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Assembly and validation of SiPM optical modules for the SCT Medium Size Telescope proposed for the CTA observatory

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Abstract

Silicon Photomultipliers are particularly suitable as optical units of Imaging Air Cherenkov Telescopes to detect the fast and low-intensity Cherenkov signal emitted by high energy atmospheric showers. The third generation of high density NUV SiPMs (NUV-HD3) produced by Fondazione Bruno Kessler (FBK) in collaboration with INFN have been used to equip optical modules intended to be integrated on a possible upgrade of the focal plane camera of the Schwarzschild-Couder Telescope prototype (pSCT) in the framework of the Cherenkov Telescope Array (CTA) project. NUV-HD3 SiPMs are $6 \times 6\,\mathrm{mm}^2$ devices based on $40 \times 40\,\mu\mathrm{m}^2$ microcells with excellent photo detection efficiency for the NUV wavelengths. Optical modules, each composed of a matrix of 4 x 4 SiPMs, have been assembled and tested in the laboratories of INFN to be integrated on the pSCT camera. In this contribution we report on the development and on the assembly of the optical modules, on their validation and on their integration on the pSCT camera.

Keywords: SiPM, Cherenkov Telescopes, Photo Detectors, Front End Electronics

1. The SCT telescope proposed for the CTA observatory

The Cherenkov Telescope Array (CTA) Consortium is developing the project to build the next generation of Imaging Air Cherenkov Telescopes (IACT) for the detection of cosmic γ-rays in the $20\,\mathrm{GeV} - 300\,\mathrm{TeV}$ range [1]. Two arrays of IACTs of different dimensions and mirror optics technologies will be deployed, one in the Southern hemisphere near Paranal (Chile) and one in the Northern hemisphere in La Palma (Spain, Canary Islands), to achieve the full coverage of the γ-ray sky. CTA is planned to be operated as an open observatory accessible to the whole scientific community, with a large amount of data taking time dedicated to observation strategies proposed by the astrophysical community besides the observation time allocated to Key Science Projects (KSPs) managed by the CTA Consortium to address a selection of scientific open problems in a

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coherent strategic approach [2].

Medium Size Telescopes (MST) based on a Davies-Cotton (DC) optics and photomultiplier (PMT) readout provide the core sensitivity of the observatory in the 100 GeV – 10 TeV energy range. A dual-mirrored version of the MST, the Schwarzschild-Couder Telescope (SCT, Figure 1), is proposed as an alternative type of medium telescope [3]. The SCT optical system is designed to provide compensation of optical aberrations and focus the light on a compact high resolution imaging camera that can be equipped with a factor of ten more imaging pixels than the more extensive DC telescope cameras, using Silicon Photomultiplier (SiPM) pixels instead of the classical PMTs. This results in a smaller point spread function (PSF), improved angular resolution and improved background rejection with respect to the single mirror solution with a similar field of view of approximately 7.5°. To achieve this, both the 9.7 m diameter primary and 5.4 m secondary mirrors are segmented and actively aligned.

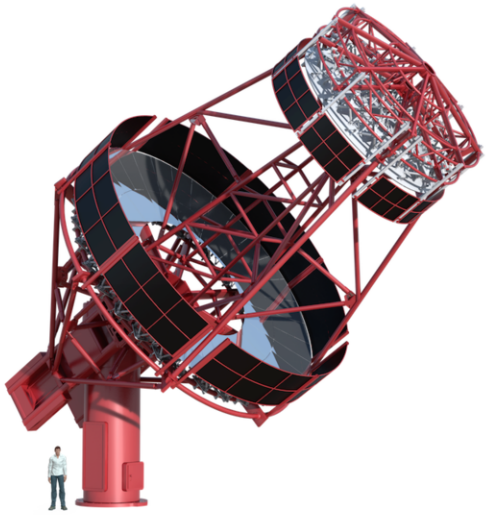


Figure 1: Rendering of the SCT telescope.

