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The FlashCam Camera for the Medium-Sized Telescopes of CTA

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The Cherenkov Telescope Array (CTA) is the next generation ground-based instrument for the detection of cosmic gamma-rays with energies from about 20 GeV up to several hundred TeV. It is envisaged to be comprised of large-, medium- and small-sized telescopes (23 m, 10–12 m and 4 m mirror aperture, respectively). Within the scope of the FlashCam project, a novel camera for the medium-sized telescopes of CTA has been developed. Its integration follows a horizontal architecture, where the photon detector plane (hosting photosensors and pre-amplifiers) is a self-contained unit interfaced through analog signal transmission cables to crates containing the readout electronics. The FlashCam design features fully digital readout and trigger electronics based on commercial ADCs and FPGAs as key components. In this way different type of digitization schemes and trigger logics can be implemented, without exchanging any hardware. The data transfer from the camera to a server is Ethernet-based, and processing rates (including event building) up to about 2 GBytes/s have been achieved. Together with the dead-time free signal digitization this allows to operate at trigger rates up to several tens of kHz. Extensive tests and measurements with a 144-pixel setup (equipped with photomultipliers and electronics) have been performed, the results of which are presented in this paper. In addition, the status of the preparations for a 1764-pixel prototype with full-scale mechanics and cooling system is reported.

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1. Introduction

Ground-based gamma-ray astronomy aims for the detection of cosmic gamma rays with energies from a few tenth of GeV up to several hundred TeV. Such radiation is emitted, for example, by astrophysical sources like pulsar wind nebulae, supernova remnants, and active galactic nuclei. During the last decades, Imaging Atmospheric Cherenkov Telescopes (IACT) have emerged as the most efficient instruments, and by now more than 100 sources are known to emit TeV gamma-rays. Both spectral and morphological information is reconstructed from the data. Currently three major IACTs are running, one at the southern [1] and two at the northern hemisphere [2, 3]. They comprise two to five telescopes placed at distances of 50–100 m. The future Cherenkov Telescope Array (CTA) [4, 5] will consist of 100–150 telescopes and is expected to increase the sensitivity by a factor of ten.

IACTs detect the Cherenkov light which is emitted when a cosmic particle hits the atmosphere of the Earth and creates an air shower. The main wavelength range of this radiation is from 300 nm to 500 nm, and the photons arrive at ground within a few nanoseconds. Since there is Night Sky Background (NSB) light present during the observations, IACT cameras should have short exposure times for signal integration. The Cherenkov flashes are very faint with of the order of 100 photons/m^2 for a 1 TeV primary gamma. IACTs therefore comprise an optical focussing system, e.g. a large primary mirror built of individual segments. Depending on the energy of the primary particle, its direction and type, the shower topology is different. In order to exploit this, the camera sensors are pixelated. This is particularly important for the discrimination of non-gamma induced air showers, which dominate the recorded events. In general, the best reconstruction results are achieved if the same shower is imaged by several telescopes.

In order to provide high sensitivity over an energy range as large as possible, CTA will employ telescopes of different sizes [6]. The Large-Sized Telescopes (LST) will cover energies from about 20 GeV to 1 TeV, the Medium-Sized Telescopes (MST) from about 100 GeV to 10 TeV, and the Small-Sized Telescopes (SST) from about 1 TeV to 300 TeV. The core energy range, where the sensitivity of the array will be best, is the domain of the MSTs which will have an effective mirror area and a field of view of about 90 m^2 and 7° per telescope, respectively. The goal is to achieve an angular resolution of $\leq 0.05^\circ$ and an energy resolution of $\leq 10\,\%$ at TeV energies. CTA will have two sites, one at the southern and one at the northern hemisphere. This will ensure complete sky coverage. The southern array will be the larger of the two and, potentially, include 4 LSTs, 25 MSTs, 50–70 SSTs, plus an extension of 25–36 Schwarzschild Couder (dual-mirror) telescopes.

FlashCam is a camera design for CTA employing a digital readout system based on fast analog-to-digital converters (ADC) as sampling units and full signal processing on Field Programmable Gate Arrays (FPGA) [7]. It can be scaled to different telescope sizes and adapted to different types of photosensors. Besides excellent performance, also low costs and low power consumption have been key aspects during the development. An overview of the concept is presented in section 2. The focus of this paper is on a Photomultiplier (PMT)-based camera for the MSTs. During the last years the hardware for a MST-FlashCam has been developed (see section 3), and a test camera with 144 pixel has been built (see section 4). With this test camera several performance and verification tests have been done, and important CTA requirements have been validated. Currently, a prototype with full-size mechanics and cooling system for up to 1764 pixel is prepared (see section 5).

