A new technique in gamma astronomy:
an innovative camera for a high-energy gamma-ray telescope array.

Vittorio Boccone, University of Geneva
Outline of the talk

• Introduction to CTA;

• A 4m Davies Cotton Small Size Telescope;

• Introduction to G-APDs

• Characterization of G-APDs
Introduction to CTA
The CTA project is an initiative to build the next generation ground-based very high energy gamma-ray instrument. It will serve as an open observatory to a wide astrophysics community and will provide a deep insight into the non-thermal high-energy universe.

http://www.cta-observatory.org/
The science of CTA

1. Understanding the origin of cosmic rays and their role in the Universe
2. Understanding the nature and variety of particle acceleration around black holes
3. Searching for the ultimate nature of matter and physics beyond the Standard Model

Galactic Gamma-Ray Sources
- Supernova Remnants
- Pulsar Wind Nebulae
- Pulsar Physics
- Star-Formation Regions
- The Galactic Centre
- X-Ray Binaries & Microquasars

Extragalactic Gamma-Ray Sources
- Active Galactic Nuclei
- Extragalactic Background Light
- Gamma-Ray Bursts
- Galaxy Clusters

Surveying the Sky with CTA

Fundamental Physics
- Dark Matter
- Quantum Gravity
- Charged Cosmic Rays

Optical Images of Stellar Surfaces

Each of those topics is a talk of its own!
**LST:** $E \leq 100$ GeV
A small number of very large telescopes, typically with about a 20 m to 30 m dish diameter,

**MST:** $100$ GeV < $E < 10$ TeV
grid of telescopes of the 10 to 15m class, with a spacing of about 100 m

**SST:** $E > 10$ TeV
large number of smaller telescopes 4-7 m spaced by more than 100 m
Energy sensitivity

Discovery sectors: < 50 GeV (Large-Size Telescopes for GRBs, pulsars, DM); > 5 TeV (Small-Size Telescopes for hadronic phenomena - connects to neutrinos, EBL (informs us on cosmological distribution of sources), intergalactic magnetic fields, unidentified galactic PeVatrons that produce CRs at the knee, acceleration of particles to the highest energies, jet formation in BHs, new physics (VLI). Multi-messenger approach: only measurements in different bands and with different messengers (from ground and from space) can help reconstructing how sources work.
2 Sites (North/South) to cover full sky of O(100) telescopes of 3 different sizes.

South site is most important site in the due to better Galactic plane exposure. Decision on site in about 1 yr (Namibian sites, Tenerife seem very good options).
Operation modes

- **very deep field (a)**
- **mixed mode (b)**
- **sky survey (c)**

Extrapolating from the intensity distribution of known sources, CTA is expected to enlarge the catalogue of objects detected from currently several tens of objects to about 1000 objects.

Ultimately, CTA aims to provide full sky coverage from multiple observatory sites, using transparent access and identical tools to extract and analyse data.

The feasibility of the performance goals listed above is borne out by detailed simulations of arrays of telescopes, using currently available technology (details are given below). The implementation of CTA does require significant advances in the engineering, construction, and very deep field mixed mode sky survey.
Technique

Clue: imaging the cascade geometry → photon direction intensity → photon energy shape → cosmic ray rejection

In reality: a short (nanoseconds) faint (few 10 ph./m²) blue flash
Effect of the pixel size

Example of LST: Effect of the pixel size (0.07, 0.10, 0.14, 0.20, and 0.28°) but identical field-of-view (of about 6°), viewing the same shower (460 GeV gamma-ray at 190 m core distance) with a 420 m2 telescope.
a 4m Davis Cotton Small Size Telescope
Physics program in the multi-TeV regime requires a rather large FoV of $\sim 10^\circ$ and reasonably good angular resolution $\sim 0.03^\circ$. Davies-Cotton design has an adequate resolution over this FoV with no need to be larger than $D \sim 4 \text{ m}$.

**Objectives:**
- Simplest telescope structure Davis cotton 4m;
- Focus on camera: FlashCam, FACT camera;
- Concept easily extensible for the 2$^{nd}$ camera generation;

**Challenges based on unique experience:**
- Innovation in photo-detection: G-APD;
- Prove mass-producibility and low cost of detector plane;
- Low maintenance parts;
- Reduce weight.
Why solid state detectors?