A prototype for the SCT solution, the pSCT telescope [4], has been successfully installed in the Fred Lawrence Whipple Observatory (FLWO) in August 2018.

The pSCT camera [5] readout concept is based on SiPM detectors for photon detection and a TARGET-7 ASIC front-end electronics. The backplanes of the camera handle and manage the data acquisition for separate camera sectors. The fully equipped camera focal plane will host 177 modules in 9 sectors. Each module is made of 64 pixels arranged over 4 Photo Detection Units (PDU), for a total of 11,328 pixels in the camera. Each sensor corresponds to a 0.064° pixel in the sky, matching the PSF of the optical system. The pSCT camera has a width of 81 cm for a total active area of 0.4 m^2.

Hamamatsu S12642 MPPCs have been originally selected to equip the pSCT camera. A possible upgrade based on the third generation of Near Ultra Violet High Density SiPMs (NUV-HD3) produced by Fondazione Bruno Kessler (FBK) in collaboration with Istituto Nazionale di Fisica Nucleare (INFN) is being investigated [6]. The performances of the NUV-HD3 SiPM devices are described in details elsewhere [7, 8, 9]. The sensors have been optimised for the detection of UV Cherenkov photons. The active area of NUV-HD3 SiPMs amounts to 6×6 mm^2, with a microcell area of $40 \times 40\,\mu m^2$. They feature a breakdown voltage of approximately 27 V at room temperature with a temperature gradient of ~30 mV/°C, a Photo Detection Efficiency (PDE) peak of ~50% at 350 nm dropping below 20% above 500 nm and a single photon dark count rate below 100 kHz/mm^2 at 20°C.

2. Packaging and tests of the telescope optical units

While single sensors are provided by the vendor, the procedures for the assembly and packaging of the optical modules have been completely developed by INFN.

Each 64 SiPM module covers an area of 54×54 mm^2 and is divided in 4 PDUs each composed of 16 pixels. INFN has designed custom 27×27 mm^2 area PCBs with 0.5 mm sensor-sensor distance to obtain uniform pixel coverage of the modules and of the camera, and compatible with the pSCT camera design.

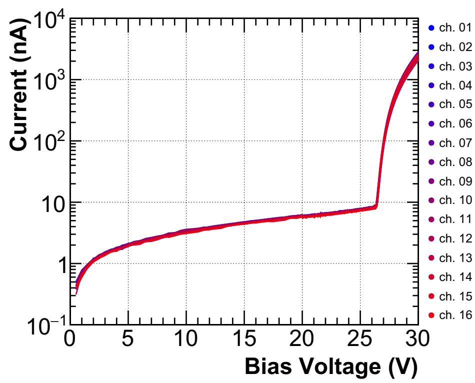


Figure 2: Profile of the current-voltage curve for 16 SiPMs of one PDU.

A manual die-bonder machine is used to dispense the conductive glue on the PCB pads and to precisely place the SiPMs on the PCBs. The alignment of the sensors has been checked with an optical metrology machine, resulting better than 40 μm. The flatness of the modules has been checked using a ruby-head touch probe machine, and the maximum deviation from planarity across the whole modules has been found to be ~80 μm, in good compliance with the optical requirements of the pSCT camera. The possibility to use semi-automatic die-bonder machines for future assemblies is under investigation.

Each SiPM anode is bonded using a 25 μm AlSi1% wire to the signal readout pad of the PCB. The breakdown voltage of each sensor is measured analyzing its dark current dependence over the bias voltage to spot any defective sensor to replace. Figure 2 shows an example of the current-voltage profile for 16 SiPMs integrated on one PDU. A batch of 38 assembled PDU modules are shown in Figure 3.

