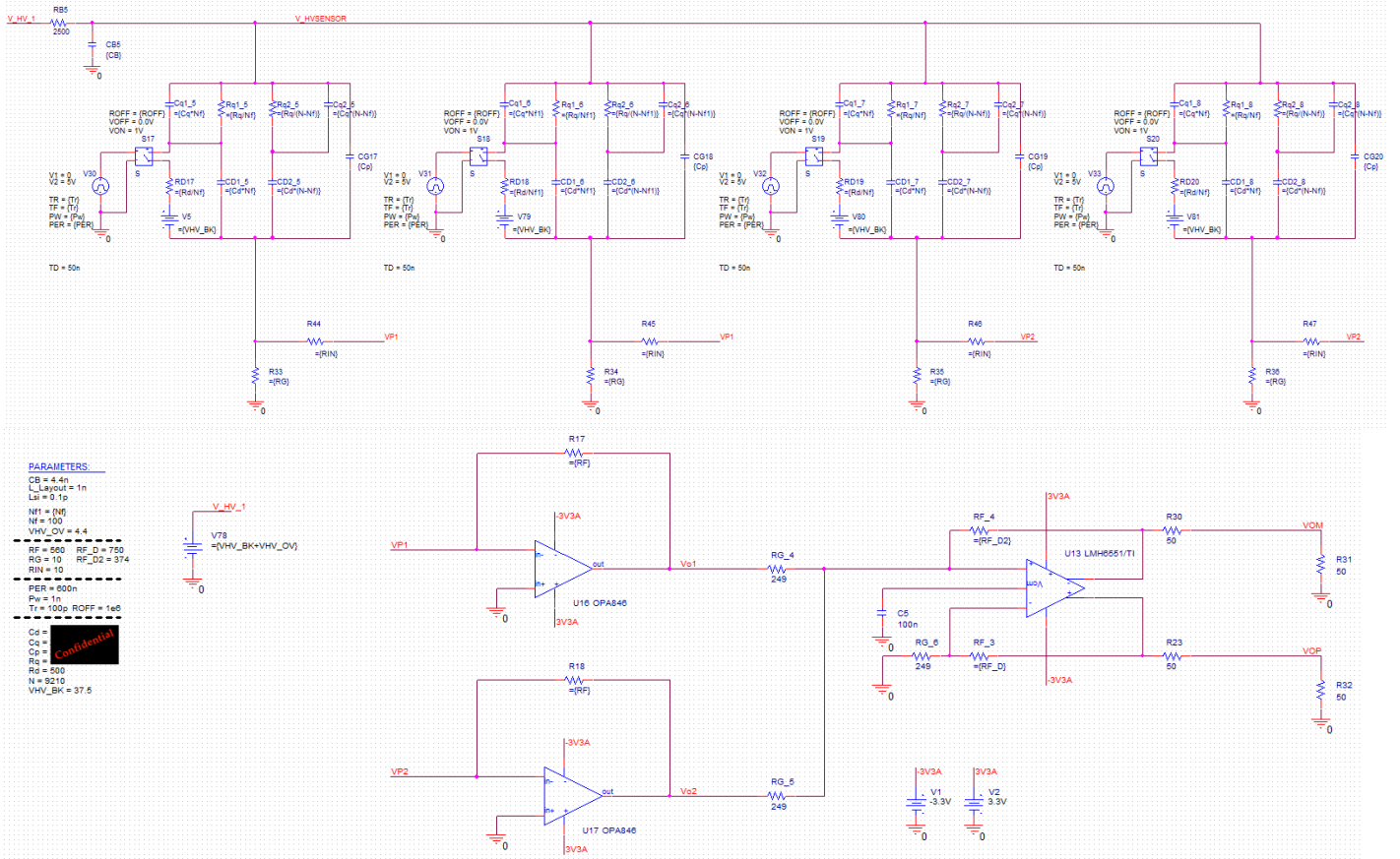


Figure 43. PSpice model of the hexagonal sensor

The Corsi parameters for the LVR3 sensor provided by Hamamatsu are confidential, so they are not given here. The LVR3 sensor is based on the low voltage resistor technology from Hamamatsu, where the thickness of the depletion region is reduced in order to improve the PDE, implying a bigger microcell capacitance. The quenching resistor is also increased to deal with higher gain. The table 6 gives the values of some electronic components that are used in the model to fine-tune the pulse shape.

Parameter	C_B [nF]	R_F [Ω]	R_{IN} [Ω]	R_G [Ω]
Original value	4.4	560	10	200

Table 6. Original values of the different parameters that are changed to handle the pulse shape

2 Pulse characterisation

In order to determine if a given pulse shape is short enough and has a comparable charge and amplitude to that of the LCT2 reference signal, five parameters, illustrated in figure 44, are defined to describe a generic pulse:

Maximum Amplitude: Amplitude of the pulse between the maximum and the baseline in units of voltage.

Charge: We usually refer the area under the pulse on a fixed integration window as the charge, even if the charge itself is given by this integral divided by the amplifier gain and the amplifier input impedance and is therefore proportional to the area of the pulse (see [16]):

$$Q = \frac{1}{G_{\text{amp}} \cdot R} \int V(t) dt \quad (R = 50\Omega) \quad (30)$$

Rising time: Time between 5-95% of the maximum amplitude (duration of the rising edge of the pulse).

Falling time: Time between 95-5% of the maximum amplitude (duration of the falling part of the pulse).

Recovery time: Time between the 5% amplitude on the rising edge and the 1% amplitude on the falling side (duration of the entire pulse, until the baseline is recovered and stable).

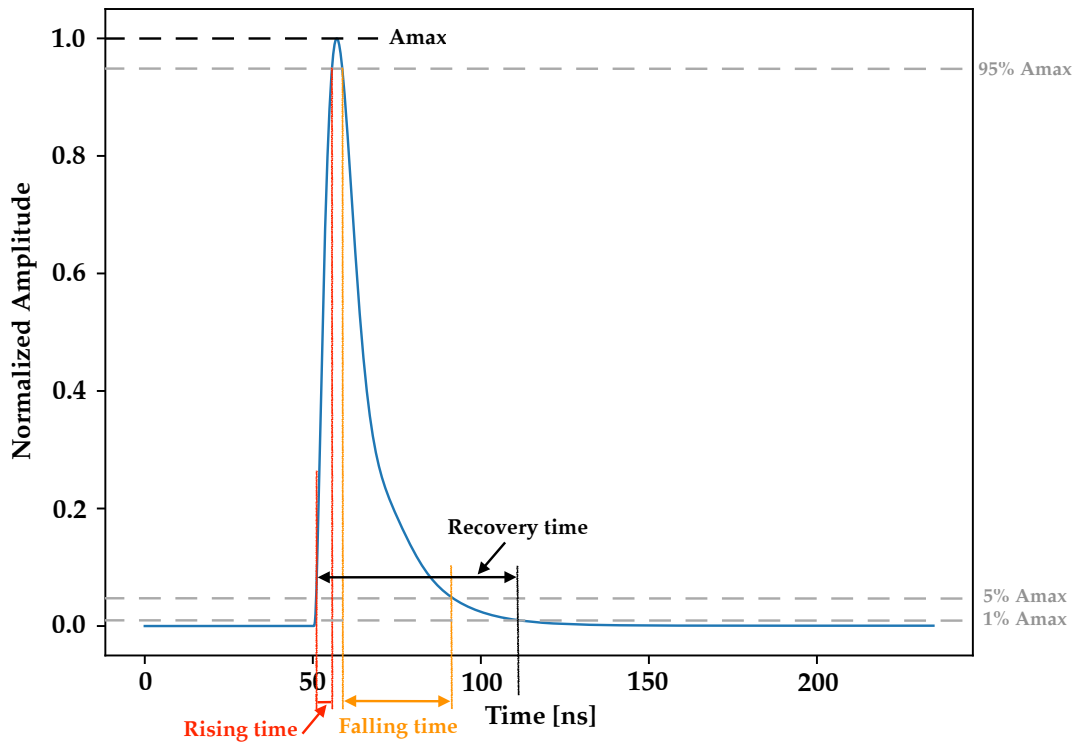


Figure 44. Characterisation of a pulse shape

3 Optimization of the pulse shape

The simulation is first performed by changing the Corsi parameters of the LCT2 to those of the LVR3 sensor. Figure 45 shows the pulse of the LCT2 sensor and the pulse of the LVR3 sensor without changing any electronic values in the circuit outside the Corsi circuits. All the signals are simulated for a light level of 100 photoelectrons (p.e.).

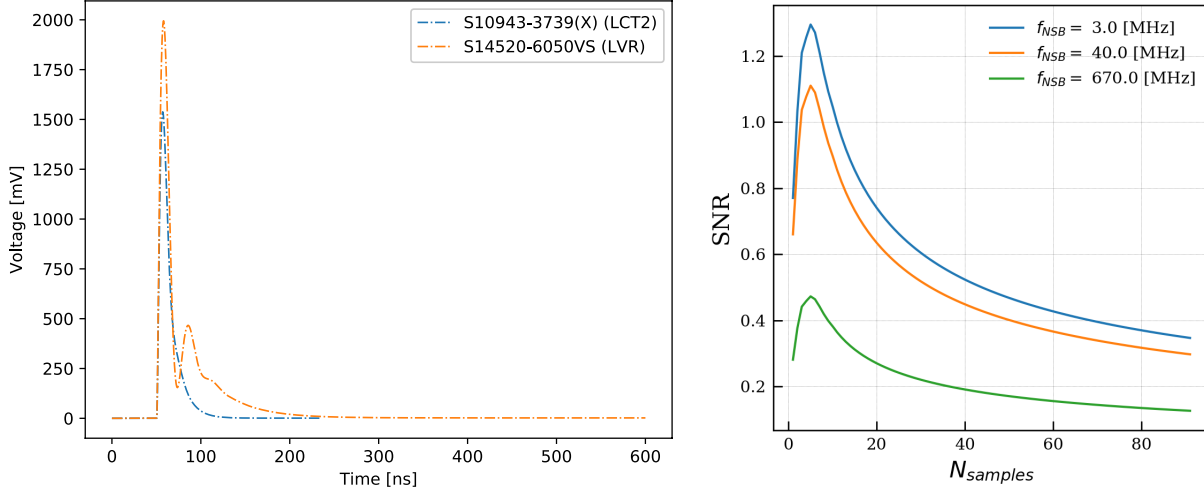


Figure 45. Simulated pulse shape with the LCT2 and LVR3 Corsi parameters and signal to noise ratio (SNR) as a function of the integration time in number of 4 ns samples (plot from C. Alispach)

As expected from the large microcell capacitance and quenching resistor of the LVR3, the pulse obtained for this sensor is quite long (see table 7 for the pulse features) and does not meet the required 30 ns integration window. Indeed, CTA requires (B-SST-1210) that "signal integration must be possible within a time window of between 20 and 30 ns with respect to the Camera trigger time for signals in the range 0-400 photons". The goal of this requirement is to keep the noise contribution reasonable since increasing the integration window would lead to an increase of the signal-to-noise ratio (SNR) (the larger is the integration window, bigger is the probability to collect afterpulses or Dark Count Rate pulses). It can be seen in figure 45 that the SNR reaches a maximum at around 20 ns integration time, and decreases very fast when increasing the integration window. More information about this can be found in this article: [arXiv:1403.3573](https://arxiv.org/abs/1403.3573). Furthermore, as can be seen in figure 45, the pulse shape is quite peculiar: it is made of a first main fast-decaying pulse, followed by a secondary bump that extends the pulse duration to about 150 ns. Such pulse shape is not satisfactory, not only for its long recovery time, but also for this secondary peak that prevents us from disentangling between a pure signal and a signal followed by after-pulses or superimposed with dark count rate signals.

Parameter	T_{rec} [ns]	t_{fall} [ns]	t_{rise} [ns]	Charge	A_{max} [mV]
LCT2 pulse	52.3	32.3	4.69	$2.35 \cdot 10^{-8}$	1538
LVR3 pulse	148.6	75.6	5.41	$4.40 \cdot 10^{-8}$	1995

Table 7. Features of the pulse obtained with the LVR3 Corsi parameters compared to those of the LCT2 pulse

The LVR3 pulse shape has therefore to be optimized to get a smooth signal (with an exponentially decaying part without any bump) with the shortest recovery time achievable. In order to optimize the waveform, the R_{IN} preamplifier input resistor and the R_G leakage resistor have to be fine-tuned.

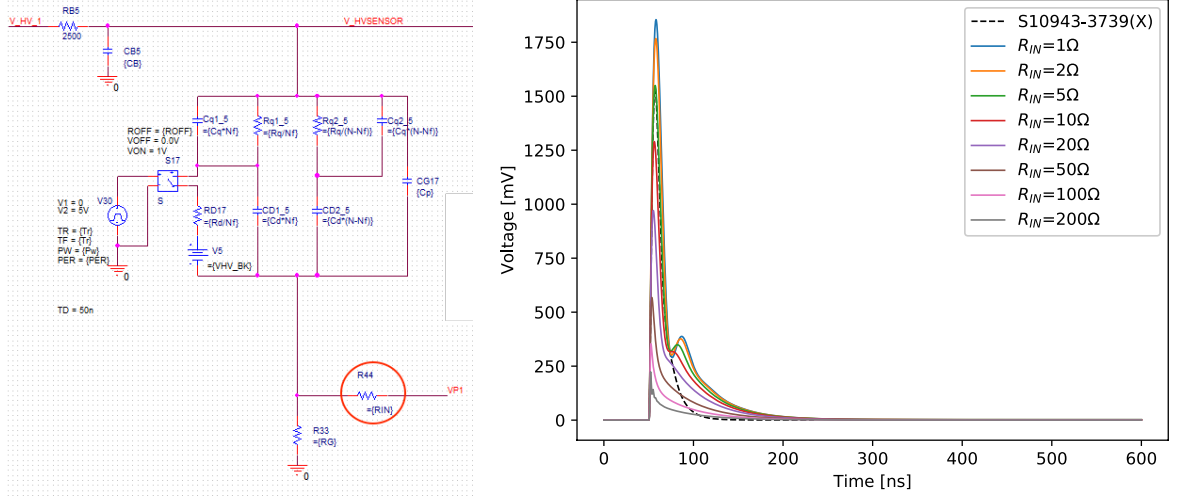


Figure 46. Position of R_{IN} in the model (left) and evolution of the LVR3 pulse shape as a function of R_{IN} (right)

The R_{IN} and R_G resistors so as their effect on the pulse shape are shown in figure 46 and 47, respectively. We see that increasing R_{IN} or decreasing R_G , which implies to reduce the fraction of the signal going to the OPA, reduces the pulse amplitude and duration and lessens the secondary bump. The impact of R_{IN} and R_G to the noise contribution has been studied and is discussed in the [Appendix A](#). The conclusion of this study is that increasing R_G reduces the noise contribution so as increasing R_{IN} . Therefore, to minimize the noise component, R_G cannot be reduced too much. Moreover, R_{IN} has to be quite lower than R_G to have acceptable conditions.

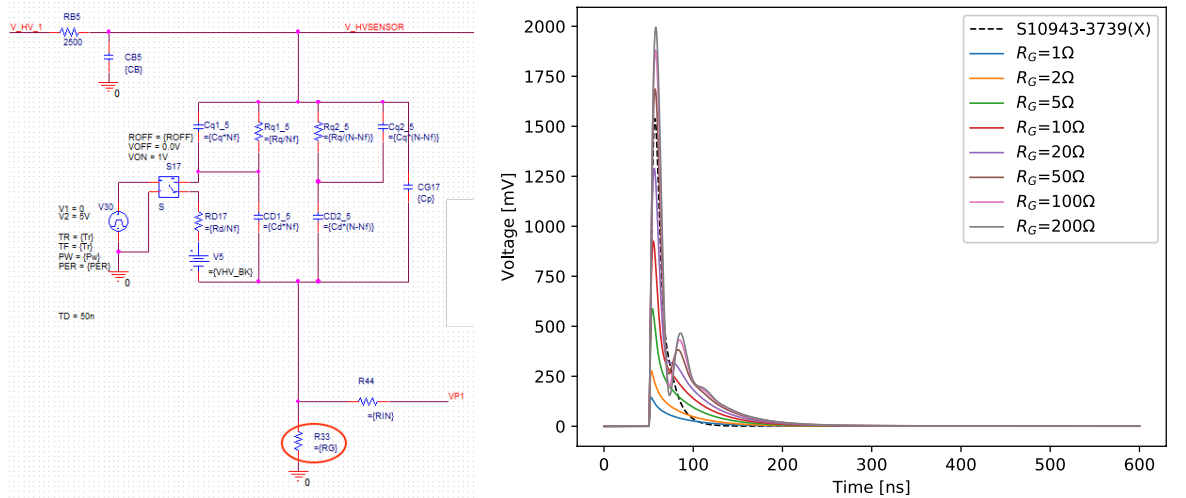


Figure 47. Position of R_G in the model (left) and evolution of the LVR3 pulse shape as a function of R_G (right)

III. PULSE SHAPE SIMULATION OF SiPM WITH PSpice®

Simulations have been performed for different (R_{IN} , R_G) configurations. The values of the charge and the recovery time for each of these simulated pulses are shown in figure 48. We see that similar amount of charge can be reconstructed compared to the LCT2 pulse, but the shortest achieved pulses are very long and far above the 30 ns required window.

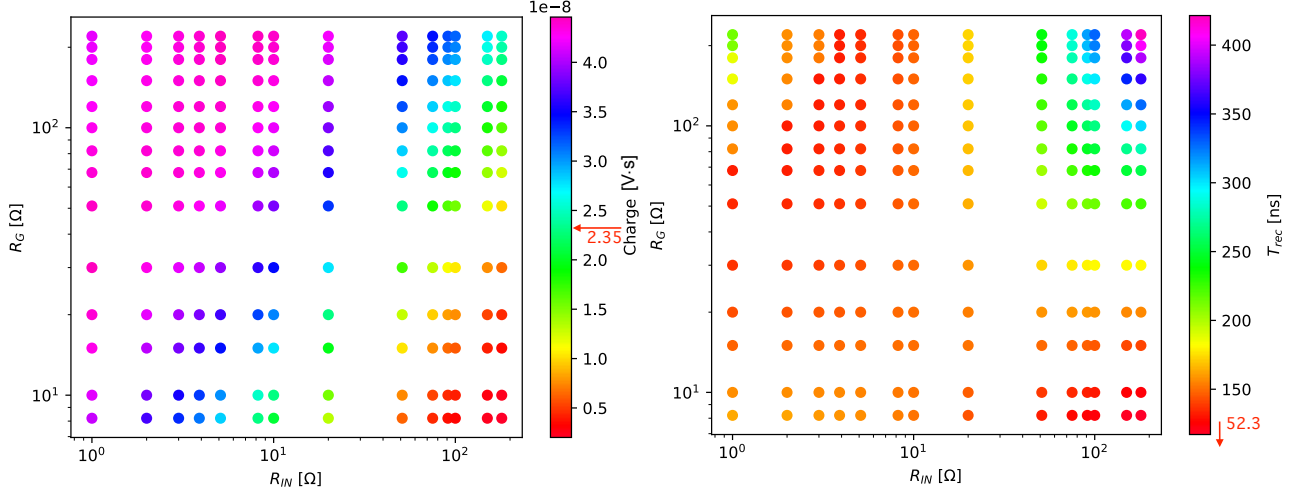


Figure 48. Evolution of the charge (left) and of the recovery time (right) in the (R_{IN} , R_G) phase space

The simulation of the pulse shape evolution as a function of the resistor R_F , parallel to the OPA, is shown in figure 49. It can be seen that increasing the resistor increases the pulse amplitude without affecting much the recovery time of the signal. R_F can therefore be used together with R_{IN} and R_G to select the shortest pulses and fine-tune the signal amplitude to have a gain similar to that of the LCT2 pulse. The effect of putting parallel capacitance to the R_{IN} , R_G , and R_F resistors has been studied, so as the effect of the bias capacitance C_B . They are discussed in the [Appendix B](#).

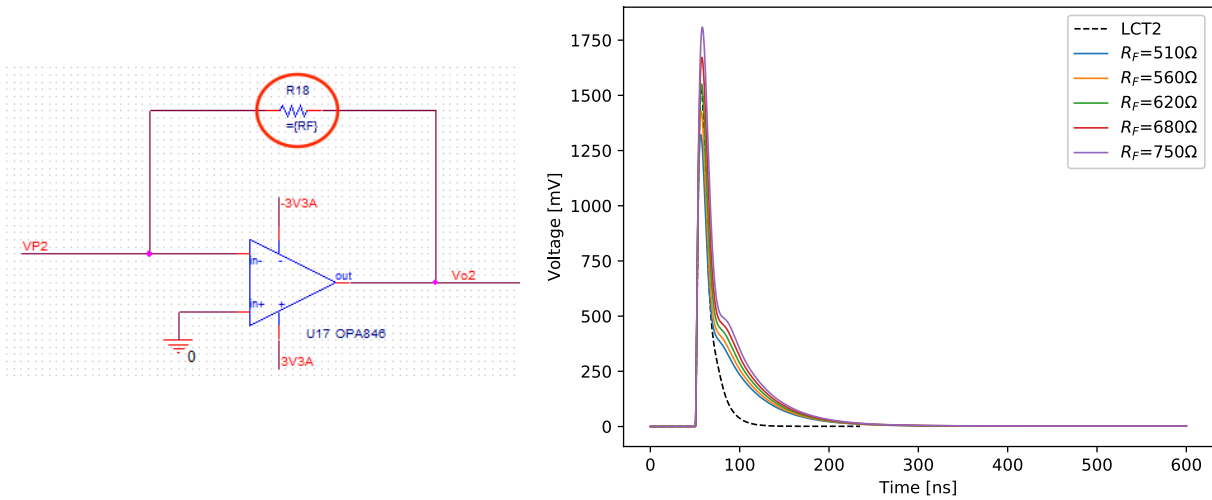


Figure 49. Position of R_F in the model (left) and evolution of the LVR3 pulse shape as a function of R_F (right)

The optimization of the pulse shape is thus performed with the three resistors R_{IN} , R_G , and R_F . Figure 50 shows two of the best pulses achieved with this optimization, while the table 8 gives the pulse parameters of nine of the best pulses compared with those of the LCT2 signal.