2. FlashCam Concept

The FlashCam design features an architecture where the Photon Detector Plane (PDP) and the readout electronics are mechanically separated. The readout boards are organized in crates and racks inside the camera, which significantly simplifies maintenance works. In addition to the photosensors, also pre-amplifiers and high-voltage (HV) generation are integrated in the PDP. A slow-control network is used for setting and monitoring the individual HV channels. The analog signals are transmitted via cables to the readout electronics where they are sampled and digitized continuously at 250 MS/s by means of fast ADCs. All further data processing is digital and FPGA-based, in particular the trigger generation. The data of triggered events is transfered from the readout boards via an Ethernet network to a camera server where the event building is performed. The digital trigger and the Ethernet readout are detailed in section 2.1 and section 2.2, respectively. In order to keep costs low, commercial components are used whenever possible.

2.1 Digital Trigger

One of the advantages of FlashCam is the digital trigger. Instead of a separate analog-based trigger branch, the digitized pixel-data are evaluated continuously (every 4 ns) inside FPGAs regarding possible air shower events. Performance- and cost-wise it is most efficient to do a trigger pre-processing and send reduced data to dedicated trigger boards. These boards receive all information necessary to provide a spatially uniform trigger. The event search algorithms are programmable and can run in parallel. Usually majority or sum triggers are implemented. Simulations have shown that using three-pixel patches on the pre-processor level gives excellent results [8]. For example, the amplitude-sum per patch can be computed and transmitted with up to 8-bit resolution to the trigger boards. There the main (camera) trigger decision takes place by further summing up different combinations of patch signals (e.g. groups of seven patches) and setting a threshold on the total sum. In this case 226 1-Gbit/s data links are needed on each trigger board. In its current implementation, the total transmission capability for trigger information of a FlashCam MST-camera is about 2.7 Tbit/s (cf. section 3.2). Once an air-shower-like event is found locally, the camera-wide data readout is triggered through a master distribution board. This board is also the interface to the CTA array trigger and timing system. FlashCam can be operated in an externally or a self-triggered mode.

2.2 Ethernet Readout

The event data are transfered from the front-end electronics to a camera server employing a high-performance protocol based on raw Ethernet. Each readout board has a 1-Gbit Ethernet interface (cf. section 3.2) and is connected to a standard network switch. If, for example, the switches are connected via four 10-Gbit lines to the camera server, 3.8 GByte/s can be transfered. This has been verified by the FlashCam team, using a cluster of computer nodes emulating the front-end electronics. Including event building, still more than 2 GByte/s can be processed. This allows to run a MST camera with 1764 pixel at trigger rates up to 30 kHz without any dead time. After event selection on the camera server, e.g. based on information from the CTA array trigger, full event information can be stored on a local disc or transfered to the CTA-wide data management at event rates of up to ~ 16 kHz.

3. Hardware Development

The development has been focussing on the CTA application. However, the readout system can be adapted also for other purposes. A FlashCam camera consists of a PDP, readout electronics, an Ethernet network, body mechanics, a cooling system, and power supply and slow control modules.

3.1 Photon Detector Plane

The PDP is comprised of 12-pixel modules (see figure 1, left) with 1.5-inch PMTs soldered to a double-PCB structure. Light concentrators are used to cover dead spaces. On the PCBs there is a pre-amplifier and HV supply (-700 V to -1500 V, 12-bit resolution) for each pixel, and a micro-controller for slow control. Three RJ45 cables are used to connect the (differential) signals to the readout crates, and a 9-pin Sub-D connector to provide 24 V and CAN-bus control. Each PDP board is equipped with a temperature sensor and the power consumption is about 0.24 W per pixel.

For CTA, a dynamic range from 1 p.e. (photoelectron) to at least 1000 p.e. is required. This can be achieved by employing a two-path pre-amplification scheme, with a low gain and a high gain channel for large and small signals, respectively. In order to reduce costs, the FlashCam team has instead developed a one-path scheme with a linear and a logarithmic range. The transition point (the clipping level) is adjustable between 100 p.e. and 300 p.e. Correspondingly, the analysis of the digitized signals is also performed in two ways. For small signals (linear regime) the full and time-resolved waveform is stored (typically 60–80 ns window) to reconstruct the pulse amplitude. For large signals (logarithmic regime) the pulse area is computed by signal integration on the FPGA.

