Large size SiPM matrix for Imaging Atmospheric Cherenkov Telescopes applications

Giovanni Ambrosi[2], Daniele Corti[1], Maria Ionica[2] , Christian Manea[1,3], Mose Mariotti[1], Ignasi Reichart[1], Riccardo Rando[1], Cornelia Schultz[1]

1) University of Padova and INFN Sezione di Padova, 2) INFN Sezione di Perugia, 3) INFN Sezione di Trento

SiPM photo detectors are nowadays commonly used in many applications. It has been shown that SiPM are "nearly ideal" light sensors for Imaging Atmospheric Cherenkov Telescopes (IACTs) [6], however this was proven, so far, only for small size telescopes (e.g. FACT [2,3]). For large size telescopes like MAGIC or the future Large Size Telescope (LST) of the Cherenkov Telescope Array (CTA) project, a pixel size of some square centimeters is needed. An analog amplifier and sum stage was built and characterized. A large and compact SiPM matrix prototype, with the associated focusing optics, was assembled into a monolithic light detector with an active area of ~3 cm^2. The performance of the electronics is tailored for IACT applications, with fast signal and adequate signal-to-noise (S/N) ratio.

Introduction

In recent years ground-based very-high-energy gamma-ray astronomy has experienced a major breakthrough, as demonstrated by the impressive astrophysical results obtained with IACTs like H.E.S.S., MAGIC or VERITAS [1]. The CTA project is under design to provide at least 10 times increase in sensitivity compared to current installations and a wider energy range down to a few tens of GeV and up to about 100 TeV.

