A Novel Camera Type for Very High Energy Gamma-Astronomy

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Abstract. **Geiger-mode avalanche photodiodes (G-APD) are promising new sensors for light detection in Cherenkov telescopes. This paper presents the realization of a small-size module employing 144 G-APDs, serving as a prototype for a larger camera. Dedicated front-end electronics have been developed for signal summation and amplification. The data acquisition system is based on the Domino Ring Sampling (DRS) chip. Gain variations of the G-APDs due to temperature or background-light variations are compensated by a high-voltage feedback system.**

***Keywords*: Cherenkov Telescope, Geiger-mode Avalanche Photodiode, Domino Ring Sampling Chip**

I. Introduction

The technique of Imaging Air Cherenkov Telescopes (IACT) has proven to be very successful in detecting very high energy (VHE, ~ 0.1–$100\,$TeV) γ-rays from cosmic sources. The key component is a fast and pixelized camera which has to resolve short (1–5 ns) flashes of Cherenkov light (300–500 nm wavelength) from air showers. A very good sensitivity is needed since, even using light-collection optics, e. g. a $1\,$TeV primary photon hitting the atmosphere only results in about 100 Cherenkov photons per m^2. Up to now, matrices of photomultiplier tubes (PMT) have always been used for this task (e. g. at MAGIC[1]). This is a well-known and reliable technology which, however, has some intrinsic disadvantages for telescope applications. First of all, PMTs are rather heavy and bulky and require a high-voltage (HV) supply of hundreds of V or even kV. Although developed since several decades, they furthermore usually still have a photon detection efficiency (PDE) of 20–30%.

Since a few years, a new type of semiconductor light sensor is being developed, the so-called Geiger-mode avalanche photodiode (G-APD) [2]. They are made up from multiple APD pixels operated in Geiger-mode, with the G-APD signal being summed up from the individual cells. In this sense, G-APDs are photon counting devices. A high gain comparable to PMTs is reached (10^5–10^6) and, potentially, higher PDEs of $\sim 50\%$. The angular acceptance has been measured to be very homogenous [3], thus allowing for interesting alternatives in the design of light collectors (Winston Cones, see [4]). The market for G-APDs is continuously growing and several manufacturers are working on their development. Thus, further improvements and cost reductions can be expected in the near future. For an IACT application under real conditions, however, several technical challenges have to be met. This mostly concerns the need to compensate for gain variations due to changes in temperature and night-sky background light (NSB).

In order to build a complete G-APD camera and work out solutions to the technical challenges, the FACT project (First G-APD Camera Test) has been launched. Starting from a small-size prototype module (see section III), a large camera with a field of view of 3–5° will be constructed. Several small tests with single G-APDs have been performed in the past [5], but a conclusive proof that these devices can replace or complement PMTs for future projects[2] is still missing.

II. General Camera Layout

In the current design, four G-APDs are combined to form a pixel. The pixels are arranged in either a rectangular or hexagonal pattern. On top of each G-APD, a non-imaging Winston Cone acts as a light concentrator (see figure 1) and cuts away a significant amount of NSB by accepting only photons with incident angles smaller than an adjustable value. The whole camera will be

[1]The Major Atmospheric Gamma-Ray Imaging Cherenkov telescope on the island of La Palma, Spain; see [1].

[2]Like the planned Cherenkov Telescope Array (CTA) [6].

