A Smart Pixel Camera for future Cherenkov Telescopes

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The Smart Pixel Camera is a new camera for imaging atmospheric Cherenkov telescopes, suited for a next generation of large multi-telescope ground based gamma-ray observatories. The design of the camera foresees all electronics needed to process the images to be located inside the camera body at the focal plane. The camera has a modular design and is scalable in the number of pixels. The camera electronics provides the performance needed for the next generation instruments, like short signal integration time, topological trigger and short trigger gate, and at the same time the design is optimized to minimize the cost per channel. In addition new features are implemented, like the measurement of the arrival time of light pulses in the pixels on the few hundred psec timescale. The buffered readout system of the camera allows to take images at sustained rates of O(10 kHz) with a dead-time of only about 0.8 % per kHz.

1 Introduction

Ground-based gamma-ray astronomy has achieved a major breakthrough with the new results from the H.E.S.S. experiment, which has reached a critical sensitivity, and allows for detailed morphological, spectroscopic and temporal investigations of a large number of VHE gamma-ray sources. Future projects beyond H.E.S.S. will aim for several goals: lowering the energy threshold into the 5-10 GeV energy range, improving the sensitivity in the energy range up to about 100 TeV by an order of magnitude, and improving the survey capability of the instruments. Ideas for such projects have already been described before with emphasis on lowering the energy threshold 1. Systems of imaging atmospheric Cherenkov telescopes (IACT) at high altitude, with O(100) telescopes are amongst the new concepts. The cameras will have a field of view about 5°-10°, covered by several thousand pixels, and have to be able to record images at rates up to several kHz. As for the present generation of cameras, a short signal integration time in the 10-20 nsec range and very short coincidence trigger gates are mandatory. Due to the large number of telescopes, the cost for the cameras will be one of the critical parameters in the layout of such systems. Therefore a camera design is needed that provides the required performance and in parallel minimizes the cost per channel. In addition maintainability and stability of operation
are important design considerations. Features that allow to continuously monitor the performance of the camera are needed and an efficient commissioning is critical in systems with O(100) telescopes.

The concept of the Smart Pixel was presented for the first time in 1999 [2] in the context of the H.E.S.S. experiment. However, this development was not pursued at the time; it was resumed with significant modifications by the end of 2002. Below we describe the design of the prototype of a Smart Pixel Camera and focus on the camera electronics that has been developed at the MPI für Kernphysik in Heidelberg. We do not describe the photon detectors (photomultipliers) and the HV supplies, since the design of the Smart Pixel Camera does not depend specifically on them. The devices used in the prototype are identical to the ones in the current H.E.S.S. cameras (Photonis XP2960 and ISEG PHQ2960, respectively).

In the following we first introduce the general architecture of the Smart Pixel Camera, then describe the pixels and their readout in more detail and finally show some first results from test measurements with a prototype.

## 2 The Smart Pixel Camera

### 2.1 Architecture of the Smart Pixel Camera

A schematic overview of the architecture of the Smart Pixel Camera is shown in Figure [1]. The main building block of the camera is the Smart Pixel (Figure [2]), which consists of a photomultiplier (PMT), an active high voltage supply (HV) and the smart pixel electronics (SPE). The SPE contains all analog processing of the PMT signal, including signal integration, timing measurement, monitoring and analog storage. All information coming from the pixel is provided as analog levels, which are multiplexed onto one analog line from each pixel. The trigger of the camera is also contained in the pixels. It consists of a programmable N out of 7 cluster coincidence, where each pixel is the center of a cluster of 7 pixels in the hexagonal pixel matrix of the camera. The pixels are plugged into a segmented backplane, where each segment serves up to 16 pixels. The backplane provides lines for the distribution of the trigger signals, for the analog bus for the pixel signals, and for the serial command bus to the pixels. All functions on the pixel are controlled by the camera controller via the serial command bus (Fig. [1]). The power distribution is also done through the backplane. Each segment is controlled by a segment controller, which has 3 main tasks: the distribution of the digital commands to the pixels, coming from the camera controller, the multiplexing of the analog signals from the pixels to an ADC and to “OR” the trigger signals coming from the pixels and to distribute them through the camera trigger FAN-in/FAN-out.

