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SiPMs in the First G-APD Cherenkov Telescope, its M@TE and other relatives

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During the past years, the performance of SiPMs has made significant progress. In more and more experiments SiPMs replace photo multipliers as classical photo detectors. While the First G-APD Cherenkov telescope (FACT) with its 1440 SiPMs is about to enter its fifth year of operation in the field on the Canary island of La Palma, many new projects emerge. One of these projects is the M@TE telescope for Monitoring at TeV Energies. Situated in Mexico and together with the FACT telescope, it will extend the time duration available for continuous monitoring each night by a factor of two. This promises a deeper understanding of the flare behavior of the brightest TeV blazars, a key to blazar modeling.

Also utilizing SiPMs, the FAMOUS telescope with its 50 cm Fresnel lens aims for the application of SiPMs in fluorescence telescopes and the extension of the field-of-view of the fluorescence detectors of the Pierre Auger observatory. The related and mostly identical IceAct Cherenkov telescope is a design study for the applicability of Cherenkov telescopes within the harsh environment at South Pole and a possible solution for a Veto detector on top of IceCube.

With AMD, a muon detector with SiPM for scintillator readout exists. Based on this experience, design studies are on-going whether SiPMs are a reasonable alternative for photo detection in the scintillating surface detectors of AugerPrime, the upgrade of the Pierre Auger observatory. Its goal is the precise measurement of the composition of ultra-high energy cosmic-ray air-showers and their primaries.

All these projects will be presented with a focus on the results from the FACT project and the design of the M@TE telescope.

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1. Introduction

It is now, in September 2015, that the First G-APD Cherenkov Telescope (FACT) is going to enter its fifth year of operation. The telescope is located at the Observatorio del Roque de los Muchachos at the Canary island of La Palma, see Fig. 1 (left). With its 1440 sensors, it is the first Cherenkov telescope utilizing semi-conductor based photo sensors (SiPM) for photo detection and the first experiment applying them outside of a well controlled laboratory environment.

Due to the application of SiPMs, an unprecedented stability of data taking has been achieved which allows for automatic and remote operation and subsequent automatic data processing. This makes it an ideal instrument for the long-term observation of the brightest TeV blazars with their violent flaring behavior. To find a model which can describe their flaring behavior and their spectral energy distribution with consistent parameters is still a challenge and considered the key to the understanding of their emission processes.

The excellent qualities of SiPMs and their successful application in more and more experiments has paved the way to a wide use of SiPMs. An example is the Cherenkov Telescope Array (CTA). For its small-size telescopes right now only SiPM based camera solutions remain, but in the meantime SiPMs are also considered a reasonable option for their large size telescopes.

While the existing and future Cherenkov telescopes are focused on high sensitivity observations from a single location, their observation time is too precious for continuous and long-term monitoring of bright blazars. For this purpose, new telescopes will be build around the globe to extend the monitoring program of FACT beyond the time-scales usually accessible from a single observatory location. As a first step, a second HEGRA mount should be refurbished with a new camera similar to the FACT camera and installed in Mexico about 6 h behind of the FACT site. This telescope will be dedicated for **M**onitoring **at T**eV **E**nergies and is therefore coined M@TE.

In parallel to these projects, a concept study for a fluorescence telescope using SiPMs (FAMOUS) is on-going and a field study exists to prove whether such a telescope can survive the harsh environment at South Pole (IceAct).

Since the application of SiPMs in the past was often limited by their high dark count rates, telescopes were ideally suited due to the higher photon rates from the diffuse night-sky background. With the latest generation of SiPMs featuring an order of magnitude less dark counts, SiPMs also become an interesting alternative for dark room experiments. An example is the detector AMD, a design study for a scintillating muon detector for AugerPrime. One goal of the new detector AugerPrime, is the installation of muon detectors to disentangle the muonic from the electromagnetic component in extensive air-showers in the Pierre Auger observatory. Studies are on-going whether SiPM can replace photo multiplier tubes in the current design of the scintillating muon detector.

The First G-APD Cherenkov telescope, the M@TE project, the combined FAMOUS/IceAct development and the muon detector AMD will be described in more details in the following.