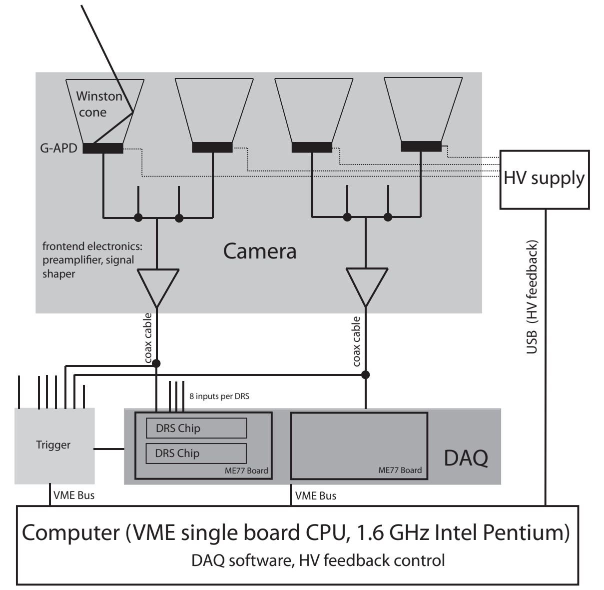

Fig. 1: Schematic overview of the G-APD camera layout (upper part) and the DAQ system (lower part, used in this form for the prototype module). A feedback system is used to regulate the bias voltage of the G-APDs in case of changing observational conditions. The camera will be mounted inside a water-tight box, while the DAQ and trigger components will be located in a counting room.

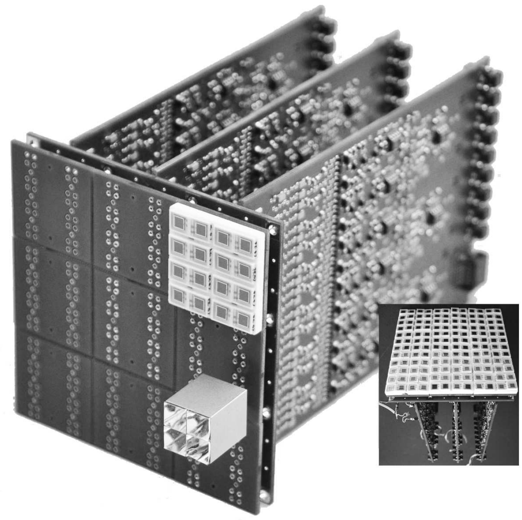

Fig. 2: Photograph of the prototype module with four pixels (16 G-APDs) assembled; for better visibility one block of four Winston Cones is mounted separately. Three amplifier boards are attached directly to the G-APD plane. The small photograph shows the fully assembled G-APD plane without Winston Cones. The active area is $8.6 \times 8.6\,\mathrm{cm}^2$.

located in the focus of a $\sim 10\,\mathrm{m}^2$ mirror dish, consisting of about 40 single mirrors with a focal length of $4.9\,\mathrm{m}$. For each pixel, signal amplification and shaping takes place at the level of front-end electronics. The signals are then sampled and, upon arrival of a trigger based on selected groups of pixels, read out and processed by the data acquisition system (DAQ, see section IV).

The G-APD plane will be actively cooled to avoid large temperature variations as well as temperature fluctuations among the sensors. Even more important than temperature-induced gain drifts are variations due to changes in the NSB. This background light produces a permanent current in the serial resistor of the readout electronics and thus reduces the effective bias voltage and therefore the gain of the G-APDs. To ensure a constant gain even under changing observational conditions, a feedback system is used. A pulsed light emitting diode (LED), installed in the center of the mirror dish, provides a strong signal with constant amplitude which is continuously monitored by the DAQ software. In this way, a change in gain is immediately recognized and an online feedback is given to the bias voltage supply.

III. PROTOTYPE MODULE

The prototype module comprises 144 G-APDs[3]. Each sensor has a sensitive area of $3\times3\,\mathrm{mm}^2$, covered by 900 cells of $100\times100\,\mu\mathrm{m}^2$ size or 3600 cells of $50\times50\,\mu\mathrm{m}^2$, respectively. The operating voltage is around $70\,\mathrm{V}$ and the internal gain $2.4\cdot10^6$. The dark count rate is below $5\,\mathrm{MHz}$ which is negligible compared to the minimal expected NSB rate of $40\,\mathrm{MHz}$ per G-APD. As light collectors, open aluminum cones with an affixed reflecting foil and a quadratic base are used (bottom side: $2.8\times2.8\,\mathrm{mm}^2$, top side: $7.2\times7.2\,\mathrm{mm}^2$, height: $2\,\mathrm{cm}$). The (negative) signals from four G-APDs are summed up, shaped and amplified in customized front-end electronics boards ($4\,\mathrm{mV}$ voltage output per μA current input, pulse decay times $< 10\,\mathrm{ns}$). Each board comprises twelve channels (48 G-APD inputs), with a power consumption of $150\,\mathrm{mW}$ per channel. Linearity exists up to an output voltage of $1200\,\mathrm{mV}$. In total, the prototype consists of 36 pixels and readout channels where each pixel corresponds to a field of view of $0.15°$ (for the mirror configuration described in section II). Dedicated bias voltage supplies have been developed, allowing to power each pixel individually and providing an interface for the HV feedback system (see sections IV and V). A photograph of the module is presented in figure 2.

