Development and characterization of near-UV SiPM for the Schwarzschild-Couder Telescope prototype for the CTA collaboration

CTA Cherenkov Telescope Array observatory
SiPM sensors for Cherenkov radiation detection
Packaging, assembly & performances

Imaging Air Cherenkov Telescopes

- $\gamma$-ray enters the atmosphere
- Electromagnetic cascade
- How CTA Detects Cherenkov Light

0.1 km² “light pool”, a few photons per m².

www.cta-observatory.org
Physics of TeV γ-ray Telescopes

The gamma-ray sky as of 2016

176 TeV sources
3033 GeV sources

Supernova remnants
AGNs
GRBs
Binaries

Dark matter

Pulsars

Starburst galaxies
Cosmic rays
Axions, ...

Spacetime

Grammar

50 years

EBL

Axions

Spacetime

Cosmic rays

3033 GeV sources

176 TeV sources

3033 GeV sources

176 TeV sources
The CTA Project

1,350 members from 210 institutes in 32 countries
Two sites (North and South) for a whole-sky coverage

Operated as on open Observatory

A factor of 5-10 more sensitive w.r.t. the current IACTs

A few large size telescopes to cover the range 20 - 200 GeV

~km² array of medium size telescopes for the 0.1 - 10 TeV domain

~4km² array of small size telescopes, sensitive above a few TeV up to 300 TeV

4 LSTs [N & S]

15 MSTs [N]
25 MSTs [S]
(24 SCTs [S])

70 SSTs [S]
CTA performances

Improvement of a factor 5-10 in sensitivity w.r.t. the current IACTs in the core energy range

Extension of the accessible energy range below 100 GeV and above 50 TeV

1. Introduction to CTA Science
1.1 Key Characteristics & Capabilities

**Differential Sensitivity**

- 5 bins per decade in energy

**Angular Resolution**

- CTA South

**Energy Resolution**

- CTA South

**Effective Area**

- CTA South
- CTA South 50 h
- CTA South 0.5 h
Camera Sensors

The current IACT generation cameras are equipped with PMTs.

CTA is evaluating the possibility to equip the focal plane camera of Small and Medium size telescopes with SiPMs

**SiPM features for Cherenkov light detection:**
- √ Smaller areas (<1cm²), hence higher pixel angular resolution
- √ Higher photo-detection efficiency at UV wavelengths (∼ 50%@ 350 nm)
- √ Fast response O(1-10) ns
- √ Not damaged by moonlight, can be operated during bright Moon nights, enhancing the duty cycle of the telescopes
- √ Can be operated with bias voltages <100V
- √ Low power consumption (µW)
- √ Light-weight
- X Noisy, dark count rates O(10-100) KHz/mm² at room temperature, but below the expected average night sky background.
The Italian Institute of Nuclear Physics (INFN) is involved in the R&D effort for the development of a possible solution for the Cherenkov photon cameras using Silicon Photomultipliers (SiPM) as UV sensitive devices.

To test the feasibility and the performance of SiPM cameras, a focal plane camera prototype module, based on High Density NUV – SiPMs produced by Fondazione Bruno Kessler (FBK) is being assembled.
FBK NUV-HD SiPM sensors

- Produced at FBK (Trento, IT)
- p-n SiPM
- Active area: 6.03 x 6.06 mm²
- Microcell size: 30 x 30 µm²
- Fill Factor: 76%
- High PDE (50%) for UV photons

- NUV-HD technology successful, development of further improvements are ongoing
FBK NUV-HD SiPM sensors

Samples of sensors are thoroughly studied in different temperature ranges in a climatic chamber to extract sensor performance informations (gain, dark count rates, crosstalk, …)

- Breakdown Voltage < 30V
- Weak temperature dependence

\[
\frac{\partial V_b}{\partial T} \approx 32 \text{ mV/°C}
\]
NUV-HD SiPM sensitivity peaks towards NUV (Cherenkov signals) with maximum PDE ≈ 50% @ 350 nm

- Wide dynamic range
- gain G=O(10^6)
• NUV-HD dark count rate DCR $<< 100$ kHz/mm$^2$ up to 20 deg
• DCR doubles every 7.0°
• Typical threshold 3 p.e.