• SST array aim for good sensitivity above 1 TeV requires:
  • larger area (cost) and
  • longer observational times (robustness against moonlight)
• pixel size naturally matches small dishes (4-6 m)
• operation with Moonlight is possible (about 30% longer times)
• Right platform for R&D (see also Dual Mirror...) in view of 2nd generation of MSTs and LSTs cameras.
• and they work!

FACT - Observation with full moonlight
CERN Courier Nov.2011
The First G-APD Cherenkov Telescope

The **First G-APD Cherenkov Telescope** (FACT) is the first imaging atmospheric Cherenkov telescope using Geiger-mode avalanche photodiodes (G-APDs) as photo sensors.

The rather small, low-cost telescope will not only serve as a technology test bench for Cherenkov astronomy, but also monitor bright active galactic nuclei (AGN) in the TeV energy range.
In the direction of gaining experience not only with the detection technique but also with the problematic of remote operation of complex system we build the new shutter for the FACT experiment;

Shutter was installed in La Palma in July 2012.
Why G-APDs?

- High yield
- G-APDs large scale mass production
- No Aging
- Higher PDE over larger spectral range
- Light
- Low Op. Voltage
- Insensitive to Magnetic Field
- Robust
- Compact
- Very good Single Electron Response
- Small variation sample-by-sample
Why G-APDs?

Peak PDE not (yet) as high as QE of Ultra-Bialkali’s?

To compare the two, we must look into the definition of the PDE and QE:

\[
PDE_{G-APD} = QE \cdot \varepsilon_{geo} \cdot \varepsilon_{trigger}(V_{ov})
\]

- \(\varepsilon_{geo}\): geometrical fill factor
- \(\varepsilon_{trigger}\): probability that the generated e/h pair starts an avalanche (depends on the depletion region)

\[
PDE_{PMT} = QE \cdot \varepsilon_{col}(V_{K-1dy}) \cdot (1 - \varepsilon_{loss}) \cdot \varepsilon_{dynodes}
\]

- \(\varepsilon_{col}\): 1st dynode collection efficiency
- \(\varepsilon_{loss}\): inelastic backscattering loss rate (~5-10% but no precise measurement exists)
- \(\varepsilon_{dynodes}\): collection efficiency of the dynodes structure

For PMT, we talk about QE~45% while for G-APD, we have PDE of the order of 40% or more for larger fill factors.

Improvements will imply the possibility to run at higher PDE, lower noise and higher stability.

- Reduction of after-pulses using purer wafers (prevent hole drifting from bulk to the avalanche zone);
- Use of trenchers to suppress crosstalk (about a factor of 8);
- Improve fill factor by replacing polysilicon quench resistor with Metal Film Resistor \(\Rightarrow\) higher PDE;
- Development are driven from other fields such as medical applications;
- Cost is now 1 \$/mm\(^2\) for large quantities;
Camera’s philosophy

1296 Pixels
9° FoV
90 cm flat-to-flat

Separation of PDP and ADC, analogue signal over CAT5/RJ45
• allows adaption of various photon detectors and pitches
• avoids data acquisition and readout electronics at the focal plane (weight)

Horizontal integration
• reduces costs

Easily scalable to SST, MST, LST
FlashCam - Architecture

- Simple concept based on commercially available chips
- Trigger decision based on digitized signals
  - No separate trigger path
  - Programmable and flexible
  - Nearly dead-time free

- Low power (<0.5 W/channel) 12-bit FADCs currently available up to 250 MS/s.
  - Extensive simulations incl. time jitter, NSB, etc., have shown that trigger performance with digital trigger options is very competitive with higher sampling speeds (e.g. 1-2 GS/s).
  - Resulting data rate (~700 MB/s) allows transmission of full pixel event information over standard gigabitEthernet infrastructure (incl. commercial switches)
FlashCam - Performances

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![](image.png)
FlashCam - Readout and Trigger

- 9 racks on Telescope support Easy air flow because crate not sealed by backplane
- Dimensions: 215mm x 400mm x 238mm

Master trigger distribution
12 xRJ45 CTI links to trigger cards + Array trigger

Flash ADC card with 24 ADCs

Trigger card (one card per mini crate)

Mini crate

Mini crate 0

Mini crate 1

Mini crate 2

Mini crate 3

Backplane

72 LVDS 1Gb/s links

patch trigger data (4-bit, 8-bit)