Figure 1: Left: The First G-APD Cherenkov Telescope in La Palma (Courtesy: José Luis Lemus). Right: An identical HEGRA mount readily installed at the site of the High-altitude water Cherenkov observatory (HAWC) in Mexico.

2. The First G-APD Cherenkov telescope

Overview The First G-APD Cherenkov telescope (FACT) is an Imaging air-Cherenkov telescope dedicated for monitoring of the brightest TeV blazars.

Blazars are assumed to be active galactic nuclei viewed along their jet axis. So far, neither their emission spectrum, nor their extreme variability are well understood. Usually models can describe both well but fail to properly explain them consistently. Nowadays, numerous simultaneous multi-wavelength observations exist ranging from radio to several TeV, but continuous monitoring at TeV energies is still not possible. Therefore, a network of small monitoring telescopes has been suggested of which FACT is supposed to be the first one [1].

Imaging air-Cherenkov telescope record electromagnetic showers induced by incident TeV gammas in the Earth atmosphere detecting the emitted Cherenkov light. To image these faint light flashes, large light collection areas and cameras sensitive on the single photon level are required.

The FACT camera is the first camera utilizing semi-conductor photo sensors. It has been installed in October 2011 on a mount of the High Energy Gamma-Ray Array (HEGRA) which is still located at its original location at the Observatorio del Roque de los Muchachos at the Canary island of La Palma. For a stable operation, the drive system was modernized to increase the reflective surface. The original disc shaped mirrors have been replaced by refurbished hexagonal mirrors yielding a total reflective area of $9.5\,\mathrm{m}^2$.

The installed camera comprises 1440 Hamamatsu MPPC S10362-33-050C as photo sensors. On top of the sensors, solid light guides are applied to increase their light collection area. With a light compression factor of $\sim$10, a field-of-view of each pixel of $0.11°$ is achieved with a sensor area of only $3{\times}3\,\mathrm{mm}^2$ providing a total field-of-view of $\sim$4.5°. For stability reasons, the light-guides are glued to the sensors and the protective front window. For data acquisition the Digital Ring Sampling chip DRS 4 has been chosen. The trigger consists of 160 discriminators each fed with the sum of nine channels in a compact layout. Each trigger channel is divided into two bias channels. Those 320 bias channels provide the bias voltage of ~ 70 V with a precision and resolution of 22 mV. For each bias channel, a current measurement with a resolution of 1.2 µA exists.

A detailed technical description is available in [2].

Achievements Despite all doubts about the applicability of SiPMs in the field, a very stable operation has been achieved. While one of the properties of SiPMs is the temperature dependence of the required operation voltage, a simple temperature controlled feedback loop is enough to re-adjust the applied voltage continuously. The challenge here is the needed high precision of the voltage adjustment in the order of 10 mV to 15 mV at an operation voltage of $\sim$72 V required to achieve a 1% gain stability. The routinely recording of dark count spectra allowed to prove a temperature independent gain of individual sensors within the resolution of the applied bias voltage. A detailed analysis of the system performance can be found in [3].

Calculating the total charge accumulated during all observations from the measured current allows to estimate the life-time of the sensors under dark conditions. If not exposed to any light, the released charge will scale with the dark count rate. Dividing the total charge by the charge released from dark counts yields an expected life-time of the sensors of more than 17 years continuous operation per sensor [5].

The robustness and durability of the sensors allowed for a stable data taking for four years now. It was only interrupted by other technical problems like leaks in the cooling pump, a broken commercial power supply and other defects not related to the sensors. The high stability of the gain made the system predictable enough for an automatic threshold setting even under variable light conditions like moon rise or set. Eventually this made full automatic data taking possible.

Having all parts of the data acquisition system accessible by Ethernet as well as all power plugs also allows for remote operation. During standard operation, remote operation is possible by exclusive use of a web browser through http://www.fact-project.org/smartfact/ where everybody can follow data taking. Consequently, shift personal is mainly required for cases of unexpected events. Automation also allowed for a high efficient data taking providing a typical duty cycle of more than 90% mainly limited by calibration measurements and the time required to re-positioning the telescope.

Data taking is currently split in five minute runs for easy handling. A dedicated data compression algorithm ensures efficient data storage [6]. Immediately after a run is finished, data analysis is automatically carried out on site. The obtained excess rates are then published as soon as possible on http://www.fact-project.org/monitoring/. In case the calculated access rates exceed certain threshold criteria, alerts are sent to other observatories [7].

