SiPM optical modules for the Schwarzschild-Couder Medium Size Telescopes proposed for the CTA observatory

G. Ambrosi[1,2], M. Ambrosio[3], C. Aramo[3], B. Bertucci[1,2], E. Bissaldi[3], M. Bitossi[3], C. Boiano[3], C. Bonavolontà[3,7], M. Caprai[1], L. Consiglio[3], L. Di Venere[4], E. Fiandrini[1,2,a], N. Giglietto[4,5], F. Giordano[4,5], M. Ionica[1], F. Liciulli[4], S. Loporchio[4,5], V. Masone[3], R. Paoletti[6,8], A. Rugliancich[6,8], L. Tosti[1,2], V. Vagelli[1,2], M. Valentino[9], and for the CTA SCT Project

[1] *INFN Perugia, Italy*
[2] *Dipartimento di Fisica e Geologia, Università degli Studi di Perugia, Italy*
[3] *INFN Napoli, Italy*
[4] *INFN Bari, Italy*
[5] *Dipartimento Interateneo di Fisica dell'Università e del Politecnico di Bari, Italy*
[6] *INFN Pisa, Italy*
[7] *Dipartimento di Fisica, Universitá di Napoli, Italy*
[8] *Sezione di Fisica, Dipartimento SFTA dell'Università di Siena, Italy*
[9] *CNR-Spin, Napoli, Italy*

Abstract. Silicon Photomultipliers (SiPMs) are excellent devices to detect the faint and short Cherenkov light emitted in high energy atmospheric showers, and therefore suitable for use in imaging air Cherenkov Telescopes. The high density Near Ultraviolet Violet SiPMs (NUV-HD3) produced by Fondazione Bruno Kessler (FBK) in collaboration with INFN were used to equip optical modules for a possible upgrade of the Schwarzschild-Couder Telescope camera prototype, in the framework of the Cherenkov Telescope Array project. SiPMs are 6×6 mm^2 devices based on 40×40 μm^2 microcells optimized for photo-detection at the NUV wavelengths. More than 40 optical modules, each composed by a 4×4 array of SiPMs, were assembled. In this contribution we report on the development and on the assembly of the optical modules, their validation and integration in the camera.

1 The SCT telescope proposed for the CTA observatory

The Cherenkov Telescope Array (CTA) Consortium is an international collaboration to build the next generation of Imaging Air Cherenkov Telescopes (IACTs) for the detection of γ rays in the 20 GeV-300 TeV range [1]. Two arrays of IACTs of different dimensions and mirror optics technologies will be deployed, one in the Southern and one in the Northern hemisphere, to achieve the full sky coverage. Medium Size Telescopes (MST) based on a Davies-Cotton optics and photomultiplier tube (PMT) readout provide the core sensitivity of the observatory in the 100 GeV-10 TeV energy range. A possible upgrade of the MST telescope based on a dual-mirror optics, the Schwarzschild-Couder

[a] e-mail: emanuele.fiandrini@pg.infn.it

Telescope (SCT), is proposed as an alternative for medium telescopes [2]. The SCT optical system is designed to provide compensation of optical aberrations and focus the light on a compact high resolution imaging camera. This results in a smaller point spread function (PSF), improved angular resolution, a wider field of view (8°) and improved background rejection compared to single mirror solution with a similar cost per telescope. The SCT camera can be consequently equipped with