7 patches (21 pixels) summed up in sliding windows

Mini Crate

Backplane

Interface / Trigger Board

≤ 8 FADC Boards

Master trigger distribution
12 xRJ45 CTI links to trigger cards + Array trigger

Flash ADC card with 24 ADCs

Mini crate

Mini crate 0

Mini crate 1

Mini crate 2

Mini crate 3

Backplane

72 LVDS 1Gb/s links

patch trigger data (4-bit, 8-bit)

7 patches (21 pixels) summed up in sliding windows

Thursday, 11 April 13
The Photo Detector Plane

- 1296 pixels (SiPM+Cones)
- 108 Modules of 12 pixels each
- Entrance window 3 mm Borofloat
- Aluminum Back Plate
- Total PDP weight ~35 kg
- Power Consumption ~100 W
- FEA study on going seems to indicate that can be made even lighter by 3-7 kg

Window clamping system (flange) is not shown. It will be fixed to the hexagonal ring (+ some seal sheet)

Borofloat window (3mm thick, OK by FEA)

Weight saving to be done (FEA will tell)
The Photo Detector Plane

A Borofloat entrance windows has 2 main advantages:

- **Optical:** can be coated with a filter to select only light between 300 nm and 720nm eliminating large fraction of NSB;
- **Mechanical:** it will be displaced under its weight only by 0.5 mm in the centre without any other fixation than the clamps on its border but various wind conditions need to be tested.
The light concentrators

**Hollow cone:**
- Length: 36.7 mm
- Comp. Factor: ~6

**Full Cone:**
- Length: 53.3 mm
- Comp. Factor: ~14.2
- Material: PMMA

Values are constrained by the telescope:
- PSF → angular pixel size → top physical size: 0.25°
- f/D and Camera diameter → Cutoff angle: 24°
The light concentrators

- **Full Cone**
  - No light with $\lambda < 350$ nm reaches the detector after 5.3 cm of PMMA;
  - Weight;
  - Diffusion by impurities in the material;
  - Possible degeneration of the materials (cone and glue) with thermal cycles;
  - Rigidity of the system, glue to entrance window prevents to substitute pixels (FACT);
  - Optical continuity (all same refractive index)

- **Empty Cone**
  - PMMA/glass entrance window reduces light (about 8% Fresnel losses)
  - Spacing between pixels (dead area)
  - Compact;
  - Lightweight.
Characterization of light collectors

- Diffused light source + few optical elements to obtain parallel rays;
- Rotation stage;
- Relative measurement (with and w/o mask) → no calibration of the photodetector needed
Characterization of light collectors

Optical transmissivity measurement on an optical bench to quantify the performance of the assembled cone.

- Directly measure of the cut-off angle.
- Compare alternative solutions for the coating materials on the reflective part.
- A pin-diode is used to measure the light w/o the cone
- Automatic procedure with step motor to move the cone and measure for different angles

We need to monitor the beam to get rid of intensity fluctuations of the light source.

Hexagonal Mask on the photosensor identical to the Winston cone top aperture.
Light collectors production

3 types of “strips” for 1 module

Type 1 (single)

Type 2 (4 cones)

Type 3 (type 2 mirror sym.)

Type 1 strip
(assembled in a dedicated jig)
Detector assembly

- back PCB of Module I
- Fixed by means of the M2 jack stands on the cone module

Seen from the back side

Module PCB
(2mm thick to get a better stiffness)
Few words about G-APDs
Photodiode types

The working mode of the junction is determined by the bias voltage (reverse);
Although each junction can work in the different modes each working mode has its own optimized junction characteristics:
• Ordinary p-i-n photodiode Gain is around unity;
• Avalanche PhotoDiodes have gain up to a factor 100;
• Geiger mode APD can reach a gain of few $10^6$. 
**Geiger mode APD**

- Also called Silicon Photo Multipliers (SiPM), Multi Pixel Photon Counters (MPPCs) from Hamamatsu, G-APDs or also single photon avalanche (photo)diodes;
- Each G-APD can detect at most 1 photon therefore there the detector is segmented in micro-cells (25÷100um) each composed by a single diodes in order to allow the simultaneous detection of more photons.
- Working few volts below Breakdown voltage therefore each pixel should be small enough reduce the probability of having too many dark counts.
- Detection of single photons;
- High gain (up to few $10^6$);
- Gain is linear with the reverse voltage;
Geiger mode APD

- Working below the breakdown voltage (A) implies that for each e/h-pair generated in the depletion region the diode will discharge (B);
- Connecting a resistor in series to the diode allows to stop the avalanche in very short time by limiting the output current (C), acting as a circuit that outputs a constant pulse at each time an avalanche is generated (by thermal effect or a real photon). Each pixel has an independent quenching resistor;