The digitization of the analog output levels provided by the pixels is done using a
FADC system running in multiplexer mode. The synchronization of the switching of the multiplexers on the pixels and on the segments and the digitization on the FADCs are done by the camera controller. The digitized signals are stored in multi-event buffers on the FADCs and can be readout asynchronously. This allows to decouple the front-end readout (digitization) of the camera from the back-end readout (reading data into the CPU memory). Currently, for the readout of the FADCs and for the programming of the pixels through the camera controller a VME-based system is implemented.

Since all electronics of the camera is installed inside the focal plane box, the only interfaces are a power cable, the computer network connection and a pair of optical fibers to connect the trigger of the camera to a multi-telescope trigger in case of stereoscopic operation [3]. Therefore, the complete camera, including the trigger, and the digitization and readout system, can be tested and characterized in the lab before installation into a telescope at some remote location.

### 2.2 The Smart Pixel Electronics

The analog signal from the PMT is split into three paths: a path for signal integration, a trigger path and a path to derive monitoring information.
2.2.1 The Pixel Trigger

In the trigger path the analog signal is fed into a high bandwidth discriminator with programmable threshold and a minimal gate width of about 4 nsec. The discriminator signal is then delayed by a programmable delay of 0 to 5 nsec in steps of 1 nsec, which is used to compensate for the different PMT transit times, depending on the high voltage applied to the PMT. The discriminator signal is then sent via the backplane to the six neighboring pixels and also to an internal programmable logic device (PLD), where the discriminator signals from the six neighboring pixel arrive. On the PLD a programmable multiplicity of at least N pixels is required to release a trigger. This condition can only be fulfilled, when at least N neighboring pixels have generated a level 0 trigger within the coincidence time determined by the discriminator gate width. If the trigger condition is fulfilled, the pixel sends the trigger signal via the backplane to the segment controller, where the trigger signals from all the pixels of a segment are "ORed" and sent to a camera trigger FAN-in/FAN-out, which receives the trigger signals from all segments and distributes them simultaneously via the segment controllers to all pixels.

In order to monitor the performance of the pixel trigger, the rate of discriminator signals and the rate of triggers generated by the pixel are also provided as analog levels.

2.2.2 Signal Integration

In the signal integration path, the signal is first amplified and then delayed by about 90 nsec using a delay line, which is based on a 12 layer printed circuit board (PCB). The PCB contains a structure of a meandering electrical line embedded in ground lines and between ground layers, shaped in a way to imitate a quasi-coaxial structure. The resulting pulse after the 90 nsec delay has a acceptable width of about 8 nsec FWHM.
After the delay line, the signal is split into two paths with a difference in amplification by a factor of 18 (hi-gain and lo-gain path). A V/I converter and a gated integrator are used to integrate the charge of the two channels. The integration is started when a camera trigger occurs. The width of the integration gate is programmable in steps of 3 nsec from 10 nsec to 25 nsec. Also the delay of the gate is programmable in steps of 1 nsec from 0 to 5 nsec, again to compensate for individual transit time differences of the PMTs. The signals from the gated integrators are connected to the pixel multiplexer.

2.2.3 Pixel timing

The precise knowledge of the time structure of the Cherenkov images might help to suppress background events offline. A cost-effective possibility is to use time to amplitude converters (TAC), which are implemented on the pixels using a constant current source and a gated integrator. Upon a camera trigger, the TACs of the pixels are started. The discriminator signals are delayed internally on the pixels by about 95 nsec (a few nsec longer than it takes to generate and distribute the camera trigger) and used to stop the TAC. The TACs therefore measure the relative trigger time of the pixel discriminators with respect to the camera trigger. If a pixel has not triggered in an event, its TAC will run into an overflow. Besides the timing measurement, this information in addition tells which pixels have triggered in a given event. The resolution of the time information is well below 1 nsec, depending on the pixel amplitude (see below). The trigger information can be used to precisely determine the trigger behavior of the discriminator (see below).

