Fast Readout of Multi-channel Detectors by using a CMOS camera

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***Abstract*. The multi-channel detectors are essential part of modern experiments. The number of readout channels for every future detector is usually much higher than before. Usually the number of channels of a detector constrains the minimal data acquisition system (DAQ) requirements and the total price of the readout system. For the future ground-based gamma-ray instruments like for example, the Cerenkov Telescope Array (CTA) the DAQ system should fulfill several stringent requirements: low power consumption, compactness, ability to record a rate of 1kHz for several thousand channels and affordable cost per channel.**

We present here an alternative to the conventional ADC system. The analog pulses from the light sensors are converted into optical signals and fed into the optical fibers, which are bundled as a fiber optic plate (FOP). The externally triggered high-speed CMOS camera coupled to a fast Gated Image Intensifier makes a photo of the FOP, when the optical signal flashes the FOP. The Gated Image Intensifier serves as an ultra-fast optical shutter and event delimiter.

***Keywords*: multichannel detectors, fast readout, Cherenkov telescopes.**

I. Introduction

The ground based γ-ray astronomy made a great progress in last 10 years. Besides new analysis methods, a large part of the success is due to the improved performances of the detectors. The imaging technique required fine-pixelized photo sensor cameras with number of channels ≥ 1000. The future ground-based experiments like The Cherenkov Telescope Array (CTA, [1]) and the Advanced Gamma-ray Imaging System (AGIS, [2]) are planning to exploit photo sensor cameras with more than 2000 channels. The data acquisition system of individual telescope should be capable to record at least 1kHz event rate. With increase of the number of channels the cost of ADC (or FADC) readout system can dominate the total cost of the detector. In the case of the wide-field of view (wide-FOV) Cherenkov telescope with the imaging camera of high resolution the number of channels can exceed 10000 and the trigger rate can be on the order of several tens of kHz. These values constrain the minimum DAQ requirements.

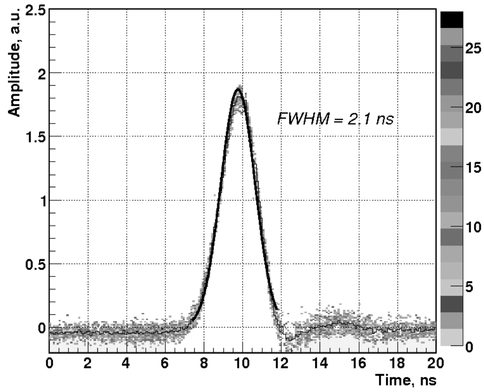


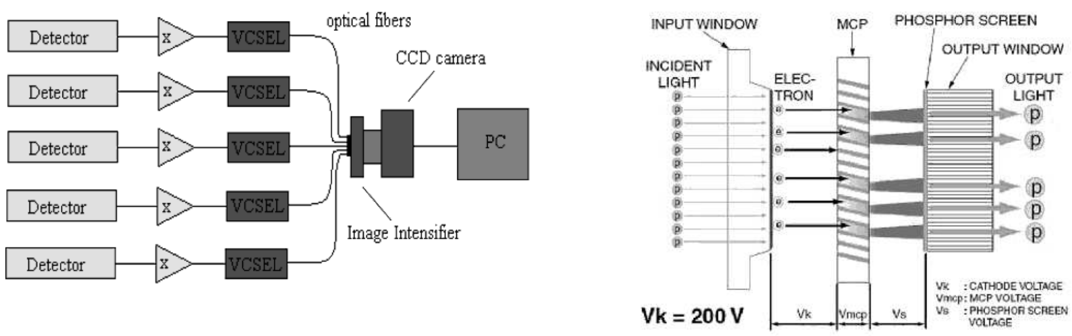
Fig. 1. Single photo electron pulse shape for the MAGIC telescope readout system, $FWHM = 2.1ns$. The typical intrinsic time spread of the Cherenkov flashes from the Extended Air Showers for the Cherenkov telescopes is 3-10ns.

II. The Readout System

The main concept of the alternative readout system for multichannel detectors discussed here was presented in [3].

The electrical analog signal from a photo sensor is converted into optical by using the Vertical Cavity Surface Emitting Laser (VCSEL) diodes, and fed into an optical fiber like it is done in currently operating MAGIC telescope [4]. All the fiber ends are bundled in one compact bunch, which has a size of only a couple of centimeters. The fibers at the end of the bundle can be glued together and polished making a "fiber optic plate"-like structure. In this way the image of the event in the detector is translated into the surface of the fiber optic plate (FOP). This image on the FOP can be photographed by using an externally triggered CMOS camera.