**NUV-HD performances are compliant with minimum requirements specified to equip the focal planes of CTA telescopes**
The SCT Telescope

Schwarzschild-Couder dual mirror optics Medium Size Telescope

Secondary mirror (5.4m diam)
Focal plane camera
Primary mirror (9.7m diam)

Dual mirror optics designed to cancel aberration and de-magnify images, to be compatible with compact high-resolution SiPM camera and resulting in a smaller point spread function (PSF) and improved angular resolution compared to the classical single mirror Cherenkov Telescope.

Mechanical stability and mirror alignment are the main challenges.
The SCT Telescope
Schwarzschild-Couder dual mirror optics Medium Size Telescope

Secondary mirror (5.4m diam)
Focal plane camera
Primary mirror (9.7m diam)

22 institutes, universities and observatories
5 institutes, universities and observatories
3 institutes and universities
1 university
1 university

• Optical Support Structure and Positioners installed in September 2016
• Complete assembly planned by end of 2017

SCT is the unique proposal of the innovative SC optics for the CTA Medium Size Telescope

Emanuele Fiandrini
Venice, EPS-HEP 2017
pSCT Telescope

Prototype demonstrator for the Medium Size SCT solution

0.4 m² active area per telescope

- Excellent optical resolution, small plate scale of dual-mirror telescope well matched to fine pixelation supported by silicon photomultipliers and TARGET readout electronics
- 11,328 6x6 mm² pixels (temperature-stabilized silicon photomultipliers)
- Pixel size 0.067° (high-resolution imaging)
- Readout directly behind focal plane
- 1 GSa/s, 10 bits effective (TARGET 7)
- 3 kW power budget
- Shares many common components with the Compact High Energy Camera for CTA Small Size Telescopes

8° field of view, 81 cm diameter

Prototype main goals:
- Demonstrate the performances of the optical system
- Gain experience with the optical alignment and operation of the SiPM camera
pSCT Telescope

FBK 6x6mm² SiPM intended to replace the original Hamamatsu MPPC solution and equip a possible upgrade of the pSCT camera
27x27mm² PCBs are equipped with 16 SiPMs to cover uniformly the exposed area

36 modules made of 16 SiPMs will be coupled to the electronic readout and the pSCT camera in the next months, to be tested in situ and to prepare for the next massive production of modules.
pSCT focal plane modules

PCB modules are assembled with SiPM sensors in the laboratories of INFN. SiPMs are positioned on the PCBs using a die-bonder machine.
SiPM module assembly tests

After quality checks, SiPMs are wire-bonded and the PCBs are protected with UV-transparent epoxy layer

Tests of SiPM homogeneity and assembly quality

![Graph showing current vs. bias voltage](image)

![Graph showing breakdown voltage distribution](image)

Placement in bonding&transport jig
Bonding (approx. 15 mins/matrix)
Bonding with 20μm Al/Si wire
Dispensing of UV-transparent protecting epoxy

Any defective sensor is replaced

Placement in bonding&transport jig
Bonding CTA Prog. 8 wires Floppy (CTA Matrix)

After quality checks, SiPMs are wire-bonded and the PCBs are protected with UV-transparent epoxy layer
Module assembly and packaging

Inspection with **ruby-head touch probe** and an **optical metrology machine** to verify the quality of the sensor alignment.

**Sensor alignment better than 30/40µm**

- Precision of SiPM center compatible with nominal with 30µm “typical” accuracy
- SiPM rotation -0.1deg with “typical” dispersion of 0.2deg
- Alignment quality homogeneous in the whole batch

**Distributions of alignment accuracy (RMS). 1 entry = 1 module**

- SiPM Center \(\Delta X\) (µm) Sigma
  - \(\mu = 30µm\)
  - \(\sigma = 9µm\)

- SiPM Center \(\Delta Y\) (µm) Sigma
  - \(\mu = 26µm\)
  - \(\sigma = 6µm\)

- SiPM Rotation\(_{xy}\) Sigma
  - \(\mu = 0.2°\)
  - \(\sigma = 0.05°\)
SiPM module readout