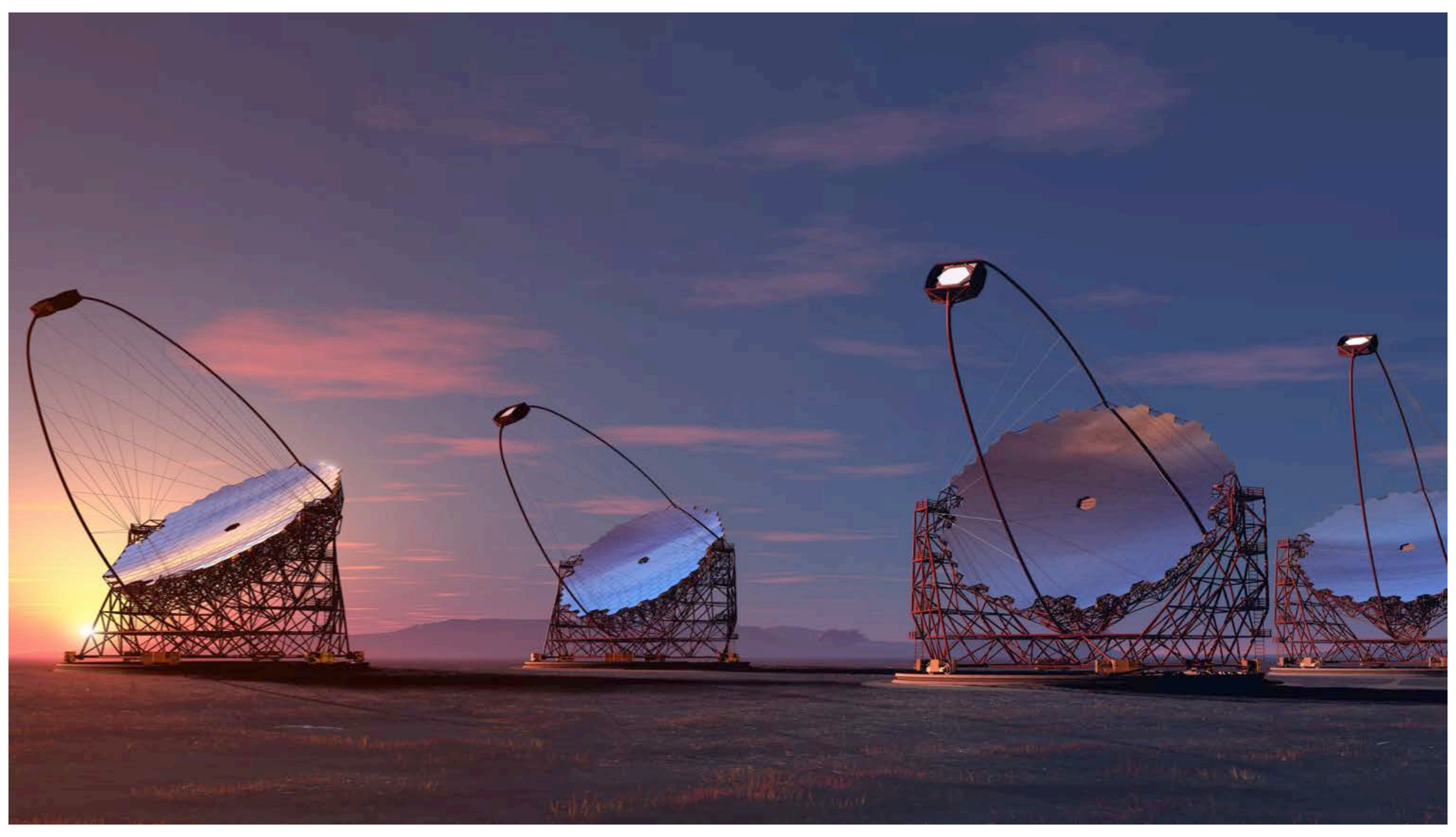

Fig. 1: An artistic view of the future big Cherenkov telescope LST of CTA.

Large scale IACTs as MAGIC, H.E.S.S.-II or the future LST (fig. 1) of CTA are designed to cover the lower energy range, so they must collect the maximum number of Cherenkov photons generated by the weak Cherenkov light flashes of few nanoseconds. For this reason, the reflective surface area and the telescope size itself have to be maximized: it is important that the efficiency of the photo-sensor will be as large as possible to capitalize on the large cost of the telescope mechanics. The baseline design of a large IACT includes a focal-plane camera based on photo multiplier tubes (PMTs).
The goal of this research is to develop a silicon-based prototype for an IACT pixel, the "basic element" of a Cherenkov telescope focal-plane camera. This will be the solid-state equivalent of a PMT (see fig. 2), having a few square centimeters of sensitive area (~1 inch pixel in diameter: 0.1° @17 m focal length in the case of MAGIC), high photon detection efficiency, good single-photon sensitivity, and time response around 2-3 ns.