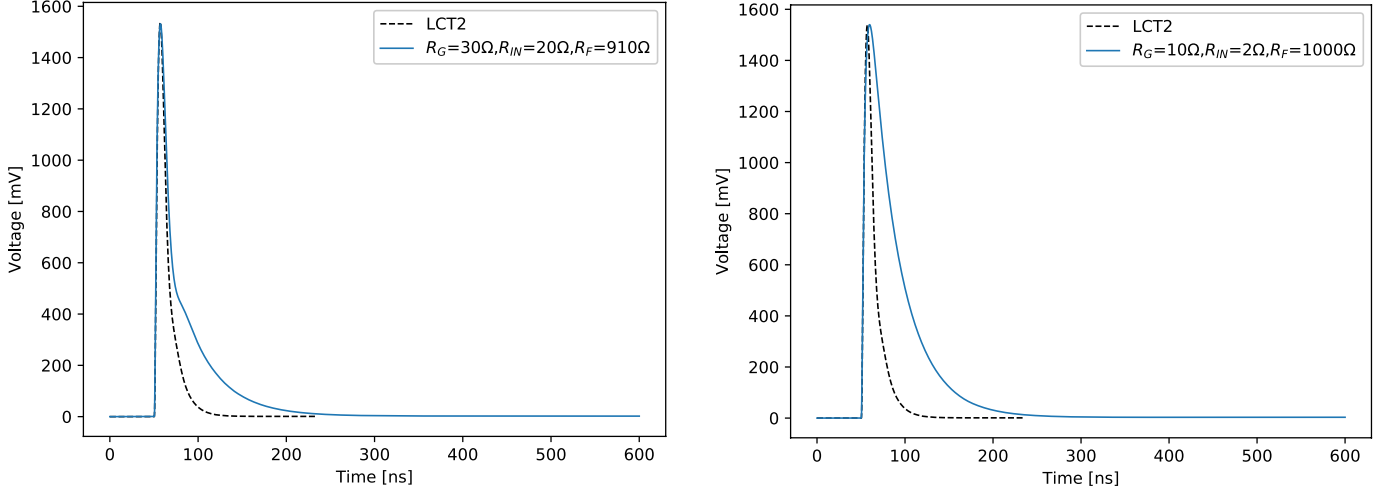


Figure 50. Optimized pulses for configurations ($R_{IN}=20\Omega$, $R_G=30\Omega$, $R_F=910\Omega$) and ($R_{IN}=2\Omega$, $R_G=10\Omega$, $R_F=1000\Omega$)

The shortest well-behaved pulses obtained after circuit optimization are still too long (~ 170 ns). The LVR3 sensor is therefore not compatible with the current front-end electronics for the required 30 ns integration window. The electronics would have to be redesigned in order to obtain short pulses with the LVR3 sensor. An ASIC implementing an option that allows to sharp the pulse shape has then been studied (see [chapter IV](#)).

R_{IN} [Ω]	R_G [Ω]	R_F [Ω]	T_{rec} [ns]	t_{rise} [ns]	t_{fall} [ns]	A_{max} [mV]	Charge [V·s]
1	10	910	174.7	6.064	100.8	1553	$6.77 \cdot 10^{-8}$
2	10	1000	176.9	5.906	102.2	1540	$6.82 \cdot 10^{-8}$
5.1	10	1300	182.5	6.015	105.7	1519	$7.04 \cdot 10^{-8}$
20	15	1600	175.3	5.180	99.10	1541	$5.63 \cdot 10^{-8}$
20	30	910	167.0	4.683	92.00	1532	$4.49 \cdot 10^{-8}$
20	51	750	168.2	4.666	92.20	1549	$4.44 \cdot 10^{-8}$
20	100	680	171.4	4.839	93.80	1605	$4.67 \cdot 10^{-8}$
20	150	620	172.6	4.635	94.40	1551	$4.51 \cdot 10^{-8}$
20	220	620	174.0	4.795	95.20	1592	$4.69 \cdot 10^{-8}$
10	200	560	52.3	4.69	32.3	1538	$2.35 \cdot 10^{-8}$

Table 8. Pulse features for some optimized configurations compared to those of the LCT2 pulse

4 Faithfulness of the electronic model

4.1 PSpice model and measurement setup of the $6 \times 6 \text{ mm}^2$ SiPM

The PSpice simulations performed for the LVR3 hexagonal sensor now have to be compared with reality. Since the hexagonal sensor is not a commercial model but was designed for the SST-1M camera, the measurements are performed with a standard $6 \times 6 \text{ mm}^2$ squared LVR3 SiPM. The model has therefore to be modified from a 4-channels SiPM with 9210 cells per channel to a single-channel sensor with 14336 cells. The model is shown in figure 51. The three unused channels are left in the model since the $6 \times 6 \text{ mm}^2$ sensor is connected to a cathode and an anode of a hexagonal board pixel.

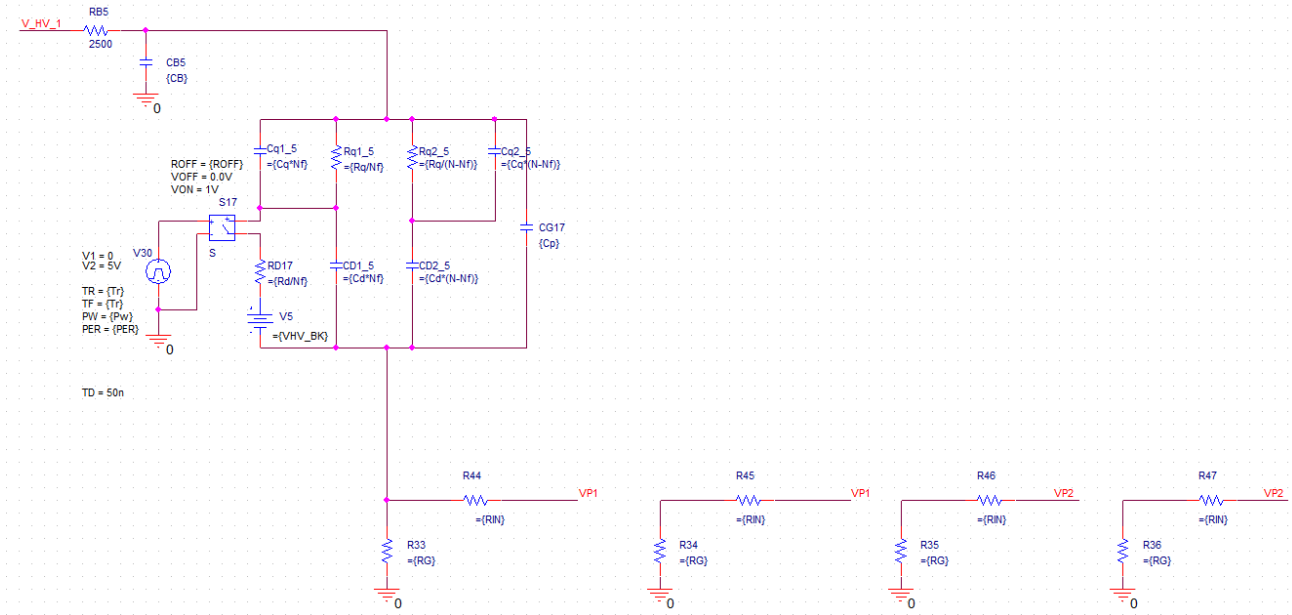


Figure 51. PSpice model of the $6 \times 6 \text{ mm}^2$ sensor

The measurement setup and the location of the R_{IN} and R_G resistors on the board are shown in figure 52. The two pins (anode and cathode) of the $6 \times 6 \text{ mm}^2$ sensor are connected via an adaptor to the cathode and one of the four anodes (A2) of a pixel on the board. The R_{IN} and R_G resistors are changed according to the tested configurations. The measurements were performed in a dark room at IdeaSquare (CERN). An LED is used as a light source. The signal is readout through an oscilloscope and stored in the computer thanks to the LabView™ program. The sensor is biased with a 4.4 V over-voltage (corresponding to 8% cross talk) and the temperature is monitored thanks to a probe placed near to the sensor.

by the OPA manufacturer and that is hard to tune. This OPA frequency response has been validated for the LCT2 sensor. A worse agreement for the LVR3 sensor can therefore be observed since the frequency ranges of the two sensors are different. Moreover, these OPA models are usually not tested for the very small currents generated by a SiPM. The third possibility is that the measured Corsi parameters provided by Hamamatsu are not exactly matching the truth behavior of the sensor.

4.3 Measurement and simulation of a single channel PCB

In order to investigate the possible parasitic contribution of the three unused channel, measurements are performed with a simpler PCB composed of only one channel. The transimpedance preamplifier based on the OPA846 is kept and the sensor used is the LVR3 3x3 mm² (3584 cells). A picture of the board and its electronic model are shown in figure 54.

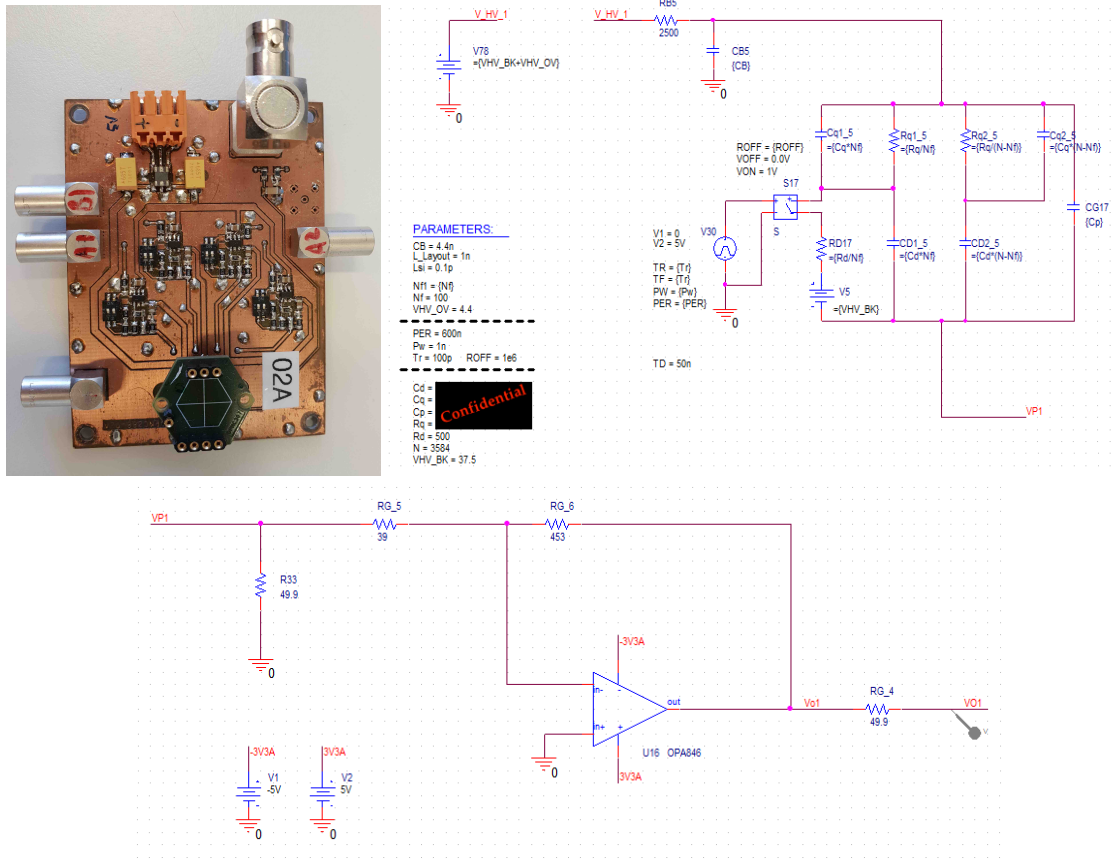


Figure 54. Picture and model of the simple PCB

It can be seen by comparing the measured and simulated pulses (figure 55) that the difference is still present and even more important with this single channel board. The difference observed with the camera board can thus not be due to some parasitic contribution from the non-connected channels. This disagreement between simulations and measurements comes therefore either from bad simulation of the OPA or from wrong Corsi parameters.

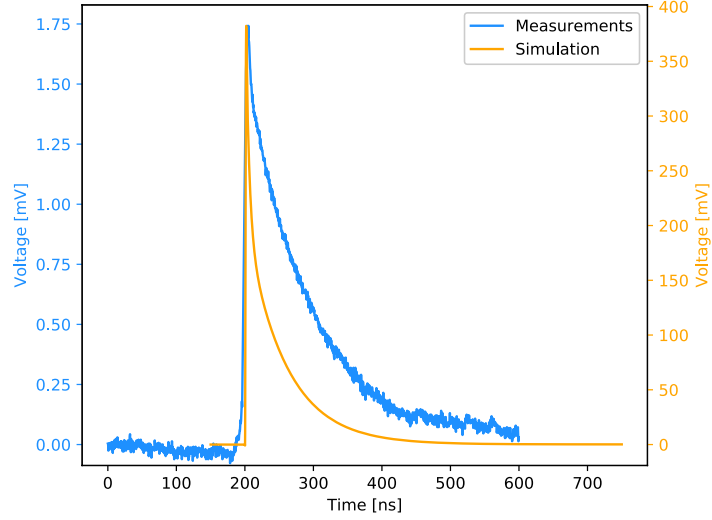


Figure 55. Comparison between PSpice simulated and measured pulses with the simple board

5 Monte Carlo simulation of the camera readout with digicamtoy

The digicamtoy Monte Carlo (MC) simulation tool [32] is used to simulate the response of the camera digitizing system (DigiCam) given an input signal template that is sampled with a 4 ns step and introducing electronic noise, cross talk, and NSB rate according to the configuration file. The simulation is done with the pulse of the $R_G=200\ \Omega$ & $R_{IN}=20\ \Omega$ configuration for the LVR3 hexagonal sensor and also for the hexagonal LCT2 pulse in order to see if the single photon resolution after digitization is comparable for both sensors. Both template pulses are shown in figure 56 together with their corresponding charge in mV-s integrated over a 20 ns window. Figure 56 is also showing the LVR3 input template coming from the PSpice simulations pulse compared to a MC produced via digicamtoy with a 4 ns sampling.

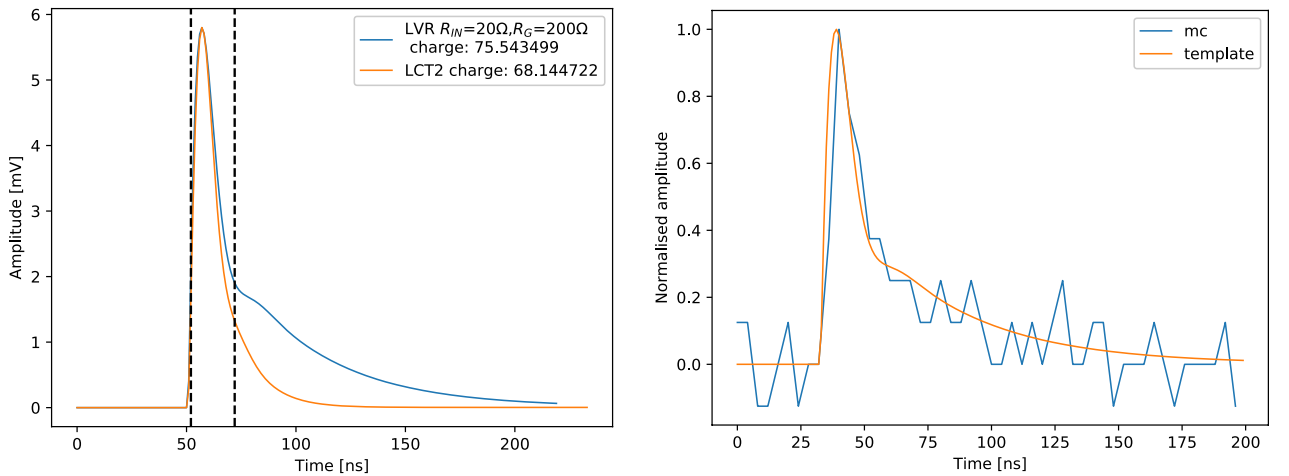


Figure 56. LCT2 and LVR3 pulses with the integration window (left) and LVR3 template pulse ($R_{IN}=20\ \Omega$, $R_G=200\ \Omega$) compared to a MC produced pulse with digicamtoy (right)

The parameters in the .yaml configuration file used in digicamtoy are shown here:

```

events_per_level: 10000    crosstalk: 0.08    gain [ADC]: 5.8
time_start [ns]: 0        gain_nsb: True    baseline: 200
time_end [ns]: 368        n_photon: [5.]    time_signal: 0.
time_sampling [ns]: 4     poisson: True     jitter: 0.3
n_pixels: 1296            sigma_e: 0.8
nsb_rate: [0.003]        sigma_1: 0.8

```

The Multi-PhotoElectron (MPE) spectrum is described by a sum of generalised Poisson distributions:

$$f(x) = A \sum_{n=0}^N P(n|\mu, \lambda) \left[\frac{1}{\sqrt{2\pi}\sigma_n} e^{-\left(\frac{x-n\cdot g}{\sqrt{2}\sigma_n}\right)^2} \right] \quad (31)$$

where:

- $P(n|\mu, \lambda) = \frac{\mu(\mu+\lambda n)^{n-1} \exp(-\mu-n\lambda)}{n!}$ is the generalised Poisson distribution, that accounts for branching crosstalk [34]
- $\sigma_n = \sqrt{\sigma_e^2 + n\sigma_1^2}$ is the noise with the electronic and the gain contributions, respectively σ_e and σ_1 . σ_n gives the width of the n^{th} peak.
- $\lambda = 0.08$ is the probability of optical crosstalk
- μ is the mean number of photoelectrons (that correspond to `n_photon` in the .yaml file for the MPE or to a number between 0 and 1 for the SPE)
- g is the gain, which also correspond to the distance between the peaks
- A is the amplitude, that depends on the statistics (number of total events considered)

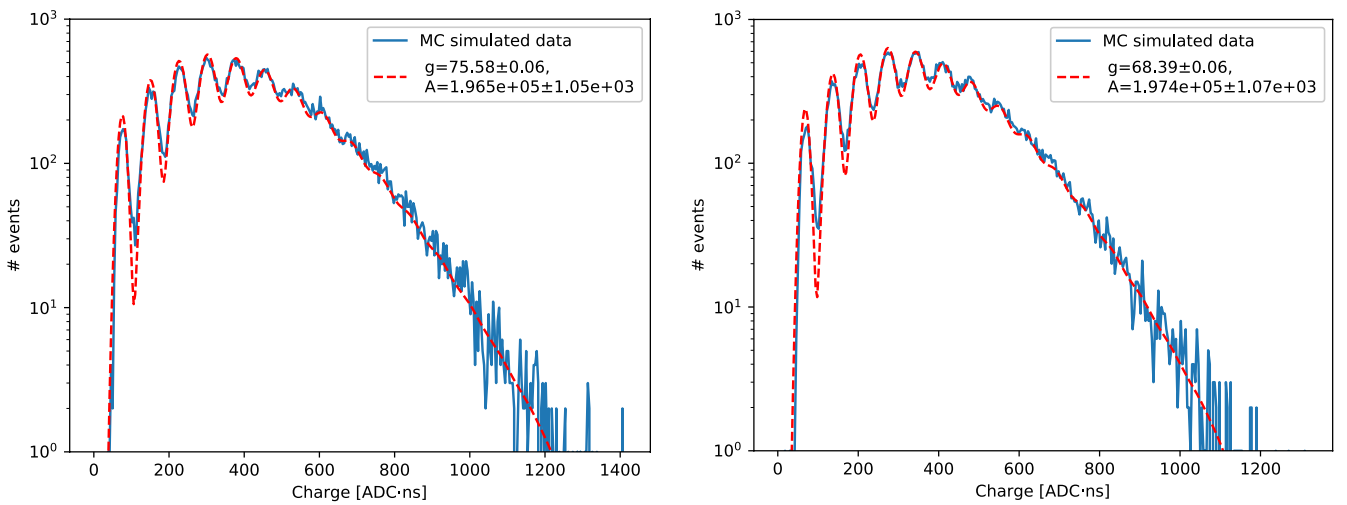


Figure 57. MPE spectrum simulated for the LVR3 (left) and LCT2 (right) sensors

The electronic noise σ_e and the intrinsic noise associated with the single photon detection (and to the gain) σ_1 can be converted from their value of 0.8 in the configuration file of digicamtoy to their expected value into the MPE given as a function of the charge. This allows us to fix these two parameters when performing the fit of the MPE in order to have only the amplitude A and the gain g (charge) as free fits parameters. They are respectively given by $\sigma_1 = \text{charge} \cdot 0.8/5.8$ and $\sigma_e = \text{charge} \cdot 0.8/5.8/\sqrt{N_{\text{bins}}}$. The resulting values are shown in the table 9.

	charge [mV·ns]	σ_1	σ_e
LCT2	68.1447	9.399	3.837
LVR3	75.5435	10.42	4.254

Table 9. Conversion of the noise using the charge obtained from figure 56

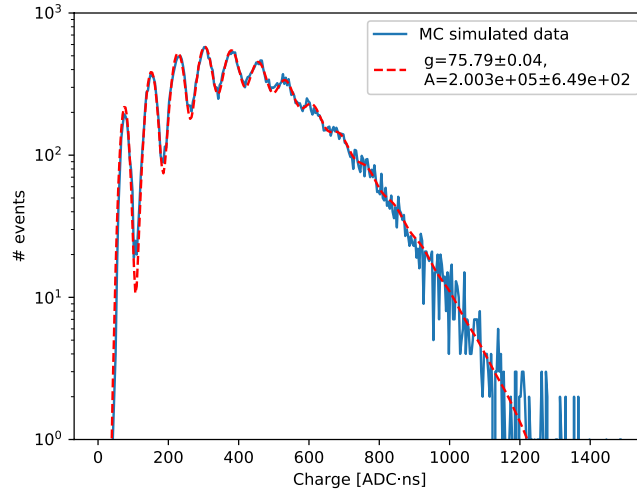


Figure 58. MPE spectrum of the LVR SiPM without dark counts

The figure 57 shows the MPE for the LVR3 and sensor so as the fit performed using the function (31). A deviation from the fit is observed for the peaks and the hollows of the MPE for both sensors. This difference is due to the fact that the fit function does not model the superposition between a signal and a NSB pulse in the 20 ns integration window (pile-up). Figure 58 shows the MPE from digicamtoy performed by removing the NSB of 3 MHz. One can observe that the fit is in better agreement with the spectrum, which confirms that the deviation from the fit is due to the fact that NSB is not accounted for. Looking back to the figure 57, we see that the spectrum for the LVR3 sensor has a nice behavior despite the long-tailed pulse since we integrate over the first 20 ns of the signal (range that contains most of the charge). We can observe that the fitted gain is very near to the expected one (75.58 ± 0.06 vs 75.54 for the LVR3 and 68.39 ± 0.06 vs 68.14 for the LCT2). This result is therefore quite satisfying since we are able to well reproduce the spectra with the Monte Carlo toy even if the pulse of the LVR3 is longer than the LCT2 pulse. But this simulation has been performed for a PSpice® simulated template pulse. The result for a measured pulse with a hexagonal LVR3 sensor is expected to be different since the simulation provides too optimistic results.

6 Conclusions

A solution to increase the efficiency of the SST-1M camera would be to adopt a sensor with better photo-detection efficiency. The front-end electronics of the camera has been simulated via the PSpice software. A fine-tuning of the electronic components has been performed in order to optimise the pulse shape of the LVR3 sensor, which has a PDE 50% bigger than the LCT2 sensor currently used on the camera prototype. Despite a detailed study of the pulse shape behavior and evolution in terms of different electronic elements, the shortest well-behaved LVR3 pulses are way too long for the required integration time of 30 ns.

The faithfulness of the electronic model has also been tested via measurements. The measured signals appear to be systematically longer than predicted. A possible explanation for this difference, that has been rejected with measurements, could have been that the channels not connected to the $6\times 6\text{ mm}^2$ two-pin sensor induce a parasitic component, increasing the signal length. The only remaining explanations for this lack of accuracy of the model are either a bad modelling of the OPA846 operational amplifier or an insufficient characterisation of the Corsi parameters by Hamamatsu.

The optimised simulated and measured waveforms being too long, a solution to sharpen the pulse shape in the pre-amplification stage has to be found. It is in this perspective that the MUSIC ASIC developed for SiPM readout has been considered (see [chapter IV](#)).