Excellent agreement of the measured excess rates with the flux synchronously measured by the MAGIC telescope on the same site observing the same object has been demonstrated [8]. In addition, the first spectrum has been been published recently [9]. This became possible after the properties of the sensors were reasonably well understood, implemented and verified in the Monte Carlo simulations.

Given the price decline of SiPMs from more than 20 €/mm^2 to less than 0.5 €/mm^2 for selected sensors between 2010 and 2015, they became ideally suited for low cost projects such as the

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Cherenkov Telescope Array (CTA) or the application in further small size monitoring telescopes.

3. Monitoring at TeV Energies – The M@TE telescope

Objectives Since the discovery of TeV emission from the blazars Mrk 421 and Mrk 501 with the Whipple telescope [10, 11], both objects are a prime target of TeV astronomy. Both object are highly variable and belong to the brightest known objects among the known TeV sky. Due to their brightness, both objects belong today to the best studied object at TeV energies.

Although existing models seem to fit individual flux states well, their variability on short to long time scales is not understood. Especially the observed variability on short time scales seems to be in contradiction with the size of the emission region suggested by the models and even more with the significantly larger size of blazar jets.

This makes the understanding of the violent temporal behavior of the observed blazar emission on long and short time scales a requirement to confine existing model and therefore the ultimate key to their nature.

Although long-term measurements exist on time-scales of months and several minutes, medium time-scales are not covered.

The longest light curve ever measured at TeV energies was published for Mrk 421 with monthly binning and spans over more than 14 years [12]. The longest uninterrupted observations at TeV energies was recorded by the Whipple 10 m telescope in collaboration with the HEGRA Telescope Array, see [13]. It consists of data from seven consecutive nights with about ten hours each. Further attempts for uninterrupted data taking on the basis of target-of-opportunity programs have been made in the past by MAGIC and VERITAS, but weather conditions never allowed successful data taking on both sites. General time consuming campaigns with these instruments are limited by the large number of possible physics targets which renders their high sensitivity too precious for long-term monitoring.

The recently inaugurated High altitude water Cherenkov observatory (HAWC) fills the gap for long-term monitoring on a regular basis, but can only provide a sensitivity on weekly scales and is also limited to a single location. Also the upcoming Cherenkov Telescope Array (CTA) is limited to a single location on either hemisphere for continuous monitoring. Of course, individual small-size CTA telescopes could be distributed to other locations, but being optimized for array operation their comparably high threshold is not well suited either.

Therefore, dedicated instruments are required to fill the gap on long-term monitoring at mid time-scales are required.

Since the HEGRA array consisted of five identical telescope mounts of which one was equipped with the FACT camera, four mounts still exists. Two of the remaining mounts are currently situated in Mexico. Since the longitudinal distance of Mexico to La Palma is about 6 h – 7 h and it latitude comparable to La Palma, a Mexican site is ideally suited to extend the monitoring capabilities of the FACT telescope within a single night.

With the Sierra de San Pedro Mártir in Baja California, Mexico has one of the sites successfully evaluated as possible host for the Cherenkov Telescope Array. This makes the site a good host for a telescope dedicated for long-term Monitoring at TeV Energies (M@TE).