- The G-APDs have excellent photon counting capabilities. The individual pulse waveforms corresponding to the different number of detected photons are clearly visible
The Gain of the detector is proportional to the capacitance of the junction and to the difference between the breakdown and reverse voltage:

$$G = \frac{Q}{q} = \frac{C(V_r - V_{br})}{q}$$
Optical cross-talk

- For an ideal detector the probability of two or more simultaneous photons thermal excitation should be negligible.
- In an avalanche breakdown, there is an average of a photons with $E > 1.14$ eV emitted per $3 \cdot 10^4$ carriers;

- These photons can trigger a breakdown in the neighboring cells.
- Higher energy photons are practically all absorbed within the same cell and infrared photons ($\gtrapprox 1100$ nm) travel over long distances without being absorbed.
- Solution: create an optical trench filled with an opaque material to stop the propagation of the optical photons from cell to cell.
Afterpulse

- Signal after-pulses in G-APDs are believed to be originated by the electrons produced in an avalanche and then remain trapped for a time which can last from nanoseconds up to several microseconds;
- The multiplication factor for those electrons depends on the recovery state of the corresponding pixel;
- If the time delay with respect to the preceding pulse is short, only pulses with small (< than 1pe) signal amplitude are generated; if the delay is larger than the pixel recovery time, a standard avalanche signal is triggered;
- These signals cannot be separated from the real, photon-induced signals and therefore deteriorate the photon-counting resolution of the devices.
Characterization of G-APDs
Measurement Plan

- Characterize devices (not only the Hamamatsu we designed) using few setups hooked to generic purpose instrumentations on GPIB, USB and VME buses;
- Setup can be used on any photodetector or light concentrators;
- Two calibrated Hamamatsu as reference;
- Define a measurement *iter* for all the devices both for the R&D phase and the camera construction.

**Measurements** | **Aim**
---|---
**IV/CV** | First test of the device (electrical), determine $R_{sh}$, $C$ and $V_{break}$ for each sensor before assembly.  
**Photo Detection Efficiency** | Verify the photo detection efficiency given by the producers, determine the working point(s) of the camera.  
**Afterpulse** | Define the afterpulse probabilities of the sensors. Can be done with the assembled camera.  
**Crosstalk** | Measure the crosstalk to evaluate its effect on the sensitivity of the camera. Can be done with the assembled camera.  
**Uniformity measurements** | Evaluate the uniformity of the sensor parameters, distribute the sensors on the camera to avoid batches  
**Pulse shape analysis** | Verify the quality of the generated signal. Can be done with the assembled camera.
Measurement setups

USB 2.0, Optical link or 1Gb Ethernet

VME For:
- PDE;
- Dark count rate;
- Pulse Shape;
- Timing;
- Xtalk;
- Afterpulse;
- Gain;
- Winston cones

GPIB/Serial For:
- IV curve;
- CV curve;
- PDE (slow control);

VME BUS
- HV power supply
- Digitizer (Future)
- Low Threshold Discriminator
- Scaler
- OnBoard CPU (Future)

USB/Serial
- X/Y Table
- MPPC under test

GPIB/Serial
- Keithley pico-Ammeter
- RC-Meter
- Pulse Generator
# Device Under Test

<table>
<thead>
<tr>
<th>Producer</th>
<th>Model</th>
<th>Ch.</th>
<th>Shape</th>
<th>Cell size</th>
<th>Dimensions</th>
<th>( V_{br} ) (typ) [V]</th>
<th>PDE [%] (peak)</th>
<th>Comments</th>
</tr>
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<tr>
<td>Ketek</td>
<td>PM3350</td>
<td>1</td>
<td>□</td>
<td>50um</td>
<td>3\times3 mm(^2)</td>
<td>30</td>
<td>&gt;40</td>
<td>With trenchers</td>
</tr>
<tr>
<td>SenSL</td>
<td>MicroSB30035-X13-E1</td>
<td>1</td>
<td>□</td>
<td>50um</td>
<td>3\times3 mm(^2)</td>
<td>25</td>
<td>25-30</td>
<td>Experimental</td>
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<td>SenSL</td>
<td>MicroSB30035-X13-E15</td>
<td>1</td>
<td>□</td>
<td>50um</td>
<td>3\times3 mm(^2)</td>
<td>25</td>
<td>25-30</td>
<td>Commercial</td>
</tr>
<tr>
<td>Hamamatsu</td>
<td>S10985-050C</td>
<td>4</td>
<td>□</td>
<td>50um</td>
<td>3\times3 mm(^2)</td>
<td>70</td>
<td>35-40</td>
<td>Commercial</td>
</tr>
<tr>
<td>Hamamatsu</td>
<td>S12516-050</td>
<td>4</td>
<td>□</td>
<td>50um</td>
<td>side = 6 mm</td>
<td>70</td>
<td>35-40</td>
<td>Custom geometry and package</td>
</tr>
<tr>
<td>Hamamatsu</td>
<td>S12516-100</td>
<td>4</td>
<td>□</td>
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<td>Excelitas</td>
<td>n.d.</td>
<td>1(4)</td>
<td>□</td>
<td>50um</td>
<td>6\times6 mm(^2)</td>
<td>n.d.</td>
<td>n.d.</td>
<td>Experimental</td>
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</table>