An additional study has been performed on the camera digitizing system, simulated via the digicamtoy Monte Carlo toy. The single photon resolution after digitization of one of the LVR3 pulses previously simulated has been compared to that of the LCT2 sensor. The results are good for the PSpice®simulated template pulse of the LVR3 sensor since the photon resolution and the reliability of charge reconstruction are similar than for the hexagonal LCT2 sensor. But the result for a measured pulse with hexagonal LVR3 sensor is expected to be not so good due to the optimism of the pulse simulation. Moreover, with a LVR3 sensor we would have a higher current, which would increase the gain drop.

Characterisation of the MUSIC ASIC with LCT5 and LVR3 SiPM

Fine-tuning the current front-end electronics to adapt the pulse shape of another sensor appears to still give very long pulses. The preamplification stage has therefore to be modified. A candidate for preamplification electronics is the Multiple Use SiPM Integrated Circuit (MUSIC) ASIC [35], developed at the University of Barcelona, that offers the possibility to apply a pole cancellation, reducing the pulse full width at half-maximum (FWHM) of the pulse, while allowing to sum the 4 channels of a pixel like for the current electronics. This is particularly interesting for big capacitance sensors such as the LVR3 SiPM. Furthermore, this ASIC could also allow to reduce the power consumption. The idea would be to use a MUSIC board per pixel to readout, sum, and amplify the signals of the 4-channels of the pixel and to send a single signal to the slow control board (SCB). The integration of MUSIC in the current camera topology is shown in figure 59. Since this ASIC is AC coupled, its current readout for slow integration has to be used in order to monitor the baseline shifts due to the variation of NSB. The readout of this slow integration output together with the summed signal for each pixel would imply to modify the SCB design.

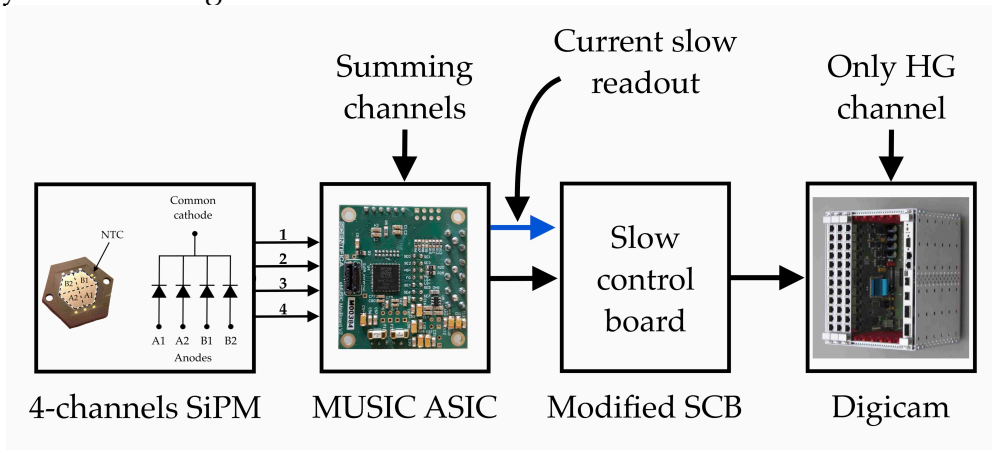


Figure 59. Integration of the MUSIC ASIC in the SST-1M camera

The MUSIC ASIC is first described, followed by the measurement setup used for the ASIC characterization. The measurements of MUSIC with the LVR3 and the LCT5 sensors are then discussed. Finally, the measurements are compared to the simulation of the ASIC performed by the team that developed MUSIC.

1 The Multiple Use SiPM Integrated Circuit (MUSIC)

The Multiple Use SiPM Integrated Circuit (MUSIC) is an ASIC that has been developed at the ICCUB (University of Barcelona) for the readout of SiPM arrays. It has 8 single-ended analog outputs and a differential output that allow to sum the individual output channels. The diagram depicting MUSIC and a picture of the board are shown in figure 60.

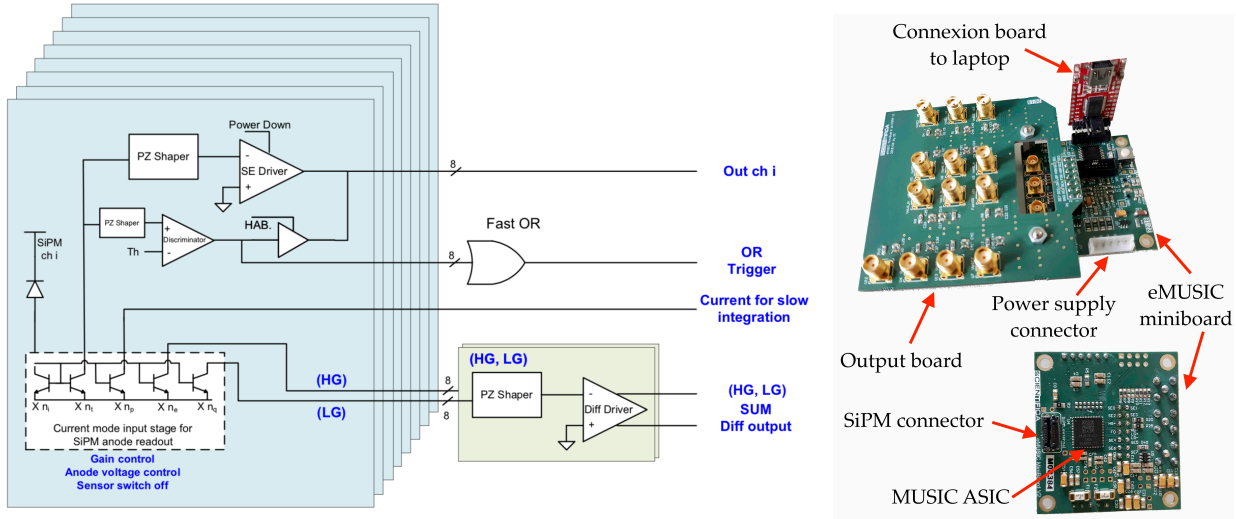


Figure 60. Functional block diagram of the MUSIC ASIC [35] and picture of the PCB

This ASIC is very interesting for our application since it contains a shaper circuit that allows to apply a so-called Pole Zero Cancellation (PZC) on the pulse shape to reduce significantly its duration. Furthermore, it allows to sum the 4 channels of a pixel together, reducing the apparent capacitance. The Pole Zero shaper circuit and an example of pulse before and after PZC are shown in figure 61. The cancellation is parameterised by two values, R and C , that correspond to different values of resistors and capacitance in the shaper circuit. The C parameter is a 5-bits following a linear distribution starting from 1.2 pF with steps of 0.1 pF. The R parameter is not following a linear distribution, and the corresponding resistor values are shown in the table 10.

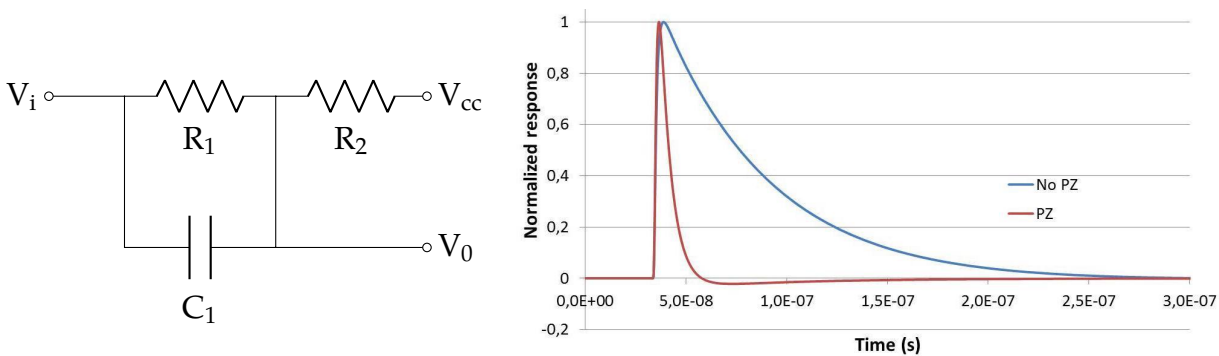


Figure 61. Pole Zero shaper circuit and example of pulse shape before and after applying PZC [35]

R_{lad}	R_1 (low atten OFF) [Ω]	R_1 (low atten ON) [Ω]	R_2 [Ω]
0	46500	18600	7650
1	48300	20400	5850
2	50100	22200	4050
3	51900	24000	2250
4	52350	24450	1800
5	52800	24900	1350
6	53250	25350	900
7	53700	25800	450

Table 10. Values of the resistors in the Pole Zero shaper circuit for the different resistance ladder configurations [36]

Furthermore, the cancellation can be attenuated by enabling the attenuation option in the ASIC configuration, corresponding to different values of the R_1 resistor (see table 10). Another option when configuring the ASIC allows to choose the transimpedance mode between high (higher gain) and low (lower gain) transimpedance. The different possible transimpedance gains for single-ended and differential outputs are shown in the table 11. Note that the differential outputs HG and LG can be used in parallel.

Gain	Sum HG	Sum LG	Single-Ended
High transimpedance	690 Ω	315 Ω	480 Ω
Low transimpedance	90 Ω	45 Ω	180 Ω

Table 11. Possible gain configurations with MUSIC [36]

2 Measurement setup

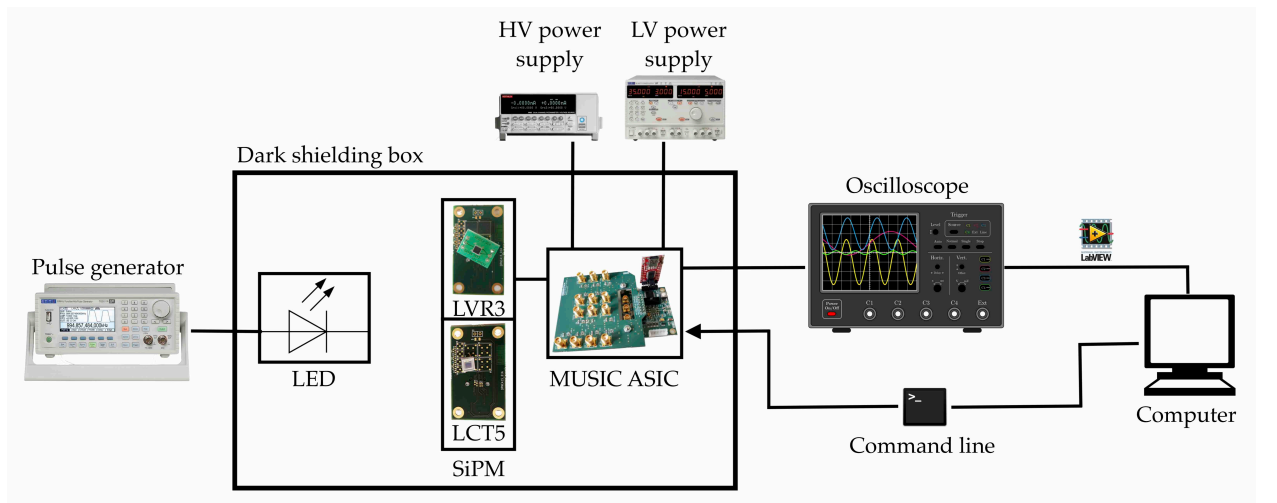


Figure 62. Schematic view of the experimental setup

The MUSIC is placed in a dark box in order to avoid external light. The sensor (either LCT5 or LVR3) is soldered on a small dedicated PCB connected to the MUSIC board. Two other boards are connected to the MUSIC board, one in order to communicate with the computer and configure MUSIC, and the other in order to readout the single-ended and differential outputs using SMA cables. An LED with a wavelength of 525 nm is placed in the dark box and connected to a pulse generator placed outside the box in order to control the light source. The MUSIC is connected to an oscilloscope via SMA connectors in order to display the signals. The oscilloscope is then connected to the computer in order to automate the data taking using the LabView™ software. Two power supplies are connected to MUSIC: the High Voltage power supply to bias the sensors ($\sim 40\text{-}50\text{V}$) and the Low Voltage power supply in order to bias the MUSIC ASIC (6.5V).

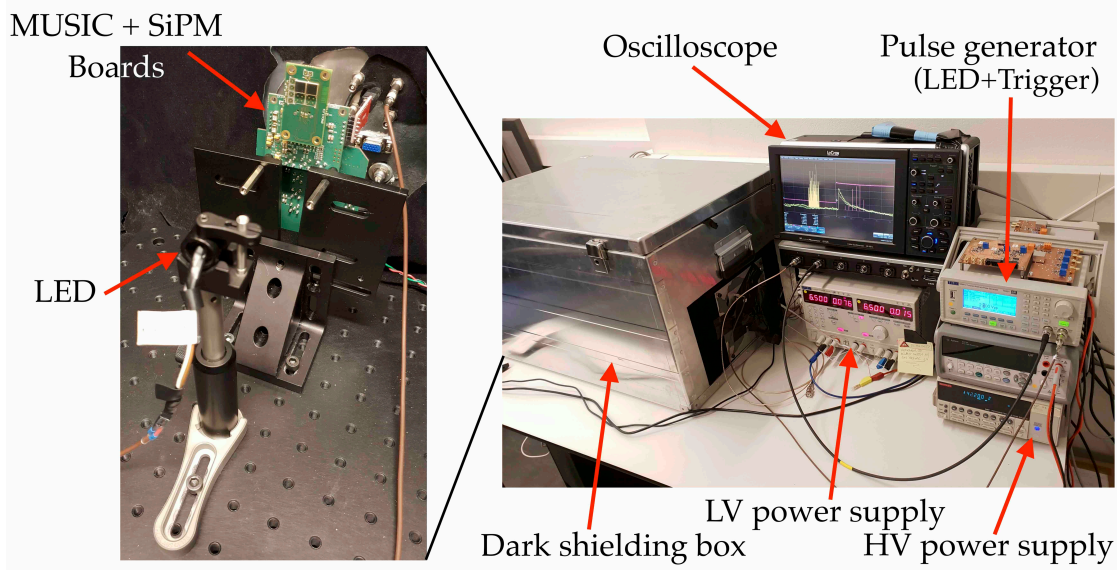


Figure 63. Picture of the experimental setup

A diagram and a picture showing the measurement setup are shown in figures 62 and 63. The light source is set with the shortest possible width (20 ns) and a frequency of 1kHz. The MUSIC is configured via the command line tool of the computer with the following command: » `mini_music.exe config -P COM13 -e 0 -u 0 -t -a -p R C`. The -P option provides the USB port ID used to connect MUSIC to the computer. The -e and -u allow to enable the single-ended channels and the channels to be summed via the differential output, respectively. The -t option allows to enable the high transimpedance mode and the -a option enables the attenuation of the cancellation. Finally, the R and C PZC parameters can be set using the -p option, R going from 0 to 31 and C from 0 to 7.

3 Measurement results

3.1 Pulse shapes and single photon sensitivity

The pulse shapes have first been measured with the LVR3 6x6mm² sensor for different PZC configurations. The evolution of the pulse shape as a function of the R and C cancellation parameters is shown in figure 64.

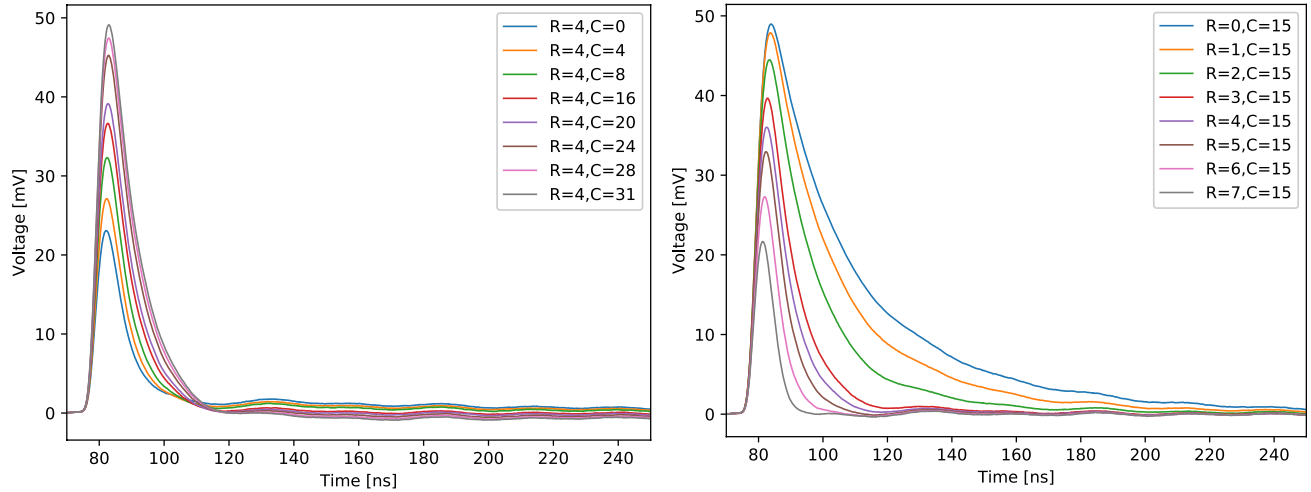


Figure 64. Evolution of the LVR3 pulse shape with the PZC parameters C and R

The pulse shape for this sensor is shown in figure 65 before and after applying a PZC. The cancelled pulse shape is shown for an intermediate configuration (R=4, C=9). We can see a parasitic oscillation after the main peak, especially for the cancelled pulse. This oscillation is not part of the real signal but is a contribution from the electronics due to LED excitation. It could easily be characterised and cancelled for later applications.

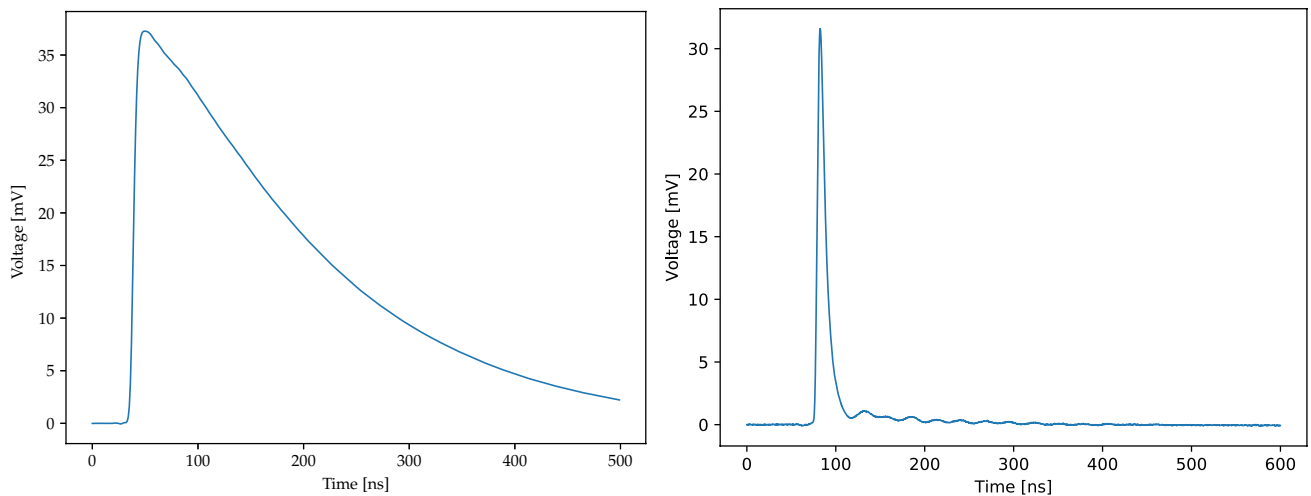


Figure 65. Pulse shape for the LVR3 sensor before and after applying a PZC (R=4, C=9)

The recovery time of the pulse for each pole zero configuration has been extracted, leading to the map in figure 66. With this map we can see that the PZC allows to start from the long 400 ns LVR3 pulse and to go down below 30 ns.

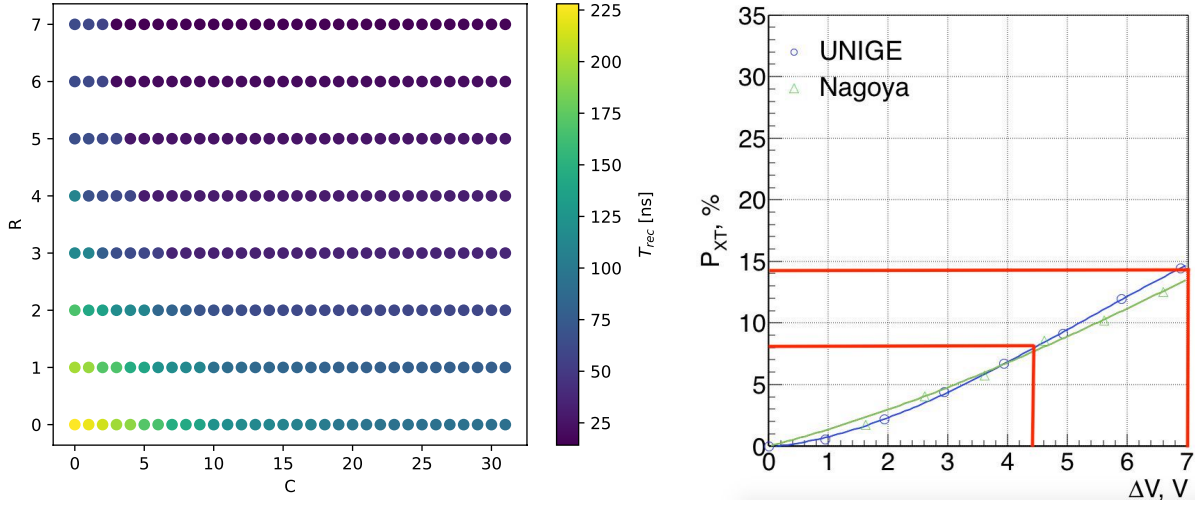


Figure 66. Recovery time of the LVR3 pulse for each PZC configurations (left) and evolution of the cross talk probability as a function of the over-voltage (right, Measurements from A. Nagai)

An important features of a SiPM is the ability to count the photons. We can see in the first histogram of the figure 67 that we are able to count photon with the $3 \times 3 \text{ mm}^2$ sensor. But when moving to a $6 \times 6 \text{ mm}^2$ sensor, we are no more able to disentangle the number of photons (middle plot). A solution to retrieve this ability is to increase the over-voltage from 4.4 V up to 7V. The problem is that with such a high voltage, the optical cross talk is increased to about 15% (see figure 66). Since a channel of the hexagonal sensor is closer to the $6 \times 6 \text{ mm}^2$ sensor than to the $3 \times 3 \text{ mm}^2$ one in terms of surface, the use of the LVR3 for hexagonal pixels would imply an increase of over-voltage to keep the photon counting ability. This would therefore increase the optical cross talk, which is not suitable for us since our working point is at 8% cross talk probability.

