Development of a 16-channel matrix of photodetection sensors for medical imaging and astrophysical applications.

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Abstract — **Recently developed near UV-photosensors are currently adopted in those applications where high sensitivity and good imaging capabilities are required, especially in fields such as astroparticle physics and medical imaging. An example of such applications is the camera of the Schwarzschild Couder Medium Size Telescope prototype (pSCT) which is in construction within the Cherenkov Telescope Array experiment. The camera consists of 177 photo-detection modules grouped into sectors of 25 modules, each based on matrixes of 64 6mm × 6mm pixels of Silicon Photomultipliers (SiPMs). Sensors produced by the Fondazione Bruno Kessler (FBK) in Italy are currently under investigation. Here we present a complete characterization of these highly sensitive near UV sensors, the assembly procedure and metrology results on several focal plane elements.**

Keywords — Silicon PhotoMultipliers; Photon Imaging; Cherenkov Telescope Array; Front-end electronics

I. Introduction

Silicon PhotoMultipliers (SiPMs) are nowadays used in many high technological fields especially in those where excellent photodetection properties are required, such as astroparticle and medical imaging applications.

SiPMs are very promising solid-state photon detectors composed of thousands of Geiger Mode Avalanche Photo Diode (GM-APD) micro-cells, working above their breakdown voltage V_{BD}. Each microcell is typically a few tens of µm wide, while the SiPM overall size ranges from $1mm^2$ up to $1cm^2$. One of the SiPM main features is its capability of photon counting in very low-intensity light conditions, down to the single photon detection. This is possible thanks to high gains and high Photo-Detection-Efficiency (PDE), with excellent time resolution. When light hits onto the detector, photons are absorbed in the pixels and generate electric current. The SiPM output signal is the analogue sum of the single cell currents, and it is therefore proportional to the number of photons detected, giving information on the light intensity.

The typical gain of each cell is of the order of 10^6. It is proportional to the over-voltage (OV), defined as the bias voltage above V_{BD} [1]. Moreover, V_{BD} typically varies with temperature by few tens of mV/°C. The high value of the gain makes SiPMs suitable for the detection of single photons hitting its active surface.

II. The IACT Technique

Very high–energy (VHE, E >1 TeV) gamma–ray astrophysics is currently dominated by Cherenkov telescopes. These telescopes detect the Cherenkov light cone produced by energetic particles in the shower produced by the interaction of cosmic rays from the outer space with the atmosphere. A large segmented mirror (>100 m^2) reflects photons into a camera of thousands of fast photo–sensors, photomultiplier tubes or SiPMs, sensitive to blue and near ultraviolet light, placed in its focal plane. These photo-sensors convert photons into electrical signals, which are subsequently read out and digitized by fast electronics. Data acquired by the camera can then be analyzed to reconstruct an image of the shower. This technique is adopted by Imaging Air Cherenkov Telescopes (IACTs) and it currently achieves the highest sensitivity in this field. In the last years, thanks to Cherenkov telescopes, a great number of very high–energy gamma–ray sources has been discovered and classified. The maximum emission of Cherenkov light occurs when the number of particles in the electromagnetic shower is largest, thus about 5–10 km above sea level, depending on the energy of the incoming particle, and it decreases considerably at lower altitude. Thus, it is convenient to build Cherenkov telescopes in sites those altitude is chosen as a trade-off between absorption of Cherenkov light in atmosphere and Cherenkov cone development. Moreover, since Cherenkov signals are very faint, data have to be taken in moonless or with moderate moon-light nights, without clouds, far away from sources of noise, with limited fluctuations in pressure, temperature and transmissivity. Ideals detectors sites are therefore at high plateau altitudes. Despite all these precautions, Cherenkov telescopes have a low duty cycle: their total observation time is limited to about 1000–1500 h/year [2].