While the size of the prototype is probably too small to distinguish between VHE γ and proton events, air showers can in general be seen. This is demonstrated in figure 3, showing the result of a simulation of a $10\,\mathrm{TeV}$ proton hitting the atmosphere and producing an air shower. Part of the produced Cherenkov light is detected in the camera as indicated, and an identification of such events seems possible even with the small prototype. The simulations have been performed using the MARS-CheObs software package [8].

[3]Hamamatsu MPPC S10362-33-100C [7] for the tests presented in this paper; the final sensors will be MPPC S10362-33-50C [7] which will also be tested with the described prototype.

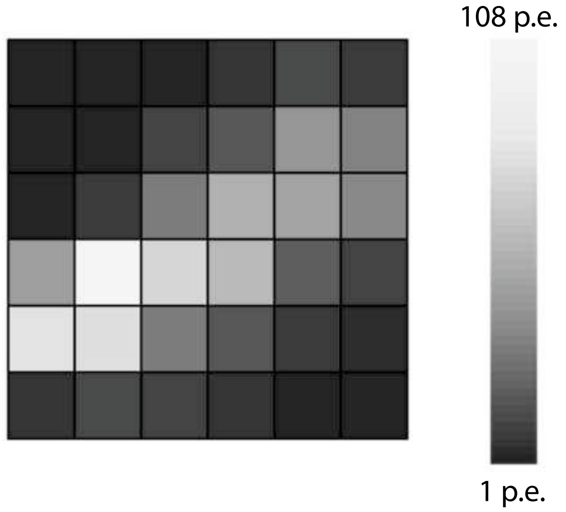

Fig. 3: Simulated air shower induced by a $10\,$TeV proton ($177\,$m impact parameter, $1.5°$ incident angle), as seen by the G-APD prototype module. The units of the grayscale axis are photoelectrons (p.e.); one square corresponds to one of the 36 pixels.

IV. Readout System

After the preamplifier boards, the signals are transferred out of the camera box by means of coaxial cables to customized linear fan-out modules which are realized as Nuclear Instrumentation Modules (NIM). Each of these modules has twelve input channels and provides two output lines plus an inverted one. While one of the former is connected to the DAQ system, the latter is used for triggering purposes (see figure 1). The trigger logic consists of a VME (VERSA Module Europa) CAEN V812 board where a majority coincidence of the innermost 16 pixels is formed. The DAQ itself is based on the DRS2 (Domino Ring Sampling) chip [9] containing ten pipelines of 1024 capacitive cells. Signal sampling is performed with a frequency of 0.5–$4.5\,$GHz, generated on-chip by a series of inverters. Such high sampling frequencies perfectly match the demands of an IACT, where an excellent timing is needed to reconstruct and identify γ-induced air showers. Each pipeline is read out at $40\,$MHz and externally digitized by a multiplexed $12\,$bit flash ADC (analog-to-digital converter).

The DAQ of the prototype camera employs VME boards to host the DRS2 chips, which are mounted on Mezzanine cards (two chips per card and two cards per VME board). In this design, eight channels of each chip are available for external signals (see also [9]). A single-board computer is used as VME controller, with an attached hard disk for data storage. On this machine, also the DAQ and HV control software is running. The connection to the G-APD bias supply module is implemented via the USB (Universal Serial Bus) standard. For a trigger rate of $10\,$Hz, typical data rates are of the order of $1\,$MByte/s which raises no problem for the DAQ. Depending on the sampling frequency of the DRS2, jitters ranging from a few up to more than $10\,$ns have been observed between the sampled signals and the trigger. For small latencies, this can be overcome by sampling the trigger itself for each chip in addition to the G-APD signals and thereby recovering the precise timing.