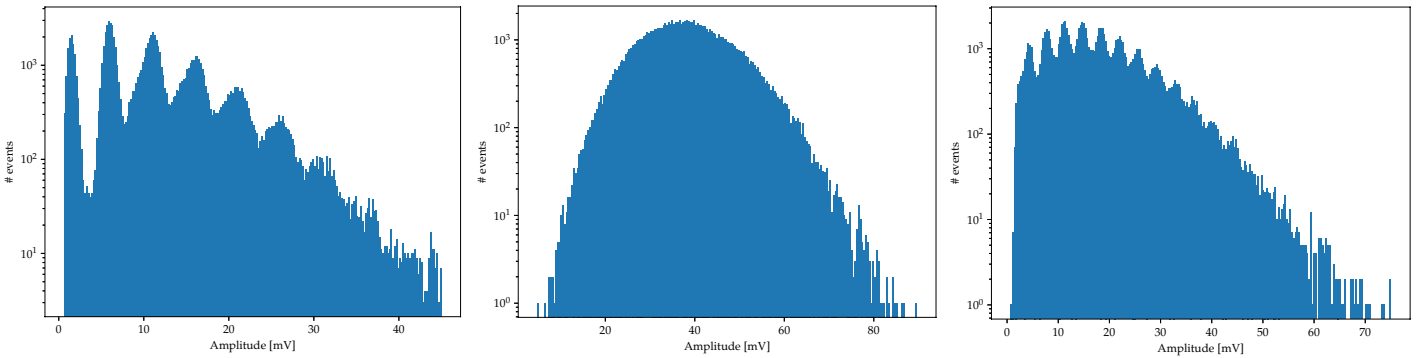


Figure 67. MPE spectrum for the LVR3 sensor: $3 \times 3 \text{ mm}^2$ and 4.4V overvoltage (left), $6 \times 6 \text{ mm}^2$ and 4.4V overvoltage (middle), $6 \times 6 \text{ mm}^2$ and 7V overvoltage (right)

The MUSIC ASIC has therefore also been characterised with a LCT5 3x3 mm² sensor. Figure 68 shows the pulse shapes of this sensor before and after applying the (R=4, C=9) cancellation.

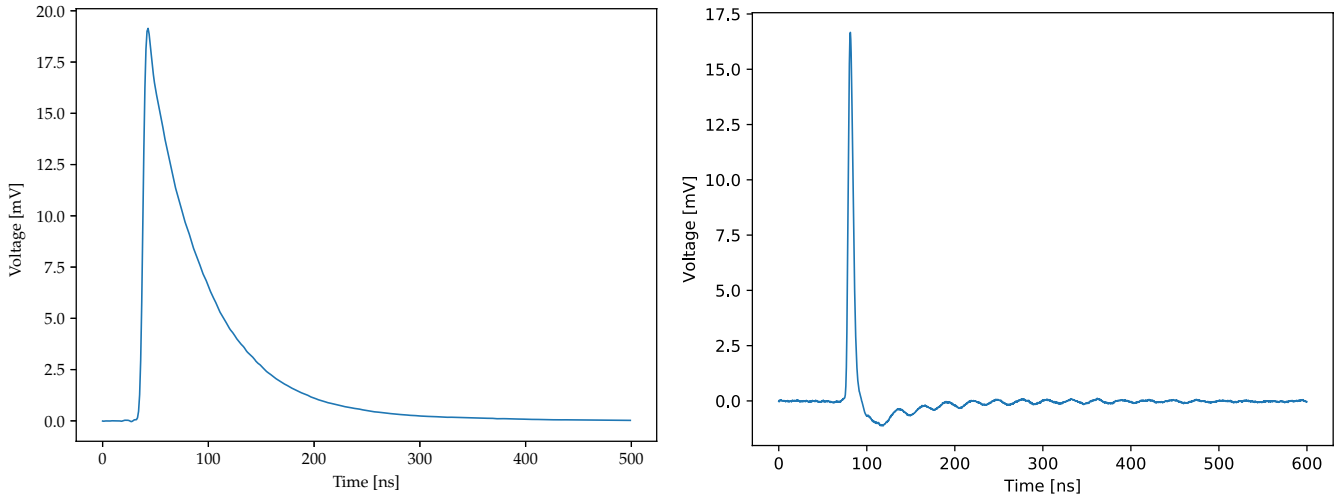


Figure 68. Pulse shape for the LCT5 sensor before and after applying a PZC (R=4, C=9)

The initial pulse has a length of 120 ns, while applying a PZC allows to have signals shorter than 40 ns, thus satisfying the required integration time (see figure 69). The measurements have been performed with the 3x3 mm² LCT5 sensor since it was the only size of LCT5 that we had. Measurements have also been performed by the team of Barcelona on the 6x6 mm² sensor, showing that we are able to count photons even with this larger sensor (see figure 70). The LCT5 coupled to MUSIC could therefore be a suitable solution for sensor/electronics upgrade.

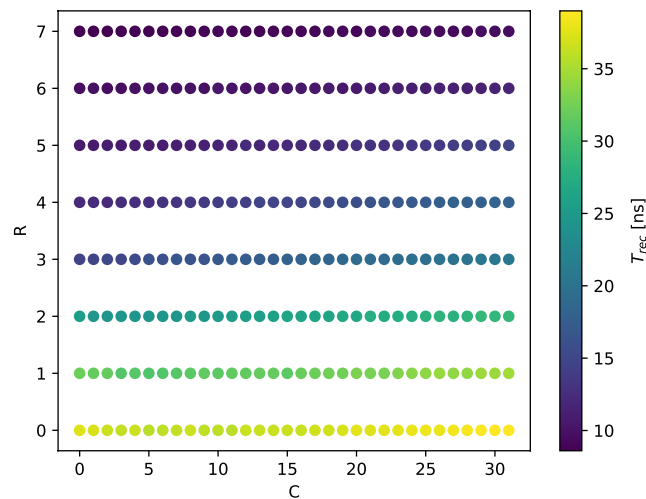


Figure 69. Recovery time of the LCT5 pulse for each PZC configurations

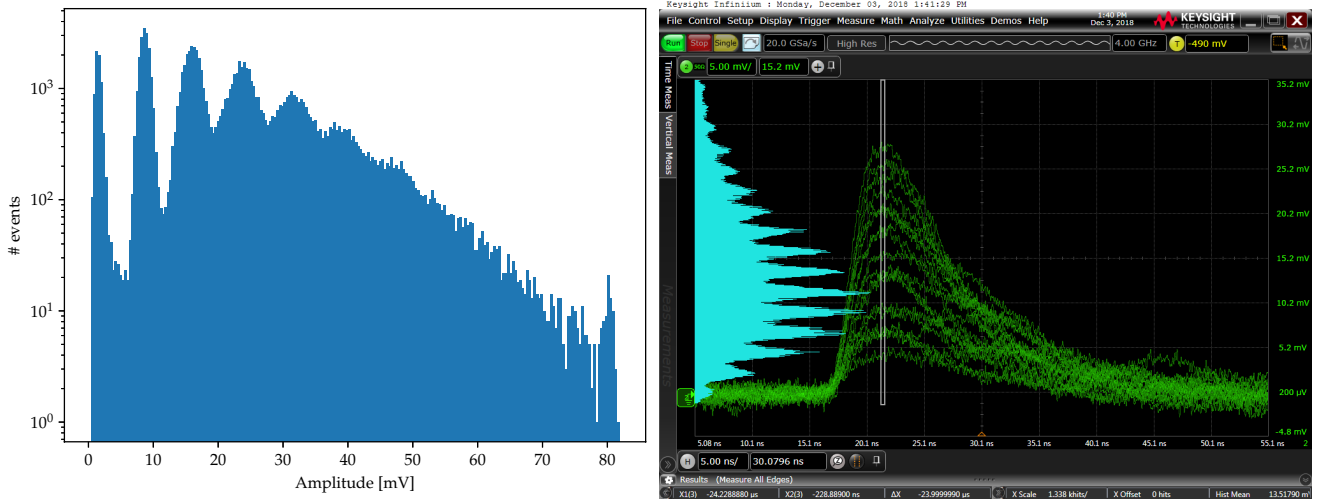


Figure 70. MPE spectrum for the $3 \times 3 \text{mm}^2$ (left) and $6 \times 6 \text{mm}^2$ (right, from S. Gómez) LCT5 sensors at 4.4V overvoltage

3.2 Linearity

The evolution of the pulse shape as a function of the light level has been measured in order to study the behavior in saturation of the LCT5 sensor coupled to MUSIC. The differential outputs are used for these measurements. The idea is to see if the High Gain channels has a nice behavior in order to use it to reconstruct signals up to a few thousand of photons with a good resolution. Indeed, in the camera, we cannot use both HG and LG outputs since the DigiCam system has only one input channel per pixel. Increasing the number of channels would increase the power consumption and the price of the whole system. Figure 71 shows the evolution of the LCT5 pulse shapes both in High Gain and Low Gain modes. The pulses are normalised in order to bring out the shape evolution. The shapes in saturation seem quite similar to the usual behavior of pulses in saturation: the amplitude saturates but the pulse duration, and therefore the charge, is still increasing above saturation.

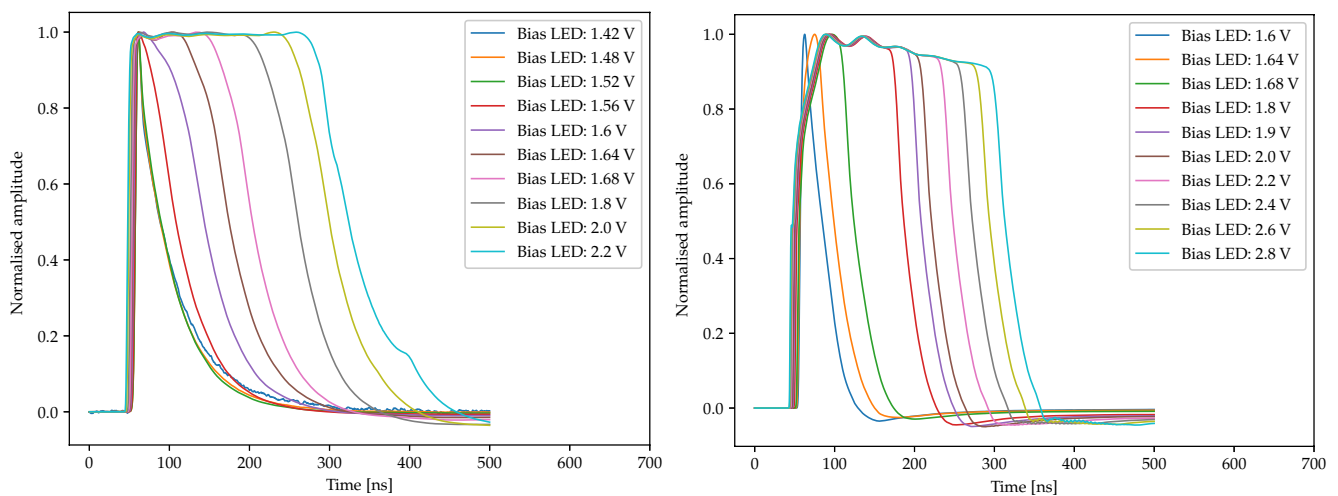


Figure 71. Pulse shapes of the LCT5 sensor as a function of light level for HG and LG differential channels

The amplitude and the charge are extracted from the previous pulses and are plotted as a function of the bias voltage of the LED for both HG and LG channels. This is shown in figure 72. Even if the measurements were performed in both High Gain and Low gain modes, the study is only carried out for the HG channel since it is the one we would use in the camera.

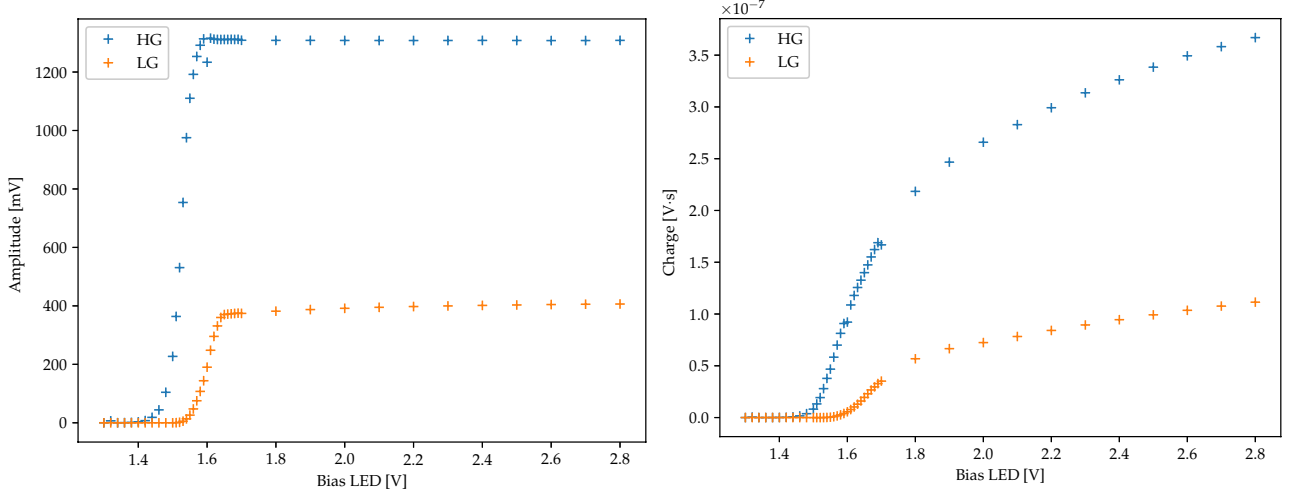


Figure 72. Amplitude and charge of the pulse as a function of the LED bias voltage

The LED has now to be calibrated in order to determine the relation between the detected light level (in number of photoelectrons) and the bias voltage of the light source. The first step is to determine the gain for the charge and amplitude. The peaks of the MPE spectrum for the charge are fitted with gaussians, in order to determine their positions (see figure 73). Not that we could use the generalised Poisson fit (31), but the fit is more precise with this multi-Gauss technique. A linear plot of the peak position vs the number of photons is then fitted to obtain the gain as the slope of the curve, which is $1\text{p.e.}=112.08\pm0.55\text{ mV}\cdot\text{ns}$.

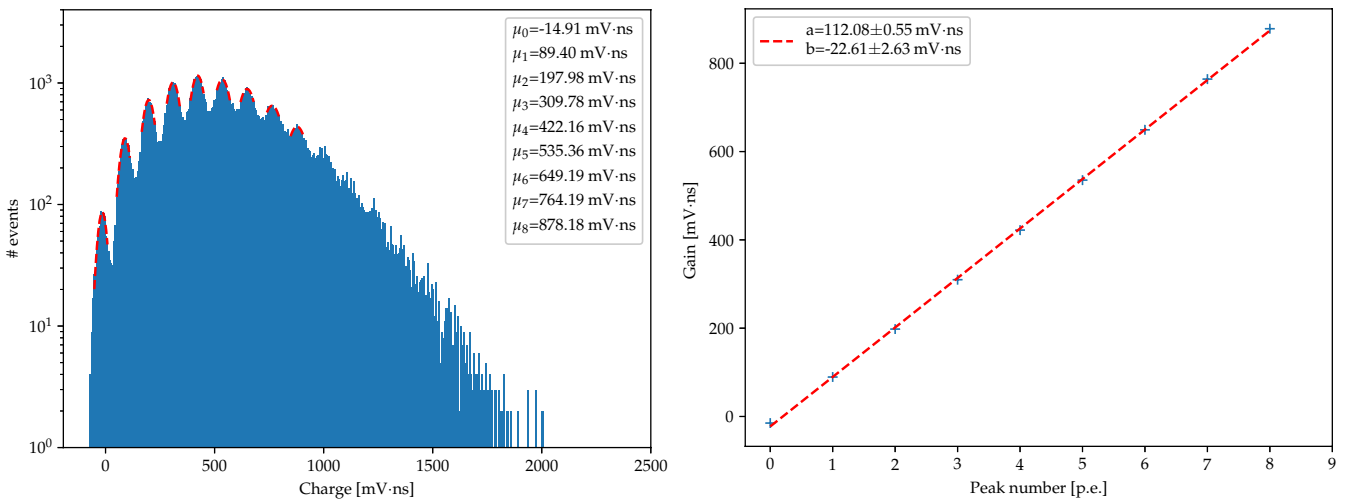


Figure 73. Determination of the conversion factor between charge and number of photoelectrons

Since the MPE fit for the amplitude was less precise, the gain for the amplitude is determined as follows: $\text{mean}(\text{charge})/\text{gain}(\text{charge})=5.05$ gives the averaged number of photoelectrons in the spectrum, which is used to compute the gain using the averaged amplitude: $\text{mean}(\text{amplitude})/5.05 \text{ p.e.}=3.4771 \text{ mV}$.

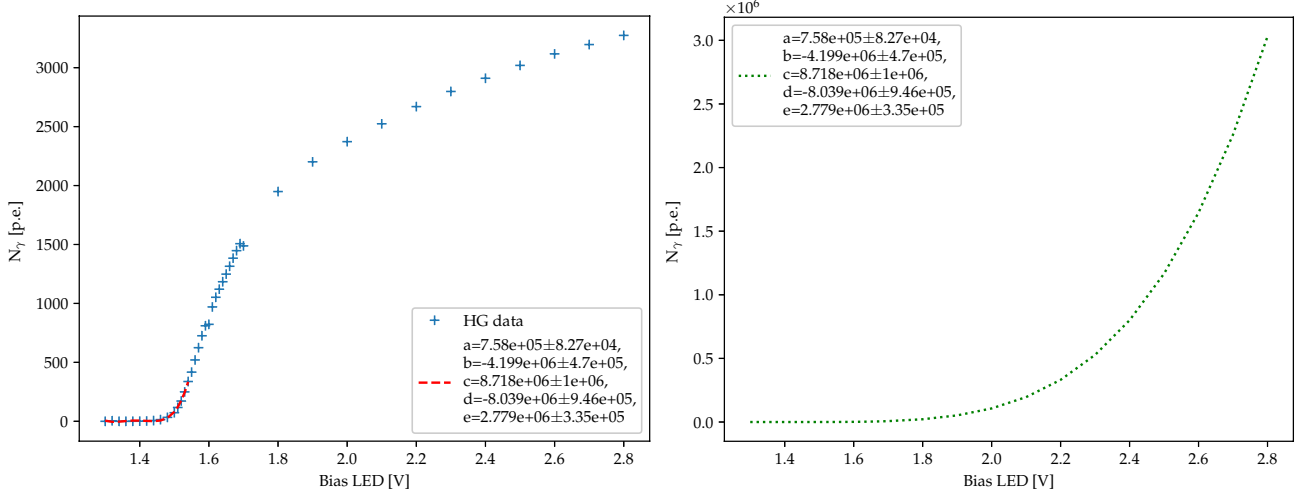


Figure 74. Polynomial fit of the non saturated part of the charge scan

The y-scale of the charge plot in figure 72 can now be converted to photoelectrons and the non-saturated part of the plot is fitted with a 4-polynomial function (the I-V characteristics of an LED is not linear [14]) in order to extrapolate the relation between number of photons and bias voltage of the LED (see figure 74). The number of photoelectrons is given by the PDE times the number of photons. Using this extrapolation the amplitude and charge can now be plotted in terms of the number of photons (see figure 75).

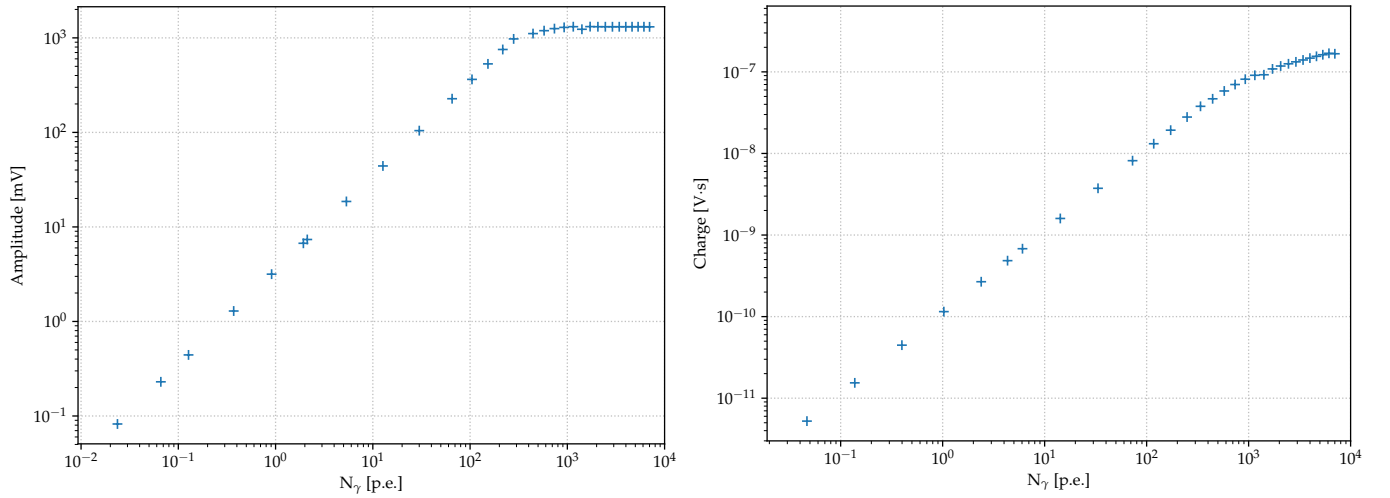


Figure 75. Amplitude and charge of the pulse as a function of the light level

The geometrical saturation due to the limited number of cells of the sensor has now to be accounted in order to plot the charge and the amplitude as a function of the detected photons. As discussed in the [chapter II](#), the geometrical saturation can be accounted by transforming the x-scale of the plots in figure 75 from number of photons to number of photoelectrons using the following formula (see figure 76):

$$N_{\text{firedcells}} = N_{\text{cells}} \left(1 - e^{-\frac{N_{\text{photons}} \cdot \text{PDE} \cdot (1 + \mu)}{N_{\text{cells}}}} \right) \quad (32)$$

where $\mu=8\%$ is the cross talk probability, $N_{\text{cells}}=3584$ cells since we are using the $3 \times 3 \text{ mm}^2$ sensor, and $\text{PDE}(\lambda_{\text{LED}})=36\%$ (see figure 76).

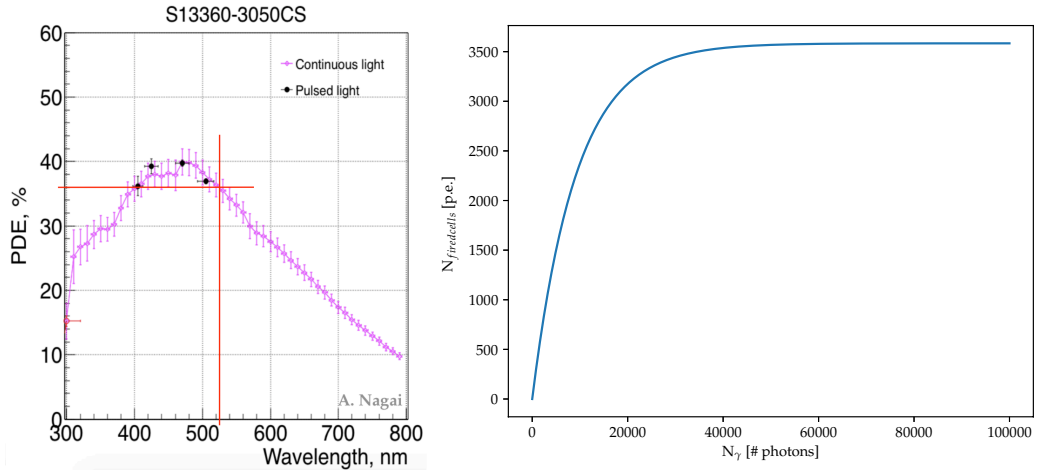


Figure 76. PDE of the LCT5 sensor as a function of the wavelength (Measurements from A. Nagai) and geometrical saturation behavior

The final calibrated plots for the charge and the amplitude as a function of the number of fired cells are shown in figure 77. We can see a good linear behavior until about 400 fired cells for the amplitude. The charge has also a good behavior in saturation.

