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# Full Length Article Photo-Trap: A low-cost and low-noise large-area SiPM-based pixel D. Guberman<sup>a,b,c,\*,1</sup>, C. Wunderlich<sup>a,d,1</sup>, G. Barillaro<sup>e</sup>, J. Cortina<sup>f</sup>, A. Paghi<sup>e</sup>, R. Paoletti<sup>a,d</sup>, A. Rugliancich<sup>a,g</sup>

<sup>a</sup> Istituto Nazionale di Fisica Nucleare (INFN), Sezione di Pisa, Largo Bruno Pontecorvo, 3, Pisa, 56127, Italy

<sup>b</sup> Departament de Física Quàntica i Astrofísica (FQA), Universitat de Barcelona (UB), c. Martí i Franqués, 1, Barcelona, 08028, Spain

<sup>c</sup> Institut de Ciències del Cosmos (ICCUB), Universitat de Barcelona (UB), c. Martíi Franqués, 1, Barcelona, 08028, Spain

<sup>d</sup> Dipartimento di Scienze Fisiche, della Terra e dell'Ambiente, Università di Siena, Via Roma, 56, Siena, 53100, Italy

<sup>e</sup> Dipartimento di Ingegneria dell'Informazione, Università di Pisa, Via Girolamo Caruso, 16, Pisa, 56122, Italy

<sup>f</sup> Centro de Investigaciones Energeticas, Medioambientales y Tecnologicas, Avenida Complutense, 40, Madrid, E-28040, Spain

<sup>g</sup> Campera Electronic Systems, Livorno, 57125, via Enrico Mayer, 69, Italy

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# ABSTRACT

The small sensitive area of commercial silicon photomultipliers (SiPMs) is often the main limitation for their use in experiments and applications that require large detection areas. Since capacitance, dark count rate and cost increase with the SiPM size, they are rarely found in sizes larger than  $6 \times 6 \text{ mm}^2$ . Photo-Trap combines a wavelength-shifter plastic, a dichroic filter and a standard commercial SiPM to build pixels of a few cm<sup>2</sup>. With this approach it can collect light over an area that can be ~10–100 times larger than the area of a commercial SiPM, while keeping the noise, single-photoelectron resolution, power consumption and likely the cost of a single small SiPM. We developed four different proof-of concept pixels sensitive in the near UV band, the largest one being of 40 × 40 mm<sup>2</sup>. We characterized them through laboratory measurements and Geant4 simulations. The optical gain we measured with the prototypes went from ~5 to ~15, while the single-photon time resolution was of ~3–5 ns FWHM. With the achieved performance Photo-Trap could be a competitive low-cost alternative for applications that require photosensors with large collection areas and low noise, such as dark matter experiments and optical wireless communication.

# 1. Introduction

Silicon photomultipliers (SiPMs) are becoming more and more popular thanks to the rapid evolution they have gone through in the last twenty years. These photodetectors combine, and often improve, characteristics of a photomultiplier tube (PMT), like high gain (~ 106), low-light level sensitivity and simple readout electronics with the benefits of photodiodes, like compactness, robustness, low-voltage operation, insensitivity to magnetic fields and tolerance to ambient light exposure (see [1] for a recent review). Most common SiPMs operate in the visible band of the spectrum, achieving a peak photodetection efficiency (PDE) that can be higher than 50%, which is much better than what standard PMTs can offer. Another unique feature of SiPMs is their excellent single-photoelectron resolution. SiPMs are employed in different research fields like high-energy physics [2], astrophysics [3], biophysics [4], quantum physics [5] and have been used or considered for several applications like medical imaging [6], optical communication [7] or LIDAR technology [8] among others.

Probably the main drawback of SiPMs is their limited physical size. While PMTs can be manufactured with diameters of a few inches, commercial SiPMs are at present rarely available in sizes larger than  $6 \times 6 \text{ mm}^2$ . This becomes a strong limitation when building large experiments/cameras or in any application in which the light that must be detected is distributed over a relatively large surface. Larger SiPMs are rarely produced mainly because their capacitance increases with size, which translates into a huge degradation of the signal-to-noise ratio (SNR) and the time resolution. Another limitation to produce larger SiPMs is that the dark count rate (DCR) increases linearly with the area.

Very large SiPM tiles were achieved by connecting several SiPMs in a combination of series/parallel configuration. This approach works particularly well in experiments that operate at cryogenic temperatures where DCR and electronic noise are largely reduced [9,10]. This is however not very practical at room temperature. Connecting SiPMs in parallel increases the capacitance. Connecting them in series rises the required bias voltage by a factor that is roughly equal to the number

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<sup>\*</sup> Corresponding author at: Dipartimento di Scienze Fisiche, della Terra e dell'Ambiente, Università di Siena, Via Roma, 56, Siena, 53100, Italy. *E-mail address:* daniel.guberman@icc.ub.edu (D. Guberman).

<sup>&</sup>lt;sup>1</sup> These authors contributed equally to this work.

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**Fig. 1. Left:** scheme showing the different components of a Photo-Trap pixel. **Right:** Examples showing how photons may interact with the pixel. (i) *Detection*: an incident photon with a wavelength within  $\Delta \lambda_0$  is absorbed by the WLS. The re-emitted photon bounces a few times and encounters the SiPM. (ii) *Rejection*: incident photons with wavelengths outside  $\Delta \lambda_0$  are either (a) rejected by the filter or (b) go through the WLS plastic without being absorbed and escape through the top. (iii) *Photon losses*: wavelength-shifted photons may (a) escape through the top with a probability given by the filter transmittance at  $\Delta \lambda_1$  or (b) be absorbed by one of the pixel components.

of SiPMs that are put in series. And in any case DCR will still increase linearly with the area.

One way of making large SiPM pixels while keeping the capacitance at a reasonable level is to sum the output currents of a few SiPMs (~ 10) into a single output. This has been successfully applied for instance in very-high-energy astrophysics [11] and medical imaging [12]. However, this solution has some limitations. Depending on the application, the sum could be performed with a dedicated an ASIC (Application Specific Integrated Circuit) like the MUSIC [13], but it will often require custom-designed electronics, which rises the cost and power consumption. Besides, since noise is also summed, there is a degradation of the SNR (and in particular the single-photoelectron resolution) and the timing performance, that increases with the pixel area. Finally, with this approach, cost and DCR still increase linearly with the area.