3.2 Readout Electronics

The front-end electronics of a FlashCam MST-camera fits inside the camera body in one and a half 19-inch racks. Mini-crates (see figure 1, middle) represent the basic unit from a functional point of view. They contain a backplane and slots for up to nine boards. The backplane is a passive PCB and distributes power and trigger data as well as clock and synchronization signals. Two mini-crates can be combined to form a 19-inch crate. All readout boards utilize a motherboard (see figure 1, right) which is a common platform including a Spartan-6 FPGA, a 1-Gbit/s Ethernet interface and a backplane connector. Also temperature, humidity and current monitoring is provided. Full functionality is given once one or two daughter cards are plugged onto the motherboard. Three different daughter-card types are used, corresponding to ADC, trigger, and master boards.

ADC boards digitize up to 24 channels with 250 MS/s and 12-bit resolution. Less than 1.3 W power is consumed per channel. The sample data are stored in ring-buffers realized inside the FPGA. These buffers can be configured to have a depth of up to 8k samples (32 μs). Usually 20 samples (80 ns) are used per waveform, and best readout performance is achieved if the data transfer to the camera server is started after 100 events. The trigger boards receive and route the pre-processed data from the ADC boards. Most of the trigger data is transmitted via the backplanes of the mini-crates, but for a uniform acceptance some data also has to be exchanged via cables between mini-crates. The event selection is performed inside the FPGA of the trigger board. The trigger signal is then distributed by the master board which is also the interface to the telescope array and distributes camera-wide a clock and synchronization signal. A fully equipped mini-crate contains eight ADC boards and one trigger board and serves a total of up to 192 channels.

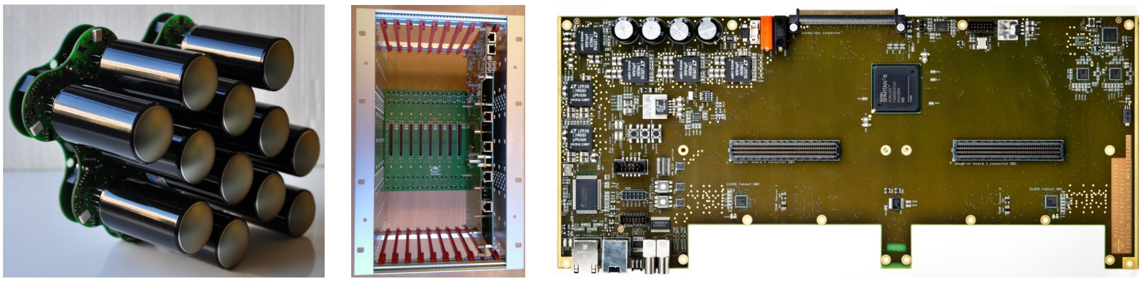

Figure 1: Left: Photograph of a PDP module with 12 1.5-inch PMTs (light concentrators not mounted). Middle: Mini-crate with backplane and slots for up to nine boards (only one inserted here). Right: Top view of a motherboard with two connectors for plug-in cards. Similar photographs in [9].

3.3 Stability Tests

The CTA telescopes will not have shelters, and therefore the cameras will be exposed to a sometimes harsh environment. In particular temperature variations are to be expected, with gradients of up to about 8 °C/h. Although a temperature control system will stabilize the conditions inside the camera (cf. section 5.2), it is important to verify the system performance against changes. Therefore tests in a climate chamber were performed. E.g. a mini-crate, with two ADC boards and one trigger board, was placed inside the chamber (see figure 2, left), and a test pulser outside. The pulses were processed and read out involving the full electronics chain.

The temperature inside the climate chamber was cycled between 5 °C and 35 °C at 30 °C/1.5 h. In figure 2 (right) the mean baseline and the mean pulse area of one channel vs. time are presented. The mean baseline varies only by 3 ADC counts (~ 0.2 p.e.), the mean pulse area by less than 0.5% which is negligible. In parallel, also the trigger transmission stability was verified. Since the relative timing between the 1-Gbit/s data streams and the receiving clock is crucial, individual delays have to be adjusted automatically. With temperature variations, the optimum sampling point changes. During the measurements, stable communication for a bit error rate as low as 10^{-14} was tested and achieved. Also a stress test with temperatures exceeding 60 °C was performed. No damage or loss of performance of the electronics was observed. Furthermore, a PDP module was exposed to bright light flashes of $> 10^6$ p.e. and was checked to still work properly afterwards.