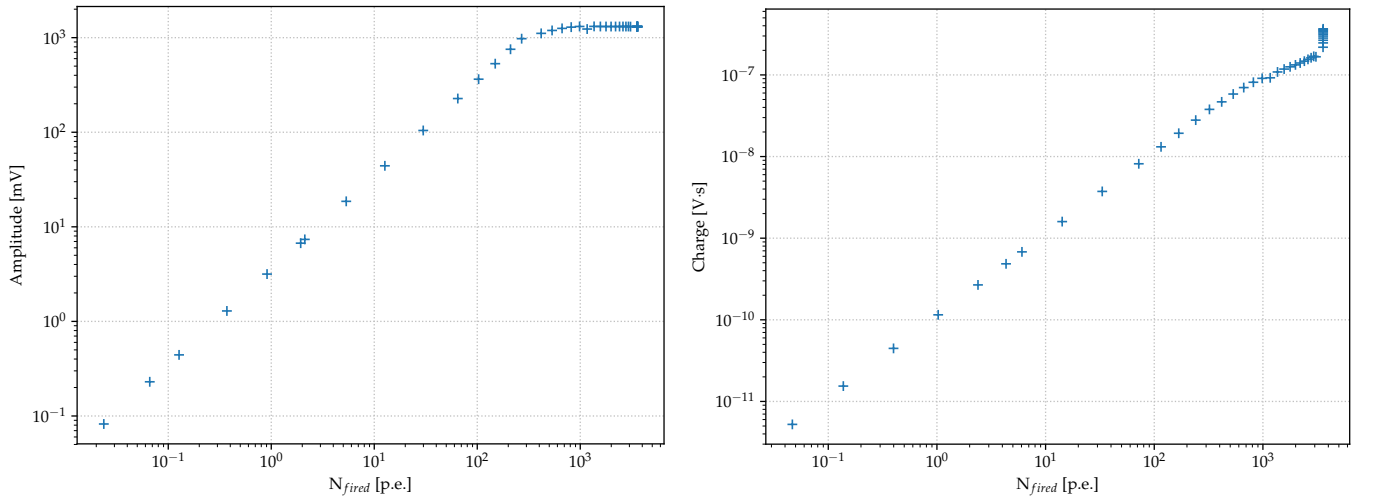


Figure 77. Amplitude and charge of the pulse as a function of the light level accounting for the geometrical saturation

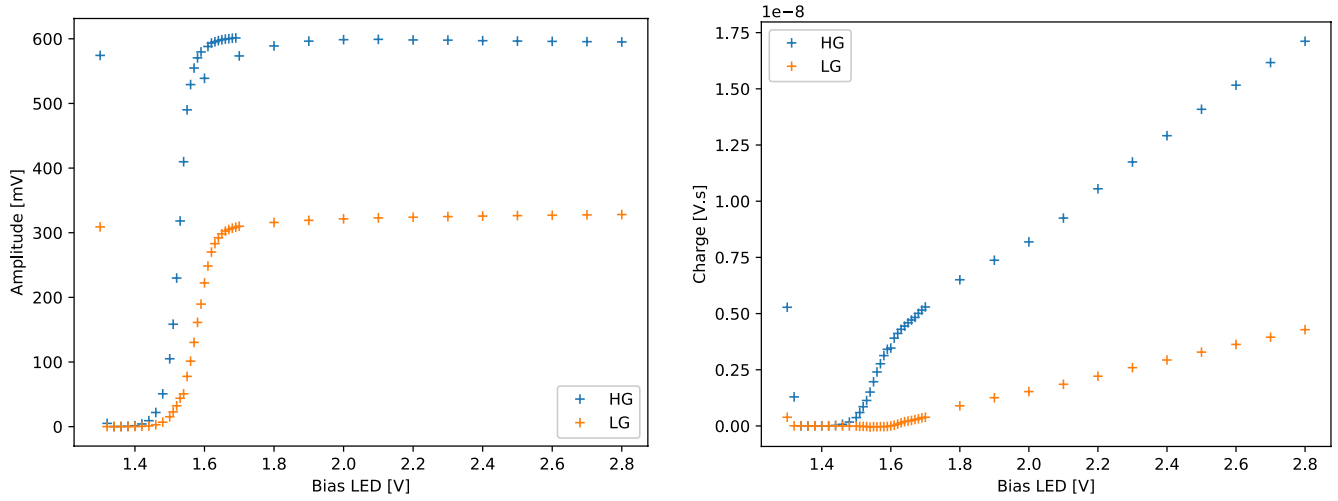


Figure 78. Amplitude and charge of the pulse as a function of the LED bias voltage for the (R=4, C=9) PZC configuration with LCT5

The same measurements have been performed for the LCT5 $3 \times 3 \text{ mm}^2$ sensor with an intermediate cancellation configuration (R=4, C=9) and for the LVR3 $3 \times 3 \text{ mm}^2$ sensor without cancellation. The calibration has not been performed for these measurements but we can see from the figures 78 and 79 that the behavior seems similar than for the LCT5 $3 \times 3 \text{ mm}^2$ sensor without cancellation.

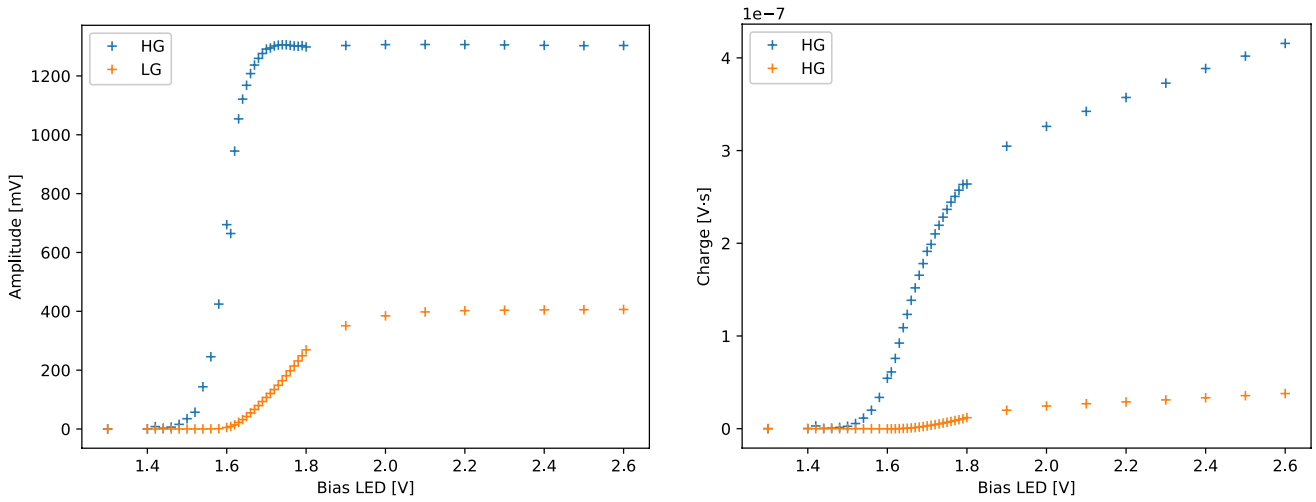


Figure 79. Amplitude and charge of the pulse as a function of the LED bias voltage for the LVR3 sensor

4 Comparison with simulations

Simulations of MUSIC have been performed by the team that developed the ASIC at Barcelona for both LCT5 3x3 mm² and LVR3 6x6 mm² sensors for different cancellations. The agreement of the simulations with measurements is expected to be better than for the simulation of the front-end electronic with the OPA846 because the MUSIC is simulated at the transistor level.

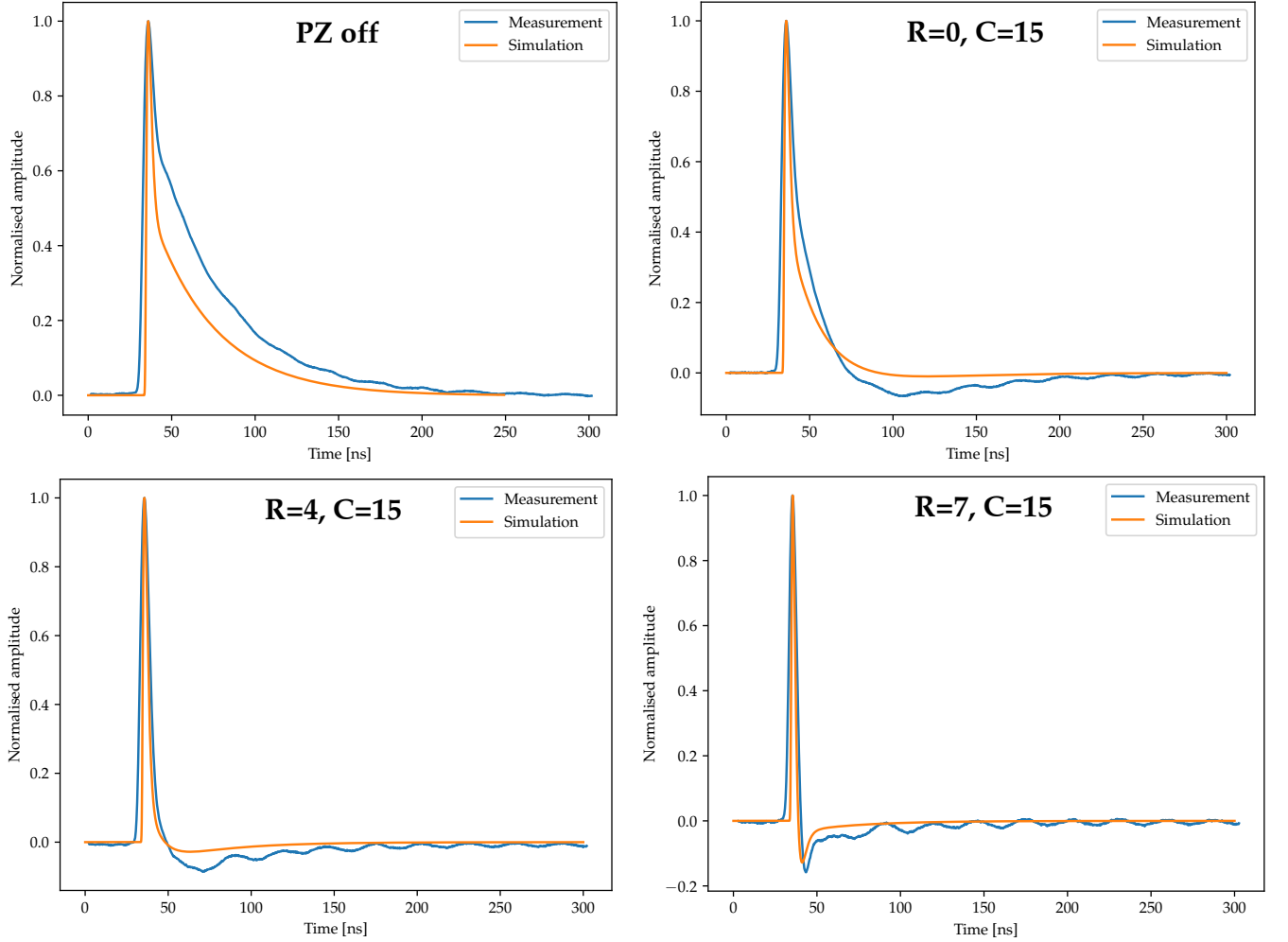


Figure 80. LCT5 3x3 mm² pulse shapes comparison between measurements and simulations for different PZC configurations

We can see from the figures 80 and 81 that the agreement between measurements and simulations is very nice when the PZC is enabled. Even the undershoot are well reproduced. The only lack of compliance between measurements and simulations comes when the PZC is off for both sensors.

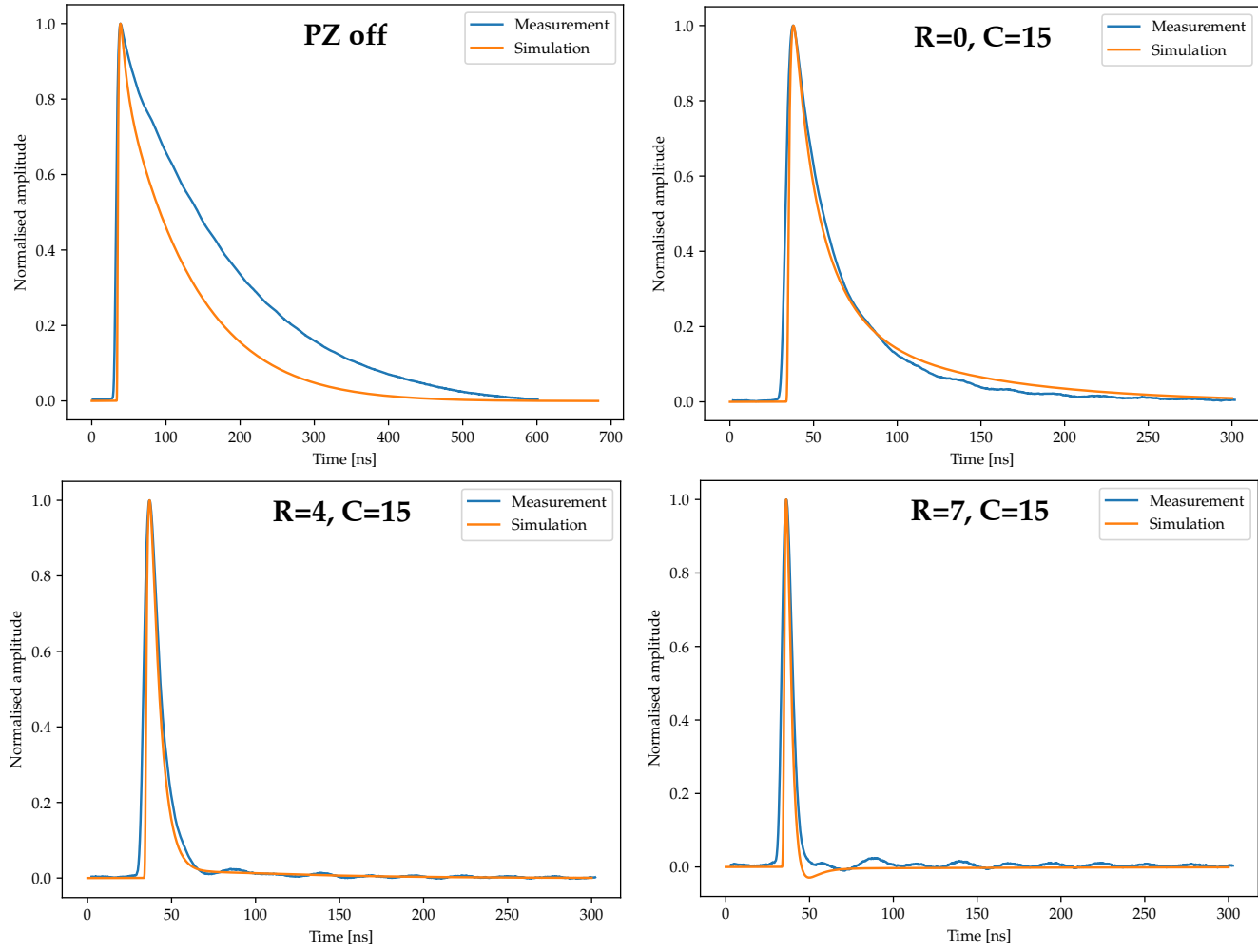


Figure 81. LVR3 6x6 mm² pulse shapes comparison between measurements and simulations for different PZC configurations

The simulation of the linearity of MUSIC with the LCT5 3x3 mm² sensor is currently under study and is therefore not discussed here.

5 Conclusions

Upgrading the sensors of the camera is a possible solution to increase its global optical efficiency. Two possible sensors are considered for this upgrade: the LCT5 and the LVR3 sensors from Hamamatsu. Despite a detailed simulation study of the front-end electronics coupled to the LVR3 sensor, fine-tuning the electronic components appears to be insufficient to have short enough pulses. An ASIC developed at the University of Barcelona for SiPM readout, called MUSIC, has therefore been studied for its interesting Pole Zero Cancellation that sharpens the pulse shapes. MUSIC has also the advantage of having summation outputs, that would allow to sum up the four channels of a pixel with a single MUSIC board.

The pulse shape of the LVR3 $6 \times 6 \text{ mm}^2$ sensor coupled to MUSIC has first been studied. It appears that the PZC allows to have very short pulses, compatible with the required 20-30 ns integration window. The problem of this sensor is that the ability of counting photon is good for the $3 \times 3 \text{ mm}^2$ sensor, but is no more present with the $6 \times 6 \text{ mm}^2$ sensor. Hence, keeping photon counting ability for a large surface LVR3 sensor (such as the hexagonal sensor) would require to increase the over-voltage, which would consequently increase by a lot the cross talk probability.

The pulse shape of the LCT5 $3 \times 3 \text{ mm}^2$ sensor has therefore been studied. Thanks to the Pole Zero shaper circuit, very short pulses are easily achievable. The photon counting ability is good for both $3 \times 3 \text{ mm}^2$ and $6 \times 6 \text{ mm}^2$ sensors. The LCT5 sensor is therefore a good candidate for the upgrade. The linearity behavior has then been studied with the LCT5 $3 \times 3 \text{ mm}^2$ sensor. The results are very satisfying since the HG channel of MUSIC, which is the channel we would use to sum the signals from a pixel, has a good linear behavior below saturation both with the amplitude and the charge of the signal. It also has a good behavior above saturation, allowing to reconstruct signals up to a few thousands of photons with a good resolution even with the small $3 \times 3 \text{ mm}^2$ sensor.

Simulations of the pulse shapes generated with MUSIC and both LVR3 and LCT5 sensors have been performed by the team of Barcelona working on the ASIC development. The pulse shapes with no PZC are longer for measurements than for simulations. But apart from this difference, the simulated pulse shapes with different configurations of PZC are matching perfectly the measured ones. This is a very good news since it means that the behavior of the sensors with MUSIC is predictable.

In conclusion, the MUSIC coupled to the LCT5 sensor would be a very nice solution for sensor/electronics upgrade. Nevertheless, with the current ASIC design, such upgrade would require to use one MUSIC board per pixel, since it does not allow sub-summations of channels. A redesign of MUSIC would therefore be needed in order to use a MUSIC ASIC for ~ 3 -4 pixels. The use of MUSIC as preamplification stage would also require to perform some modification of the Slow Control Board to readout the current output of MUSIC in order to monitor baseline shift. The power consumption with the current preamplification stage is 400 mW per pixel. The use of MUSIC would thus allow to reduce power consumption to 100 mW per pixel in the case of one ASIC per pixel. The power consumption could be better by using an ASIC per ~ 3 -4 pixels. Nevertheless, the MUSIC is more expensive than the current preamplification electronics, but the use of MUSIC would increase the cost of the overall telescope of only 2%.

Characterisation of the uniformity of the entrance window of the camera

A second SST-1M telescope is under construction. A new entrance window for the second camera has been manufactured with an improved coating compared to the first prototype. The large $\sim 1 \text{ m}^2$ surface of the window makes the coating process complicated. In order to achieve the more uniform result, the process is performed in a large coating chamber. For a better uniformity, the window is rotating during the coating process. An anti-reflective coating is applied on the exterior surface of the entrance window in order to minimise Fresnel losses while the other surface is coated with a dichroic filter that allows to cutoff high wavelengths ($>540 \text{ nm}$). Cutting off high wavelengths is important since the SiPM are sensitive to them and it is the wavelength region where the NSB has the biggest contribution. Furthermore, Cherenkov light is fainter above 540 nm . The window transmittance spectrum and uniformity have to be characterised. The characterisation setup is first depicted, followed by the measurement results on the second window. These results are then compared to the first window that has been characterised a few years ago. Finally, a study on the impact of window non-uniformity on image reconstruction is presented.

1 Measurement setup

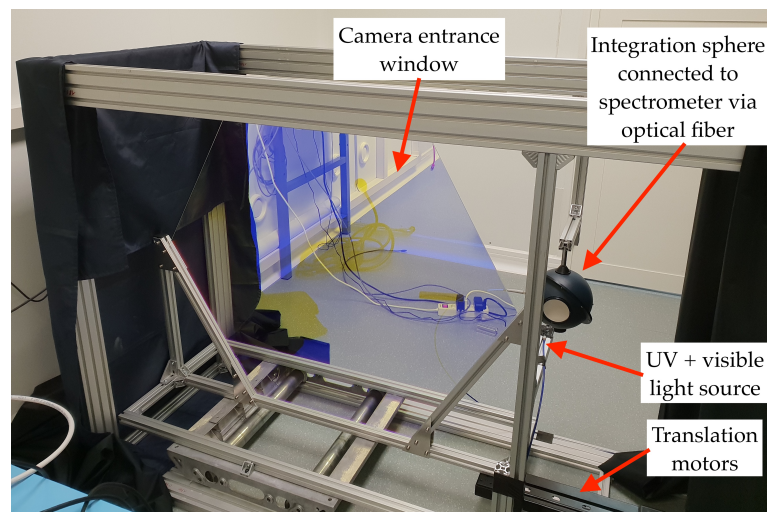


Figure 82. Picture of the measurement setup

The measurements have been performed in the clean room of the DPNC (UniGe). Figures 82 and 83 respectively show a picture and a sketch of the measurement setup used to characterise the camera entrance window. The window is placed between the light source and an integration sphere. The integration sphere collects the photons and is connected to an Avantes spectrophotometer that measures the photon flux as a function of the wavelength. A transmittance spectrum is then computed by the software using a reference spectrum. A double light source is used in order to cover both blue and ultraviolet wavelengths. The window is moved horizontally along a rail thanks to a motor controlled from the computer. The motor is moved by step of 20 mm in order to scan the positions along the center-corner diagonal of the window. The window is then moved of 60° by hand to scan a second diagonal. This procedure is repeated for each of the 6 diagonals. The whole setup is covered with a dark cloth in order to avoid external light. At the beginning of each series of measurements, a dark spectrum, with light source off, and a reference spectrum, with light on and without the window, are taken in order to have a reference point to produce the window spectra.