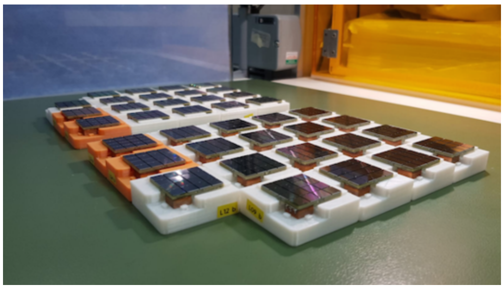
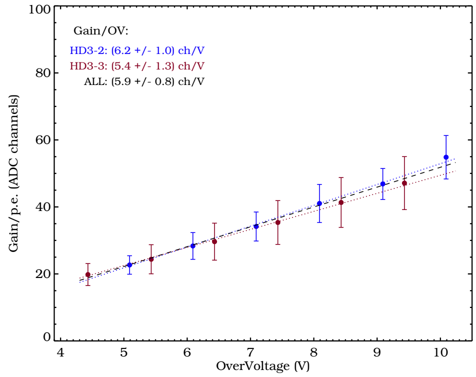


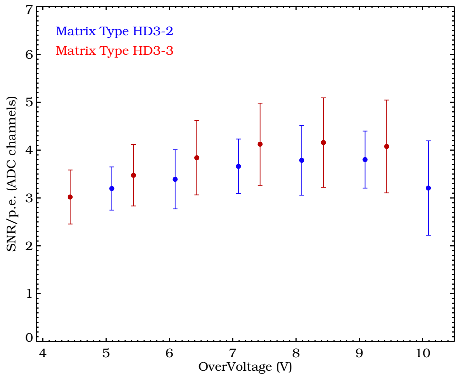
Figure 3: A batch of 38 PDU modules integrated and tested in the laboratories of INFN and stored in transportation boxes.

After the assembly, the performances of the modules have been tested with a dedicated electronics setup [10]. The 16 SiPMs of each module have been illuminated with a 380 nm pulsed laser. The charge signal of the 16 sensors has been acquired using a CAEN V792 QDC over a fixed integration time of 30 ns. The output signal of each SiPM has been consequently amplified using a custom 16-channel front end board to match the dynamic range of the QDC.

The uniformity of the signal response for more than 50 modules has been investigated in details in the bias voltage range from 31 V to 36 V. The measurement campaign has been performed on PDUs equipped with sensors selected from the first production of NUV-HD3 SiPMs, using two different silicon substrates with different purities (HD3-2 and HD3-3). The charge distributions have been analyzed to measure the gain and SNR of each channel. The average values over all channels for the gain and SNR shown in Figure 4 confirm the good level of uniformity for the module performances, with minimal differences between HD3-2 and HD3-3 substrates.



(a)



(b)

Figure 4: Average values for gain (a) and SNR (b) for more than 50 modules integrated with HD3-2 (blue) and HD3-3 (red) SiPMs.

3. Validation of the FEE readout chain

The pSCT digitization and readout electronics is based on the TARGET-7 ASIC [11] 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. Each TARGET board hosts 4 chips to perform the digitization of the 64 SiPM channels of each module. The readout boards are hosted directly behind the sensor modules inside the camera mechanics.

In order to adapt the current board design to the readout of the pSCT FBK modules, the pre-amplification stage of the digitization board has been optimized for the signal of NUV-HD3 SiPM sensors. Moreover, a mezzanine DC-DC converter has been introduced to match the bias voltage for the NUV-HD3 sensors.

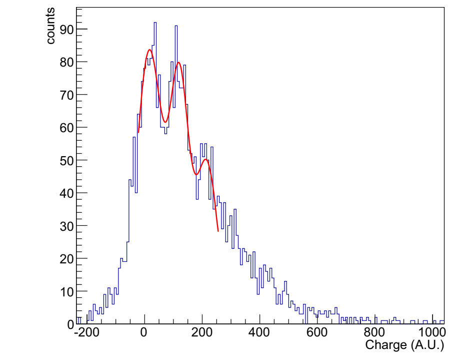


Figure 5: Distribution of the integrated signal over 16 ns of one channel readout with TARGET-7. The red line represents a multigaussian fit to the data.