As discussed in [14], mirrors, lenses and light guides can be used to increase the collection efficiency of a photodetector. However these are typically bulky solutions that are usually conceived and tailored for specific applications. One way to achieve large detection areas consists in combining SiPMs with passive light collectors that act as 'traps' for photons. Solid light concentrators based on wavelength shifters (WLS) have been widely employed in the field of solar energy to increase the harvesting of solar photons [15]. WLS have also been used in highenergy physics to improve the performance of large ionizing radiation detectors, often based on scintillators [16]. In [17] the authors introduced ARAPUCA, a large device conceived for detecting the deep UV light (127 nm) of liquid argon scintillation. In ARAPUCA photons are confined inside a large volume defined by reflectors and a dichroic filter in which two WLS were deposited. Part of the wavelength-shifted photons are detected with SiPMs. At the same time, in [18] it was proposed to use WLS plastics to trap optical photons and build compact, low-cost, large-area SiPM pixels. In this so-called 'Light-Trap' approach photons are mainly trapped by total internal reflection (TIR) at the walls of the WLS plastic. One of the main novelties of the Light-Trap was that for the first time it proposed to use these light-trapping schemes to build pixels that could substitute standard PMTs as photodetectors for visible light. In [14] a Light-Trap pixel of 15 mm diameter sensitive to near UV light was built and characterized. The advantage of these solutions based on light collectors is that it is possible to achieve a sensitive area a few tens or hundred times larger than that of a standard SiPM, while keeping the noise, capacitance, SNR and cost of a single SiPM. Besides, it is easily scalable in size and requires very simple electronics. The main drawback is its low efficiency, since a large fraction of the photons either escape or are absorbed without reaching the SiPM. Besides, the Light-Trap approach requires the refractive index of the incident medium to be significantly lower than that of the WLS plastic

( $\sim$  1.5) to achieve a sufficiently low critical angle for TIR. In practice this limits the use of the Light-Trap only to applications where the incident medium is air or vacuum.

In this work we introduce *Photo-Trap*, a large-area SiPM pixel that combines a commercial dichroic filter with a Light-Trap. The filter can help overcoming the two mentioned limitations of the Light-Trap: it allows to increase the efficiency and relaxes the condition on the refractive index of the incident medium. We developed and characterized in detail four different Photo-Trap prototypes, with active areas of  $2 \times 2 \text{ cm}^2$  and  $4 \times 4 \text{ cm}^2$ . In Section 2 we introduce the Photo-Trap concept. In Section 3 we describe the pixel prototypes we built and the experiments and simulations performed to characterize them. In Section 4 we present the results, which we discuss in Section 5, where we also comment on possible applications in which Photo-Trap could have an impact. The main conclusions are summarized in Section 6.

# 2. Photo-Trap operation principle

A scheme showing the different components of a Photo-Trap pixel is shown in the left panel of Fig. 1. A plastic volume (refractive index  $n \simeq$ 1.5) is coupled to a SiPM. The plastic is doped with a WLS that absorbs light in a wavelength range  $\Delta \lambda_0$  and re-emits at longer wavelengths ( $\Delta \lambda_1$ ). The sides and the bottom of the WLS plastic are surrounded by highly reflective walls. At the front there is a dichroic filter with very high transmittance in  $\Delta \lambda_0$  and very high reflectivity in  $\Delta \lambda_1$ .

Photons with wavelengths within  $\Delta\lambda_0$  that reach the front part of the pixel will go through the filter, enter the plastic volume and be absorbed by the WLS. For each photon absorbed by the WLS, a photon with a wavelength within  $\Delta\lambda_1$  will be re-emitted with a probability given by the quantum yield of the WLS. Wavelength-shifted photons are re-emitted isotropically and a fraction of them is trapped inside the pixel until they eventually reach the SiPM. The rest of the re-emitted photons escape or are absorbed (see right panel of Fig. 1). Photons can be trapped either by TIR at the plastic surface, or by reflections in the detector walls and filter. To guarantee TIR, there should be a very narrow air gap between the WLS plastic and the reflective walls and filter. The wider this gap is, the higher the chance that a photon escapes.

With Photo-Trap it is possible to achieve a significant increase in the total collection area without increasing the pixel noise, capacitance or power consumption. This way it is possible to build a pixel of a few  $\rm cm^2$  with the single-photoelectron resolution, capacitance and DCR of a SiPM of a few  $\rm mm^2$ . The cost per unit area should be low, especially if the WLS plastics and filter are mass-produced.

A parameter that is often used to evaluate the performance of detectors based on optical concentrators is the optical gain G, which

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Fig. 2. Left: Picture of Prototype I without the filter showing the different pixel components. Right: Prototype I seen from top with the filter mounted.



Fig. 3. Transmittance (blue solid line) and reflectance (red solid line) at normal incidence of the Asahi ZUV0400 shortpass filter (data provided by the manufacturer). Black dots show the transmittance measured in the lab at 340, 375 and 460 nm. The plot also shows the absorption (gray dashed line) and re-emission (gray dotted line) spectra of the EJ-286 WLS plastic.

Table 1

Main physical differences of the four Photo-Trap prototypes.  $S_{WLS}$  and  $S_{SIPM}$  are the areas of the WLS plastic and the SiPM, respectively. The SiPMs of prototypes II and IV consist of 4 SiPMs of  $3 \times 3 \text{ mm}^2$  connected in parallel.

| Prototype nr. | $S_{ m WLS}$                | $S_{ m SiPM}$              |
|---------------|-----------------------------|----------------------------|
| I             | $20 \times 20 \text{ mm}^2$ | $3 \times 3 \text{ mm}^2$  |
| П             | $20 \times 20 \text{ mm}^2$ | $3 \times 12 \text{ mm}^2$ |
| III           | $40 \times 40 \text{ mm}^2$ | $3 \times 3 \text{ mm}^2$  |
| IV            | $40 \times 40 \text{ mm}^2$ | $3 \times 12 \text{ mm}^2$ |

depends on the wavelength  $\lambda$  and the angle of incidence (AOI)  $\theta$  and can be defined as:

$$G(\lambda, \theta) = \frac{S_{WLS}}{S_{SIPM}} \epsilon(\lambda, \theta) \tag{1}$$

 $S_{WLS}$  and  $S_{SIPM}$  are the areas of the WLS plastic and the SiPM respectively, and  $\epsilon$  is the *trapping efficiency* of the pixel, which we define as:

$$\epsilon(\lambda,\theta) = T_F(\lambda,\theta) T_{WLS}(\lambda,\theta) A_{WLS}(\lambda) Y_{WLS} C_{eff}(\Delta \lambda_1) \frac{PDE_{SiPM}(\Delta \lambda_1)}{PDE_{SiPM}(\lambda)}$$
(2)

 $T_F$  is the filter transmittance and  $T_{WLS}$  is the Fresnel transmittance at the top surface of the WLS plastic (~ 96 % at normal incidence if the incident medium is air and the refractive index of the WLS plastic  $\simeq 1.5$ ).  $A_{WLS}$  and  $Y_{WLS}$  are the WLS plastic absorption and reemission (quantum yield) probability, respectively,  $PDE_{SiPM}$  is the PDE of the SiPM and  $C_{eff}$  is the collection efficiency: the fraction of the wavelength-shifted photons that reaches the SiPM. The pixel is essentially blind to all wavelengths outside  $\Delta \lambda_0$ , which in some applications can be useful for background rejection.