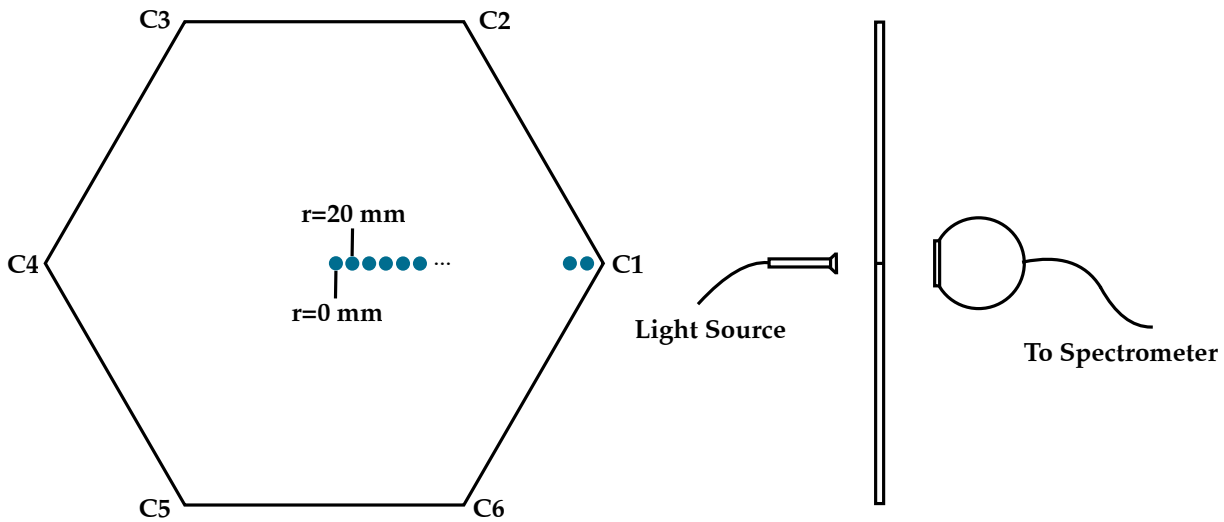


Figure 83. Sketch of the measurement setup

2 Uniformity and efficiency of the new window

A reference sample of about one square centimeter has been coated following the same procedure as for the window. The spectrum of this sample is compared with the spectrum of the window at 240 mm from the center in figure 84. It can be noticed that the coating of the window is of lower quality compared to the sample since the transmittance between 300 nm and 550 nm is almost constant and above 90%, while the variation of the window spectrum is more important and the transmittance of the window is in average around 85% in this range. The coating of the sample is indeed of better quality because of the small 1 cm^2 surface of the sample, which shows the difficulty of large surface coating.

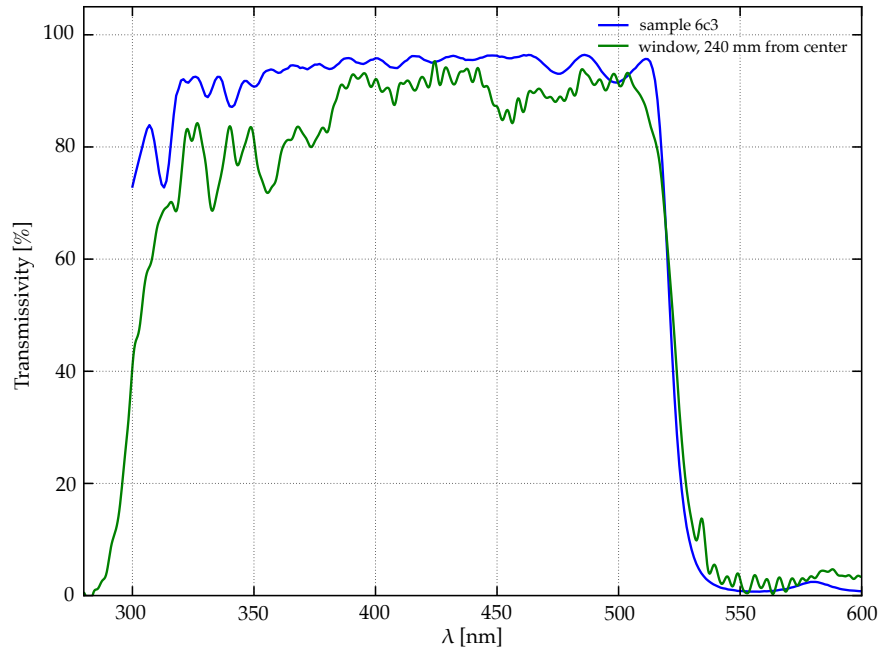


Figure 84. Transmittance spectrum of the window at 240 mm from the center compared to the spectrum of a sample coated with the same procedure as the window

The figure 85 shows the evolution of the transmittance spectrum along a radial diagonal. It is clear that the spectrum in the center of the window has a narrower transmittance window in the region of interest. This can be explained by the centrifugal force due to the rotation of the window during the coating process. The spectrum in the border of the window, around 520 nm, has quite a different behavior above 550 nm. Nevertheless, apart from the center of the window, the spectrum seems quite steady along the window diagonal. The radial uniformity of the window is therefore not perfect, especially in the center and in the outer part.

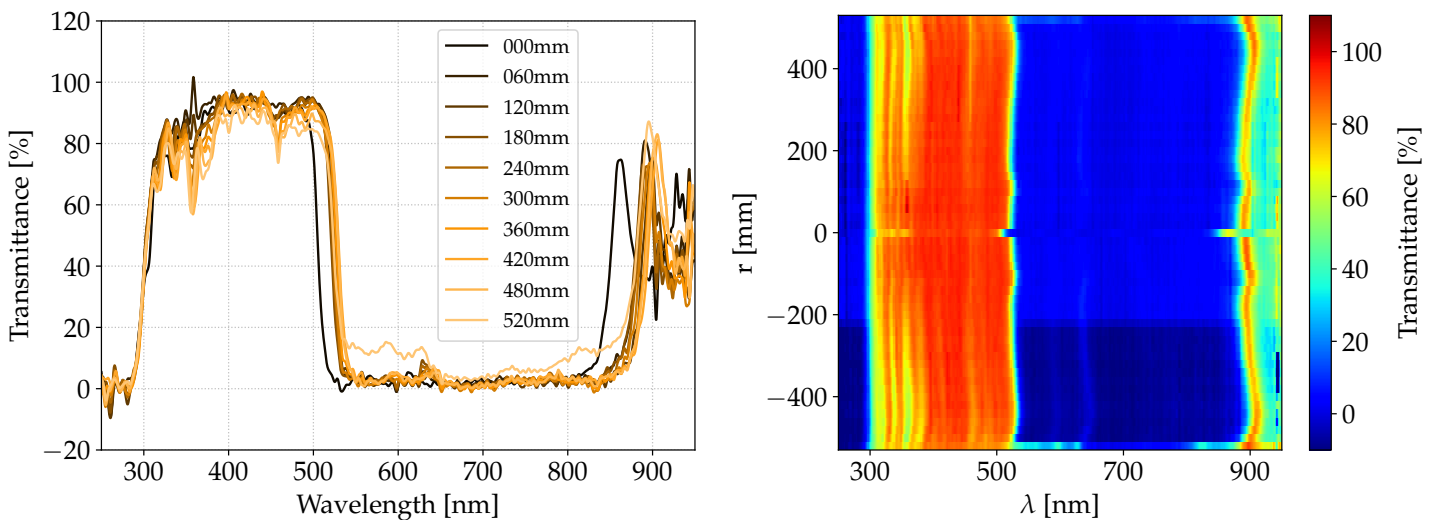


Figure 85. Transmittance spectrum as a function of the radial distance to the center of the window

The mean spectra along the six center-to-corner diagonals of the hexagonal window are shown in figure 86. The spectra of the six corners appear to be very similar to each other, implying that the circular uniformity of the window is very good. This is quite expected because of the rotation of the window during the coating process.

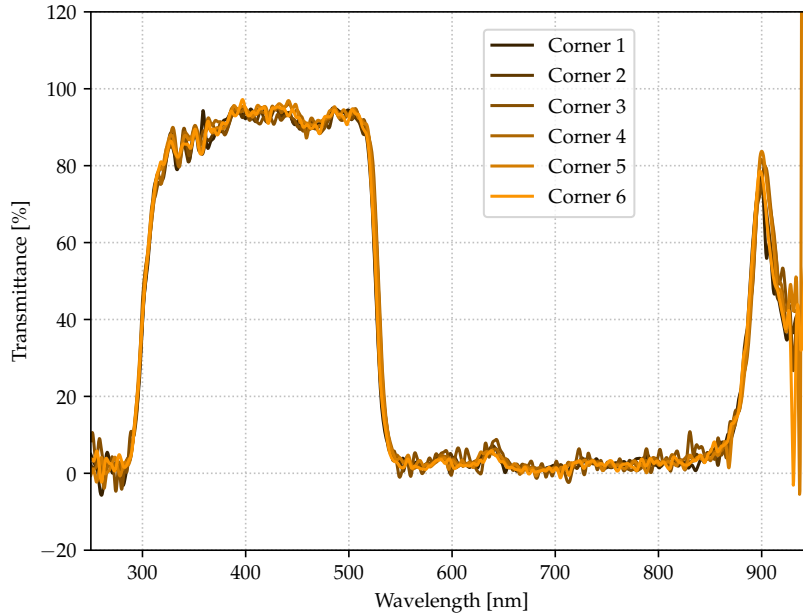


Figure 86. Mean transmittance spectrum along the six center-to-corner diagonals of the hexagonal window

To characterise the overall optical efficiency of the camera the transmittance spectrum of the window has to be combined with other components. The transmittance spectrum between 300 nm and 550 nm is first weighted by the Cherenkov spectrum and by the PDE of the silicon photomultiplier, which are shown in figure 87. The resulting spectrum is then multiplied by 0.88, which correspond to the cone transmittance, and by 0.92, to account for the dead space between pixels (calculated as the area of a pixel multiplied by the number of pixels and divided by the area of the whole camera). The cumulative of this renormalised spectrum gives the optical efficiency of the camera. An example is shown with the mean spectrum of the whole window in figure 87. The resulting optical efficiency is 18.70% with LCT2 sensors and 25.42% with LCT5 sensors, which allows to go above requirements.

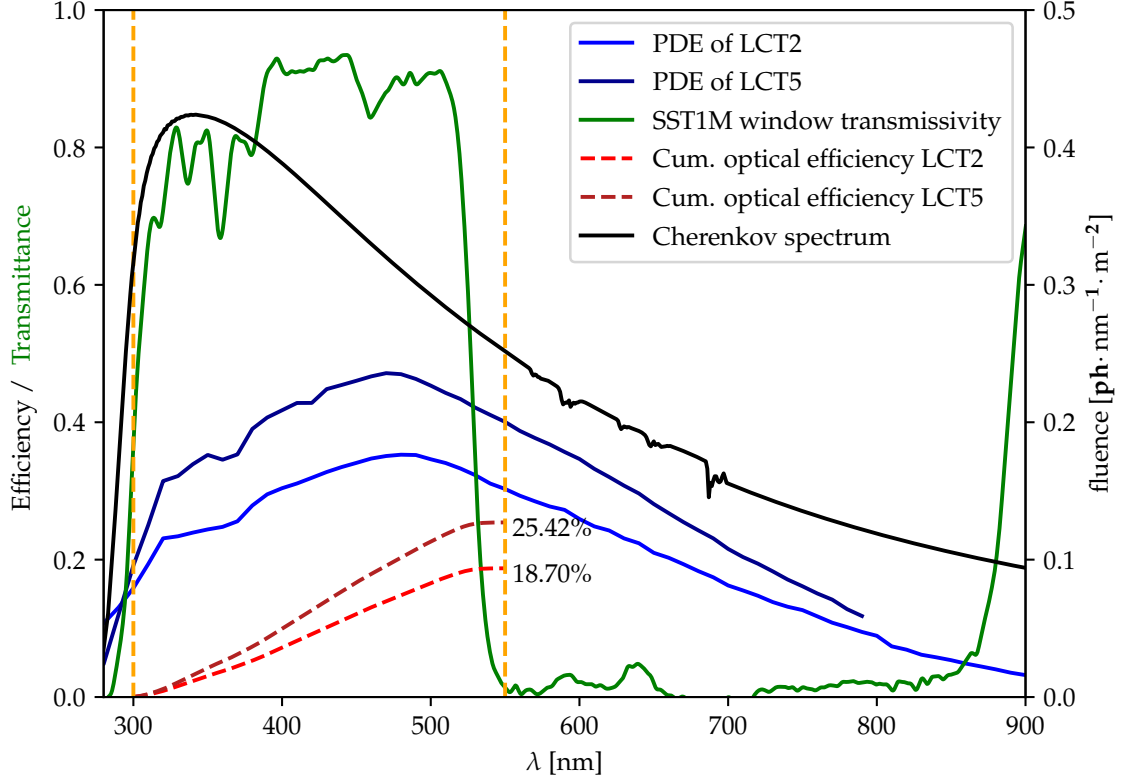


Figure 87. Ingredients used for the calculation of optical efficiency

The spectra for the six corners are averaged for each distance from the center, which allows to compute a mean optical efficiency as a function of the radius. This is shown, considering LCT2 sensors, in figure 88. It can be seen that the mean optical efficiency of the window is of $18.74 \pm 0.15\%$, which is below requirements. The improvement of the coating is therefore not sufficient to pass the requirements.

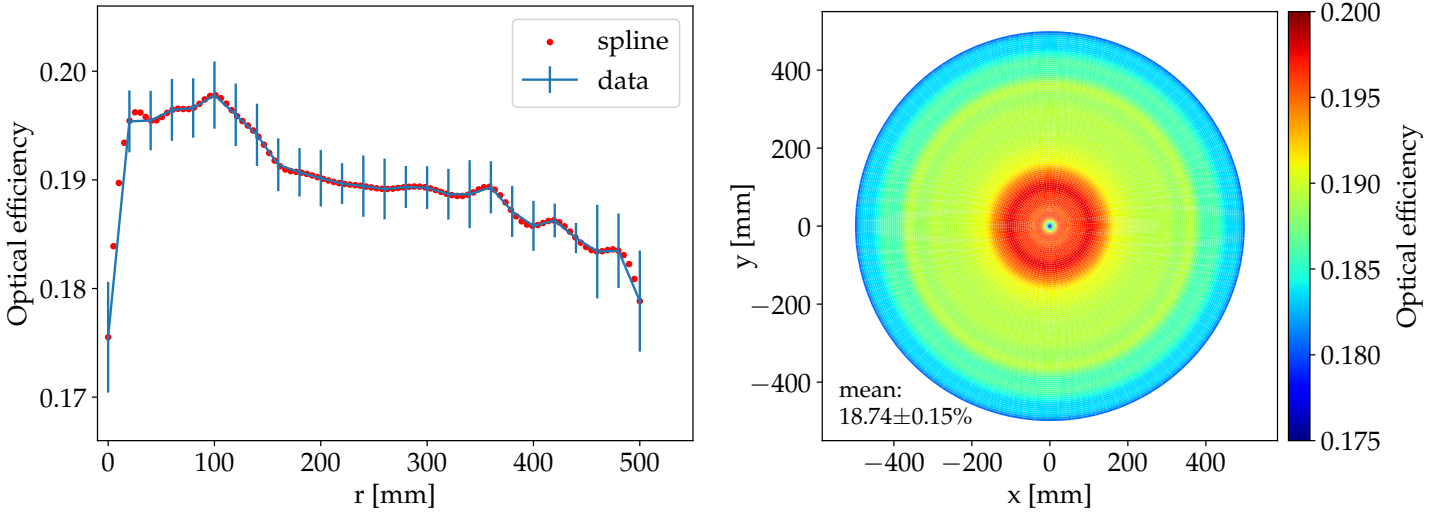


Figure 88. Optical efficiency as a function of the distance to the center of the window

The optical efficiency as a function of the radius can also be computed with the LCT5 PDE. As can be noticed in figure 89, upgrading the sensors to LCT5 would allow to reach an optical efficiency above 24% on the whole window, which is far above requirements. It is important to have such margin on the optical efficiency to compensate for the possible ageing of the cones and to reduce the cleaning frequency of the window and of the mirrors.

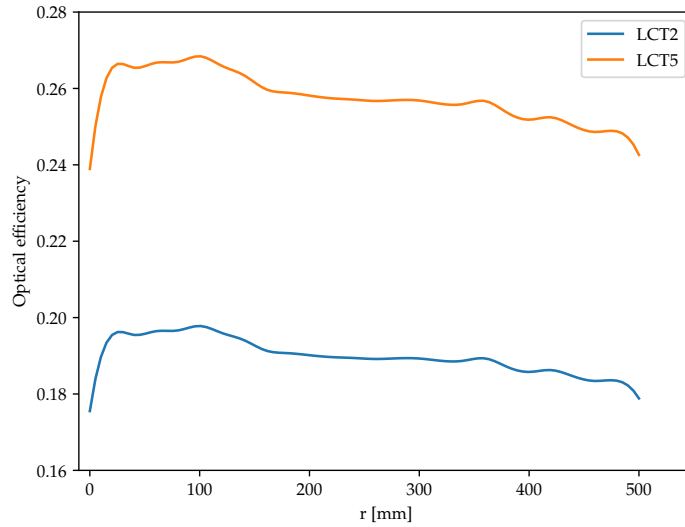


Figure 89. Averaged optical efficiency as a function of the radius with the LCT2 and LCT5 PDEs

2.1 Angular dependency

The evolution of the transmittance as a function of the incidence angle of the light on the surface of the window has been measured.

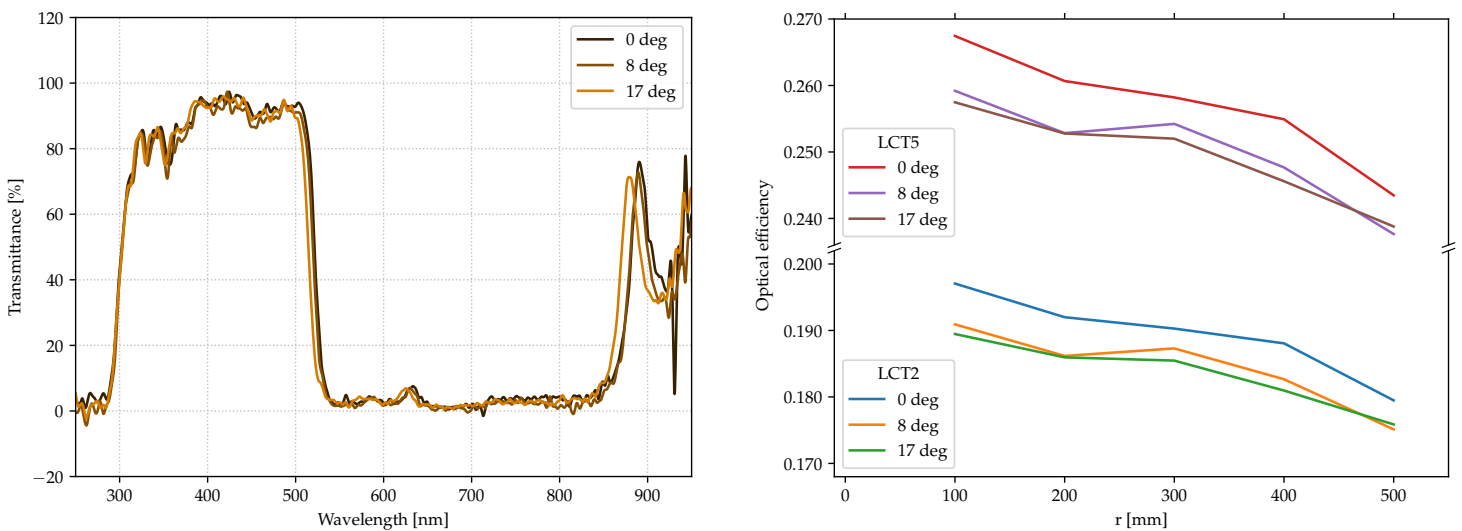


Figure 90. Transmittance spectrum as a function of the incident angle (left) and optical efficiency vs radius for different incident angles and for both LCT2 and LCT5 (right)

We see in figure 90 that the spectrum at 200 mm from the center is a bit narrower when increasing the incident angle to 8° and 17° . The optical efficiency as a function of the radius for the three measured incident angles and for both LCT2 and LCT5 sensors is also shown in the same figure. An important drop in optical efficiency is observed between 0° and 8° , while between 8° and 17° (which is the range containing most of the incident photons, see figure 91), the optical efficiency seems more stable. Despite this drop of optical efficiency, we see that using the LCT5 sensor would allow to be above requirements even for big incident angles.

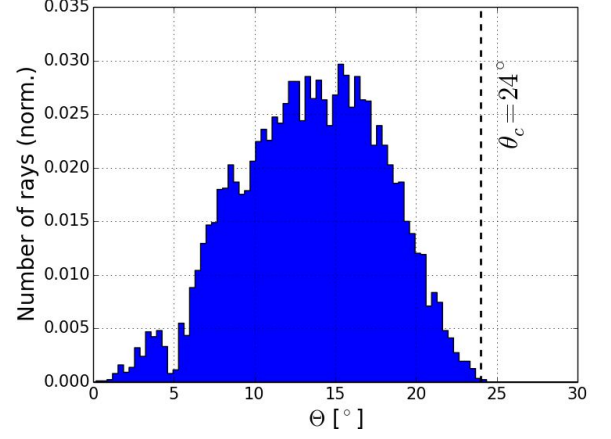


Figure 91. Angular distribution of the incident angle on the camera plane of the photons reflected by the mirrors [17]

2.2 Transmittance for each pixel position

A mean transmittance value is extracted from the mean spectrum of each radius, leading to a curve of the mean transmittance (renormalised by the Cherenkov spectrum) of the window as a function of the radius. Since the window is quite circularly uniform (see figure 86), a curve of the transmittance as a function of the radius averaged on the six corners can describe the whole camera plane. Since the measurements were taken every 2 cm, a spline is used to interpolate the value of the transmittance as a function of the radius with a thinner resolution. This spline is then circularly mapped, like it was done before for the optical efficiency, which leads to a two-dimensional continuous map of the transmittance of the window across its surface (see figure 92). The average value of the transmittance across the surface of a given pixel can then be computed, resulting into the second plot of figure 92, where we see the mean transmittance of the window for each pixel of the camera. The averaged transmittance over the pixels is 78.70%.

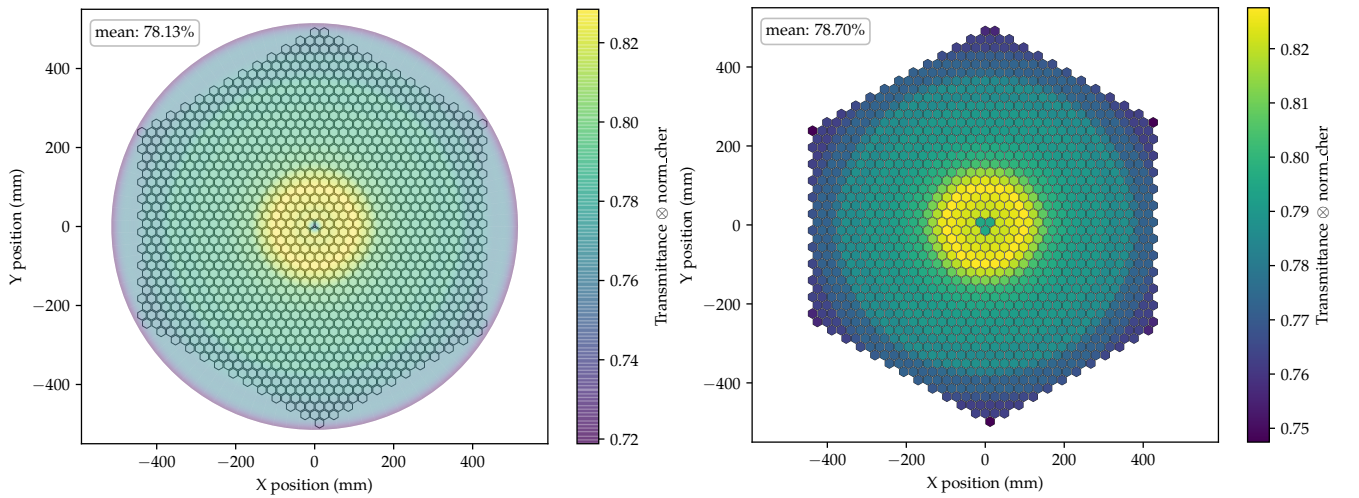


Figure 92. Continuous map of the window transmittance (left) and interpolated values of the transmittance for each pixel (right)

3 Comparison with the first window

The mean spectrum of the new window is compared to that of the first prototype window in figure 93. We see that the $\sim 90\%$ transmittance interval is thicker for the new window. Reaching lower wavelengths improves the optical efficiency. Note that the peaks of transmittance below 250 nm are due to the fact that the source emits a very low flux of photons at low wavelengths, implying a bad reference spectrum below 250 nm.