However, the internal CMOS camera shutter is not fast enough for the events with durations of several nanoseconds. Signals with $FWHM \approx 2ns$ are produced by fast photomultiplier tubes (see Fig.1). The total time spread of the event can be $10 - 20ns$. In order to optimize the signal to noise ratio the exposure time of the CMOS camera should be reduced to the event duration. For this purposes a gated Image Intensifier unit is introduced before the CMOS camera that serves as a fast optical shutter. The block-diagram of the data



(a) (b)

Fig. 2. Block diagram of the proposed data acquisition system a) and Image Intensifier operation scheme (courtesy of Hamamatsu) b).

acquisition system is shown on Fig.2a.

A. Image Intensifier

The Image Intensifier operation principle is shown on Fig.2b. The light emitted by optical fibers hits the photocathode of the Image Intensifier, inducing electrons. In the "open" state of the Image Intensifier, these electrons are accelerated by the voltage $V_k \sim 200V$ to the micro channel plate (MCP) where an electron multiplication process, similar to photomultiplier dynode system, takes place. The amplified electron beam from the MCP output hits the phosphor screen, inducing amplified light that is transmitted by the fiber optic plate to the output window of the Image Intensifier. If the voltage between the photocathode and the MCP V_k is reversed, the primary electrons cannot reach the MCP and the Image Intensifier is in the "closed" state. This feature can provide a contrast of 10^9 between the open and the closed states of the intensifier unit. The switching between states can be as fast as $1-2ns$ and the minimum open state duration can be as short as $5-20ns$, what provides the required exposure time of the CMOS chip.

In our tests we used the C9016-21 Image Intensifier from Hamamatsu with the gate duration of $20ns$.

B. CMOS camera

The crucial parameters of CCD/CMOS cameras in the proposed application are the maximum frame readout rate and the dynamic range. CCD chips usually provide better uniformity of the image and have a hight sensitivity, but due to serial charge readout the maximum frame rate is limited to a few hundreds frames per second (fps), even for the reduced frame resolution. The CMOS chip has integrated switches directly on the pixel and the readout speed is not limited by the charge transfer time. Thus, CMOS chips can easily reach a full frame readout rate above thousand fps and even can reach 5000-10000 fps with reasonable resolution (512x512). The CMOS camera will have a substantially higher noise compared to a CCD but it is not an advantage in the applied scheme because of the very intense light from the VCSELs, that needs to be attenuated. The CCD chips with dual or multiple readout can approach the CMOS scheme. In the table below some of commercially available high-speed imaging cameras are listed. All cameras, except the one from Hamamatsu, are based on the CMOS technology.

TABLE I
HIGH SPEED IMAGING CAMERAS

Company	Resolution	Readout rate, fps
MIKROTRON	512x512	5000
Optronis	1280x1024	1000
Imaging Solutions	512x512	5000
LaVision	1024x1024	3000
PCO	2016x2016	1100
Hamamatsu (CCD)	640x480	150

The dynamic range D of the camera we define as $D = C_{well}/3RMS_{read}$, where C_{well} is the pixel full-well charge capacity (in electrons) and RMS_{read} is the readout noise variance in equivalent electrons. All cameras listed above have a dynamic range more then 1000. This value is high enough for the proposed application.

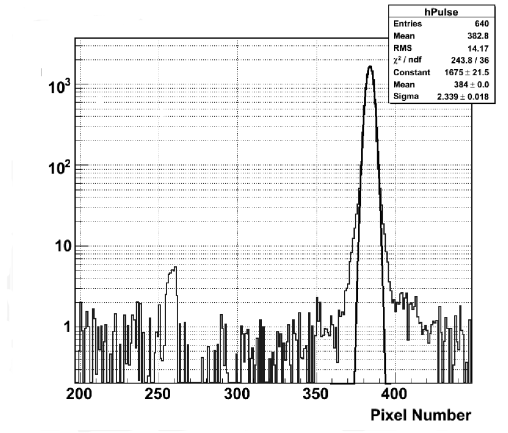
III. RESULTS

The first prototype of the fast readout system was mounted in the electronic laboratory of the Max-Planck-Institute für Physik (MPI). The preliminary tests, presented in this paper were done with the integrated solution offered by Hamamatsu: the Image Intensifier Unit C9016-21 was coupled with relay lenses to the Hamamatsu C9300-221 High Speed CCD camera with 8x8 pixel grouping option.