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**S12516-050**

**S10985-050C**

**S12516-050**

**SenSL**

**MicroSB30035-X13-E1**

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*Thursday, 11 April 13*
The S12516(X) sensor

4 Common Cathode channels

Variants
- 100 um (2282 px/ch)
- 50 um (9210 px/ch)

Thermistor

M2 fixation holes
The S12516(X) sensor

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>min.</th>
<th>typ.</th>
<th>max.</th>
<th>Unit</th>
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<tbody>
<tr>
<td>Effective active area/channel</td>
<td>–</td>
<td>–</td>
<td>23.38</td>
<td>mm²</td>
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<tr>
<td>Number of channel</td>
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<td>–</td>
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<tr>
<td>Number of pixels/channel</td>
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<td>–</td>
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<td></td>
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<tr>
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<tr>
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<td>900</td>
<td>nm</td>
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<tr>
<td>Peak sensitivity wavelength</td>
<td>λp</td>
<td>440</td>
<td></td>
<td>nm</td>
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<td>Recommended operating voltage range *2</td>
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<td>60</td>
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<td>Vop variation between channels</td>
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<td>–</td>
<td>0.15</td>
<td>0.3</td>
<td>V</td>
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<tr>
<td>Dark count/channel at Vop</td>
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<td>–</td>
<td>4.2</td>
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<td>pF</td>
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<td>Photon detection efficiency at λp *3</td>
<td>–</td>
<td>50</td>
<td>65</td>
<td>%</td>
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<tr>
<td>Crosstalk probability</td>
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<td>%</td>
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<td>Temperature coefficient of reverse voltage</td>
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<td>56</td>
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<td>mV/°C</td>
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<tr>
<td>Gain at Vop</td>
<td>M</td>
<td>2.4 x 10⁶</td>
<td></td>
<td>–</td>
<td></td>
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</table>

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<tr>
<th>Serial No.</th>
<th>ch.</th>
<th>Vop[V]</th>
<th>Gain</th>
<th>VopVariation[V]</th>
<th>0.5p.e. Dark[Mcps]</th>
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<td>1</td>
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<td>B1</td>
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100 µm cells

zoom
The S12516(X) sensor

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<tr>
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<td>9210</td>
<td>–</td>
<td>–</td>
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<td>μm</td>
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<td>50</td>
<td>–</td>
<td>%</td>
</tr>
<tr>
<td>Crosstalk probability</td>
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<td>10</td>
<td>15</td>
<td>–</td>
<td>%</td>
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<tr>
<td>Temperature coefficient of reverse voltage</td>
<td>–</td>
<td>56</td>
<td>–</td>
<td>–</td>
<td>mV/°C</td>
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<tr>
<td>Gain at Vop</td>
<td>M</td>
<td>–</td>
<td>7.5 x 10⁸</td>
<td>–</td>
<td>–</td>
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### Table (continued)

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<tr>
<th>Serial No.</th>
<th>ch.</th>
<th>Vop[V]</th>
<th>Gain</th>
<th>VopVariation[V]</th>
<th>0.5p.e. Dark[Mcps]</th>
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<td>1</td>
<td>A1</td>
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<td>71.39</td>
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<td>1.7</td>
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<tr>
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<td>A1</td>
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<td>7.50E+05</td>
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<td></td>
<td>B1</td>
<td>71.36</td>
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<td>1.7</td>
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<tr>
<td></td>
<td>B2</td>
<td>71.34</td>
<td></td>
<td></td>
<td>1.7</td>
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</tbody>
</table>

50 μm cells
The S12516(X) sensor
The light is be generated using a pulsed LED (NEMO-IFIC pulser). Different wavelength are used (355, 390, 470, 525, 572, 595, 637 nm).