Note that, for an homogeneous flux,  $G(\lambda)$  can be obtained as:

$$G(\lambda) = \frac{\mu_{Photo-Trap}(\lambda)}{\mu_{SiPM}(\lambda)}$$
(3)

where  $\mu_{Photo-Trap}$  and  $\mu_{SiPM}$  are the mean number of photons detected by Photo-Trap and by a SiPM with the same area of the one used to build the pixel, respectively. The optical gain can also be understood as the number of SiPMs of area  $S_{SiPM}$  that would be needed to collect the same light than a Photo-Trap pixel of area  $S_{WLS}$ .

Finally, the PDE of Photo-Trap is related to its trapping efficiency as:

$$PDE_{Photo-Tran}(\lambda) = \epsilon(\lambda) \ PDE_{SiPM}(\Delta\lambda_1)$$
(4)

## 3. Materials and methods

We built four proof-of-concept pixels and characterized them in the laboratory. We compared the measurements we took with Geant4 simulations of the system, which allowed us to study with more detail some of the key aspects that could have an impact on the performance of Photo-Trap.

# 3.1. Proof-of-concept pixels

The four prototypes we built differ essentially in their sensitive area (size of the WLS plastic they employ) and in the size of the SiPM they use. Their main physical characteristics are summarized in Table 1. A picture of Prototype I, with and without filter, is shown in Fig. 2.

All pixels use an EJ-286 WLS plastic from Eljen Technology. It absorbs light in the wavelength range between 320 nm and 380 nm and re-emits at blue wavelengths (peaking at  $\sim$  425 nm, see Fig. 3). The reemission time follows an exponential distribution with a characteristic decay time of  $\sim 1.2$  ns. When ordering the WLS plastic samples we required that the concentration of EJ-286 dopant was enough to absorb > 99 % of 350 nm photons within 1.5 mm thickness of the plastic. The plastics were cut by Eljen in sizes of  $20 \times 20 \times 3 \text{ mm}^3$  and  $40 \times 40 \times 3 \text{ mm}^3$ . The  $20 \times 20 \times 3 \text{ mm}^3$  samples were procured in substrates of Polyvinyltoluene (PVT) and Polystyrene (PS), polished with two different techniques: (1) diamond-milled only and (2) additionally to diamond-milled, hand polished using moist polishing compounds of sub-micron particle size. The goal was to evaluate whether the substrate material or the polishing technique had some impact on the performance. The  $40 \times 40 \times 3 \text{ mm}^3$  samples were ordered only in PVT with the second optical polishing technique. A picture of one of the PVT samples is shown in the left panel of Fig. 4.



Fig. 4. Left: One of the  $20 \times 20 \times 3 \text{ mm}^3$  PVT samples supplied by Eljen. Center: Readout board with a  $3 \times 3 \text{ mm}^2$  SiPM. Right: Readout board with four  $3 \times 3 \text{ mm}^2$  SiPMs connected in parallel.



Fig. 5. Scheme showing the setup used to characterize the Photo-Trap prototypes. The light of the LED could be collimated or diffused, depending on the measurement to be performed. The Photo-Trap prototypes could be moved in the (*x*,*y*) plane and rotated on the *y*-axis. We also placed a reference sensor near the prototypes.

All pixels were equipped with a commercial ZUV0400 shortpass interference filter from Asahi Spectra [19]. This filter is  $\sim 1 \text{ mm}$  thick and has an area of 50  $\times$  50 mm<sup>2</sup>, with a clear aperture of 46  $\times$  46 mm<sup>2</sup>. At normal incidence it has a cut-off wavelength at 400 nm and a transmittance/reflectance curve that matches quiet well the spectral characteristics of the EJ-286 (see Fig. 3).

The pixels employ MICROFJ-30035-TSV SiPMs from Onsemi [20], which have an active area of  $3.07 \times 3.07 \text{ mm}^2$ . The main reason for using these SiPMs was their small chip size  $(3.16 \times 3.16 \text{ mm}^2)$  which allowed us to minimize dead space when building the pixel. These sensors have a breakdown voltage of ~ 24.6 V at 22 °C. We performed all our measurements at an over-voltage of 3.4 V, at which these sensors provide a peak PDE of  $\sim$  41 % according to the manufacturer. At this over-voltage we measured a DCR of  $\sim 100 \text{ kHz/mm}^2$  and a crosstalk probability of  $\sim 13$  %, which is consistent with the specifications from the datasheet. The SiPMs were mounted on custom-made compact readout boards that let us switch between two different preamplifiers from Advatech [21]: AMP-0604 (x20 - 60 gain, ~ 5 ns rise time) and AMP-0611 ( $\times 10-20$  gain, ~ 0.7 ns rise time). Two readout boards were built (see center and right panels of Fig. 4), one designed to host a single SiPM, the other one to hold four of them connected in parallel, approaching a single SiPM of  $\sim 3 \times 12 \text{ mm}^2$  (i.e., with the same area of a  $6 \times 6 \text{ mm}^2$  SiPM).

We used the optically transparent gel SS-988 from Silicone Solutions [22] to couple the SiPM to the WLS plastic. According to the manufacturer this gel has a refractive index of  $\sim 1.466$  and > 99.9%

transmittance at ~ 420 nm. Custom-made 3D-printed plastic holders were built to mount all the pixel components. For the reflective walls we used a 2 mm thick Optopolymer<sup>®</sup> film from Berghof Fluoroplastics [23]. These films provide ~ 98 % diffuse reflectivity above 400 nm.

## 3.2. Laboratory measurements

We characterized the four Photo-Trap prototypes in the laboratory using the setup shown in Fig. 5. We illuminated the prototypes with different PicoQuant PLS-Series pulsed LEDs, peaking at ~ 340 nm, ~ 370 nm and ~ 460 nm (FWHM of ~ 9 nm, ~ 20 nm and ~ 30 nm respectively). The LEDs were driven by a PDL 800-B PicoQuant LED driver, generating pulses with a typical width of ~ 800 ps. The output signal was recorded either with a CAEN DT5720 digitizer or with a LeCroy SD 3010 oscilloscope. The Photo-Trap prototypes were mounted on a platform that allowed to rotate the sensor and to move it along the (*x*,*y*) plane (detector plane, orthogonal to the direction of the incident beam).

# 3.2.1. Optical gain

To obtain the optical gain we measured the ratio of the signal collected by the Photo-Trap prototypes to the one collected by a reference sensor, given the same spatially homogeneous incident flux (see Eq. (3)). Our reference sensor was a single 'naked' SiPM of  $3 \times 3 \text{ mm}^2$ . LED pulses were flashed at a frequency of 1 kHz. We placed a Teflon diffuser right after the LED and made sure that there was an uniform

flux at the detector plane. For these measurements we used the AMP-0604 amplifier with which, thanks to its higher gain, it was easier to identify peaks of a few photoelectrons (phes). We acquired 400 ns long waveforms with the CAEN DT5720 digitizer at 250 MS/s and extracted the signal as the maximum amplitude found within a 40 ns window.