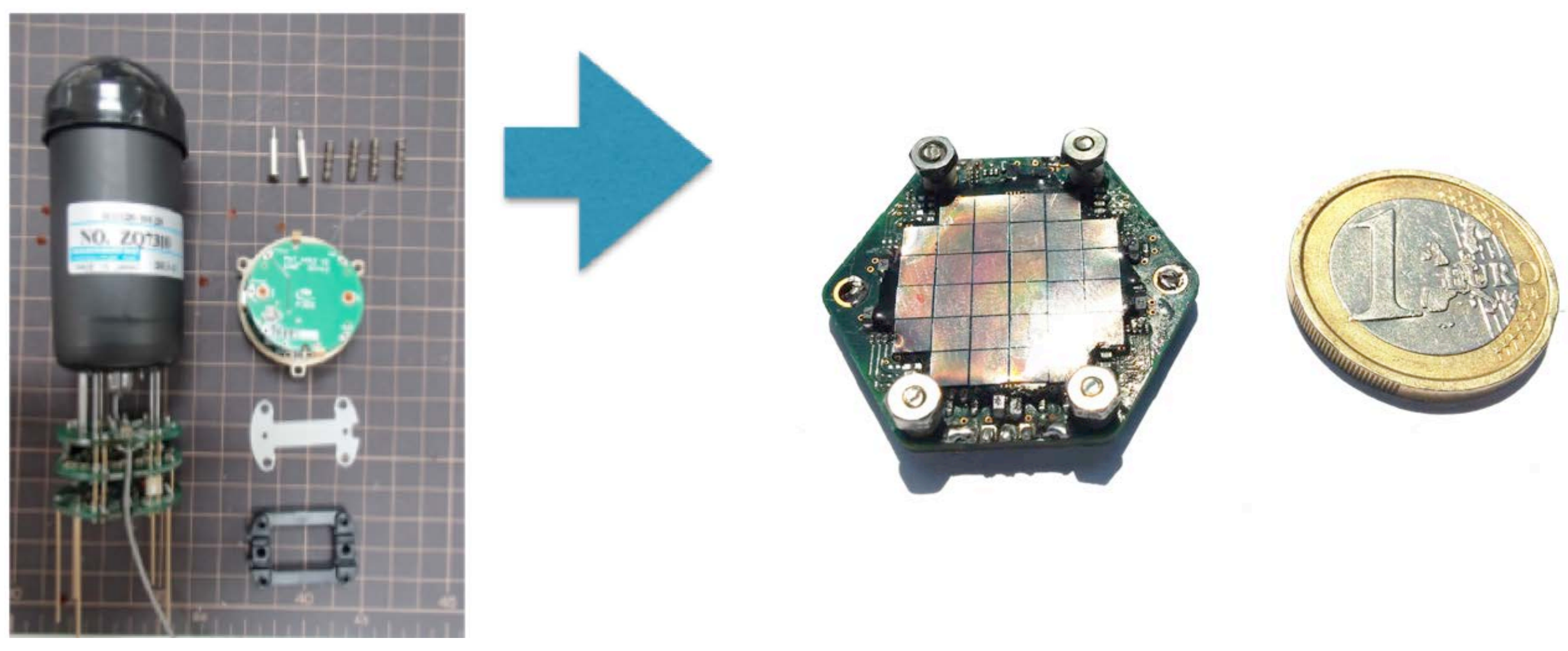

Fig. 2: Comparison of a PMT sensor (left) and its electronics with respect to a SiPM matrix with integrated electronics in the same PCB (right).

The SiPM detectors are an almost ideal device to be used in the focal plane of a Cherenkov telescope, given their high detection efficiency and the fact that their relatively large dark count is irrelevant, since the night sky glow causes a large photon background. Large size detectors, however, have not yet been built. The problems encountered in the construction of large, monolithic photon sensitive silicon devices are mainly related to the large detector capacity, which significantly increases the noise time of the sensor, and to the low device yield due to the natural occurrence of defects on the silicon wafers. A good compromise is to segment the detector into elements of small size, and summing the output signal electronically, e.g. through an analog high speed adder.

SiPM pixel: system description

The overall layout of the SiPM pixels will be identical to those of the PMT camera, i.e. each sensor will cover 0.1° and match the exit window of the light concentrator with hexagonal entrance pupil. The SiPM pixel will be composed of a matrix of sub-elements, totaling a few square centimeters of active area (fig. 4 for a schematic layout). Each sub-element will be connected to a simple passive high-pass filter, to differentiate the signal and to decouple the capacitance of the element from the other elements, thus keeping the pulse rise-time around 1 ns. The signals from all the elements will be summed up in an adder circuit and then propagated to the acquisition electronics.
The dark count rate will be typically around 100-200 kHz/mm^2, i.e. 50-100 MHz per pixel at 25°C: since the minimum night-sky background light will be of the order of 250 MHz, no cooling of the sensor will be necessary. The goal dynamic range should be >2000 (photoelectrons) phe, which is more than sufficient for the important shower energy range from a few GeV up to 250 GeV. Above ~250 GeV most border pixels of a shower image are still in the dynamic range while the central saturated pixels can be either extrapolated or determined with a lower precision from the base width of the truncated pulses (time-over-threshold).