The G-APD signal is amplified and then read-out using a digitizer (LeCroy oscilloscope) or a VME charge sensitive ADC. Signal acquisition is triggered/gated by the light pulser to avoid the effect of after pulses crosstalk and dark counts (thermal noise).

The detector PDE is be done relatively to a NIST calibrated Hamamatsu photodiode (S1337-1010BQ). A diffusive light source can be obtained either by using an integrating sphere or a light diffuser. The advantage of using an integrating sphere is that the setup (if well assembled) will be self-contained and naturally light-tight.
Prototype of the PDE setup

- **Detector collar**
- **S1337-1010BQ Calibrated Photodiode**
- **LED diode**
- **Interchangeable mask**

- **Port 1:** Ø 7mm mask for pin-diode
- **Port 2:** Ø 1mm mask (fiber holder)
- **Interchangeable LED**

**Thursday, 11 April 13**
PDE Measurement

- Use method based on zero poissonian statistics (naturally independent of after-pulsing and cross-talk);
- Measure the PDE as a function of bias over-voltages ($\varepsilon_{\text{trigger}}$ depends on the overvoltage);
- G-APDs illuminated with short low intensity light flashes (~ 10-20 nsec) and the triggers N(0) are counted where no photoelectron was detected by the SiPM;

$$P(0) = e^{-\mu} = \frac{N(0)}{N_{\text{total}}}$$

$$\Rightarrow \mu = -\ln \frac{N(0)}{N_{\text{total}}}$$

- where $P(0)$ is the probability that no photoelectron is detected if the SiPM is illuminated by one light flash.
- From the signal of the photo-diode one can calculate the mean number of photons ($N_{\text{photons}}$) at the position of the SiPM as will be explained later and finally obtain the PDE:

$$\text{PDE} = \frac{\mu}{N_{\text{photons}}}$$
The thermally emitted electron hole couple are indistinguishable from the real signal therefore we have also to take into account the probability of having a fake signal while not having any photon detected;

This effect is evaluated by opening a second integration windows 300 ns before the trigger comes and evaluating the mean number of detected photon when no signal is supposed to be detected;

The resulting formula for the calculation of the PDE will be:

\[
\mu = - \log \frac{N_{\text{sig}}(0)}{N_{\text{tot}}^{\text{sig}}} + \log \frac{N_{\text{bkg}}(0)}{N_{\text{tot}}^{\text{bkg}}}
\]
PDE Measurement

- Waveforms are acquired with a 8bit, 1GS/s oscilloscope;
- Offline analysis is performed to remove the DC offsets and calculate the integrals of the two region of interest;
- For each wavelength we determine the breakdown voltage by fitting the gain as a function of the bias voltage;
- The PDE is then calculated for each bias voltage and wavelength;
- As the breakdown voltage can change with the temperature we evaluate the PDE for an over-voltage ($V_{ov}$) of +2 V so measurement of different sensors can be compared easily.
- The measurement procedure for 1 channel (7 wavelengths) is still very long (~1 day);
- The implementation of a VME (next weeks) readout (QDC) will increase the acquisition speed and reduce the data processing, by about a factor 10, in addition mode channels could be acquired at the same time.

### Gain vs. Vbias

- $V_{break} = 70.07 \text{ V}$
- $C_{1G-APD} = 0.065 \text{ pF}$

### HEX 50um #2, Ch. A2, $T = (27.5 \pm 0.2) ^\circ \text{C}$

- $V_{ov} = 2 \text{ V}$
Preliminary PDE results

PDE - Hamamatsu

S10985-050C Datasheet, incl. xtalk & afterpulse
S11828_3344-050C (Astri), $T = 26^\circ C$, $V = 1.6V$
S10985-050C #238, $T = 28\pm 1^\circ C$, $V = 2V$

HEX 50um, S/N 1-B1, $T = (30.5\pm0.5)^\circ C$
HEX 50um, S/N 1-A2, $T = (29\pm1)^\circ C$
HEX 100um, S/N 1-B1, $T = (27.5\pm0.3)^\circ C$

Under Evaluation also other devices from Ketek and SensL.