4. 144-Pixel Camera

A major step in the FlashCam verification process has been the construction and operation of a 144-pixel test camera. In figure 3 (left) a photograph of the PDP of this camera is shown (front view). Two types of PMTs are installed, 36 Hamamatsu R11920 (in the center) and 108 Photonis XP2960 tubes. One mini-crate (with six ADC boards and one trigger board) connected to an Ethernet switch is sufficient for the data readout. The PDP of the test camera is located inside a light-tight box and irradiated by a pulsed laser diode (70–500 ps pulse length, 405±10 nm wavelength). A neutral density filter wheel with a nominal transmittance between 0.1% and 100% is used to control the light intensity. In order to simulate NSB conditions, a DC light source is furthermore located inside the box.

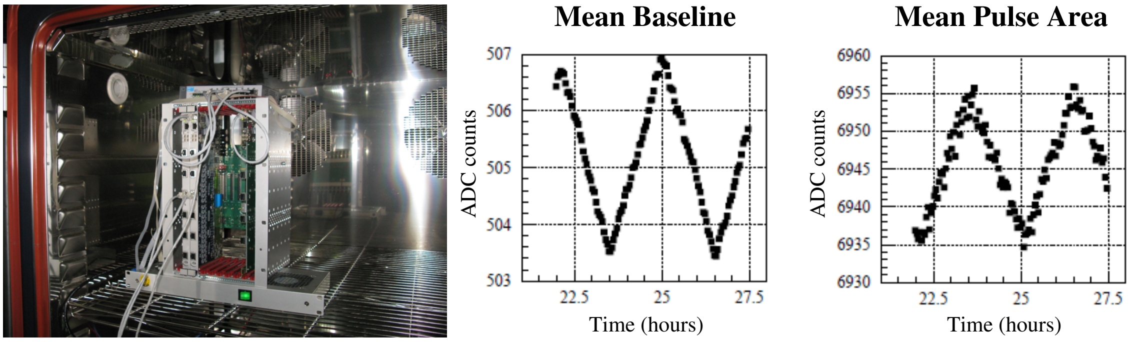

Figure 2: Left: Climate chamber setup for temperature tests. Right: Mean baseline and gain (pulse area) of one readout channel as a function of time. The temperature was cycled between 5 °C and 35 °C.

The conversion from ADC counts to p.e. is obtained from single-photon-electron response spectra. Such spectra are recorded with an additional attenuator between the laser diode and the filter wheel. One p.e. corresponds to about 15 ADC counts (amplitude) and 100 ADC counts (pulse area), respectively. Stepping through the transmittance of the filter wheel, the charge resolution (RMS) can be measured over three orders of magnitude. Below ∼ 100 p.e. pulse amplitudes are reconstructed from the waveforms recorded, while for larger signals the pulse area is calculated instead (cf. section 3.1). Figure 3 (right) presents the results obtained for two (out of 144) pixels at a NSB level expected for standard observation conditions (∼ 130 MHz/pixel). Each data point represents the mean value from 2000 events. As can be seen, the CTA requirement (red dashed line) is fulfilled over the full dynamic range.

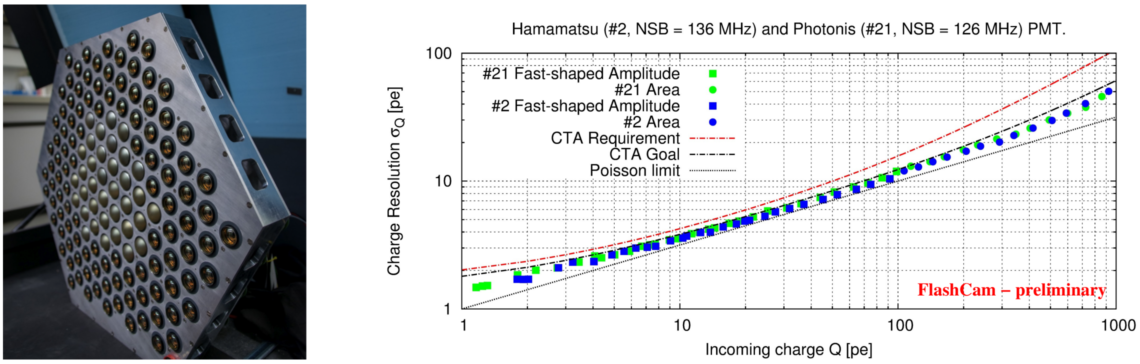

Figure 3: Left: Front view of the PDP of the 144-pixel test camera. Right: Charge resolution obtained. The two different colors correspond to two different pixels (out of 144). Squares and circles represent amplitude (below ∼ 100 p.e.) and pulse area reconstruction results, respectively. The red dashed line indicates the CTA requirement. Measurements performed at about 130 MHz/pixel background light. See also [10].