III. The CTA Consortium

The CTA Consortium is developing two new observatories for VHE gamma–rays, one placed at the La Palma island for the

Northern hemisphere, and the other one in Chile for the Southern hemisphere. CTA will enlarge the detection area, achieve better angular resolution and improve the sensitivity with respect to the current generation of IACTs. With its innovative design, the detection rates will definitely increase, in particular for the VHE transient phenomena, and move the observational horizon even further away. Each CTA site will be composed by an array of tens of telescopes of different sizes. In order to provide a broad energy coverage from ~20 GeV to 300 TeV, the best solution is to build three classes of telescopes with different mirror size [3] (See Figure 1):

- Large–Size Telescopes (LSTs) will cover the low–energy range (~20 GeV – 1 TeV), will have a mirror size of 23 m and will be installed in the central region of the array.
- Medium–Size Telescopes (MSTs), will cover the medium–energy range (~100 GeV –10 TeV), will have a mirror size of 12 m and will be installed on an area of ~km^2.
- Small–Size Telescopes (SSTs), will cover the high–energy range (few TeV– ~100 TeV), will have a mirror size of 4 m and will be installed on an area of ~3–4 km^2.

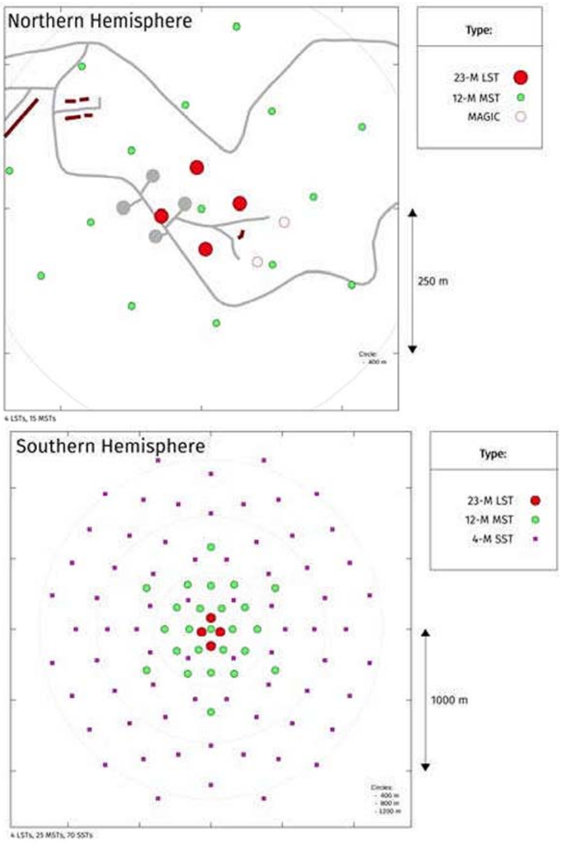

Figure 1. Possible layouts for the Northern (top) and Southern (bottom) sites of CTA.

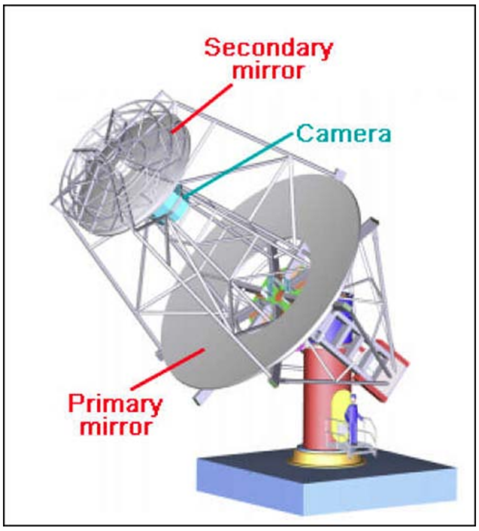

Figure 2. Schematic view of SCT.

IV. THE SCHWARZSCHILD–COUDER MEDIUM SIZE TELESCOPE

A dual mirror version of the MST has been proposed as a higher–performance telescope with respect to the one mirror design. The Schwarzschild-Couder Telescopes (SCTs) have not been used in Cherenkov astronomy so far, but this dual mirror implementation allows improved compensation of optical aberrations. Moreover, it also guarantees the de-magnification of the images, achieving better angular resolution as a result of a very large number of camera pixels over a wider FoV. The two mirrors, one 9.7 m and the other one 5.4 m in diameter, are both segmented and have active alignment. SCT's mechanical design is illustrated in Figure 2. The SCT camera, positioned in the focal plane of the secondary mirror, is composed of SiPMs placed in modules, with front-end electronics that provides trigger and data acquisition hardware. Compared with a single-mirror MST camera, which has a diameter of about 2.5 m, the SCT camera occupies only 0.8 m in diameter, keeping the same field of view.

