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Towards a new generation of photodetectors: The VSiPMT

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Summary. — The VSiPMT (Vacuum Silicon PhotoMultiplier Tube) is an innovative design we launch for a revolutionary hybrid photon detector. The main idea is to replace the classical dynode chain of a PMT with a SiPM, which therefore acts as an electron detector and amplifier. The aim is to match the large sensitive area of a photocathode with the performances of the SiPM technology. The VSiPMT will have many attractive features and its strongest points are the low power consumption and the excellent photon-counting capability. We proved the feasibility of the idea thanks to an R&D project, started with a Geant4-based simulation study and carried on with an essential experimental activity where we tested the performances of a special non-windowed MPPC by Hamamatsu as electron detector and current amplifier. In this work, we present the results of the full characterization of the first industrial prototypes of VSiPMT.

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1. – Introduction

Photon detection is a key factor to study many physical processes in several areas of fundamental physics research (*i.e.* particle and astroparticle physics, biomedicine) as well as industrial application (*i.e.* medical equipment, environmental measurement equipment and oil well logging).

Focusing the attention on photodetectors for particle astrophysics, the future experiments aimed at the study of very high-energy or extremely rare phenomena (*e.g.* dark matter, proton decay, neutrinos from astrophysical sources) will require additional improvements in linearity, gain, quantum efficiency and single-photon-counting capability. Even if, to date, the characteristics of the classical PMTs seem to be unrivalled, they

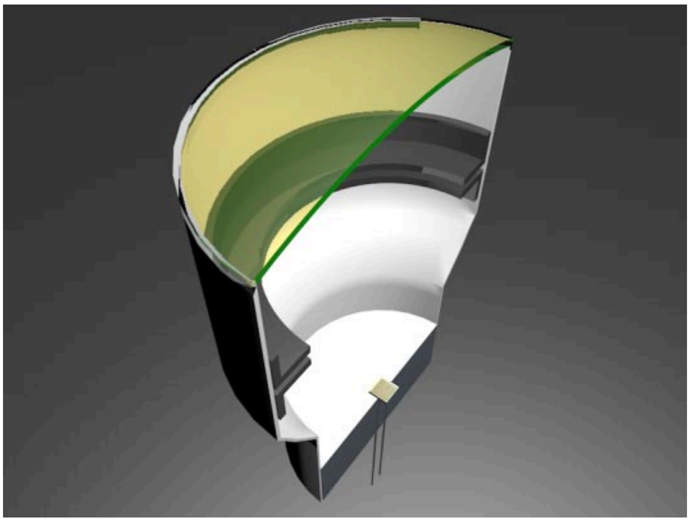

Fig. 1. – The VSiPMT conceptual design.

suffer of many drawbacks such as linearity-to-gain relation, difficulty in single-photon-counting, complexity of construction, sensitivity to magnetic fields and faults in cryogenic environments.

To overcome these limits, we invented a new high-gain, silicon-based photodetector, the Vacuum Silicon Photomultiplier Tube (VSiPMT), that meets the target of the experiments mentioned above [1].

The innovative idea is to replace the traditional dynodes chain of a PMT with a SiPM (fig. 1), which acts as an electron detector and then as a current amplifier with a gain of 10^5–10^6, that is somewhere around the typical gain of a standard PMT.

The realization of the VSiPMT will initiate a new generation of photodetectors which exhibit several attractive features such as: excellent single-photon detection, small size, high gain, negligible power consumption, weak dependence on magnetic fields.

2. – The VSiPMT prototype

The VSiPMT feasibility has been studied by leading several Geant-4 based simulations and then by testing the response of a special non-windowed MPPC by Hamamatsu to an electron beam radiation: the MPPC showed excellent electron-counting capabilities providing the first proof of feasibility of the device [2-4]. After we obtained two industrial VSiPMT prototypes by Hamamatsu (fig. 2): EB-MPPC050 (ZJ5025) and EB-MPPC100 (ZJ4991).

From fig. 2 it is intuitive to notice that the absence of the dynode chain and thus of the associated divider has several and very important consequences:

1. The device is more compact.

2. There are only three connections: two cables to supply powers to the photocathode and MPPC (the thin cable on the right and the lemo cable on the left, respectively) and one SMA output for signal readout.

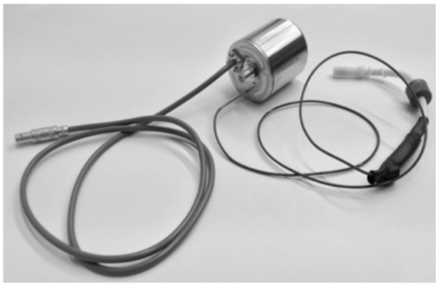

Fig. 2. – The VSiPMT prototype by Hamamatsu.

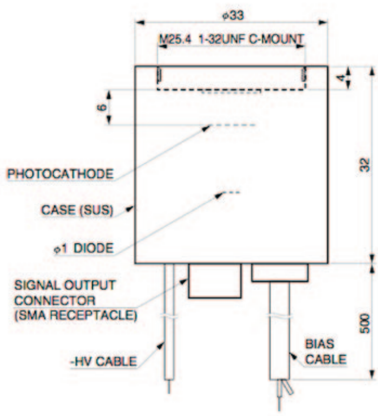

Fig. 3. – The scheme of the VSiPMT prototype realized by Hamamatsu.

Both the prototypes have the same envelope with a $7 \times 7\,\mathrm{mm}^2$ entrance window and a GaAsP photocathode with a 3 mm diameter and a spectral response in the range between 300 and 750 nm (fig. 3).