The measurements were also done simulating higher NSB levels using five different settings of the DC light source inside the light-tight box. By turning the laser diode completely off, also the baseline broadening can be studied at different background light levels. From these measurements it was verified that the effective NSB integration time is less than 10 ns, and that FlashCam fulfills the CTA requirements event at higher light-background rates than required.

5. Full-Size Prototype

In parallel to the operation of the 144-pixel test setup (see section 4), the FlashCam team has started the construction of a full-size prototype camera. This prototype can serve up to 1764 pixel and has the dimensions and interfaces such that it can be mounted on a real MST structure. The mechanical structure of the prototype camera has been finished already and is detailed in the following. In addition, a tested concept for the cooling system is discussed.

5.1 Mechanics

The body of the camera has a volume of about $3 \times 3 \times 1.1\,\mathrm{m}^3$ (height, width, depth). It is designed as a walk-in camera, with easy access via two backdoors to the readout electronics and the PDP (see section 3). All electronics (including power supplies and switches) is placed in two 19-inch racks which are integrated in the body structure. The walls of the camera consist of a light-weight composite material. In front of the PDP there is a shutter which is opened and closed like a roller jalousie in order to keep shadowing effects on the telescope mirror as small as possible. Once the shutter and the backdoors are closed, the camera is light- and water-tight. Including all components, the weight of the camera is about 1.6–1.7 tons. First rotation (stability) tests have already been performed.

5.2 Cooling System

The total power consumption of a FlashCam MST-camera with 1764 pixel is about 4.5 kW, assuming an efficiency of 85% for the internal power supplies and excluding the cooling unit on ground. Most of the heat (~ 2.7 kW) is dissipated inside the electronics crates which will be cooled actively by forced air-flow. Several air-to-water heat exchangers will be placed inside the camera for this purpose. They will be connected via a closed water loop to a cooling unit on ground which will comprise a large water-to-air heat exchanger and, optionally, a chiller. Depending on the exact realization of the system, and the anticipated power consumption, the chiller is probably needed only for the warmest outdoor temperatures under which all CTA systems are required to operate (-15 °C to 25 °C total range).

A series of tests with a mockup camera with real dimensions were performed in order to verify the cooling concept and to get rough numbers for the operational parameters. One volume-quarter of the camera was set up with insulating walls and dummy electronics boards, faking the heat dissipation of four mini-crates (~ 880 W). Also one ADC board was installed and read out to get realistic on-board temperatures. Several geometrical arrangements were tested, where e.g. the positions and number of fan units were changed. The (extrapolated) outcome of these measurements was that the cooling unit should provide water with a temperature of 20 °C to 25 °C (or lower[1]) at a water flow of the order of 10 ℓ/min (or higher). An effective air flow of about 150–200 m^3/h (or higher) is needed per mini-crate. In such a scenario the average camera temperature will be around 30 °C, and it takes about 15–20 minutes until the system is in thermal equilibrium.

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[1] In order to avoid condensation on cold surfaces, however, the water temperature should always be kept above 16 °C. Depending on the conditions, it might therefore be needed to heat the water.

6. Conclusions and Outlook

FlashCam is an excellent option for CTA cameras. The concept of separating the photon detector plane from the readout electronics allows to adapt or upgrade the system to different types of photosensors and to have easy access for maintenance works. FlashCam features a fully digital trigger which is FPGA-based and derived from digitized signals only. Thus no separate analog trigger branch is needed and different event search algorithms can be programmed. A front-end readout system based on standard network hardware and a raw Ethernet protocol has been implemented and tested. The data readout and processing is dead-time free up to event rates of more than 30 kHz. Using a test setup with a 144-pixel camera it has been validated successfully that FlashCam fulfills the CTA requirement on charge resolution over the full dynamic range (1 p.e. to 1000 p.e.), even in the presence of background light of several hundred MHz per pixel.

Currently, the construction of a full-scale camera prototype with 1764 pixel is ongoing. The body is already finished and first verification tests on the mechanical structure have started. The prototype will be (partially) equipped with photosensors and electronics, including all necessary auxiliary components like the power supplies and the cooling system. Both laboratory and outdoor tests are planned, the latter also together with a prototype of a MST mount to check all interfaces. The final verification step will be to operate a complete MST system on the CTA site.

Acknowledgments

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