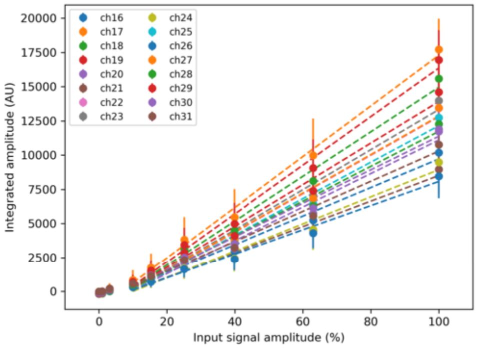
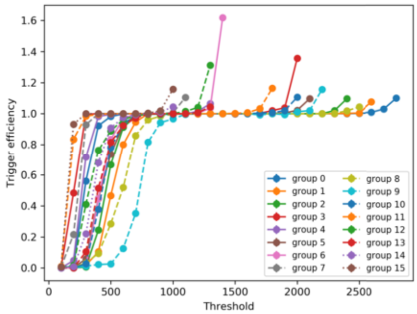


Figure 6: Average value of the charge distribution as function of the light intensity for 16 channels of one TARGET ASIC.

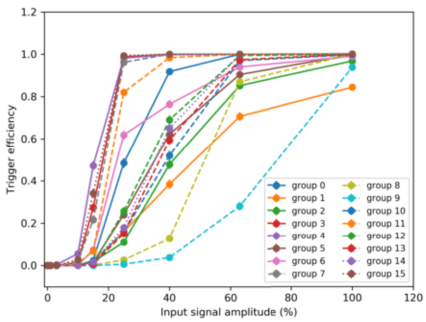
Extensive quality control tests have been performed on nine TARGET modules to validate their functionalities [12]. First, for each ASIC, the mean and the RMS of the electronics pedestals of the 16k capacitors have been evaluated in absence of light signal to be subsequently subtracted from the raw waveform data. Then, the SiPM modules coupled with the TARGET board have been illuminated with a NUV laser equipped with intensity filters. Figure 5 shows an example of a charge spectrum acquired with the TARGET board in conditions of low light intensity. Figure 6 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 deviation from linearity at low light intensities is expected from the Poisson nature of the count statistics.

The operation of the TARGET-7 internal trigger has been verified by varying the intensity of the light for a fixed trigger threshold (amplitude scans) and by varying the trigger threshold for a fixed light intensity (threshold scans). 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. Figure 7 shows the trigger efficiencies resulting for an amplitude and threshold scan of 16 trigger groups, where one group corresponds to the trigger granularity of 4 adjacent pixels. The efficiencies are normalized to the known number of laser pulses. The values for efficiencies larger than 1 for high DAC threshold values (corresponding to a low physical threshold) are due to dark noise triggers. The spread in the efficiency profiles will be corrected by the calibration of the trigger circuit for each trigger channel.

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).



(a) Threshold scan



(b) Amplitude scan

Figure 7: Threshold scans (a) and amplitude scans (b) to measure the trigger efficiency for 16 trigger groups of one TARGET board.

4. State of the art and prospects

Nine modules (36 PDUs), for a total of 576 SiPMs, have been recently assembled using the latest production of NUV-HD3 SiPMs (HD3-4). The modules will be integrated, together with 16 modules based on Hamamatsu MPPCs, in the pSCT camera to complete its central sector and to start the camera commissioning operations measuring the first lights. One additional sector of the pSCT telescope (25 modules, 1600 SiPMs) is planned to be integrated with FBK NUV-HD3 SiPMs 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 Cherenkov light measurements.

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 TARGET C board 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 TARGET 7 board [13]. 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 prove the 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.

Acknowledgements

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