Module signal readout using “TeV Array Readout with GS/s sampling and Event Trigger” (TARGET7) board

- 16 input channels
- Analogue ring buffer of 16384 capacitors
- Switched Capacitors Array
- Storage of analogue waveforms in a limited period of time @ 1GSa/s sampling frequency
- Compact chip for high density channel camera

Pre-amplifier stage
pulse shaping
pole zero cancellation network
two-stage AD8014

4x SiPM module connectors
4x TARGET7 ASICS
SiPM module readout

Backplane of the pSCT camera hosting 2 TARGET7 modules @ Univ of Wisconsin (US)

After assembly, SiPM modules are tested simulating the whole pSCT readout chain

Experimental setup for SiPM module tests and characterization @ INFN Bari (IT)
SiPM module readout

Modules are being characterized in terms of gain, dark rate, crosstalk.... at the end of the TARGET7 readout chain
Conclusions

• **FBK NUV-HD SiPM** technology has been tested and its performances are compatible with the requirements to equip the focal planes of CTA telescopes.
• **Multi-SiPM modules** have been developed to equip a possible upgrade of the Medium Size Schwarzschild-Couder telescope prototype pSCT.
• **Assembly, packaging and tests of multi-SiPM modules** is ongoing, and 36 modules are planned to be installed on the pSCT camera by September 2017.
# CTA Telescopes

<table>
<thead>
<tr>
<th>Telescope</th>
<th>Large</th>
<th>Medium</th>
<th>Small</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>LST</td>
<td>MST</td>
<td>SCT</td>
</tr>
<tr>
<td>Number North array</td>
<td>4</td>
<td>15</td>
<td>TBD</td>
</tr>
<tr>
<td>Number South array</td>
<td>4</td>
<td>25</td>
<td>TBD</td>
</tr>
</tbody>
</table>

## Optics

<table>
<thead>
<tr>
<th>Optics</th>
<th>LST</th>
<th>MST</th>
<th>SCT</th>
<th>SST-1M</th>
<th>ASTR SST-2M</th>
<th>GCT SST-2M</th>
</tr>
</thead>
<tbody>
<tr>
<td>Optics layout</td>
<td>Parabolic mirror</td>
<td>Davies-Cotton</td>
<td>Schwarzchild-Couder</td>
<td>Davies-Cotton</td>
<td>Schwarzchild-Couder</td>
<td>Schwarzchild-Couder</td>
</tr>
<tr>
<td>Primary mirror diameter (m)</td>
<td>23</td>
<td>13.8</td>
<td>9.7</td>
<td>4</td>
<td>4.3</td>
<td>4</td>
</tr>
<tr>
<td>Secondary mirror diameter (m)</td>
<td>—</td>
<td>—</td>
<td>5.4</td>
<td>—</td>
<td>1.8</td>
<td>2</td>
</tr>
<tr>
<td>Eff. mirror area after shadowing (m²)</td>
<td>368</td>
<td>88</td>
<td>40</td>
<td>7.4</td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td>Focal length (m)</td>
<td>28</td>
<td>16</td>
<td>5.6</td>
<td>5.6</td>
<td>2.15</td>
<td>2.28</td>
</tr>
</tbody>
</table>

## Focal plane instrumentation

<table>
<thead>
<tr>
<th>Focal plane instrumentation</th>
<th>PMT</th>
<th>silicon</th>
<th>silicon</th>
<th>silicon</th>
</tr>
</thead>
<tbody>
<tr>
<td>Photo sensor</td>
<td>0.10, hex.</td>
<td>0.18, hex.</td>
<td>0.07, square</td>
<td>0.24, hex.</td>
</tr>
<tr>
<td>Pixel size (degr.), shape</td>
<td>—</td>
<td>7.7/8.0</td>
<td>8.0</td>
<td>9.1</td>
</tr>
<tr>
<td>Field of view (degr.)</td>
<td>4.5</td>
<td>4.5</td>
<td>9.6</td>
<td>1984</td>
</tr>
<tr>
<td>Number of pixels</td>
<td>1855</td>
<td>1764/1855</td>
<td>11328</td>
<td>1296</td>
</tr>
<tr>
<td>Signal sampling rate</td>
<td>GHz</td>
<td>250 MHz / GHz</td>
<td>GHz</td>
<td>250 MHz</td>
</tr>
</tbody>
</table>