2.3 Digitization scheme and dead time

The pixels provide their event information (hi-gain and lo-gain amplitude and time information) and monitoring information, like PMT anode current, pixel trigger rate and temperatures as analog levels. As explained above, the pixel information is multiplexed onto one analog line. The analog lines of 16 pixels are then multiplexed onto one analog line for the segment, which is connected to a FADC channel. By switching the segment and pixel multiplexers, the corresponding signals can be selected and digitized. For "normal" events, the two amplitudes (hi-gain and lo-gain) and the time information per pixel are digitized. In monitoring events, also the remaining values are digitized. The switching of the multiplexers and the digitization is done at a frequency of 10 MHz. Since each segment with 16 pixels is connected to one FADC channel, the digitization of an event with 3 event-related values per pixel takes only 4.8 µsec. Since the data is written directly into a multi-event buffer on the FADC, the front-end dead time per event amounts to only 4.8 µsec plus about 2 times 1.5 µsec.
high gain (FADC units)

1600 1700 1800 1900 2000 2100

entries

0

100

200

300

400

500

600

amplitude (p.e.)

10 20 30 40 50 60 70

relative amplitude resolution

0

0.1

0.2

0.3

0.4

0.5

gate width 19 ns
gate width 13 ns

Figure 3: a) Single photoelectron spectrum of a pixel. b) Relative amplitude resolution of the pixels as a function of the light pulse amplitude. The line describes the $1/\sqrt{N_{p.e.}}$ law, which is the limit given by poisson fluctuations of the number of photoelectrons at the photocathode.

charge-up and reset time of the analog levels on the pixel. This dead time is independent of the number of pixels or segments in the camera, since the digitization of different segments is done in parallel.

The event buffers on the FADCs (Model: SIS3300) can be read out asynchronously with 64 Bit block-transfer in DMA mode via the VME bus, while new events are written to the buffers. With this data transfer scheme a rate of about 38 MByte/sec has been reached. Due to the decoupling of the front-end from the readout of the back-end, up to a mean event rate of about 5-6 kHz, the dead time of the camera is given only by the front-end dead time of about 8 $\mu$sec / event. If the camera uses significantly more than about 1000 pixel or operates at a higher mean event rate, the readout of the FADCs has to be done using more than one CPU (on a segmented VME backplane) and the back-end bandwidth of the system then scales with the number of CPUs used.

3 First Test Measurements

After two iterations of prototyping of the pixel electronics, a larger batch of pixels has been produced in order to be able to test the performance of a prototype camera after system integration. The prototype camera contains 64 pixels (as of April 2005) and uses the full digitization and triggering scheme, but also the final power supply and cooling system, in order to test possible impact of these devices on the performance or noise of the system. The electronics is mounted in a camera housing, which can
contain up to 1020 pixels and which can be used in a future prototype telescope. The camera is set up in a dark room, where it can be illuminated with a high rate of LED pulses with a pulse width of 3 nsec and amplitudes of a few photoelectrons per pixel, and also with a pulsed N₂-laser through a scintillator and a programmable neutral density filter wheel, with 3 nsec pulses and intensities up to a few thousand photoelectrons per pixel. Figure 3 a) shows an example of a single photoelectron spectrum, (as obtained by illumination with the pulsed LED) together with a fit to the spectrum. From the fit one obtains a typical value of 0.2 p.e. electronics noise of the hi-gain channel and an amplitude resolution of 0.45 p.e. of the single photoelectron peak. In figure 3 b) the amplitude resolution of the hi-gain channels as a function of the light pulse amplitude is displayed. It can be seen that the resolution is close to the limit given by poisson fluctuations of the number of photoelectrons at the photocathode. The resolution of the TAC is demonstrated in figure 4 a), where the time difference between two pixels is plotted. As expected, the time resolution depends strongly on the light amplitude (figure 4 b)). At amplitudes close to the discriminator threshold the resolution is about 1 nsec, and reduces to < 500 psec at amplitudes larger than 10 p.e. .

As mentioned above, the time information of each pixel also tells if a pixel has triggered in a given event. Therefore the trigger information of a pixel can be related to its amplitude information, allowing to measure precisely the trigger threshold of each pixel during normal operation. This is illustrated in figure 5 a), where the trigger probability of a pixel is plotted against the measured light amplitude. Figure 5 b) shows the measured trigger threshold of a pixel in units of photoelectrons as a function of...
the preset threshold in digital units. Such measurements can be used to calibrate and monitor the pixel thresholds.

4 Summary and Outlook

The Smart Pixel Camera is a promising concept for future IACT systems. The first tests indicate that the camera provides the performance needed in such telescope systems. Due to the highly multiplexed readout and the high integration of the electronics, the total cost per channel of such a camera is significantly below current designs. Further tests with up to 200 pixels are planned.

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References

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