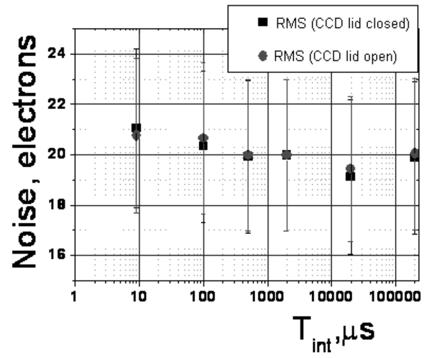
The images of a bunch of optical fibers were recorded with the rate of 150Hz. The Image Intensifier Unit was operated in the gated mode with $20ns$ open state duration - an exposure time of the phosphor screen. The spot of used fiber had a $FWHM \approx 5$ pixels (in one dimension, see Fig.3a). Thus, for the distance between the spots of 10 pixels, one can place ~ 3000 fibers at one frame with 640x480 resolution.

When the Image Intensifier Unit is in the closed state and the CCD shutter is open, the dark noise of the image RMS_{dark} can be approximately described by the following relation:

$$RMS_{dark}^2 = RMS_{phos}^2 + RMS_{CCD}^2 + RMS_{read}^2$$

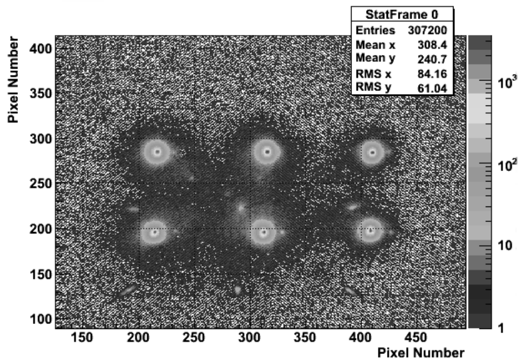


(a)

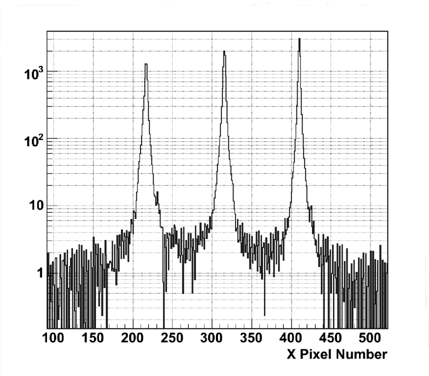


(b)

Fig. 3. (a) 1-D profile of the image for two fibers (dark current substracted). The spot from the fiber occupies around 5 pixels (1-D $FWHM$). Signals (arbitrary units) are equivalent to 3 and 1000 photoelectrons in photomultiplier tube. (b) Dark noise of the CCD frame in equivalent electrons versus the CCD integration time. Squares: CCD lid is closed, circles: CCD lid is open and the phosphor screen shines to the CCD chip.



(a)



(b)

Fig. 4. (a) An example of an image of 6 fibers with substracted CCD dark current with the 20ns phosphor screen exposure time. Signals corresponding to $\sim$ 1000 PHes charge in photomultiplier. (b) 1-D profile of 3 spots from the upper row (arbitrary units).

where RMS_{phos} - is the dark noise of the Image Intensifier phosphor screen and RMS_{CCD} - is the dark noise of CCD chip. These two terms are expected to raise with a square root law when the frame integration time is increased. The last term RMS_{read} - is the readout noise of the CCD chip, which does not depend on the frame integration time. As presented on Fig.3b, the dark noise of the image showed no dependence on the CCD integration time in a very wide range. Moreover, the frame dark noise stayed constant for open and closed CCD camera lid (see Fig.3b). Thus, the dark noise of the image was dominated by the readout noise of the CCD chip, what makes this parameter crucial for selecting the appropriate CCD/CMOS chip. A sample image of the six fibers and corresponding 1-D spots profiles are shown on Fig.4.

IV. Conclusions

The preliminary results obtained with the Hamamatsu test setup at MPI Munich showed a good feasibility of the proposed readout system. The performance is mainly constrained by the CCD chip, which was used in the experimental mount. A commercially available CMOS chips can fullfill the application requirements: frame rate above 5000 fps and a dynamic range ≥ 1000. Other constrain is the significant delay time between the system trigger and the actual opening of the Image Intensifier unit. In order to synchronize the signal pulse with an open state of the Intensifier unit the signal should be additionally delayed.

Currently we are preparing tests with an improved setup: a CMOS camera from the company MIKROTRON with the readout rate of 5kHz for the 512x512 frame resolution and the C9548-03 Hamamatsu Image Intensifier unit.

References

[1] *www.cta-observatory.org*

[2] *http://www.agis-observatory.org*

[3] R. Mirzoyan et. al. *A concept for the readout of multichannel detectors by using analog signal transmission via optical fibres coupled to a fast CCD*, AIP Conf. Proc. – June 2, 2000 – Volume 515, pp. 358-362

[4] C. Baixeras et al. *Nucl. Instr. and Meth. A* 518 (2004) 188