As described in [24], the mean number of photons  $\mu$  collected by a detector can be obtained as

$$\mu = ln(N_{\rm ON})/ln(N_{\rm OFF}),\tag{5}$$

where  $N_{\rm ON}$  and  $N_{\rm OFF}$  are the probabilities of having no SiPM cells fired when the LED is ON and OFF, respectively. This expression is valid under the assumption that the number of detected photons and dark counts recorded in each event follow a Poisson distribution. It provides a method to obtain  $\mu$  that is independent on the SiPM optical crosstalk and afterpulsing probability. By obtaining  $\mu$  both for Photo-Trap and the reference detector we could calculate the optical gain and the trapping efficiency using Eqs. (1) and (3).

A single measurement of  $\mu$  consisted of 50k waveforms obtained with the LED ON, followed by other 50k waveforms with the LED OFF. For each measurement we systematically: (1) cleaned the WLS plastic and reflectors; (2) mounted the pixel components; (3) took the measurements; (4) removed all components from the holder (except for the reflectors that were stuck to the holder).

# 3.2.2. AOI dependence

Fig. 3 shows the filter transmittance curve at normal incidence. As the angle of incidence (AOI) of the incoming light increases this curve will change, typically moving towards shorter wavelengths. This implies that the field of view (FOV) of Photo-Trap should be wavlength dependent. To characterize this we first measured the filter transmittance at 340 and 370 nm as a function of the AOI. In this case the LEDs were operated in continuous mode. The filter was located on a rotating stage and a collimator was placed between the filter and the LED. This way we could achieve a non-symmetric light spot of ~ 5 mm FWHM at the center of the filter. We placed a  $3 \times 3 \text{ mm}^2$  SiPM behind to collect the light that passed through it. We obtained the filter relative transmittance by measuring the SiPM current with and without the filter, for different AOIs ranging from 0 to 70°.

To measure the response of Photo-Trap we replaced the filter by Prototype I and recorded the current measured by this pixel at different AOIs.

## 3.2.3. Position-dependent efficiency

We also studied the spatial dependence of the trapping efficiency. Also in this case we operated the LEDs in continuous mode and we employed the collimator. With the limitations imposed by our setup (especially by our LED, as described in Section 3.2.2) we could not generate a very precise map of the position dependence of the efficiency. But these measurements were still useful to obtain a set of qualitative maps that could support those generated with simulations where the beam size and position could be fully controlled (see Section 3.3).

To build this maps we fixed the position and intensity of the LED and moved the prototypes along the detector plane, building a 2D-grid with a lattice spacing of 2 mm. We recorded the SiPM current in each (x,y) point of the grid.

#### 3.2.4. Time resolution

To study the timing properties of Photo-Trap we flashed the prototypes and the reference sensor with LED pulses at 1 kHz. Here we also used the diffuser to achieve an uniform flux along the area of the sensors. For these measurements we used the AMP-0611 amplifier which had a faster rise time and acquired 190 ns long waveforms with the oscilloscope at 10 GS/s. As we were aiming to measure the single-photon time resolution (SPTR) of the sensors, we kept only those waveforms corresponding to single-phe events, i.e. waveforms with a maximum amplitude between 0.5 phe and 1.5 phe. We defined the arrival time as the time (relative to the trigger) at which the pulse rising edge reached 60 % of the amplitude of the single-phe pulse.

# 3.3. Simulations

We simulated the pixels with Geant4 [25]. These simulations were mainly conceived to explore those aspects that were harder to study with our experimental setup, like the position dependence of the trapping efficiency or the impact of the surface roughness. In the simulated system optical photons are fired towards a PVT volume with the absorption and re-emission properties of the Eljen EJ-286 WLS plastic. All photons, wavelength-shifted or not, are tracked until they either reach the SiPM, are absorbed somewhere else or escape. The SiPM is treated as a perfect detector with 100 % detection efficiency and the results are later scaled by the PDE of the sensor.

To study the impact of surface roughness we tried some of the different models available in Geant4 to process the interaction of photons in the boundaries of the WLS plastic: the *Glisur* model (*polished* and *rough*) and the DAVIS *Polished\_LUT* and *Rough\_LUT* models [26]. In the Glisur model the surface finishing is controlled by a single parameter (*polish*) that goes from 0 to 1 and determines the scattering distribution of the photons at the boundaries. The closer to 1 it is, the more similar it is to a perfectly polished surface. The DAVIS models rely on look-up tables that determine the direction of a photon that reaches a boundary. These tables were optimized for LYSO crystals but have proven to be accurate to describe other systems like a NaI(TI) crystal surrounded by a MgO diffuse reflector [12]. In fact, since in our experience the DAVIS *RoughTeflon\_LUT* model was the one that better described the interaction of optical photons with diffuse reflectors, we used it to simulate the bottom and side reflectors.

The system also includes a thin volume (0.1 mm thick) that optically couples the SiPM to the PVT volume. This volume has the same area of the SiPM and the refractive index and absorption properties of the Optical coupling gel SS-988 from Silicone Solutions employed in the prototypes. Another volume was defined to simulate the filter, where the bottom surface was treated as a dichroic-dielectric boundary. The filter had the transmittance spectrum of the Asahi ZUV0400 filter we used in our prototypes. Since we ignored and could not measure with our setup how the filter transmittance spectrum changed with the AOI, in the simulations we assumed the non-realistic case in which it was constant at all AOIs.

# 4. Results

## 4.1. Optical gain and trapping efficiency

Fig. 6 shows an example of the single-phe spectra obtained with prototypes III and IV in measurements with LED ON. Since the prototypes have the same capacitance and DCR as the reference sensors, they provide essentially the same SNR/single-phe resolution of a  $3 \times 3 \text{ mm}^2$  or a  $6 \times 6 \text{ mm}^2$  SiPM. The pedestal and the first-phe peak can be easily distinguished. This was important for obtaining  $\mu$  through Eq. (5), since we used it to calculate the optical gain *G* and trapping efficiency  $\epsilon$  of the prototypes.

Fig. 7 shows the distributions of *G* and  $\epsilon$  that we measured at 340 nm for all prototypes. For each measurement ('Measurement ID'), performed as described in Section 3.2.1, we obtained a value of *G* and  $\epsilon$ , which is shown in the plot. We obtained results at different levels of the pixel construction: without reflectors or filter ('WLS only'), after adding the reflectors ('WLS + Reflectors') and after adding the filter ('Full Pixel'). The filter allows to increase *G* by ~30%. The average values found for each prototype at 'Full Pixel' level are shown in Table 2. In general, the trapping efficiency is higher in prototypes with lower  $S_{\rm WLS}/S_{\rm SiPM}$  ratio, where the mean number of bounces that a photon should perform before reaching the SiPM is lower (note that this includes the photons that directly reach the SiPM without reflections). If photons undergo less reflections before hitting the SiPM the escape and absorption probability should be lower. Optical gain, instead, is higher in pixels with higher  $S_{\rm WLS}/S_{\rm SiPM}$  ratio. This is just because these



Fig. 6. Single-phe spectrum obtained with the LED ON with Prototype III (left) and Prototype IV (right).