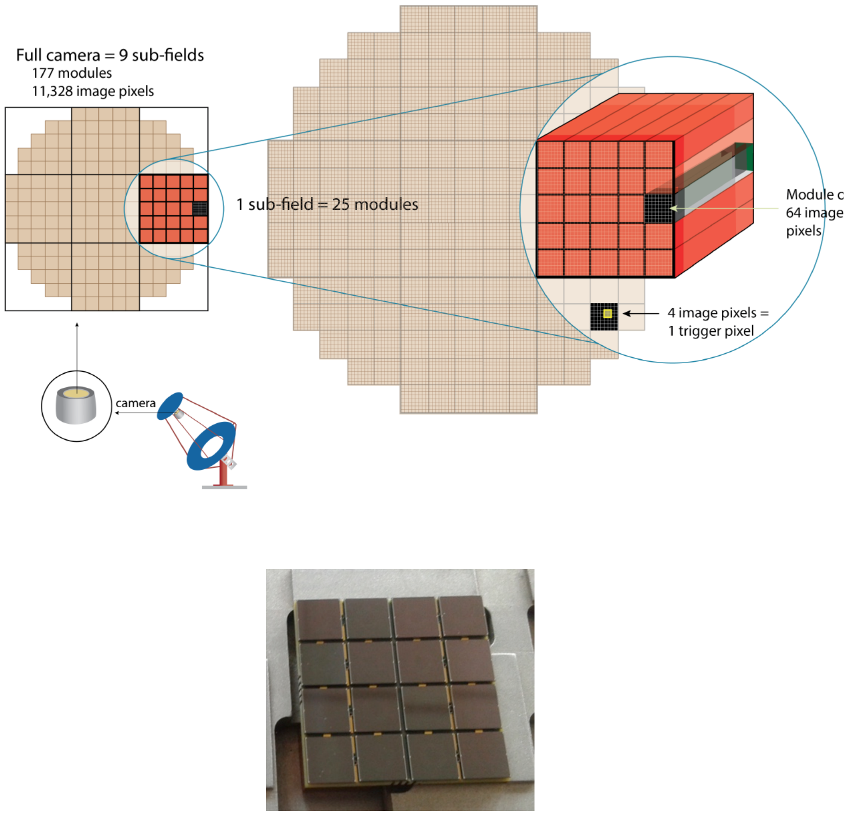

Figure 1. Top: scheme of the focal plane of the pSCT telescope. Bottom: Photo Detection Unit (PDU) made of 4×4 SiPMs.

imaging silicon photomultipliers (SiPM) pixels. The installation of a prototype for the SCT solution, the pSCT telescope [3], has been successfully completed at the Fred Lawrence Whipple Observatory (FLWO) in August 2018 and it is curreny being commissioned.

The pSCT camera [4] readout concept is based on SiPM detectors for photon detection and a TARGET-7 ASIC front-end electronics (see Sec. 3). The backplanes of the camera handle and manage the data acquisition for separate camera sectors. The fully equipped focal plane of the telescope, shown schematically in the top panel of Fig. 1, has a diameter of ~81 cm for a total active area of 0.4 m^2. It will host 177 modules in 9 sectors or sub-fields. Each module is made of 64 SiPMs arranged in 4 independent Photo Detection Units (PDU) equipped with 16 SiPMs, that constitute the single pixels of the pSCT camera. A PDU is shown in the bottom panel of Fig. 1. The pSCT camera will be equipped with a total of 11328 pixels. Each sensor corresponds to a 0.067° pixel in the sky, matching the PSF of the optical system. Hamamatsu S12642 SiPMs have been originally selected to equip the pSCT camera. A possible upgrade based on the third generation of Near Ultra Violet High Density (NUV-HD3) SiPMs produced by Fondazione Bruno Kessler (FBK) in collaboration with Istituto Nazionale di Fisica Nucleare (INFN) is being investigated [5]. The performances of the NUV-HD3 SiPM devices are described in [6]. The sensors have been optimized for the detection of UV Cherenkov photons. The active area of NUV-HD3 SiPMs is 6×6 mm^2, with a microcell area of 40×40 μm^2. They feature a breakdown voltage of ~27 V at room temperature with a temperature gradient of ~30 mV/ °C, a Photo Detection Efficiency (PDE) peak of 60% at 350 nm dropping below 20% above 500 nm and a single photon dark count rate below 100 kHz/mm^2 at 20 °C.