Signal conditioning and adder circuit

The signal conditioning starts with a passive high-pass filter to keep the fast transient of avalanche charge, while mitigating the longer tails. This choice is made to keep the integration time short: long integration times cause a larger impact of the background light counts to the signal noise, which is the most detrimental effect for the Cherenkov image quality, together with poor statistics.

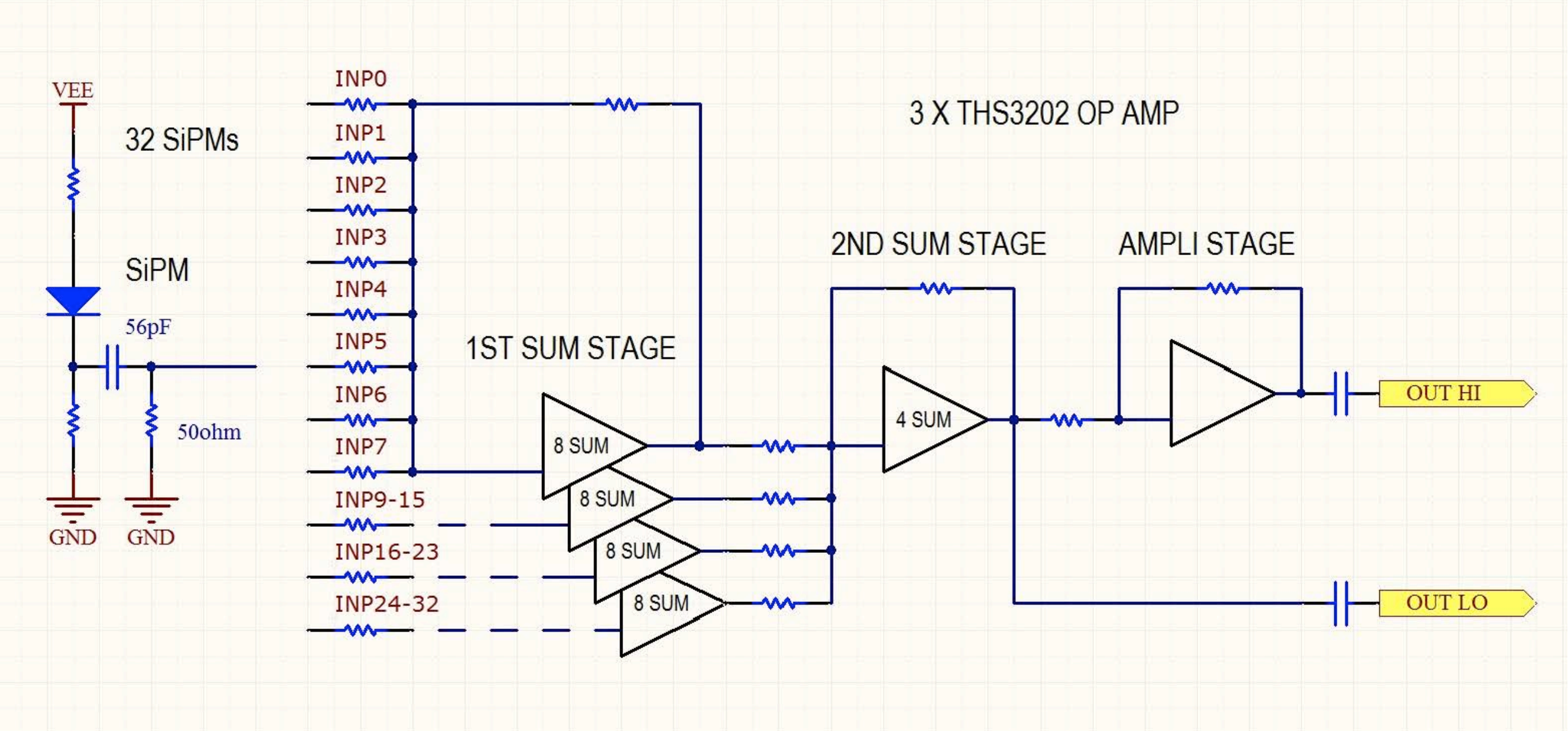

Fig. 3: Signal conditioning with a passive filter in the left, in the right the adder circuit for a total of 32 sensors.