Fig. 7. Optical gain and trapping efficiency of all prototypes at different construction levels: without reflectors or filter ('WLS only', gray), after adding the reflectors ('WLS + Reflectors', blue) and after adding the filter ('Full Pixel', black). In the case of Prototype I the results are shown for different substrate materials (PS and PVT) and polishing techniques (1 and 2, see Section 3.1).

#### Table 2

Mean optical gain G and trapping efficiency  $\epsilon$  of the four Photo-Trap prototypes measured at 340 nm.  $S_{\rm WLS}$  is the area of the WLS plastic and  $S_{\rm SIPM}$  the area of the SIPM.

| Prototype nr. | $S_{ m WLS}/S_{ m SiPM}$ | G              | e [%]          |
|---------------|--------------------------|----------------|----------------|
| Ι             | ~ 42                     | 9.2 ± 0.4      | $21.7 \pm 1.0$ |
| II            | ~ 10                     | $5.0 \pm 0.3$  | $47.5 \pm 2.4$ |
| III           | ~ 170                    | $15.8 \pm 0.9$ | $9.3 \pm 0.6$  |
| IV            | $\sim 42$                | $10.7~\pm~0.7$ | $25.1~\pm~1.7$ |

pixels compensate their lower efficiency with a much larger collection area.

Probably the main reason behind the spread in the values of the obtained G lies behind the pixel construction process. Since the sensors were continuously mounted and unmounted (see Section 3.2), some characteristics like the amount of optical grease used or the alignment of the different components could change from one measurement to the next one. Besides, we observed a degradation of the trapping efficiency after several iterations of taking the same WLS plastic in and out. In these cases the efficiency would increase again when replacing the reflectors and/or WLS plastics with new ones. We should remark that

#### Table 3

Mean G of Prototype III measured at 340 nm using different WLS plastic samples: a new one (WLS 1), one that was used for a long time and exhibited scratches (WLS 2) and one intentionally scratched using sand paper (WLS 3).

| Construction level | WLS 1          | WLS 2          | WLS 3          |
|--------------------|----------------|----------------|----------------|
| WLS only           | $6.9~\pm~0.3$  | $4.6 \pm 0.2$  | $2.7~\pm~0.1$  |
| WLS + Reflector    | $11.8 \pm 0.5$ | $9.7 \pm 0.4$  | $5.5~\pm~0.2$  |
| Full Pixel         | $15.6~\pm~0.6$ | $15.5 \pm 0.6$ | $11.7~\pm~0.5$ |



Fig. 8. Angular dependence of the Photo-Trap efficiency and of the filter transmission at 340 nm and 370 nm relative to the transmission/efficiency at normal incidence.

the observed degradation only appeared after unmounting several times the same pixel: if we left the same pixel untouched for a few days and took measurements regularly we found that the trapping efficiency remained very stable (within  $\sim 3\%$ ).

We further investigated the impact of this 'wear and tear' effect by comparing the results obtained with Prototype III using three different WLS plastic samples. *WLS 1* was a 'new' sample that had no visible scratches on its surface. *WLS 2* was a sample that we used for a long period that had visible scratches after all the times it had been taken in and out from the pixel. *WLS 3* was a sample that we intentionally scratched using sand paper. The results obtained with these three samples are summarized in Table 3. They show that the surface finishing can have a strong impact on the trapping efficiency of the pixel. Especially at the 'WLS only' level, where it was ~ 35 % (~ 60) % lower in *WLS 2 (WLS 3)* than in *WLS 1*. The addition of the reflectors helped recovering some of the escaping photons and this degradation turned to be ~ 18 % and ~ 45 % in *WLS 2* and *WLS 3*, respectively. The efficiency improved significantly after adding the filter. In the case of *WLS 2* it even reached the level of *WLS 1*.

For Prototype I, Fig. 7 shows the results obtained using different substrate materials/polishing techniques. Since these results are not significantly different, it would seem that the final surface roughness obtained with both polishing techniques in both materials is not different enough to have a strong impact in the performance.

## 4.2. AOI dependence

In Fig. 8 we show the filter transmission and the trapping efficiency of Photo-Trap as a function of the incident angle, both relative to the transmission/efficiency at normal incidence. At 370 nm the angular response of Photo-Trap is dominated by the filter and the two curves are very close to each other. Photo-Trap sensitivity is barely flat up to ~ 30° and drops to ~ 50 % at ~ 50°. At 340 nm, the sensitivity is flat up to ~ 45° and drops to ~ 50 % at ~ 55°. At 340 nm the trapping efficiency of Photo-Trap seems to start dropping before the filter transmission does. Probably the main reason for this difference

comes from the limitations imposed by our setup. At large AOIs we are more sensitive to the effects introduced by a non-negligible beam size: light may impact over a broader surface of Photo-Trap, which, as it will be shown in Section 4.5, has a position-dependent sensitivity (while when measuring the filter transmission we only collect the light that goes directly into the small area of the SiPM). At large AOIs we are also more sensitive to the alignment. Besides the limitations imposed by our setup, we do expect an additional degradation of the angular response of Photo-Trap that becomes more significant at larger AOIs. This degradation is related to Fresnel losses. While close to normal incidence we expect ~ 5 % of the light to be reflected in a medium with a refractive index of 1.58 like PVT, at 60° this amount increases to ~ 20 %.

# 4.3. Position-dependent efficiency

Fig. 9 compares the spatial dependence of the trapping efficiency of the prototypes that we measured in the laboratory with the simulated ones. The plots associated to the simulations were obtained using the Davis Polished LUT model to describe the interaction of the photons at the boundaries of the WLS plastic, since, as it will be shown in Section 4.5, it was the model that provided a better agreement with the experimental data. The trapping efficiency was normalized to the efficiency at the pixel center.

As anticipated in Section 3.2.3, with our setup we could not achieve a very-high level of precision. In the experimental data it would seem that the collection efficiency is more homogeneous than what the simulations suggest, but this is very likely an artificial smoothing resulting from the non-negligible size of our light spot. As could be expected, the plots obtained in the laboratory are less symmetric than those obtained with the simulations, which is probably related to our LED source as well, but also to our hand-made pixel construction. The experimental results were still useful to support the overall trend that we could observe much better with the simulations: (i) trapping efficiency is barely flat (within 10 %) over most of the pixel area, (ii) it achieves its maximum close to the SiPM and (iii) its minimum close to the corners of the side that contains the SiPM. Our interpretation is purely geometrical: when a photon is absorbed and isotropically wavelength-shifted, the probability of directly hitting the SiPM without experiencing any reflection is higher close to the SiPM and lower in the mentioned corners. In fact, for Prototype II, in which the SiPM covers 60 % of the WLS-plastic side, the sensitivity is more homogeneous than in the other prototypes. Prototype III shows the opposite scenario.