SensL is going to provide for evaluation their new B-series

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Thursday, 11 April 13
Crosstalk measurement

- The crosstalk will be measured comparing the rate of 0.5 pe ($R_{0.5}$) with the rate >1.5 pe ($R_{1.5}$).
- The rate as a function of the pulse height is measured by counting the discriminated signals for different thresholds (CAEN V814) with a scaler (CAEN V560). The probability of crosstalk will be determined as the ratio:

\[ P_{\text{crosstalk}} = \frac{f_{1 \text{ pe}}}{f_{>1 \text{ pe}}} \approx \frac{f_{>0.5 \text{ pe}}}{f_{>1.5 \text{ pe}}} \]

- The position of the $R_{0.5}$ and $R_{1.5}$ points is determined by the valleys of the first derivative of the rate itself;
- The measurement will be performed inside a light-tight black box which will prevent contamination from the ambient light, for different G-APD bias voltages (Gain).
So far we measured only the crosstalk probability for the hexagonal sensors and a SenSL experimental device;

We express the crosstalk as a function of the gain and as a function of the overvoltage as both are very important for the determination of the working point.

The $V_{ov}=2\text{V}$ working point is often used as a standard candle as it is (often but not always) the best compromise between the PDE and the crosstalk;

Although the very high gain the 100um hexagonal detector has a very large crosstalk, twice as large as the other 100um Hamamatsu sensor.

Hollow points are from a S10363-050C and 100C 3x3mm2 Hamamatsu sensors. P.Eckert et al. Nuclear Instruments and Methods in Physics Research A 620 (2010)
Crosstalk/Dark count rate

- The information of the DC rate $R_{0.5}$ is essential to study the background that the sensors will induce to the camera;
- The typical dark count rate is often specified in the datasheet but it is strongly temperature dependent, and might present disuniformities over large batches.
- For a camera whose operational temperature spans over more than 20° C it’s a characteristic which must not be forgotten.
- The $R_{0.5}$ was therefore determined for different bias voltages and detectors. As we have sensors with different size, for convenience also calculate the dark count rate per unit of area.
Afterpulse

(next future)

- The dark count rate and cross talk measurement setup will be upgraded with a Time to Digital Converter;
- Using this TDC we will be able to determine the after-pulse time different distribution of the signals;

*Oscilloscope trace from our detectors*

Uniformity measurement (future)

- The uniformity of the gain and response of the single G-APD cells (as well as the cross-talk and afterpulse) will be measured performing a 2D scan of the G-APD with a point-like light source (LED coupled to a single mode optical fibre and focussing optic) with a resolution of about 1 µm.
- The DAQ and the light source will be common with the setups of the other measurements while a new focussing optic to reach beam size of about 1 µm and a micro positioning X/Y-scanning table will need to be purchase;
The measurement of the I-V is done directly with a Keithley 6487 picoammeter/voltage source controlled with a computer;

We need to minimize parasitic current flow to achieve a good measurement.

\[ I_{tot} = I_{meas} + I_{par} \]
The measurement of the C-V G-APD characteristic requires an additional LCR meter (in our case the HP-4236B LCR meter);

The Keithley 6487 pico-ammeter/voltage source is added in series to the AC source in order to provide sufficient bias for our purposes, a specific decoupling box for this purpose was given us by Maurice Glaiser (PH/DT CERN);

<table>
<thead>
<tr>
<th>device under test</th>
<th>Capacitance</th>
</tr>
</thead>
<tbody>
<tr>
<td>S12516-050 µm, S/N 2</td>
<td>810 ± 10, 840</td>
</tr>
<tr>
<td>S12516-100 µm, S/N 1</td>
<td>860 ± 10, 840</td>
</tr>
<tr>
<td>S10985-050C, S/N 238</td>
<td>315 ± 10, 320</td>
</tr>
</tbody>
</table>

Figure 12: device under test

Table 2: Results of the CV measurement compared to the specification.