An eight layers FR4 printed circuit board (PCB) has been designed taking care of the net connections and component positions, respecting the golden rules in low noise electronic systems. Screw holes are connected to the inner ground plane in order to guarantee the SiPM heat dissipation. Two matrix layouts have been considered, 32 3x3 mm and 9 6x6 mm elements, to compare different sensor segmentations for this kind of application and select the best one.

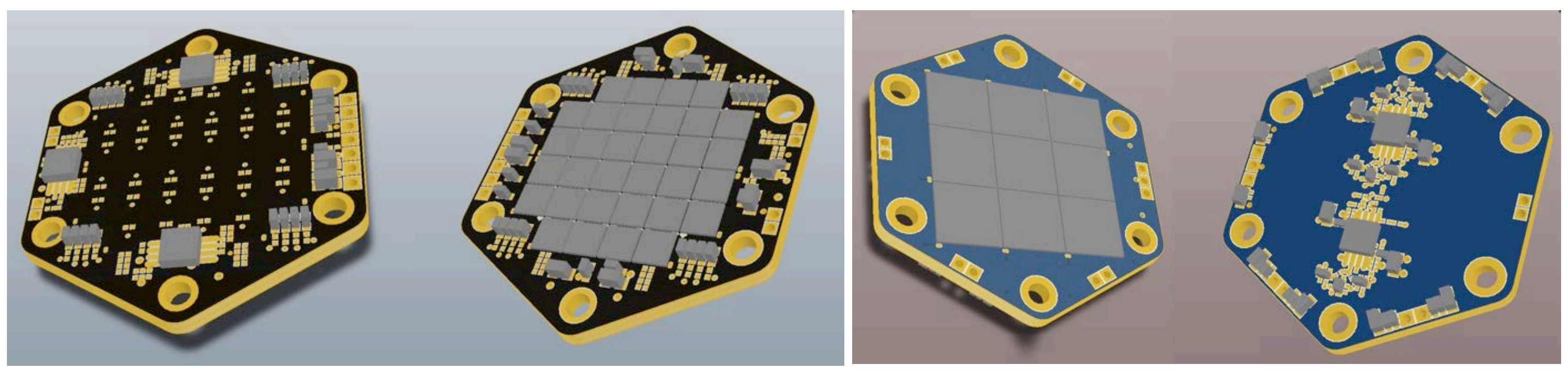

Fig. 4: Layout for a 32 3x3 mm and a 9 6x6 mm pixel PCB.

SiPM are connected to the first sum amplifier, via a biasing circuit, where the signals are picked up on precision resistors and decoupled through a C-R filter. The adder circuit is made by a 2 steps. The operational THS3202, chosen for this application, is a dual current feedback amplifier type, with high slew rate and the better low noise characteristics at high working frequency. The first sum step bundles eight sensors per amplifier to limit the input capacitance. The four respective outputs are summed at the second stage where the output signal is amplified to match the gain required by the data acquisition.

Light concentrator optics

The goal of the camera optic is to map the focal plane into the pixelized camera avoiding dead areas between pixels and to compress the hexagonal entrance pupil area into the sensor area. The angular pixel size is ~0.1° = 3 cm for MAGIC and 5 cm for LST. The area compression ratio is limited by the optical input acceptance (F/D main optic design) and the angular acceptance of the SiPM.
To optimize the performance of the camera optics in terms of compression ratio, the incident angle distribution to the photo-sensor and a maximized photon flux, detailed ray tracing simulation (fig. 5) have been performed and different possible solutions are under investigation for the MAGIC telescopes and for the LST.