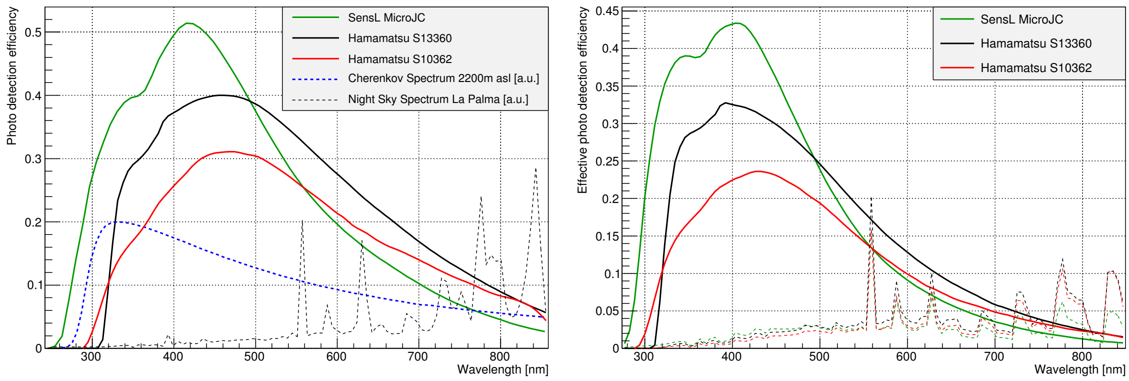

Figure 2: Left: The photo detection efficiency of the Hamamatsu SiPM used in FACT (red), the recent device from Hamamatsu (black) and the latest development from SensL (green). For comparison, the Cherenkov spectrum at 2,200 m a.s.l. (blue) and the spectrum of the diffuse night sky background at La Palma (dashed, black) is shown. Right: This Cherenkov spectrum weighted with the wavelength dependent photo detection efficiency of the three devices (solid) and the weighted night sky background (dashed).

Technology One of the remaining HEGRA mounts, is already installed at the site of the High altitude water Cherenkov observatory (HAWC), see Fig. 1 (right). The second mount will be installed at Sierra de San Pedro Mártir. As for the FACT telescope, the drive system will be modernized and mirrors will be replaced with new hexagonal mirrors. The telescope at the HAWC site will be used for commissioning of the camera featuring an easier access. After successful commissioning, the camera will be move to Sierra de San Pedro Mártir providing better weather conditions and a lower altitude. Replacing the three main components of the camera, the sensors, the data acquisition boards and the bias power supply with recent developments, will improve the performance as compared to the FACT camera but also lower costs significantly.

As data acquisition electronics, electronics based on the Target-chip is foreseen, originally developed for the CTA consortium [14]. The Target based electronics features a performance comparable to the DRS 4 based system applied in the FACT camera for about half the price.

The M@TE project is also favored by the significant improvement SiPMs underwent during the past years. Nowadays, sensors are generally available for less than 1 €/mm^2 if purchased in large quantities. Internal crosstalk has been reduced to typically less than 10%, and with an afterpulse probability below 1% and their occurrence within the first nano-seconds after the primary pulse, they can generally be neglected. Dark count rates are reduced to less than 100 kHz/mm^2.

All those properties have never been a real issue for Imaging air-Cherenkov telescopes. Here, the main improvements comes indirectly from the decrease of internal crosstalk which allows operation at significantly higher over-voltage, which is the voltage above the breakdown voltage at which the SiPM is biased. This does not only increase the photo detection efficiently to 40% – 50% at the peak but also decreases the dependency from the applied voltage by roughly a factor of four. This relaxes the precision of the applied voltage required to achieve a $\sim$1% gain stability from about 15 mV to about 50 mV. At the same time, it lowers the temperature sensitivity, usually 20 mV/K – 60 mV/K, accordingly.

The photo detection efficiency of recent sensors being a reasonable choice for a Cherenkov telescope is summarized in 2. In addition, their effective performance for the expected Cherenkov spectrum, the diffuse night-sky background light and the spectrum of moon light is compared. With sensors from the SensL MicroJC series [15], the effective light collection efficiency will increase by $\sim$55% as compared to the Hamamatsu S10362 used in the FACT camera. The currently available Hamamatsu S13360 devices [16] would show a gain of $\sim$33%. Due to their lower spectral response at higher wavelengths, the MicroJC device would suppress the dark night spectrum by $\sim$13% and amplify the detected number of photons from moon light by only $\sim$9%. Depending on light conditions, this yields an increase of 1.48 – 1.65 for the SensL MicroJC and 1.18 – 1.21 for the Hamamatsu S13360 in $S/\sqrt{N}$ compared to the FACT sensors for the detection of the Cherenkov spectrum. The main disadvantage of the SensL MicroJC series is their two times longer recovery time as compared to the Hamamatsu devices.

Since in a Cherenkov telescope, the background light is not uniform nor stable over time, the drawn currents are not constant. Therefore, the supplied voltage has to be compensated for a possible voltage drop in the circuit. For the FACT telescope, this has been achieved by adjusting the voltage based on the measurement of the current and the analytical calculation of the corresponding voltage drop. A much easier solution is to correct the voltage drop in the analog circuit already and ensure a constant voltage output. Such a circuit has already been implemented and successfully tested [17]. Its application will simplify operation significantly.