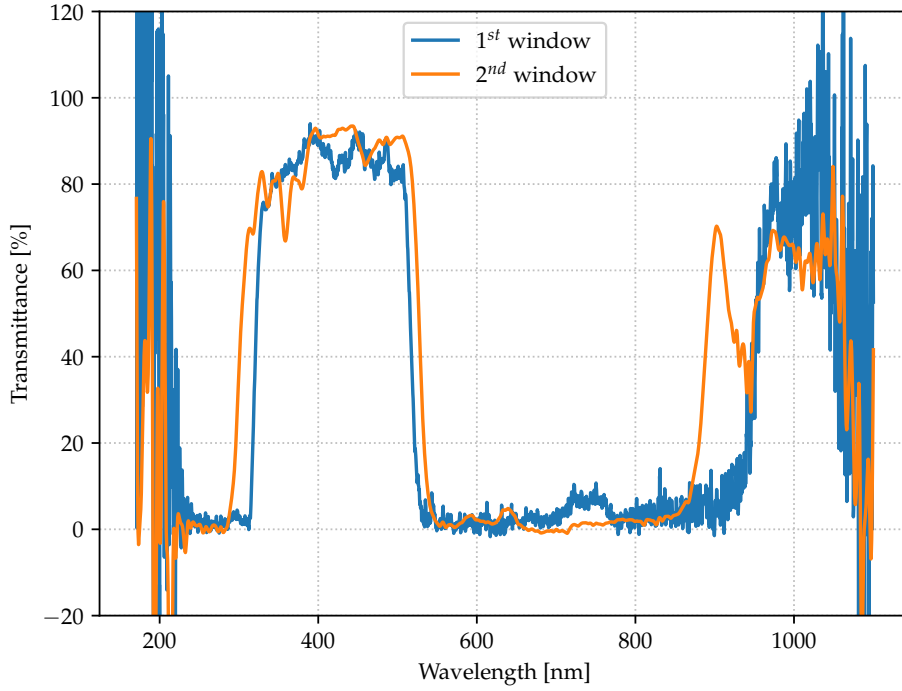


Figure 93. Transmittance spectrum of the new window compared to that of the first window prototype

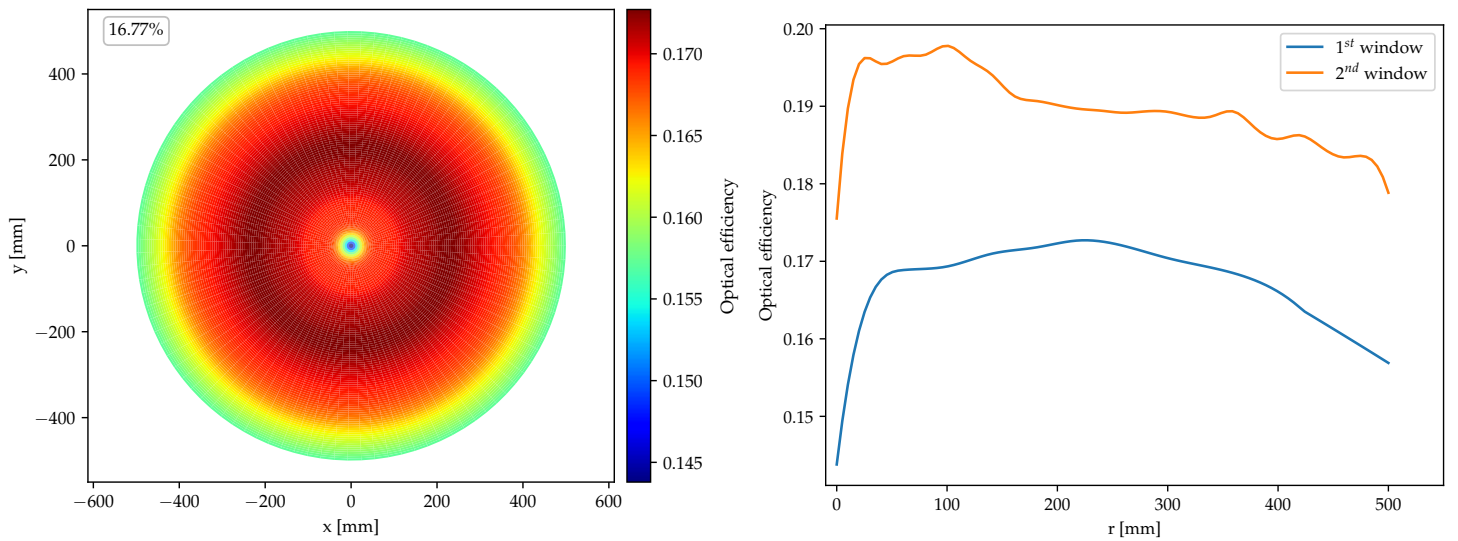


Figure 94. Map of the radial optical efficiency for the first window (left) and optical efficiency as a function of the radius for both windows (right)

The figure 94 shows the optical efficiency in terms of the radius for the first window. The average optical efficiency of the first window is 16.77%. The improvement of the coating has therefore induced an increase of about 10% of optical efficiency. We see from the comparison of the optical efficiency between the two windows that the uniformity of the coating has also been improved. It can also be seen by extracting the mean transmittance per pixel for the first window (see figure 95) that the uniformity across the camera has been improved with the new window.

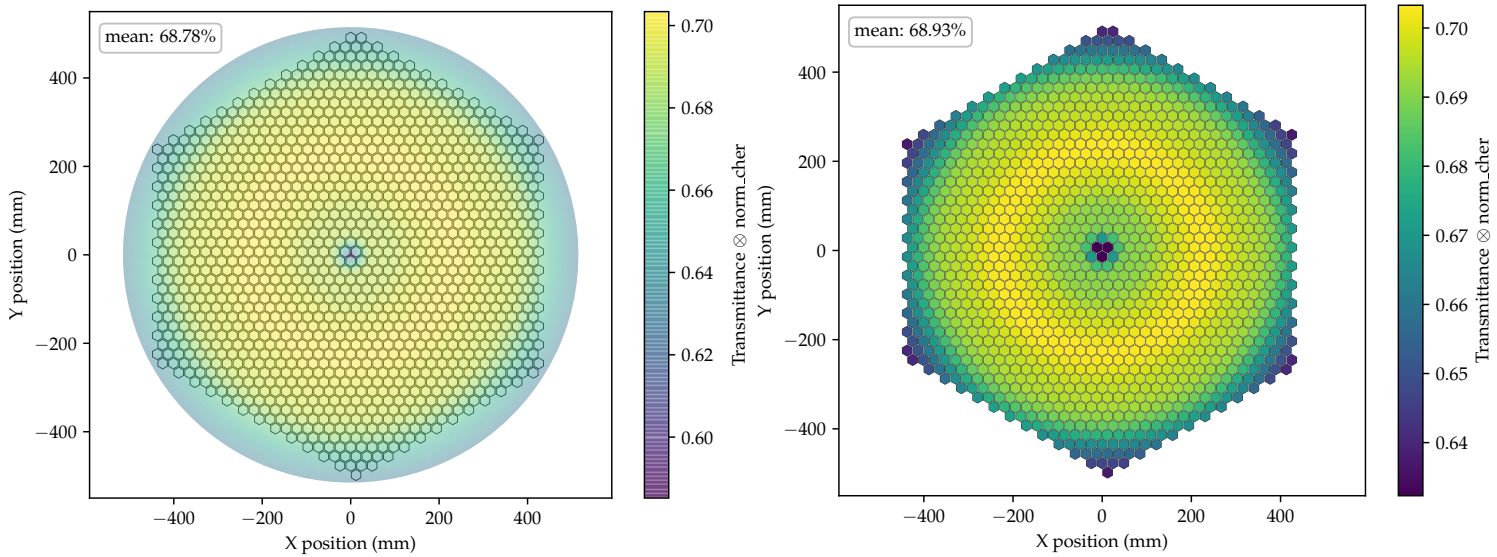


Figure 95. Continuous map of the first window transmittance (left) and interpolated values of the transmittance for each pixel (right)

4 Impact of the window non-uniformity on image reconstruction

4.1 Implementation of window flat-fielding correction factors in the camera analysis pipeline

In order to account for the non-uniformity of the entrance window in the data analysis, correction factors have been computed for each pixel. The flat-fielding factor of a pixel is computed as the mean transmittance of this pixel normalised by the mean transmittance of the whole window. A function has been implemented in the `digicampipe` pipeline used to analyse the data in order to correct for the non-uniformity. The correction factors are stored in a text file for each window, and the user just has to call the function with the wanted window number to apply the correction to the data. The factors for both windows are shown in figure 96. A study has then been performed to study the non-uniformity impact on event reconstruction on both real and simulated showers. This study is discussed in the following sections.

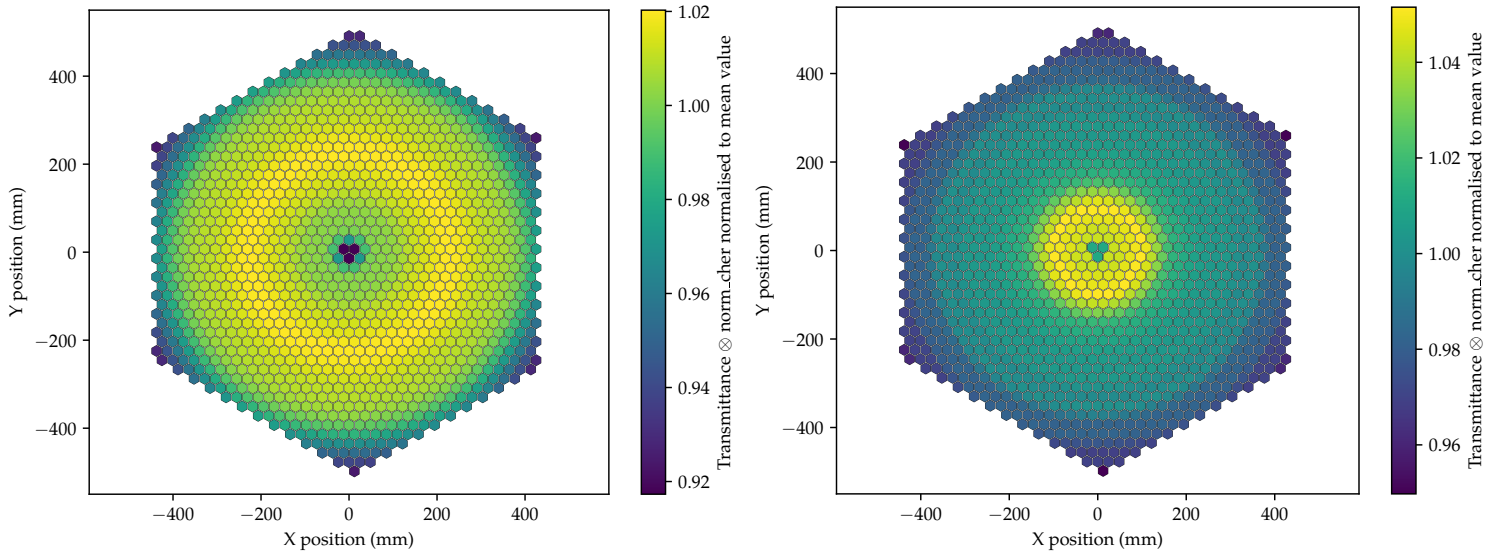


Figure 96. Correction factor for each pixel for the first (left) and the second (right) entrance windows

4.2 Effect of the non-uniformity on measured data-set

The impact of the entrance window non-uniformity on image reconstruction has first been studied on real data. The study presented here has been performed on observation data of the Crab source during the nights of the 10th and the 12th of October 2018 at Krakow, Poland (location of the SST-1M first prototype). In order to characterise the significance of the non-uniformity on the analysis, the Hillas' parameters discussed in the [chapter I](#) are used.

4. Impact of the window non-uniformity on image reconstruction

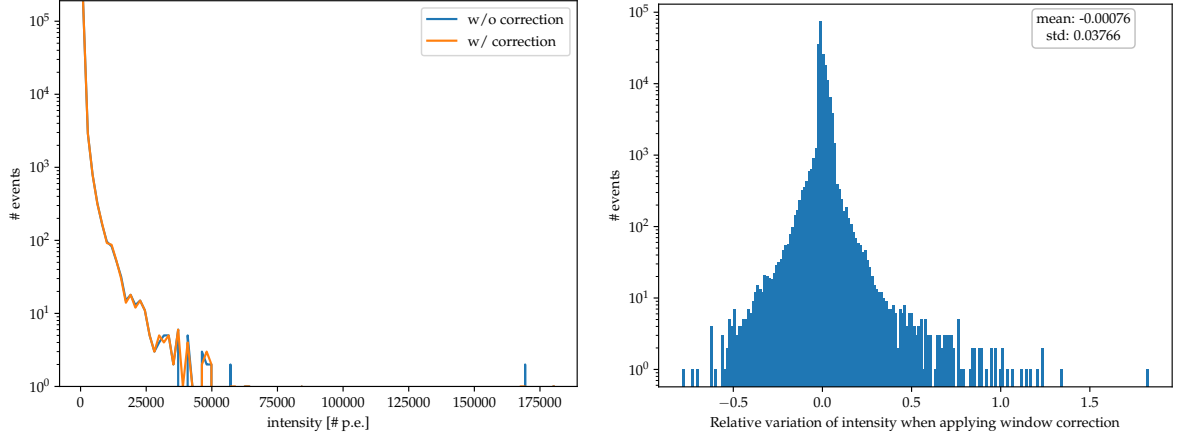


Figure 97. Distribution of the intensity before and after correction (left) and distribution of the relative difference induced by the correction (right) for the Crab observations

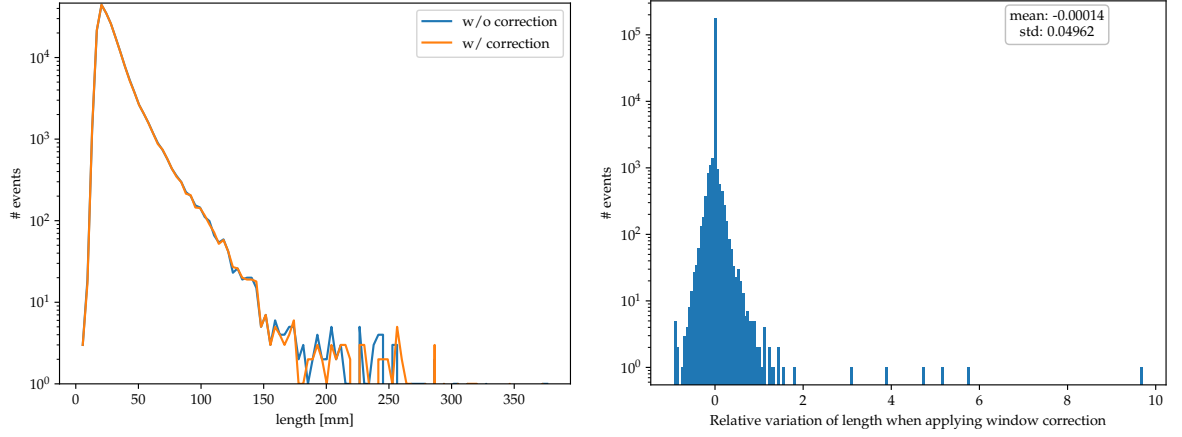


Figure 98. Distribution of the length before and after correction (left) and distribution of the relative difference induced by the correction (right) for the Crab observations

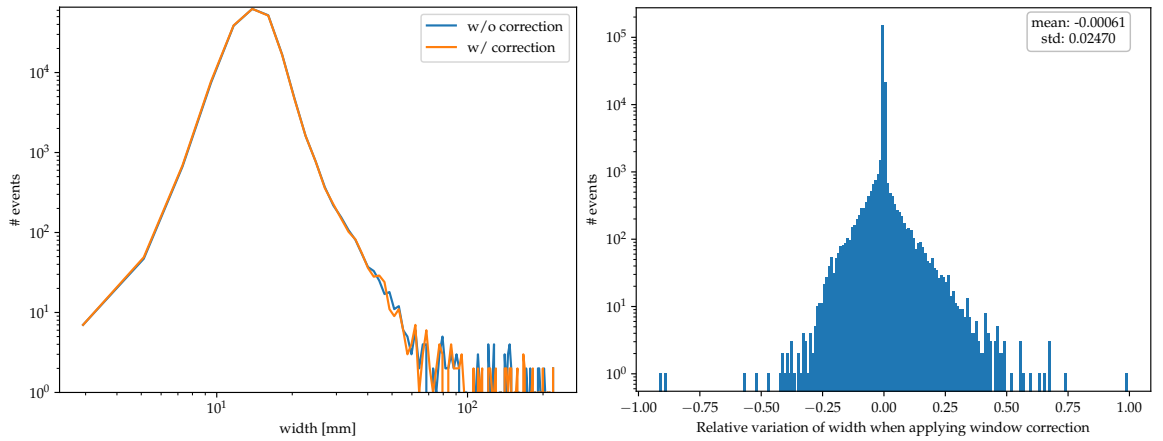


Figure 99. Distribution of the width before and after correction (left) and distribution of the relative difference induced by the correction (right) for the Crab observations

The distributions of the intensity, width, and length of the events before and after applying the flattening correction are shown in figures 97, 98, and 99. The histograms of the relative difference induced by the correction of these three parameters are also shown in these figures. The mean relative/absolute difference and its standard deviation for all the Hillas' parameters are given in the table 12. It can be concluded from these histograms and values that the effect of the window non-uniformity on the event reconstruction is very low. Indeed, the mean relative differences for the intensity, the width, and the length are below 0.1%. The relative difference for the kurtosis is as well smaller than 0.1%. For the other parameters, absolute differences have been computed to avoid divergences (for instance in the case of an event in the center of the FoV with $r \approx 0$). The absolute differences are smaller than mrad for the angles and smaller than mm for distances, which is way smaller than the pixel size. The effect of the correction is therefore very small on all the image parameters.

Parameter	intensity	length	width	kurtosis
Mean relative difference	$-7.628 \cdot 10^{-4}$	$-1.379 \cdot 10^{-4}$	$-6.099 \cdot 10^{-4}$	$5.494 \cdot 10^{-4}$
Standard deviation	$3.766 \cdot 10^{-2}$	$4.962 \cdot 10^{-2}$	$2.470 \cdot 10^{-2}$	$2.287 \cdot 10^{-2}$

Parameter	r [mm]	ϕ [rad]	ψ [rad]	skewness [mm]	alpha [rad]	miss [mm]
Mean absolute difference	$-1.325 \cdot 10^{-1}$	$-1.797 \cdot 10^{-4}$	$-1.062 \cdot 10^{-3}$	$8.464 \cdot 10^{-4}$	$-3.974 \cdot 10^{-4}$	$-2.419 \cdot 10^{-1}$
Standard deviation	2.049	$7.422 \cdot 10^{-2}$	$2.518 \cdot 10^{-1}$	$5.939 \cdot 10^{-2}$	$4.438 \cdot 10^{-2}$	$1.032 \cdot 10^1$

Table 12. Mean and standard deviation of the relative/absolute difference induced by the correction on each parameter on the Crab data

4.3 Effect of the non-uniformity on MC simulated on-axis gammas

The same study is now presented on simulated on-axis showers. The showers were simulated by Rafał Moderski with the Corsika package and the instrument response with the sim-telarray simulation package for the observation conditions of Krakow. A cut has been applied on the simulated data to only keep the events with 1 island. The distributions before and after correction of the intensity, length, and width are respectively shown in figures 100, 101, and 102. The distributions of the relative differences for these three parameters are given in the same figures, and the mean and standard deviation of the relative/absolute difference for each image parameters are given in the table 13.

4. Impact of the window non-uniformity on image reconstruction

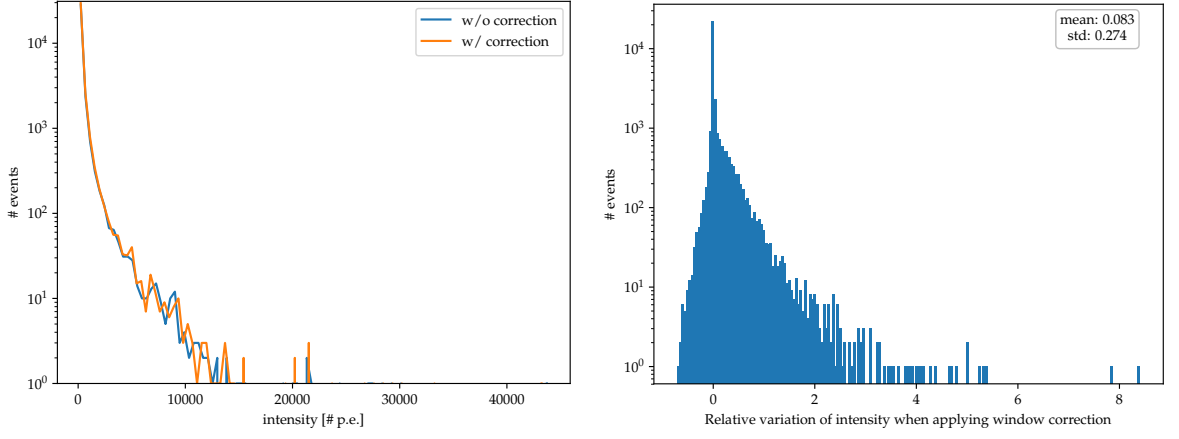


Figure 100. Distribution of the intensity before and after correction (left) and distribution of the relative difference induced by the correction (right) for the simulated showers

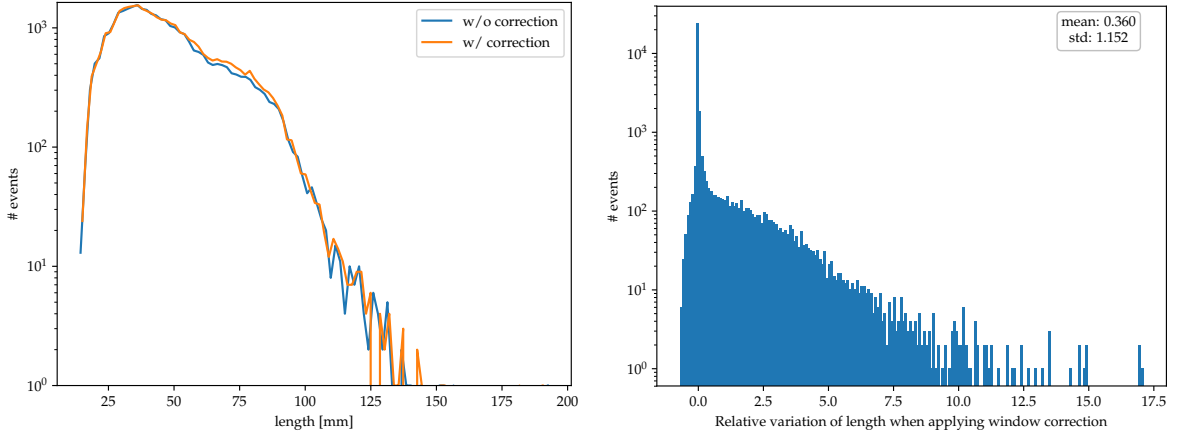


Figure 101. Distribution of the length before and after correction (left) and distribution of the relative difference induced by the correction (right) for the simulated showers

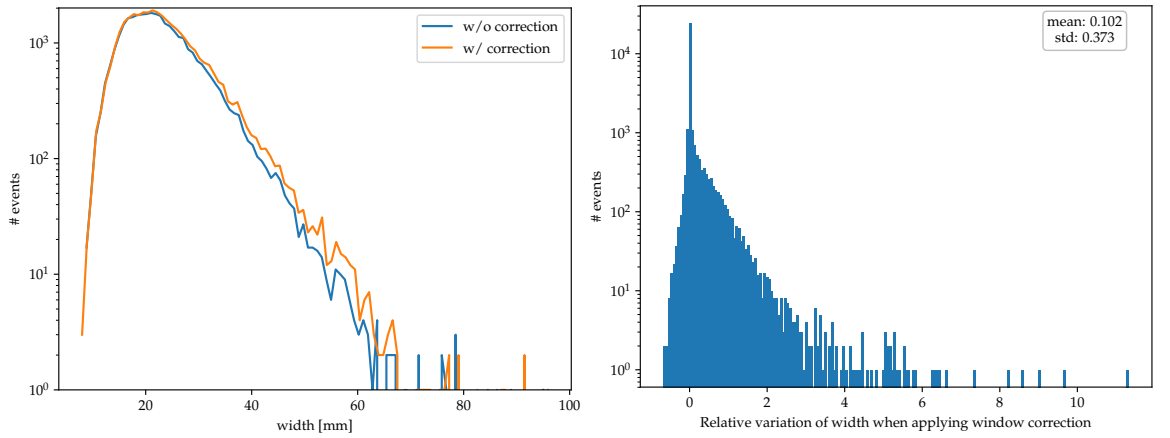


Figure 102. Distribution of the width before and after correction (left) and distribution of the relative difference induced by the correction (right) for the simulated showers

The averaged effects on the length and width are respectively about 36% and 10% and a change can be observed in the corresponding histograms (figures 100, 101, and 102). The effect on the intensity is about 8%. The effect is therefore quite significative on the simulated events. This is due to the fact that the simulated events are all on-axis showers, meaning that the impact of the non-uniformity is maximal due to its radial nature. It is therefore important to correct for this effect in the analysis chain.