References

Conclusions

• We are developing a new generation camera for the SST using GAPDs and horizontal integration which could be a good candidate also for the 2\textsuperscript{nd} generation cameras for larger telescopes;
• Innovative large area sensor developed with Hamamatsu but we are not bound to any contract. Contact are ongoing also with SenSL, Ketek and Excelitas;
• First result on these new sensors are promising, more to come;
• The project is progressing with an impressive speed even with a limited manpower but still many things to do;
• The camera is being designed so that the assembly and the construction of most of the parts can be outsourced to companies;
• The challenge is to have a full scale prototype in 2014, but a full camera prototype cannot be ready before April 2015. (Availability of electronics and funding profile);
• In the meanwhile we are going for a 144 pixel prototype (proof of concept) by the end or 2013-beginning 2014;
• Meanwhile we keep working and learning about the operation of the only existing G-APD camera (FACT).
Backups
Telescope Parameter’s Book

Camera
- Total Weight (incl. mini-crates) ~ 300 kg
- PDP weight = 25 kg + mechanical structure
- Cable weight on quadrupod.
- Total Power Consumption <3 kW
- Mini Crates = 9

Mirror
- Diameter $D = 3.98 \text{ m}$
- $f/D = 1.4 \text{ f} = 5.6 \text{ m}$
- FoV: 9°
- Mirror facets = 19
  - Facet hex side-to-side=78cm
  - Facet spacing = 2cm
  - Facet material = SIMAX
  - Facet thickness = 16 mm in the center, 25 mm in the corner
  - Facet mass = 23 kg
  - 73% allowable stress with 200 km/h wind.
- $D_{80}$ at 4° = 0.23°
- $D_{80}$ with HESS misalignment = 0.26°
- Angular range: elevation -13° to 105°; azimuth full 360°
- Normal modes of oscillation = 3.93; 4.75; 11.74 Hz

Photon Detector Plane
- Nr. of Pixels = 1296
- Pixel angle = 0.25°
- Winston Cones
  - Hex empty cone upper part = 2.32 cm side to side
  - Length of cone 3.62 cm
  - Theta_cutoff = 24°
  - Compression factor = 6.05
  - Thickness of cone = 0.5 mm
- PMMA window = 3 mm ?
- Sensor
  - Hexagonal G-APD dimension:
    - side to side = 9.44 mm,
    - total (including cone thickness) = 10.4 mm
  - 4-channels
  - Total area sensor = 93.5 mm² (23.4 mm²/Ch.)
  - Soft resin $n = 1.41$
We propose a Davis Cotton SST

- $f/D = 1.4$
- $D = 4$ m, $f = 5.6$ m
- FoV = 10 deg
- Angular pixel size: 0.28 deg
- Physical pixel size (diameter): 2.70 cm
- Side for an hexagonal sensor is: 0.5 cm
- $N_{\text{pixels}}$ is: $\sim 1300$
- Mirrors, two solutions:
  - 18x 80 cm;
  - 36x 60 cm (better for angular res.).
FACT camera assembly
FACT camera assembly
FACT camera assembly
The S12516(X) sensor

INDEX

thermistor chip

Silicone resin

(4x) 50um pixel pitch - 23.38mm2 - MPPC ch

(8x) non-magnetic PIN (Phosphor bronze)

PWB
Single photon spectrum

spe Spectrum Ch.1 (ampli x200)

| p0   | 0.4548 ± 0.0094 |
| p1   | 3.164 ± 0.006  |
| p2   | 0.4698 ± 0.0024|
| p3   | 1268 ± 13.7    |
| p4   | 682.7 ± 7.6    |
| p5   | 264.6 ± 4.4    |
| p6   | 88.03 ± 2.37   |
| p7   | 24.49 ± 1.17   |
| p8   | 7.018 ± 0.698  |
| p9   | 1.907 ± 0.341  |

Charge [pC]

0  5  10  15  20  25  30

Events

10^3

10^2

10

1

spe Spectrum Ch.3 (ampli x200)

| p0   | 0.4169 ± 0.0107 |
| p1   | 3.244 ± 0.007   |
| p2   | 0.5066 ± 0.0027 |
| p3   | 1164 ± 13.3     |
| p4   | 640.9 ± 8.2     |
| p5   | 241.3 ± 4.4     |
| p6   | 75.89 ± 2.35    |
| p7   | 23.48 ± 1.29    |
| p8   | 5.628 ± 0.639   |
| p9   | 1.544 ± 0.305   |

Charge [pC]

0  5  10  15  20  25  30

Events

10^3

10^2

10

1
PDE Measurement options

a) PDE measurement with integrating Sphere

- If area of open ports <5% of the sphere area, light can be considered purely diffusive;
- Ratio of the port can be measured with two photodiodes

b) PDE measurement without integrating Sphere

- Require slightly larger dimensions and a “large” light tight box;
- Ratio of the port can be measured with two photodiodes.