The SCT Camera consists of 177 modules assembled as shown in Figure 3. Each module houses 64 SiPMs with an active area of 6 mm × 6 mm. The camera is divided into 9 sectors; each sector powers and reads out 25 modules. A first camera prototype (pSCT) is currently under construction in Arizona. It will be equipped with 16 modules using Hamamatsu SiPM sensors procured and assembled in the USA, and 9 modules using FBK SiPMs, produced and assembled in Italy by the Istituto Nazionale di Fisica Nucleare (INFN).

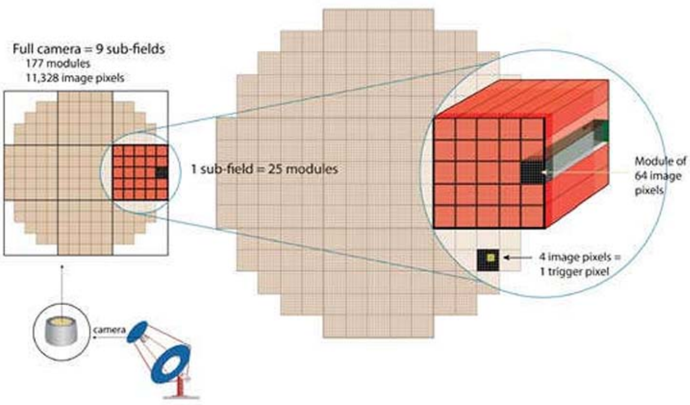

Figure 3. Sketch of the SCT Camera.

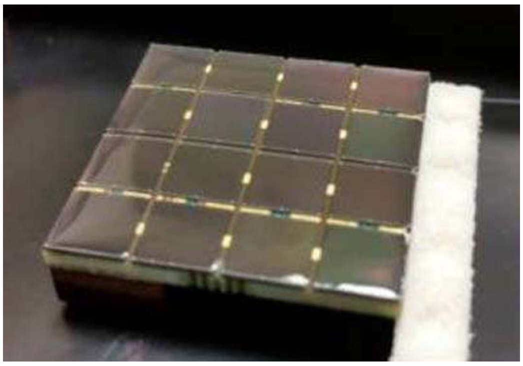

Figure 4. FBK SiPM matrix for pSCT.

A. Sensors

Figure 4 shows one of the matrices designed and assembled by the INFN team in Italy. It consists of an array of 4×4 sensors. Each SiPM has a pixel size of 30 micrometers and is designed with the NUV high–density (HD) technology.

We developed a complete test procedure in order to examine each matrix prior its installation into the module and then the camera. The first step consists of metrology measurements, using a ruby-head touch probe and an optical metrology machine. The sensor quality alignment resulted to be better than 30–40 µm. Next, we checked the values of V_{BD} of all sensors belonging to the matrix, in order to assure their uniformity. Figure 5 shows the measurement of the reverse IV curves for the 16 SiPMs of a matrix.

Finally, we illuminated a matrix with a laser operating at 380 nm with a very low intensity level. Figure 6 shows the corresponding charge distribution, which exhibits the excellent single photoelectron capability resolution of these FBK sensors, read out by an optimized electronics [4].

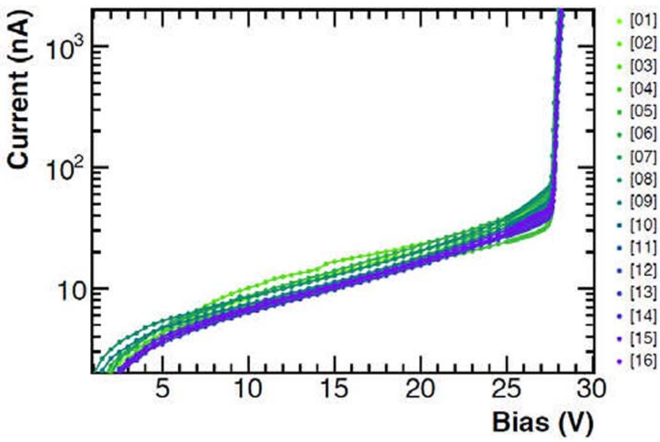

Figure 5. IV curves for 16 FBK sensors of a matrix.