## Structure

<table>
<thead>
<tr>
<th>Structure</th>
<th>LST</th>
<th>MST</th>
<th>SCT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mount</td>
<td>alz-az, on circular rail</td>
<td>alt-az positioner</td>
<td>alt-az positioner</td>
</tr>
<tr>
<td>Structural material</td>
<td>CFRP / steel</td>
<td>steel</td>
<td>steel</td>
</tr>
<tr>
<td>Weight (full telescope, tons)</td>
<td>100</td>
<td>85</td>
<td>~85</td>
</tr>
<tr>
<td>Max. time for repositioning (s)</td>
<td>20</td>
<td>90</td>
<td>90</td>
</tr>
</tbody>
</table>

Credits: The CTA Consortium
Imaging properties used to separate γ/h initiated showers and to determine energy and incoming direction of γ-ray. The experience with current IACTs has shown that a stereoscopic image reconstruction highly improves the telescope performances.
Differently from current generation experiments, CTA will be operated as a proposal-driven open observatory.
Current Telescopes

H.E.S.S. (Namibia)

VERITAS (Arizona)

MAGIC (La Palma)

Performances:
- Sensitive to primary photons in the 100 GeV – 10 TeV energy range
- Energy resolution ~20%
- Duty cycles < 15%
- Angular resolution ~ 0.1° at high energies
High density technology in NUV

NUV High-Density (HD) technology:
Lower dead border region → Higher Fill Factor
Trenches between cells → Lower Cross-Talk

6x6 NUV-HD SiPM

6 bonding pads
(at the 4 corners and at center of two sides, internal to the “active” area)

Nominal chip size (cut-line center): 6.28x6.8mm²

Effective chip dimension (after cut):
- Typical: 6.23mm
- Min: 6.21mm
- Max: 6.24mm

Active area:
- X: 6.06mm
- Y: 6.03mm (5.88mm at the bonding pads)

Micro-cell size (pitch): 30x30μm²

Micro-cell geometrical fill factor: 76%

Number of micro-cells: 40394

SiPM effective area: 36.34 mm² (taking into account bonding pads dead regions)

SiPM active area: 27.64 mm² (taking into account 76% microcell geom. fill factor)
SiPM NUV – HD 6mm x 6mm, 30μm cell

Matrix assembly through pSCT

SiPM 6.23x6.23 mm^2
Modules 27x27mm^2
FillFactor = 16 x 6.23x6.23 / (27x27) = 85%
With SiPM we get about 65%
Module assembly and testing

Module = focal plane module (FPM) + front-end electronics (FEE)

MRI pSCT project plans to produce 25 modules, which will populate single backplane board (fully populated pSCT camera consists of 177 modules).
Module assembly and packaging

Inspection with **ruby-head touch probe** and an **optical metrology machine** to verify the quality of the sensor alignment.

*Sensor alignment better than 30/40µm*
FBK NUV-HD SiPM sensors

NUV-HD SiPM sensitivity peaks towards NUV (Cherenkov signals) with maximum PDE ≈ 50%

- Wide dynamic range
- gain G = O(10^6)

![Graph showing PDE (%) vs. Wavelength (nm) with data points for Cherenkov Light and Night Sky.

![Graph showing Gain vs. OverVoltage (V) with different gain values and OverVoltage settings.

![Graph showing Gain vs. Charge (fC) and Gain vs. Number of Photoelectrons with various voltage settings.

Cherenkov Light [a.u.] (La Palma, 2200m)
Night Sky [a.u] (La Palma, 2200m)
Development and characterization of near-UV sensitive Silicon Photomultipliers for the Schwarzschild-Couder Telescope prototype for the CTA collaboration

Emanuele Fiandrini University of Perugia - I.N.F.N. Perugia (IT)

www.cta-observatory.org