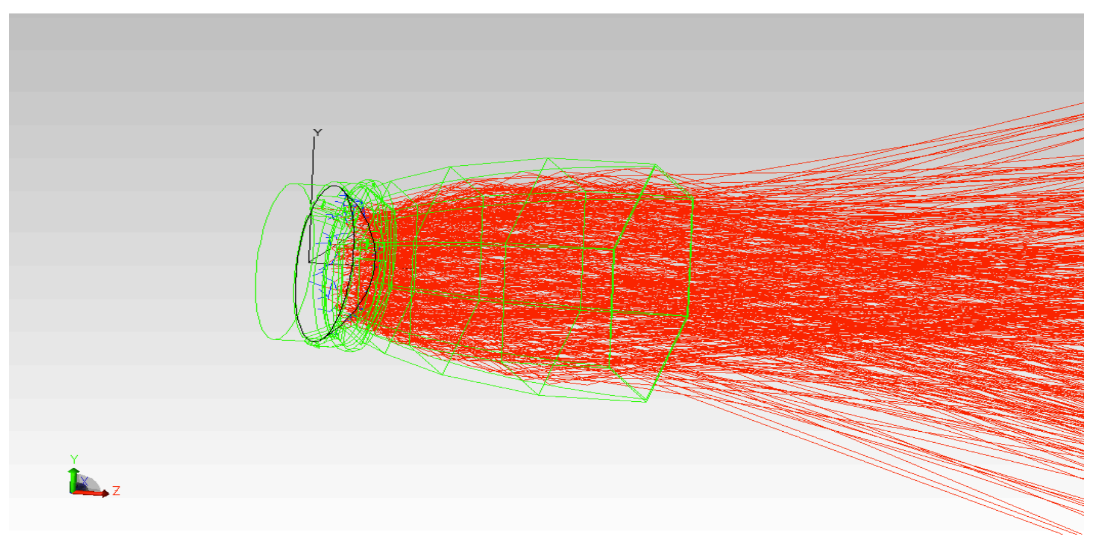

Fig. 5: Ray tracing simulation of a pixel Winston Cone adapted by a plane convex lens at the exit window.

A straight forward solution would be to equip the exit window of the current Winston Cone (WC) with a plane convex lens (PCL), while other solutions consider alternative WC designs as well as solid concentrators with layouts adapted to the possible dimension of a SiPM-based photo-sensor. Among the solutions studied, preliminary results indicate that solid concentrators provide a slightly better performance compared to the adaption of the existing WC by a PCL. The study of alternative WC designs is still at an early stage. Different types of PCLs of adequate material, i.e. with a high transmission in the wavelength range of interest, have been ordered, while the realization of a solid concentrator prototype is ongoing. At the next phase of the design study, the ray tracing results will be compared to measurements, and the design study will be extended to the LST camera optics.

Results

As a demonstrator we built and characterized a 16 3x3mm^2 (fig. 6) sensor, on a structure designed to be compatible with the pixel size of the MAGIC telescope (the total active area is about half of the exit window of the MAGIC light concentrator, so some additional concentrator would be required, e.g. a lens). The performance of this sensor is compatible with the operational requirements: single-phe resolution (S/N ratio ~3), ~3mV/phe output signal, 2-3 ns peak width, linearity up to ~100 phe. The power consumption of the adder stage is ~360mW (SiPM power consumption not included).