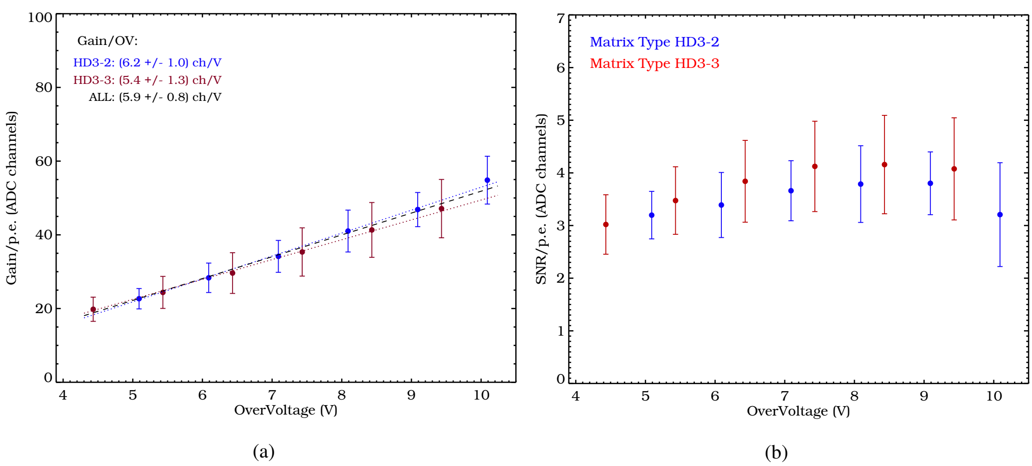

Figure 2. Average values for gain (a) and signal to noise ratio (SNR) (b) for more than 50 modules made of HD3-2 (blue) and HD3-3 (red) SiPMs.

2 Packaging and tests of the telescope optical units

The single SiPMs are designed and produced by FBK without any packaging on PCB. The assembly and packaging procedure of the optical modules was developed and made at the INFN laboratories. The basic mechanical unit is the PDU, made of 16 pixels. Four PDUs form a 64 pixels module that covers an area of 54×54 mm^2. INFN designed custom 27×27 mm^2 PCBs with 0.5 mm sensor-sensor distance and such that the same spacing is present between adjacent PDUs in a module. To precisely place the SiPMs on the PCBs and dispense the glue on the pads, a manual die-bonder machine was used. The alignment of the sensors has been checked with an optical metrology machine, resulting better than 40 μm. The maximum deviation from planarity across has been found to be ~80 μm, in good compliance with the optical requirements of the pSCT camera. Then, ultrasonic wire bonding from the top of the SiPMs to the PCB bonding pads to read out the current signal was made with a 20 μm Al/Si wire. The breakdown voltage of each sensor is measured analyzing the dark current as a function of the bias voltage to spot any defective sensor. Finally UV transparent resin was dispensed on top of the PDUs for mechanical protection.

After the assembly, each module was illuminated with a 380 nm pulsed laser. The charge signal of the 16 sensors has been read out signals from the 16 channels simultaneously using a DAQ system consisting of a charge to digital converter CAEN V792 QDC to obtain the charge of the signal. The integration time was set to 30 ns. The output signal of each SiPM was then amplified using a custom 16-channel front end board to match the dynamic range of the QDC [7]. The uniformity of the signal response for more than 50 modules have been investigated in the bias range from 31 V to 36 V. The average values for the gain and signal to noise ratio (SNR) shown in Figure 2 confirm the good level of uniformity for the modules performances.

3 Validation of the FEE readout chain

The pSCT digitization and readout electronics is based on the TARGET-7 ASIC [7], developed for the efficient signal readout of photosensors in high density cameras. The TARGET-7 ASIC handles first-level trigger -based on the signal of 4 adjacent sensors- and digitization for 16 channels. A switched capacitor ring buffer of 16384 units samples the analog signal at 1 GS/s with a maximum buffer depth of 16 μs. Extensive quality control tests have been performed on 9 TARGET modules to validate their functionalities. First, for each ASIC, the mean and the RMS of the electronics pedestals of the 16k capacitors have been evaluated in absence of light signal. Then, the SiPM modules coupled with the TARGET board have been illuminated with a NUV laser equipped with intensity filters. Figure 3(a) shows an example of a charge spectrum acquired with the TARGET board in conditions of low light intensity and 3(b) shows the average integrated amplitude as function of the light intensity for 16 channels of one PDU. The trend confirms the linearity of the digitizer. The operation of the TARGET-