## 4.4. Time resolution

Fig. 10 shows the measured and simulated arrival time distribution of single-phe events for all prototypes. The experimental distributions were fitted with Equation 2.3 from [27], which is a Gaussian convoluted with an exponential that is often used to describe the SPTR distributions of SiPMs:

$$f(x,\mu,\sigma,\lambda) = \frac{\lambda}{2} e^{\frac{\lambda}{2}(2\mu+\lambda\sigma^2-2x)} \left[ 1 - \operatorname{erf}\left(\frac{\mu+\lambda\sigma^2-x}{\sqrt{2}\sigma}\right) \right]$$
(6)

where  $\mu$  is the mean of the Gaussian distribution,  $\sigma$  the standard deviation and  $\lambda$  is the characteristic decay time of the exponential function (see [27] for the details.

In Table 4 we show the SPTR we obtained, defined as the FWHM of those fits, for all four prototypes. The measured SPTR of the reference sensors was  $(1.3 \pm 0.2)$  ns for the  $3 \times 3$  mm<sup>2</sup> SiPM and  $(2.7 \pm 0.2)$  for the  $3 \times 12$  mm<sup>2</sup> SiPM. As the amplifier we used was not optimized for ultra-fast timing applications, these values are higher than what can be found with state-of-the-art SiPMs and fast-timing electronics. Besides, these numbers are also affected by the jitter of the LED (which is not as stable as a laser). Still, the contribution of the light source and the SiPM is sub-dominant with respect to the contribution introduced by



Fig. 9. Position-dependent trapping efficiency for all prototypes obtained with experimental measurements (left) and Geant4 simulations (right).

| Table 4 |    |     |      |       |
|---------|----|-----|------|-------|
| Summary | of | the | main | perfo |

| able 4     |          |             |            |        |            |             |   |       |        |       |        |        |     |
|------------|----------|-------------|------------|--------|------------|-------------|---|-------|--------|-------|--------|--------|-----|
| Summary of | the main | performance | parameters | of the | Photo-Trap | prototypes. | а | For a | a SiPM | DCR o | of 100 | kHz/mr | n². |

| Prototype nr. | $S_{ m WLS}/S_{ m SiPM}$ | G              | е<br>[%]       | SPTR (FWHM)<br>[ns] | DCR <sup>a</sup><br>[kHz/mm <sup>2</sup> ] |
|---------------|--------------------------|----------------|----------------|---------------------|--|
| T             | ~ 42                     | 92 + 04        | $21.7 \pm 1.0$ | 32 + 03             | 23   |
| I             | ~ 10                     | $5.2 \pm 0.3$  | $475 \pm 24$   | $3.2 \pm 0.3$       | 9.0  |
| III           | ~ 170                    | $15.8 \pm 0.9$ | $9.3 \pm 0.6$  | $4.3 \pm 0.3$       | 0.7  |
| IV            | ~ 42                     | $10.7~\pm~0.7$ | $25.1 \pm 1.7$ | $5.2 \pm 0.3$       | 2.3  |



Fig. 10. Comparison of the measured and simulated arrival time distributions for Prototype I (upper left), Prototype II (upper right), Prototype III (lower left) and Prototype IV (lower right). The arrival time distribution of the reference sensors that correspond to each prototype are also shown.

Comparison of the measured optical gain (Meas.) with the values obtained with the simulations using different models to describe the surface roughness of the WLS plastic: Perfectly polished (Pol), Davis Polished LUT (Davis Pol.), Glisur *polish* = 0.7 (Glisur 0.7) and Davis LUT Rough (Davis Rough).

| Nr  | Pixel level      | Meas.          | Pol.      | Davis Pol. | Glisur 0.7 | Davis Rough |
|-----|------------------|----------------|-----------|------------|------------|-------------|
|     | WLS only         | $3.5 \pm 0.4$  | 9.2       | 4.2        | 1.5        | 1.4         |
| Ι   | WLS + Reflectors | $7.2 \pm 0.5$  | 14.8      | 6.4        | 5.9        | 2.9         |
|     | Full Pixel       | $9.2~\pm~0.4$  | 12.7–14.6 | 7.6–14.1   | 8.6-13.3   | 7.0-10.4    |
|     | WLS only         | $2.5 \pm 0.1$  | 3.1       | 2.6        | 1.6        | 1.5         |
| II  | WLS + Reflectors | $3.8 \pm 0.2$  | 5.1       | 3.6        | 3.7        | 2.5         |
|     | Full Pixel       | $5.0~\pm~0.3$  | 5.0-5.6   | 4.2-6.0    | 4.7-6.0    | 4.5–5.7     |
|     | WLS only         | 6.9 ± 0.3      | 16.6      | 4.8        | 2.6        | 2.1         |
| III | WLS + Reflectors | $11.9 \pm 1.1$ | 33.1      | 7.9        | 8.9        | 3.8         |
|     | Full Pixel       | $15.8~\pm~0.9$ | 33.5–35.4 | 11.5-26.1  | 18.9–30.4  | 13.6-20.4   |
|     | WLS only         | $4.2 \pm 0.3$  | 8.5       | 4.6        | 2.7        | 2.1         |
| IV  | WLS + Reflectors | $8.1 \pm 0.8$  | 15.0      | 6.5        | 7.0        | 3.4         |
|     | Full Pixel       | $10.7~\pm~0.7$ | 15.7-17.0 | 9.3-16.0   | 13.2-17.5  | 10.4-14.2   |

the Photo-Trap pixel itself. This implies that even if the SPTR of the prototypes could be reduced using a faster amplifier we should still expect it to be between  $\sim 2$  and 4 ns, depending on the pixel size. In Section 4.5 we discuss the reasons behind the time jitter introduced by Photo-Trap and the comparison with the different Geant4 models used to describe the surface roughness of the WLS plastics.

## 4.5. Simulations

In Table 5 we compare our measurements of the optical gain with those obtained with the simulations using different models for the surface roughness of the WLS plastic. The results were computed at the three stages of the pixel construction introduced in Section 4.1:



Fig. 11. Left: Time taken by the simulated wavelength-shifted photons to reach the SiPM as a function of their total path length in Prototype I. Inset: same plot for the case of instantaneous re-emission. Right: Arrival time profiles for fixed photon path lengths. Projections in the arrival time axis that correspond to the green, red and black bands in the left panel.

'WLS only', 'WLS + Reflectors' and 'Full Pixel'. The best one for testing the different surface roughness models is 'WLS only', since at this level the optical gain should only depend on a few parameters: the WLS plastic response (absorption and re-emission probability), the surface roughness of the plastic sample and the properties of the optical coupling layer (thickness and transmittance). The last one should be sub-dominant if the thickness of the optical coupling layer is low (0.1–0.5 mm) and its transmittance is high as in our case.

After adding the reflectors ('WLS + Reflectors' level) two additional parameters have an impact on the efficiency of Photo-Trap: their reflectance and the thickness of the air gap that separates them from the WLS plastic (which in our simulations was set to 0.1 mm). In [14] it was shown that the thicker this gap, the worse the trapping efficiency. With the addition of the filter two more parameters affect the achievable optical gain: the filter transmittance and the distance between the filter and the WLS plastic. Since the results at 'Full Pixel' level have a strong dependence on the thickness of the gap between the filter and the WLS plastic and in the experiments we were not able to measure nor control it, in Table 5 we give a range of values that correspond to thickness that goes from 0.1 to 1 mm. The larger this gap, the higher the probability that photons escape.