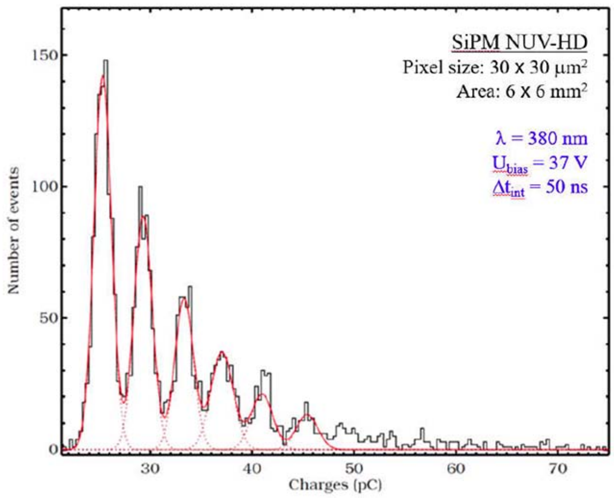

Figure 6. Charge distribution for one of the 16 sensors of the matrix, flashed with a laser at 380 nm.

From the charge distribution analysis, we then derived the gains and signal–to–noise ratios (SNRs) of all sensors. We demonstrated that, among the 16 devices, the uniformity of the gains (Figure 7) and the SNRs (Figure 8) is well within few percent, thus highlighting the excellent quality of the whole fabrication process, from die sensors to the bonding machinery and the final glue deposition.

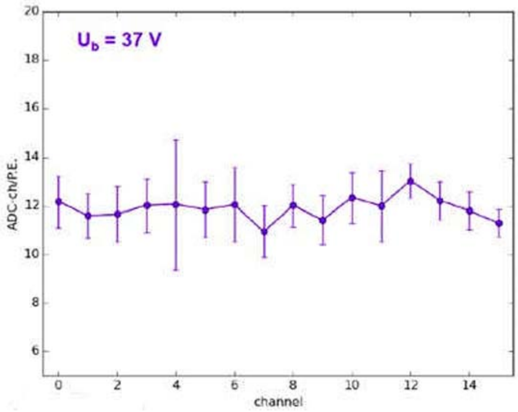

Figure 7. Gain values for the 16 sensors.

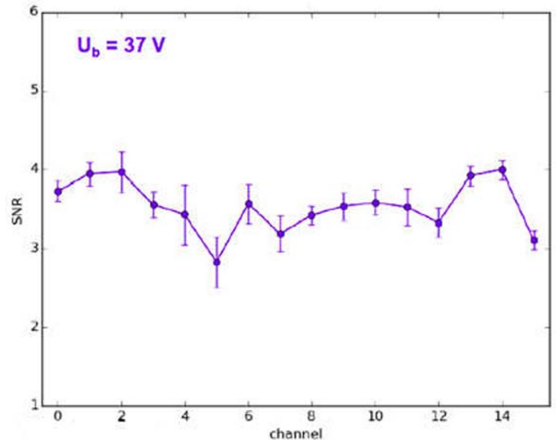

Figure 8. SNR values for the 16 sensors.