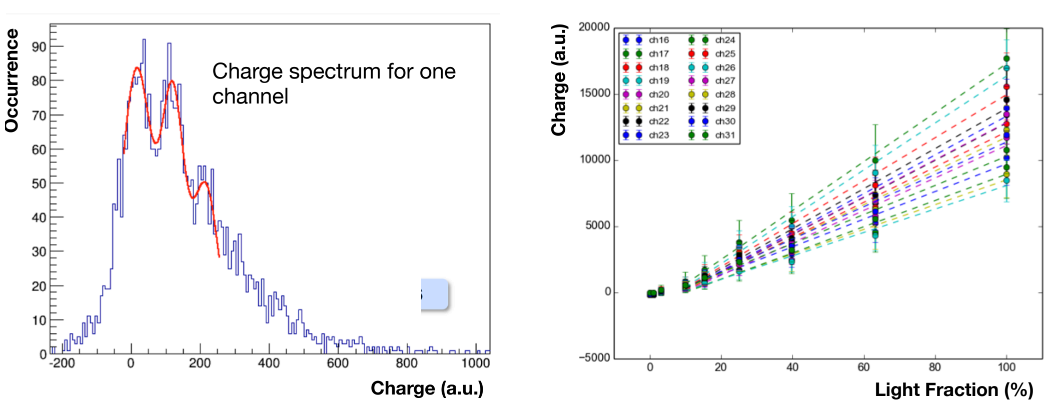

Figure 3. (a) Integrated signal over 16 ns of one channel with TARGET7. The red lines represent the gaussian fit used to find the peaks. (b) Average value of the charge distribution as function of the light intensity for 16 channels of one TARGET ASIC.

7 internal trigger has been verified by varying the intensity of light for a fixed trigger threshold and by varying the trigger threshold for a fixed light intensity. The trigger threshold is set by a DAC ranging from 0 to 3500 counts, where an increase of the DAC value corresponds to a lower physical threshold on the signal. The FEE quality control campaign has confirmed the performances of the

electronics modules before their integration on the pSCT camera, identifying defects for less than 1% of the channels (4 defective electronics channels out of 576).

4 State of the art and prospects

Six modules were installed on the pSCT telescope camera to populate a fraction of the central camera sector for validation and tests *in situ*. An additional batch of 9 modules (36 PDUs), for a total of 576 SiPMs, has been recently assembled using the latest production of NUV-HD3 SiPMs (HD3-4) and the modules are ready to be integrated in the camera to complete the central sector and measure the first lights. One additional sector of the pSCT telescope (25 modules, 1600 SiPMs) is planned to be integrated and operated in 2019. The experience gained from camera operations will be significant to confirm the possibility to operate a large, fast and compact SiPM camera for the medium size telescopes of the CTA observatory. An additional technological advance is represented by the development of new ASIC boards based on the TARGET paradigm. The new concept separates the sampling and digitization on a board (called TARGET C) and the trigger functions on the companion T5TEA ASIC to reduce the trigger noise induced by noise pickup from the analog sampling circuitry of the TARGET7 board [8]. An additional preamplifier ASIC, the SMART board intended to further decouple the analog pre-amplification from the digitization process, is currently being prototyped for the pSCT by INFN. The new FEE design is planned to be integrated with the pSCT backplanes together with the complete integration of the 177 sectors of the pSCT camera in the next future. The existing prototype will be successful proof of concept for the overall design of the SCT telescope, and the experience gained with the commissioning and operations will provide important feedbacks to open for the SCT telescope production for the CTA observatory.

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https://www.cta-observatory.org/consortium_acknowledgments/

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