Software While the anticipated changes in the hardware require a re-design of parts of the control and calibration software, the high level software can be taken over from the FACT collaboration. Due to the modular design of their control software, only the readout of the data acquisition and the bias control will require adaption to the expected hardware changes. High level control software, as web-interfaces for scheduling and remote control will only need minor or no adaption.

4. The FAMOUS/IceAct telescope

In parallel, similar projects are on-going based on the same technological ideas and recent developments, for example a combined fluorescence (FAMOUS, [18]) and Cherenkov telescope (IceAct, [19]). It features a 50 cm diameter Fresnel lens for light collection, a 64-pixel camera and allow for a total field-of-view of 15°. For both applications, recent sensors and a Target-chip based readout electronics is foreseen. Since fluorescence light is limited to a small waveband between 280 nm and 450 nm, an additional filter is used in the fluorescence version. The FAMOUS telescope aims on the prof-of-concept for the application of SiPMs in fluorescence telescope and the extension of the field-of-view of the Fluorescence Detectors (FD) of the Pierre Auger Observatory. A 64-pixel prototype will be finished within the coming months. Simple calibration and field tests are scheduled before the telescope is eventually sent to the Pierre Auger site where it is planned to be operated in coincidence with the existing telescope for demonstration purpose. A 7-pixel prototype was finished about a year ago and has already recorded first Cherenkov showers. It is now used as the IceAct prototype, a field study for the application of Cherenkov telescopes at South Pole. It is currently on its way to South Pole and is expected to provide first data until the end of 2015. Investigations are currently on-going whether a compact size Cherenkov telescope is possible solution for a Veto array above the IceCube detector.

5. SiPMs for AugerPrime

For the upcoming upgrade of the Pierre Auger detector, called AugerPrime, SiPM are considered a possible options as well.

The upgrade plan foresees a scintillating detector on top of each water Cherenkov detector (WCD), to use the different information provided by both detector to disentangle the muonic component in extensive air showers from their electromagnetic component. Each detector will contain 40 scintillator bars read out by wavelength shifting fibers with a diameter of 1 mm^2. Both ends of each fiber, 96 in total, are connected to the read out by a single photo sensor. So far, a single 1" photo multiplier tube has been considered.

While the temperature dependence of SiPMs is well understood and can easily be corrected by adapting the bias voltage accordingly, the dynamic range of a SiPM is intrinsically limited by the number of contained Geiger-mode avalanche photo diodes. However, since the hit pattern of diffuse light is statistically distributed, their dynamic range exceeds the number of cells by a factor of three to five. It could be shown that with up to four sensors, the dynamic range of a photo multiplier can be achieved or even exceeded. Using more than a single sensor also solves the problem of the smaller light sensitive area of SiPMs requiring a light compression factor of two or less. Given the low internal crosstalk probability of recent sensors, even with four sensors, the dark count rate of those is still low enough to be well below the signal amplitude which is amplified by their higher photo detection efficiency.

Although with a different data acquisition concept, such a muon detector with a SiPM readout has already been developed proving the general applicability of SiPMs and serving as test bench. This detector (AMD) comprises 64 quadratic scintillator tiles of 900 cm^2, each connected to a 1 mm^2 SiPM through a wavelength shifting fiber. For data acquisition of all 64 channels, two EASYROC chips are used. Further details and first measurements are found in [20].

6. Conclusion

Many on-going developments, and the successful application of SiPMs in various projects during the past years, have made SiPMs a standard technology for photo detection not only in the laboratory but also under harsh environmental conditions. An example for this achievement is the successful operation of the First G-APD Cherenkov telescope for four years now. The IceAct project will soon prove the applicability even under one of the most extreme environmental conditions existing on Earth, at South Pole. Promising studies are on-going whether recent sensors are suitable to replace photo multiplier tubes under dark room conditions.

With the M@TE telescope, a second generation of a low cost instrument for monitoring purpose will soon be existing and extend the continuous monitoring of the brightest TeV blazars to twice the time currently accessing from a single site per night.

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