The simulations are consistent with what was suggested in Section 4.1: the optical polishing of the plastic surface has a strong impact on the pixel performance. When we assumed a perfectly polished WLS plastic we found an optical gain that was much higher than the one we measured (by more than a factor 2 at the 'WLS only' level). The rougher models (Glisur and Davis LUT Rough) instead underestimated the overall efficiency. In the case of the Glisur model we performed a scan on the *polish* parameter, but none of them seemed to agree with our measurements (Table 5 shows the results for *polish* = 0.7). The Davis Polished LUT model is the one that better agreed with our measurements of the optical gain, providing a reasonable prediction for all prototypes at the 'WLS only' and 'WLS + Reflectors' levels. Only in Prototype III the mismatch with our measurements goes above 30%.

With the addition of the filter the difference between the optical gains predicted by the different models become significantly smaller. This is consistent with what we found in Section 4.1, where we showed that the filter was useful to minimize the impact of a poor optical polishing of the WLS plastic surfaces.

As introduced in Section 2, in Photo-Trap there are different ways in which photons can be lost. In the simulations it is easy to find and classify the reasons behind this losses. Before adding the filter most losses could be associated to photons escaping through the top surface of the detector. For instance, when using the Davis Polished LUT model for simulating Prototype I we found that  $\sim 70\%$  of the incident photons would escape. After adding the filter the losses associated to photon escaping become comparable to those associated to absorption at the bottom and side reflectors. Of course the final balance will depend on the characteristics of the filter, reflectors and of the pixel construction in general (e.g., optical polishing of the WLS plastics, thickness of the gaps between WLS plastic and reflectors/filter) but it is clear that with the addition of the filter the impact of the walls reflectivity becomes critical. In this sense, in terms of efficiency the best scenario is found when photons are trapped inside the WLS plastic since, at least *a priori*, TIR should be 100% efficient.

Fig. 10 compares the measured arrival time distribution of singlephe events with the simulated ones. Since the SiPM response was not included in the simulations, we added to the raw arrival time distributions that we obtained with Geant4 an additional artificial jitter that followed the measured arrival time distributions of the reference sensors. In this case the results predicted by the different models are not so different. The difference is only noticeable in prototypes I and III (and only in Prototype III is particularly significant). The LUT Davis 'Rough LUT' model was the one that better reproduced our measurements of the arrival time, matching very well the experimental distributions in all prototypes. The fact that none of the Davis models provides a perfect matching with all our measurements is not particularly surprising since they were developed for LYSO crystals where the surface finishing that can be obtained is quiet different to what can be achieved with plastics. If we look at the full picture, the Davis Polished LUT model seems to be the one better describing our prototypes and hence the one that we would suggest to use for optimization studies. It provided the better predictions of the trapping efficiency and a reasonable prediction of the time response.

As discussed in Section 4.4, the Photo-Trap concept introduces a jitter on top of the intrinsic one of the SiPM. In [14] we suggested that this degradation should be the result of two effects: the exponential decay time of the WLS and the time that the wavelength-shifted photons spend traveling and bouncing inside the detector before reaching the SiPM. To confirm this hypothesis we produced Fig. 11. The left panel shows the time taken by the simulated photons in Prototype I to reach the SiPM (i.e., before introducing any arrival time jitter associated to the SiPM) as a function of the total distance they have traveled since they were wavelength shifted (photon path length). The contributions



Fig. 12. Time taken by the simulated wavelength-shifted photons to reach the SiPM (time response of the SiPM is not included) in prototypes I (left) and III (right) for two different scenarios: (i) an exponential WLS re-emission profile with a characteristic time constant of 1.2 ns like for the EJ-286 (black) and (ii) instantaneous re-emission (red).

from the photon path length and the re-emission can be individuated in the inset in the same panel and in the plot of the right panel, respectively. The inset shows again the photon path length vs arrival time, but for the case in which we set the re-emission time of the WLS to be instantaneous. As can be seen, in this non-realistic case the arrival time of the photons is proportional to the total path length as expected. The right panel of Fig. 11 shows the arrival time distribution for three fixed photon path lengths, where we can see the characteristic exponential profile of the re-emission time of the WLS. Fig. 12 compares the arrival time distributions in prototypes I and III (without including the SiPM response) for the case of instantaneous re-emission (arrival time depends only on the photon path length) and for the case in which we simulate the exponential profile of EJ-286. The plot shows that the decay time of the WLS seems to have a dominant contribution to the SPTR of Photo-Trap, even in Prototype III where photons may need to travel larger distances before hitting the SiPM.

# 5. Discussion

We introduced Photo-Trap as a low-cost, low-noise, large-area SiPM pixel. We demonstrated that with the proposed solution it is possible to achieve large pixels with very good signal-to-noise ratio. This happens because Photo-Trap allows increasing the collection area while keeping constant the capacitance and the DCR. We built prototypes with a sensitive area of  $4 \times 4$  cm<sup>2</sup>, which are probably among the largest existing SiPM pixels with single-phe resolution at room temperature. The prototypes achieve a trapping efficiency of ~ 10 – 50% (which translates into a peak PDE of ~ 5–25%) with a SPTR of ~ 3–5 ns FWHM.

Photo-Trap inherited from the Light-Trap the idea of building largearea SiPM pixels for detecting visible light by trapping optical photons by TIR inside wavelength-shifter plastics [14]. In this work we did not only present an updated and improved design, we also studied for the first time some key factors affecting its performance like the  $S_{\rm WLS}/S_{\rm SiPM}$  ratio and the surface roughness of the WLS plastics. From the operation point of view, the main upgrade of Photo-Trap with respect to the Light-Trap is the addition of a dichroic filter. In our measurements we found that the efficiency increased by ~ 30% after adding the filter. Simulations suggest that this improvement could be higher if were able to control and minimize the distance between the filter and the WLS plastic.

Besides, we have also found that the filter can play a key role on minimizing the impact of the surface roughness of the WLS plastic on the performance, even when using a WLS plastic sample that had several visible scratches. This is relevant because it can contribute to relax the requirements on the quality of the optical polishing of the WLS plastics, which is likely to be one of the main causes of their cost.

Besides the filter and the surface roughness, there are several factors that affect the trapping efficiency of a Photo-Trap pixel. Some of them, like the reflectivity of the surrounding materials or the thickness of the air-gap between reflectors and the WLS plastic have been discussed in [14]. In this work we have also shown how the  $S_{\rm WLS}/S_{\rm SiPM}$  ratio impacts the achievable gain/trapping efficiency. The choice of the WLS plastic and SiPM sizes should then be optimized as a compromise between sensitivity, signal-to-noise ratio and cost, depending on the application.