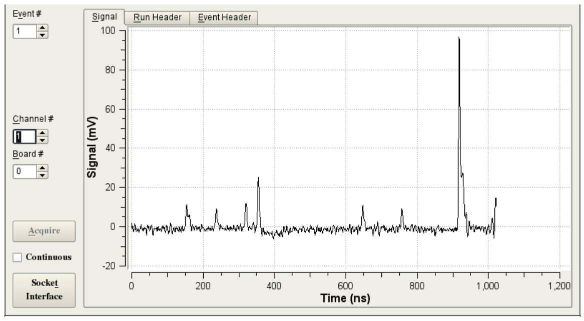

Fig. 4: Online raw data display of the readout system. For one pixel and event, the full DRS2 pipeline of 1024 samples can be seen, containing the signal of a LED pulser and several dark current events.

V. First Measurements

Figure 4 shows a screenshot of the online raw data display of the DAQ. The prototype camera was illuminated with a LED pulser (sub-ns signal width) and the DRS sampling frequency was set to $1\,$GHz. Thus, one bin on the horizontal time axis corresponds to one sample. The whole pipeline is displayed for one particular pixel and one event, triggered in this case directly by a logical signal provided by the pulser. On the right hand side, at about $920\,$ns, the LED signal is visible. The various small signals correspond to the dark current of the G-APDs. In figure 5, the functionality and response time of the feedback system is demonstrated. The prototype was set up at room temperature in a light-tight box for this measurement and constantly illuminated (same LED pulser as above). The signal amplitude was monitored for some time on one pixel and a target value was defined (40 in arbitrary units). The starting HV setting for the monitored pixel was $70.9\,$V. In the following, the light conditions were changed in three steps during which the box was opened by $\sim 1\,$cm, opened another time by $\sim 1\,$cm and then closed by $\sim 1\,$cm. The feedback system regulated the G-APD bias voltage to follow these conditions as indicated in the figure. Afterwards, the box was completely closed and the voltage went back to $70.9\,$V (not shown).

VI. Summary and Outlook

A prototype module of a G-APD-based camera for Cherenkov telescopes has been built and is currently being tested in the framework of the FACT project. First laboratory measurements show very promising results concerning the technical feasibility and towards large-scale applications in VHE gamma-astronomy. A key challenge is to avoid gain variations due to changes in

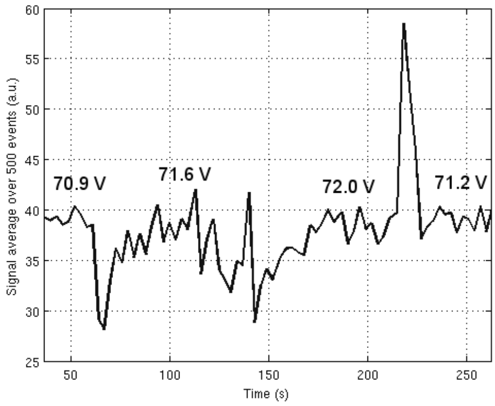

Fig. 5: Demonstration of the functionality of the HV feedback system for one pixel. Under changing light conditions, the G-APD bias voltage was readjusted online as indicated (see also text).

temperature or in the NSB light intensity. The solution presented in this paper makes use of a HV feedback system with which the gain of the G-APDs can be readjusted. Special hardware has been designed and constructed for this task. Also for the analog signal processing on the front-end level, dedicated electronics boards have been developed. For the data acquisition, the DRS2 chip is employed.

The next step with the small-size prototype will be to perform field tests, including the installation of the camera module in a telescope. Under real and changing observational conditions, the HV feedback will be tested and first Cherenkov light from air showers will be recorded. Based on the experiences gained, a large camera with a field of view of 3–5° will be constructed. This device is foreseen for the DWARF telescope [10] which will perform monitoring of strong and varying sources like the blazar Markarian 501 [11].

The data acquisition of the full G-APD camera will be upgraded to use the DRS4 chip [12], probably integrated in an Ethernet-based readout system instead of the VME solution. In addition, the $100 \times 100\,\mu\text{m}^2$ cell-size G-APDs will be replaced by $50 \times 50\,\mu\text{m}^2$ ones which comprise more cells and are therefore less influenced by the NSB conditions.

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