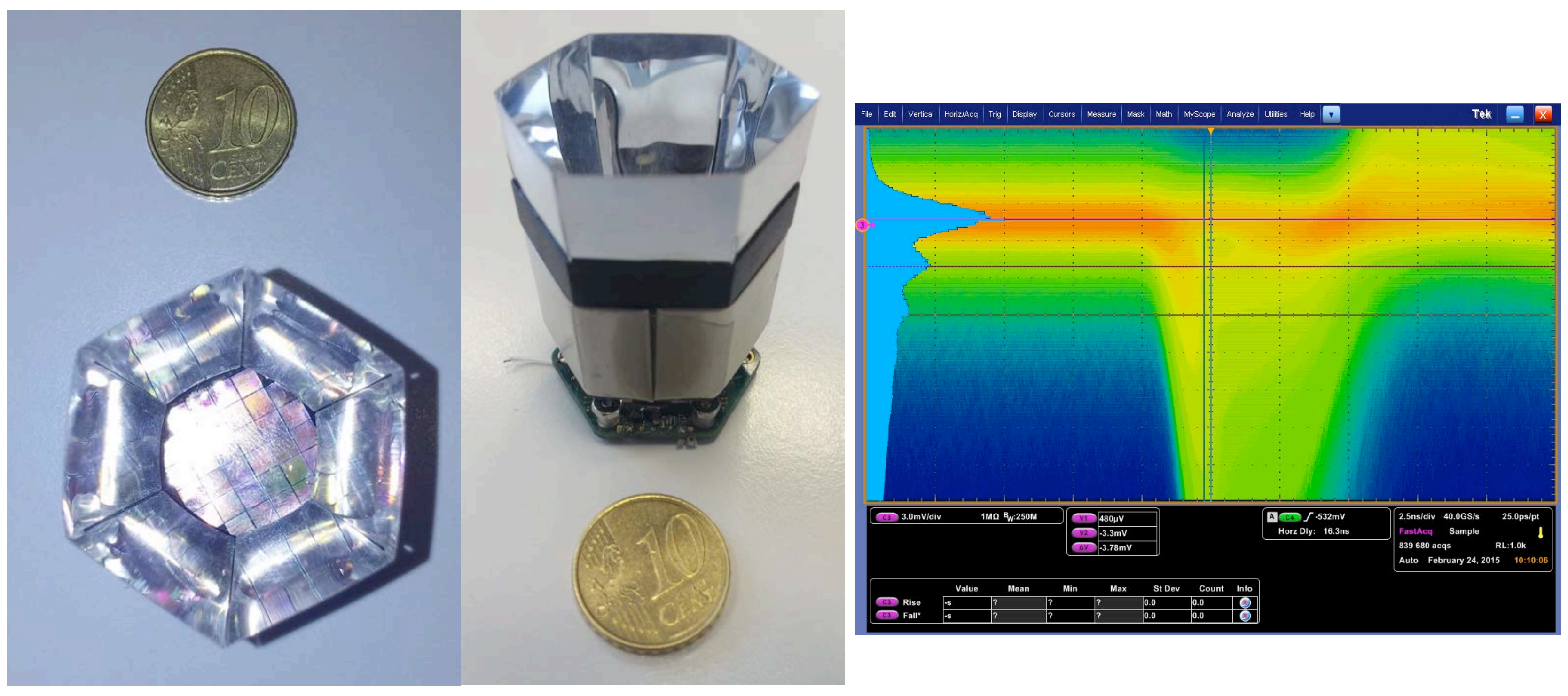

Fig. 6: SiPM matrix with 32 sensors and light concentrator for MAGIC pixel (left), 16 sensor added signal seen with a digital oscilloscope in a laser test stand box (right).

We are currently assembling the two aforementioned alternative sensors, with doubled active area to be equivalent to the MAGIC PMT surface. One additional improvement will be the selection of a batch of SiPM sensors with similar gain: no gain adjustment was attempted for the first prototype. We expect that part of the width of the 1-phe height distribution is due to the slightly different gain of each SiPM sub-element; instead of a complex gain adjustment circuit, we will populate our pixel selecting SiPMs with similar gain.

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