According to the simulations, in all prototypes the trapping efficiency is reasonably flat over most of the pixel area. However, we can identify a region of higher efficiency close to the SiPM and zones of lower efficiency in the nearest corners to the SiPM. The efficiency would be more homogeneous if we could distribute a few SiPMs along the pixel, but this would also complicate the mechanic and electronic design.

Systems that use WLS plastics for increasing the collection area provide larger FOVs than systems based on lenses (and with a more compact design). The prototypes we built have a relatively large FOV (> 45° at 340 nm, > 30° at 375 nm). Since the FOV mainly depends on the angular dependence of the filter transmittance, this could be another important criteria to take into account when selecting a filter for a specific application.

The time resolution of Photo-Trap depends on the characteristic reemission time of the WLS and on the total path length that photons follow before reaching the SiPM. We have found that the decay time of the WLS will limit the SPTR. Faster re-emission times were reported in quantum dots [28]. Indeed, the possibility of using quantum dots instead of WLS fluors could be interesting to be explored, as in principle it should be possible to achieve narrower re-emission/absorption bands and they typically offer higher quantum yields. Distributing SiPMs in different parts of the pixels could also help improving the timing performance, as the mean photon path length would be reduced.

In general, it is likely that an industrial manufacturing process of the pixels would not only reduce their cost, but would probably allow to increase their efficiency. Mainly because it would be easier to control the thickness of the gaps between the WLS plastic, filter and reflectors.

Table 6 compares some of the main characteristics of Photo-Trap with typical values from commercial PMTs and SiPMs. Clearly one of

#### Table 6

Comparison of the main characteristics of Photo-Trap with those of standard high-gain photosensors. <sup>*a*</sup> Typical values at ~375 nm; <sup>*b*</sup> at room temperature and assuming a SiPM DCR of 50 kHz/mm<sup>2</sup>. For this comparison we considered the DCR per unit area of PMTs to be negligible.

|   | PMT [31]        | SiPM [1,27]      | Photo-Trap     |
|---|-----------------|------------------|----------------|
| PDE <sup>a</sup>                        | ~ 35 %          | ~ 50 %           | ~ 5 - 25 %     |
| SPTR (FWHM) [ns]                        | $\sim 0.1 - 10$ | $\sim 0.1 - 0.4$ | $\sim 2 - 5$   |
| DCR <sup>b</sup> [kHz/mm <sup>2</sup> ] | -               | ~ 50             | $\sim 0.3 - 5$ |
| High Voltage                            | Yes             | No               | No             |
| Sensitive to magnetic fields            | Yes             | No               | No             |
| Operative under ambient light           | No              | Yes              | Yes            |
| Largest Area [cm <sup>2</sup> ]         | $\sim 10^{2}$   | $\sim 10^{-1}$   | $\sim 10^1$    |
| Capacitance/mm <sup>2</sup>             | Low             | High             | Low            |
| Cost/mm <sup>2</sup>                    | Low-Medium      | High             | Low            |

the main drawbacks of Photo-Trap is its lower PDE, which in some applications might be compensated with an increase in the collection area. The wavelength-sensitivity band of Photo-Trap is also typically narrower, since it is dominated by the absorption spectrum of the WLS and the transmittance of the filter. This could be a limitation in some applications where the spectrum of the signal is broad (e.g., Cherenkovlight detection). However, in other cases it can be seen as an advantage as it may be useful for rejecting background light (for instance, in LED-driven applications that target a narrow wavelength range). A broader sensitive spectrum could be obtained by combining different WLS plastics, or even by doping the same plastic with several of them. A narrower one could of course be achieved just by selecting a different dichroic filter. The position-dependent efficiency of Photo-Trap could also be a limitation for some applications where uniformity in the light-collection is crucial.

Another drawback of Photo-Trap is its timing performance, which clearly limits the use of Photo-Trap in ultra-fast-timing applications like Positron Emission Tomography. Nevertheless, the time resolution that can be achieved with Photo-Trap is reasonably good for several applications. For instance, its performance is comparable to the one of the PMTs used in high-energy astrophysics experiments like MAGIC [29] or IceCube [30].

Probably the main advantage of Photo-Trap is that it offers a lowcost and low noise solution to build photodetectors of a few cm<sup>2</sup> without several of the limitations associated to PMTs, such as highvoltage operation, bulkiness, fragility or sensitivity to magnetic fields. This increase in the pixel size can be achieved without increasing the noise or power consumption, providing a very low DCR and capacitance per unit area. In this sense, Photo-Trap could be suitable for those applications in which sensitivity increases with the collection area (for instance, in large Cherenkov Detectors like HAWC [32] or SWGO [33], despite the relatively narrow sensitive spectrum), in those where SNR is highly affected by dark counts or background light or simply when power-consumption, compactness or cost are the main drivers. One possible application that combines most of these requirements could be optical wireless communication (OWC [34,35]). Many OWC systems require large collection areas to increase the sensitivity to the noncollimated light of LEDs, large FOVs to be less sensitive to alignment and low noise and large background rejection for achieving larger SNR (that may translate into larger optical links). In fact, different works have proposed to use WLS plastics [36,37] and SiPMs [38-43] in OWC, but as far as we know, there have been no proposals of combining both of them to build an OWC receiver.

## 6. Conclusions

In this work we presented Photo-Trap as a low-cost approach to build large-area SiPM pixels with very low noise (DCR of  $\sim 1$  to 10 kHz/mm<sup>2</sup>) and capacitance at room temperature. We built four proof-of concept pixels which differed in their sensitive area

 $(20 \times 20 \text{ mm}^2 \text{ and } 40 \times 40 \text{ mm}^2)$  and the size of the SiPMs they used  $(3 \times 3 \text{ mm}^2 \text{ and } 3 \times 12 \text{ mm}^2)$ . With these prototypes we measured optical gains ranging from ~ 5 to 15 and trapping efficiencies that went from ~ 9 to 48%. In this sense the dichroic filter played an essential role: with its addition the trapping efficiency increased by ~ 30%, while at the same time we found that it can minimize the impact of the surface roughness of the WLS plastics on the performance. With these pixels we measured a SPTR of ~ 3–5 ns and a field-of-view of ~ 40° at 375 nm and of ~ 50° degrees at 40 nm. A pixel like Photo-Trap could be suitable for those applications that require large collection areas, high background rejection and low cost, noise and power consumption.

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# CRediT authorship contribution statement

**D. Guberman:** Supervised the whole research, Designed the detectors, Responsible for the funding acquisition, Designed the mechanics, Built the prototypes, Performed the study that defined the criteria for the filter selection, Performed the simulations, Wrote the paper, Conceptualization. **C. Wunderlich:** Designed the mechanics, Built the prototypes, Performed the experimental measurements and analyzed the data, Wrote the paper. **G. Barillaro:** Performed the study that defined the criteria for the filter selection. **J. Cortina:** Conceptualization. **A. Paghi:** Performed the study that defined the criteria for the filter selection. **R. Paoletti:** Designed the electronics. **A. Rugliancich:** Designed the electronics.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

# Data availability

Data will be made available on request.

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