Parameter	intensity	length	width	kurtosis
Mean relative difference	$8.265 \cdot 10^{-2}$	$3.600 \cdot 10^{-1}$	$1.018 \cdot 10^{-1}$	$3.089 \cdot 10^{-2}$
Standard deviation	$2.737 \cdot 10^{-1}$	1.152	$3.730 \cdot 10^{-1}$	$2.688 \cdot 10^{-1}$

Parameter	r [mm]	ϕ [rad]	ψ [rad]	skewness [mm]	alpha [rad]	miss [mm]
Mean absolute difference	-1.522	$-5.978 \cdot 10^{-4}$	$1.634 \cdot 10^{-3}$	$-2.564 \cdot 10^{-3}$	$6.202 \cdot 10^{-2}$	5.340
Standard deviation	$2.592 \cdot 10^1$	$7.279 \cdot 10^{-1}$	$5.525 \cdot 10^{-1}$	$4.900 \cdot 10^{-1}$	$2.801 \cdot 10^{-1}$	$3.257 \cdot 10^1$

Table 13. Mean and standard deviation of the relative/absolute difference induced by the correction on each parameter on the simulated data

5 Conclusions

A new entrance window has been manufactured for the second SST-1M camera with an improved coating. The window transmittance spectrum has been characterised across its surface. The new window appears to have a more uniform coating, and to have a better transmittance in the range of interest (300-550 nm). Despite the improvement of transmittance of the window, the optical efficiency of the camera is still below the requirement of 20% and an upgrade of the sensors is anyway needed. The optical efficiency as a function of the light incident angle has been measured, and it is above requirements with the LCT5 sensor even near the cone cutoff angle. The spectrum and uniformity of the new window have been compared to that of the first window. The width of the transparent range and the uniformity of the window have both been improved. An averaged transmittance value of the window for each pixel has been extrapolated and renormalised to the mean window transmittance. A factor extracted from the data is applied for each pixel in the camera pipeline in order to apply a flat-fielding correction to account for the window non-uniformity. The effect of this non-uniformity on event reconstruction has finally been studied on both real and simulated data. The impact of this non-uniformity appears to be small on real data, but significative for simulated on-axis event, due to the radial nature of the non-uniformity. This non-uniformity is anyway accounted in the analysis pipeline, allowing the user to flatten the data to account the window, if wanted.

Summary and outlooks

This thesis has been performed at DPNC (University of Geneva) in the context of the future generation experiment of Cherenkov telescopes, the Cherenkov Telescope Array (CTA). More precisely, this work has been executed in the frame of the SiPM-based digitizing camera of the SST-1M single mirror telescope designed for CTA. The aim of this work was to investigate different solutions to improve the optical efficiency (conversion factor from photons to photoelectrons) of the SST-1M camera, whose minimal required value is 20% since the last update of the B-TEL-1170 requirement.

The first solution that has been investigated to improve the efficiency of the camera was to upgrade the current LCT2 SiPMs to LCT5 or LVR3 SiPMs to increase the PDE of the photosensors. Due to their higher microcell capacitance and quenching resistor, the LCT5 and LVR3 sensors are expected to induce longer signals than the LCT2 SiPM used for the first camera prototype. A first optimization study for the LCT5 sensors had already been performed by Eng. Yannick Favre at DPNC. The LVR3, that has a capacitance and quenching resistor even bigger than LCT5, has been considered in the first part of this work because of its higher PDE and for questions of technology harmonisation between the different SST projects. The sensors coupled to the preamplification stage have therefore been simulated in PSpice® in order to optimise the pulse shape generated by the LVR3 sensor by fine-tuning the electronic components of the front-end electronics. Despite this optimisation, the better achievable pulse shape appeared to be still too long, which would oblige us to increase the integration window if working with such signals. But increasing the integration window is not compatible with the 20-30 ns required integration time (B-SST-1210). Indeed, increasing this integration time would reduce the signal-to-noise ratio since the probability of integrating noise would be higher. The electronic simulation has also been compared to measurements, from which we get even worse results (longer pulses). The digitization of the signal by the DigiCam digitizing system has also been simulated using the digicamtoy Monte Carlo toy. The photon counting ability with the simulated LVR3 pulse appears to be similar to that of the LCT2 pulse, but the real result is expected to be bad because of the difference between simulations and measurements of pulse shapes.

Since the fine-tuning of the electronics has appeared to be insufficient to optimise the pulse shape, a solution to upgrade the electronics has also been considered. The Multiple Use SiPM Integrated Circuit (MUSIC), developed at the University of Barcelona for SiPM readout, offers the possibility of sharpening a pulse shape using a so called Pole Zero Cancellation (PZC). The MUSIC has therefore been characterised with both LVR3 and LCT5 sensors. The cancellation is able to reduce the pulse duration enough to fit within the

required integration time. But the photon counting ability at reasonable over-voltage (that corresponds to a 8% cross talk probability) for a large sensitive surface ($6 \times 6 \text{ mm}^2$) is only possible with the LCT5 sensor, making the LVR3 sensor non suitable for our application. The behavior of the ASIC coupled to the LCT5 sensor has also been studied as a function of the incoming light level. It has a good linearity until saturation, and the good behavior above saturation allows to reconstruct signals up to thousands of photons. Finally, simulations of the ASIC have been performed by the team that developed MUSIC. The simulations match very well the measured pulses for the different PZC configurations that have been tested. The only difference between measured and simulated pulses has been observed when the cancellation is disabled.

Another possible solution that has been investigated to improve the optical efficiency of the camera is the enhancement of the transmittance of the entrance window. A new entrance window has been manufactured for the second SST-1M telescope. Its transmittance spectrum has been measured across its large 1 m^2 surface. The uniformity and transmittance of the new window have been compared with those of the first prototype window. The uniformity so as the transmittance spectrum of the window has been improved. But this improvement of transmittance is not sufficient to pass the 20% efficiency requirement while keeping the LCT2 sensors. Hence, the photosensors must still be upgraded. The impact of the non-uniformity of the window on event reconstruction has also been studied using Hillas' parameters. Even if this impact seems limited on real data, it is quite important on simulated on-axis showers, due to the radial nature of the non-uniformity. A flat-fielding correction has therefore been implemented in the camera pipeline (digicampipe) to correct for this transmittance non-uniformity.

A good solution to satisfy the requirement on the camera overall optical efficiency is therefore to upgrade the sensors to LCT5 and the preamplification stage to MUSIC. This would require a non-negligible adaptation of the design of the SCB to continuously readout the MUSIC current output in order to monitor baseline shifts due to changes of NSB. This is necessary since MUSIC is AC coupled. The use of MUSIC as preamplification stage would allow to save power. The uniformity and transmittance of the entrance window have been improved and the non-uniformity of the window is now accounted in the data analysis chain. An upgrade of the sensors combined with the improved entrance window would lead to an averaged optical efficiency above 25% and therefore far above requirements. This margin can be useful to reduce the frequency of window and mirrors cleaning, and is also important to compensate for possible light guides ageing.

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Appendix A

Evolution of noise contribution as a function of R_{IN} , R_G and R_F

In order to better understand the impact of changing the values of resistors in the circuit, the noise evolution as a function of these resistors can be simulated. A current is introduced after the Corsi circuit in the model to simulate the noise signal (see figure 103). The noise contribution is decreasing when increasing the value of R_{IN} , meaning that biggest values of R_{IN} should be favored for two similar pulses.

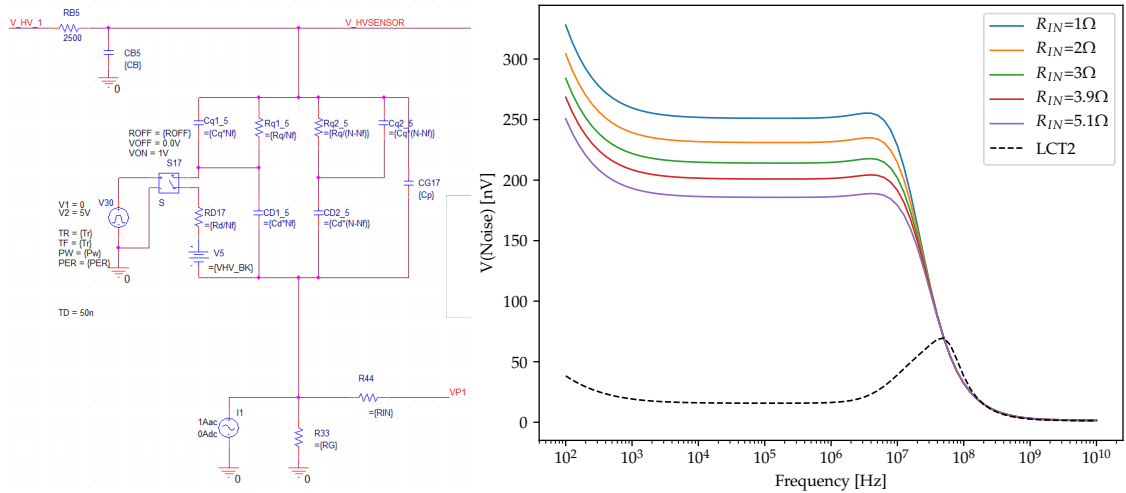


Figure 103. Simulation of the noise in the electronic model (left) and evolution of the noise contribution as a function of R_{IN}

The figure 104 shows the evolution of the noise contribution as a function of R_G and R_F , compared to the noise spectrum of the LCT2. Increasing R_G reduces the low-frequency noise but increases a bit the high-frequency component of the noise, while decreasing R_F reduces the overall noise contribution.

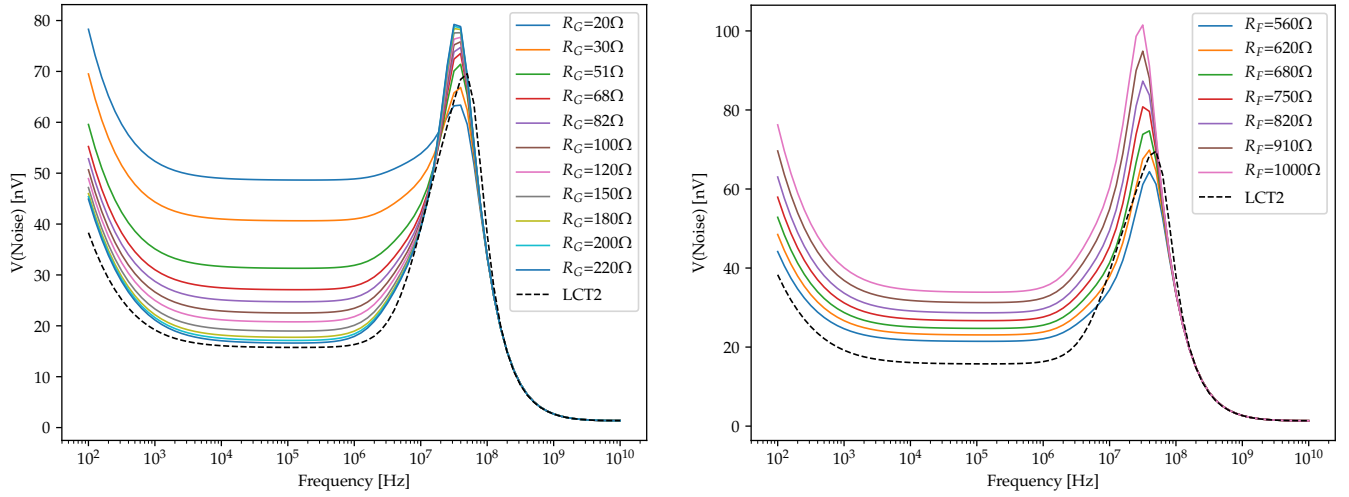


Figure 104. Evolution of the noise contribution to the signal as a function of R_G (left) and R_F (right)

In the case of similar pulse shapes, the configuration with the highest R_{IN} and R_G and the lowest R_F has therefore to be preferred.

Appendix B

Influence of different electronic components on the LVR3 pulse shape

Bias capacitance C_B

The evolution of the pulse shape with the LVR3 sensor as a function of the bias capacitance has been simulated. The currently used bias capacitance is 4.4 fF. Figure 105 shows the bias capacitance in the model so as the evolution of the pulse shape. It can be seen that dividing the bias capacitance by a factor 4 would allow to have very short pulses. The R_F resistor could afterward be increased to keep the same amplitude gain as for the LCT2 pulse. This would therefore be a good solution to have very short pulse shapes with the LVR3 sensor. The problem is that decreasing the value of the bias capacitance reduces the noise filter. The bias capacitance is already very low with the current electronics, and diminish its value would lead to a non-suitable signal to noise ratio (SNR).

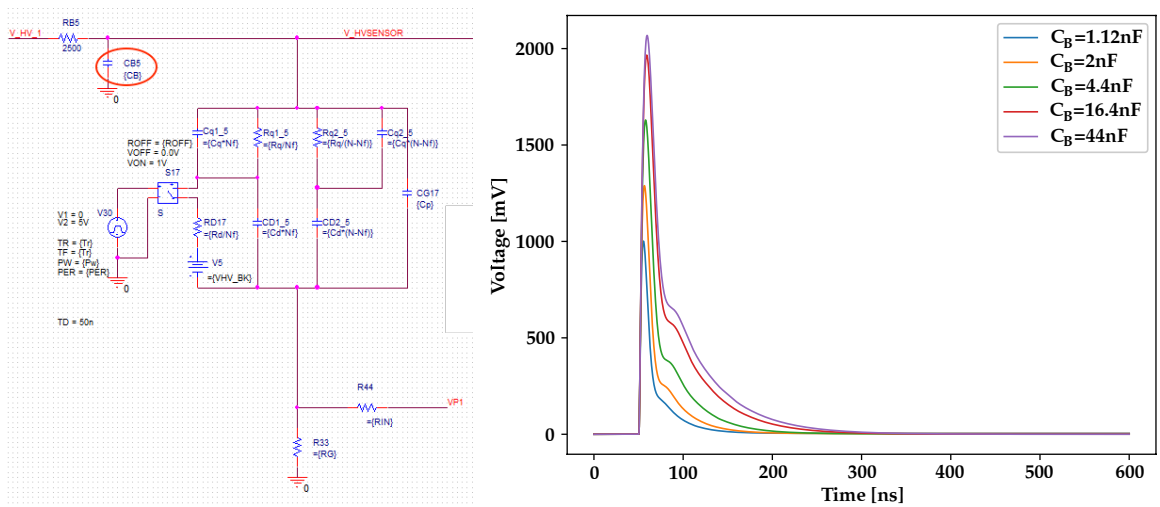


Figure 105. Evolution of the pulse shape as a function of the bias capacitance C_B

Bias capacitance parallel to R_{IN} , R_G , and R_F

The effect of introducing a capacitor parallel to the R_{IN} , R_G , and R_F resistors has also been studied. Figures 106, 107, and 108 show the modifications brought in the model in order to perform such simulations and the corresponding pulse shape evolution for the three resistors mentioned above, respectively. It can be seen that the effect of the C_{IN} capacitor is very weak on the pulse shape, while increasing the C_G capacitor slightly soften the secondary bump of the pulse, but not enough to be used to reduce the pulse length. Finally, adding the C_F capacitor has a very strong effect on the pulse shape. Increasing the capacitance value lessen the amplitude of the signal but increases in the mean time the duration of the pulse, which is opposite to what is needed for the LVR3 pulse.

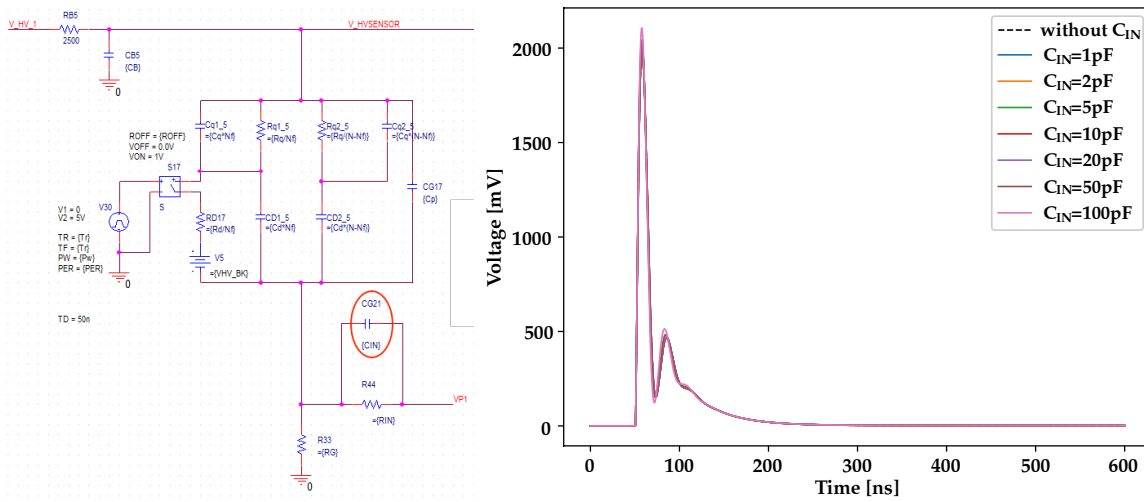


Figure 106. Evolution of the pulse shape as a function of the capacitance parallel to R_{IN}

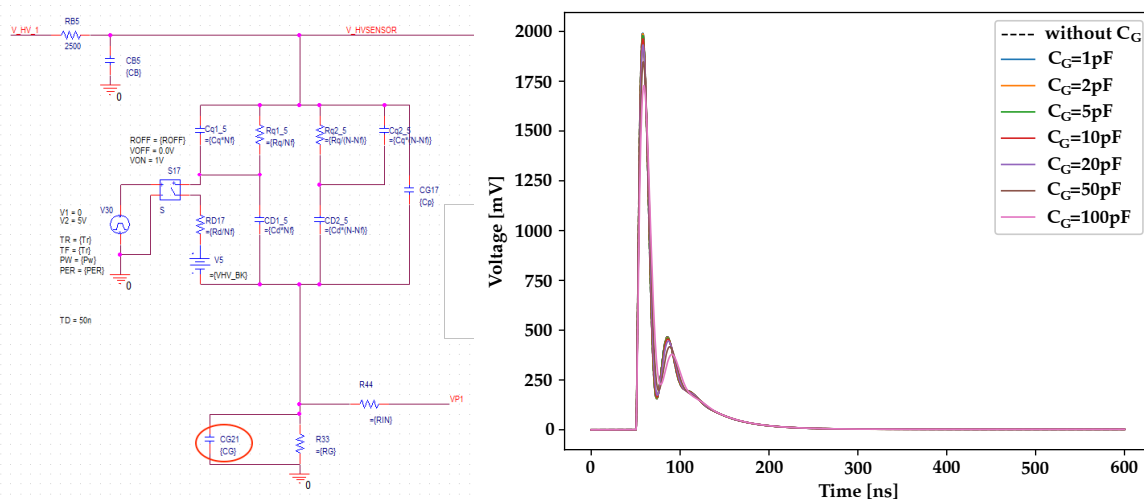


Figure 107. Evolution of the pulse shape as a function of the capacitance parallel to R_G

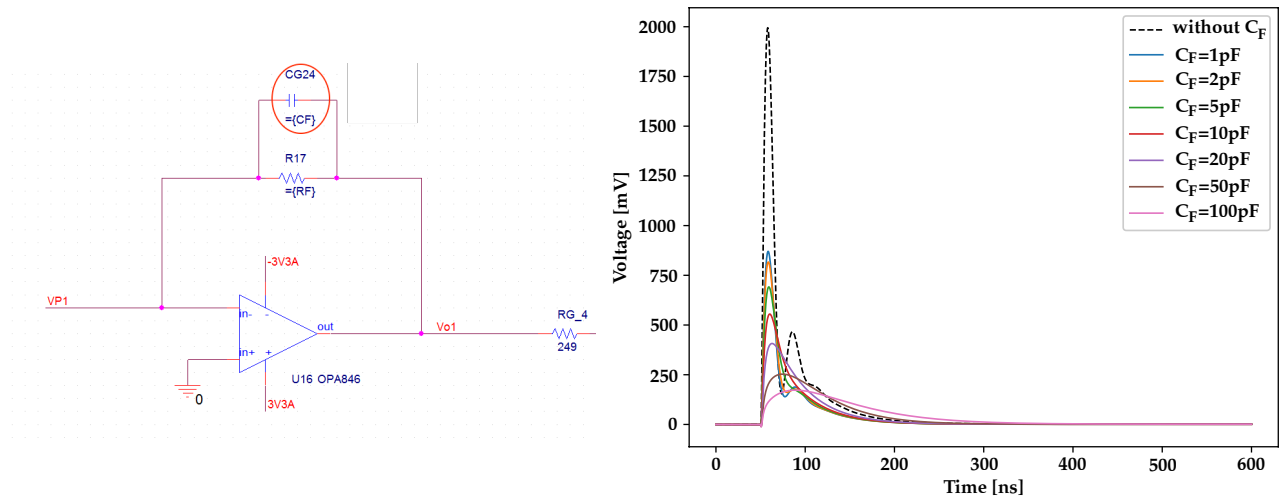


Figure 108. Evolution of the pulse shape as a function of the capacitance parallel to R_F