B. The Front End

The SCT camera of the Cherenkov Telescope Array will consist of thousands of photosensor pixels. In order to efficiently acquire and store electric signals from so many channels, the front-end electronics should be integrated with high reliability and low cost per channel, given their high density in the camera. To this aim, the TeV Array Readout with GSa/s sampling and Event Trigger (TARGET) chip will be used, whose compact design has been optimized to match the high density pixel camera of CTA telescopes [5, 6]. This Application Specific Integrated Circuit (ASIC) has 16 parallel input channels which record full waveforms with a sampling rate of 1 GSample per second. Coincidence between distant telescopes requires deep sampling buffer (> 16 µs); for this reason each channel has an analogue ring buffer of 2^{14} =16384 capacitors (16384 ns at 1 GSa/s). The TARGET chip can operate with external trigger and it is also able to form its own: analogue sampling occurs continuously, while digitization only occurs when triggered. The digital waveform is stored in a local Field Programmable Gate Array (FPGA) until it is transferred to the processing system in case trigger occurs. The TARGET ASIC is based on an analogue sampling memories technology which consist in a circular buffer of switched capacitors used in turn to record the signal waveform at a given sampling rate. This technology is known as Switched Capacitor Array (SCA) and offers good performance in the storage of fast analogue waveforms in a limited period of time for thousand of channels. With modern integrated circuits, SCA chips can be very compact, with low cost and low power consumption, along with minimal signal distortion. Figure 9 shows the full board which houses the preamplifier stage and four TARGET7 [6] chips digitizing four matrices of 16 SiPMs (thus reading out 64 channels).

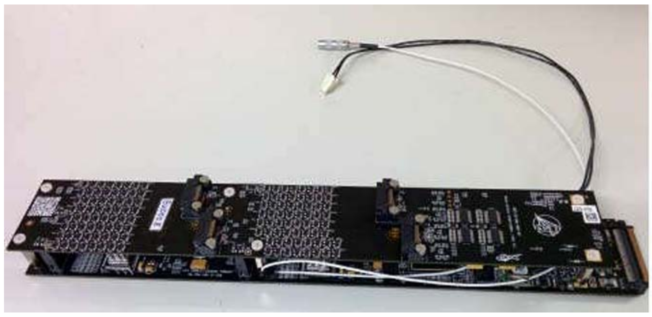

Figure 9. Front End Board of the SCT Camera.

C. Module Performance

We tested the whole chain (with the sensors coupled to the electronics) by illuminating the SiPMs and reading out the TARGET signal. The laser signal occurs at 200 ns from the beginning of the acquired waveforms, as shown in Figure 10. Integrating the waveform signal over a time window of about 20 ns we finally derived the charge distribution (Figure 11). We demonstrate that the sensor resolution capabilities is only slightly worsened by the TARGET digitization process. The SNR is reduced down to a value of about 3 (~20% less).

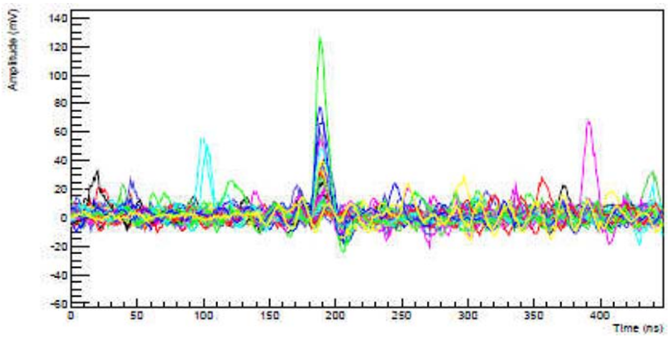

Figure 10. Waveforms digitized with the TARGET chip.

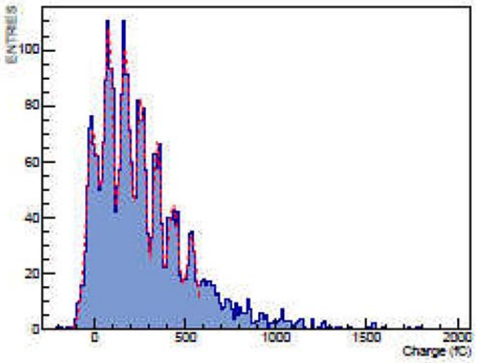

Figure 11. Charge distribution of SiPM signal flashed with a laser and digitized with the TARGET.

V. CONCLUSIONS

Within the SCT collaboration, a 4×4 sensors matrix has been designed, developed and tested. A quality control of the whole production process has been set up. Some tests with an integrated, low power and low cost front–end electronics have also been done showing a good SNR. The first modules will be installed on the SCT prototype in summer 2017 and the data taking will start by the end of 2017. Such a solution of photo detection modules could be used not only for astro-particle applications, as discussed, but also for all those applications where the imaging requests are severe.

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