The two devices differ in the characteristics of the MPPCs used. The differences are resumed in the table I.

TABLE I. – *Table of the VSiPMT characteristics.*

Prototype	ZJ5025	ZJ4991
MPPC Area (mm^2)	1×1	1×1
Cell Size (μm)	50	100
Total Number of Cells	400	100
Optimized Configuration	p^+nn^+	p^+nn^+
MPPC Operation Voltage (V)	72.5	72.4
Photocathode Power Supply (kV)	-3.2	-3.2

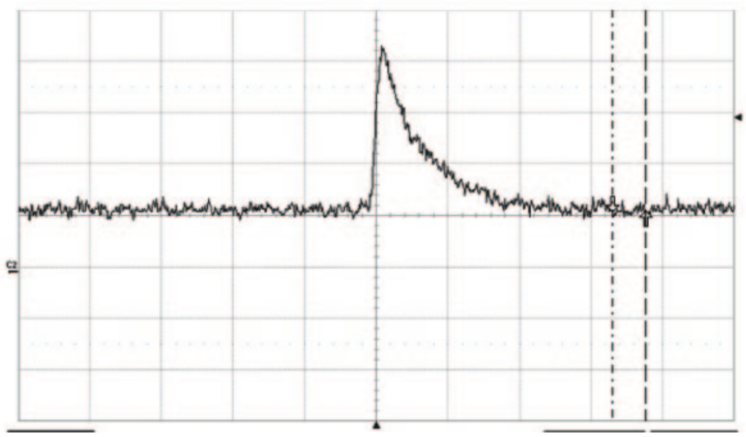

Fig. 4. – The amplified VSiPMT single photoelectron signal.

3. – The amplifier

The typical VSiPMT single photoelectron signal amplitude is around few mV, thus an external amplification stage is required.

Therefore we built three amplifiers based on the AD8009 OpAmp by Analog Device, a 5 GHz bandwidth Operational Amplifier used in non-inverting configuration. The three versions present different gains (10, 15 and 20 V/V, respectively), 50 Ohm input impedance, driving 50 Ohm output line.

In fig. 4, the aspect of the output signal of the amplifier with gain 20 is shown. Final typical amplitude turns out to be few tens of mV with rise time of few ns.

4. – The VSiPMT characterization: tests and experimental setup

Both the prototypes have been subjected to many tests in order to provide a full characterization of the device.

All the tests can be scheduled in the following sections:

- signal quality, stability and photon-counting capability;
- efficiency stability;
- gain;
- photocathode scan;
- transit time spread;
- afterpulses and dark counts.

For the characterization tests a picosecond pulsed laser emitting in the blue region (407 nm) has been used. The laser light is sent through a system of optical fibres to the VSiPMT and its intensity can be varied by using differently calibrated filters. The laser beam intensity is continually monitored by a power meter. The amplified signal

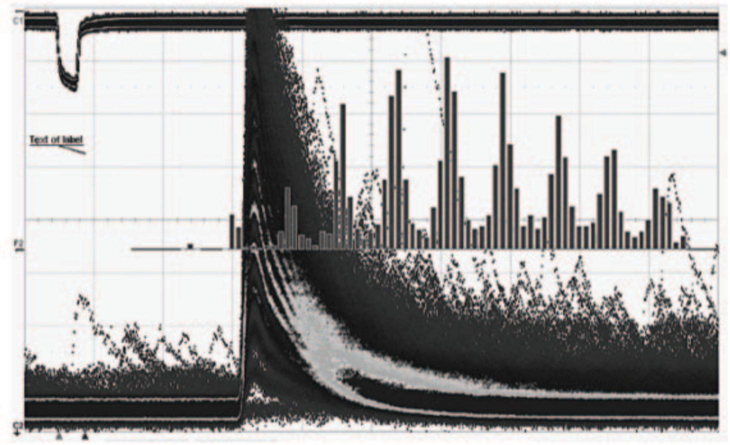

Fig. 5. – A typical ZJ5025 signal.

output is directly sent to the oscilloscope which is triggered in synchronization to the laser.

The measures are taken into a shielded dark box and the laser beam power is filtered to obtain few photons per pulse. The oscilloscope threshold is setted to 0.5 photon equivalent.

5. – Signal quality, stability and photon-counting capability

First of all the VSiPMT signal has been studied by lighting the photocathode with a low-intensity laser beam. Under these conditions a typical signal appears as in fig. 5.

Figure 5 is a snapshot of the screen of the oscilloscope: the "family" of wave forms is obtained by collecting 10000 triggers and by overlaying responses for multiple triggers. The oscilloscope was set to 5 mV/div vertical scale and 20 ns/div horizontal scale. Well-separated peaks are detected, stating excellent photon-counting capabilities of the devices.

The peak-to-valley ratio has been measured to be something around 60 in the single-photon condition.

The stability of the signal has been proved by acquiring it with a computerised digitizing system (CAEN V1724E, 12 bit, 4 ns sampling rate): 100000 wave forms with low-intensity laser light have been acquired every 20 min for 20 hours. As evident in fig. 6 the devices show an excellent stability in time.

6. – Detection efficiency: stability and uniformity

The photon detection efficiency of the devices can be factorized as follows:

$$PDE_{VSiPMT} = QE \cdot \epsilon_{MPPC},$$

where QE is the photocathode quantum efficiency and ϵ_{MPPC} is the MPPC electron detection efficiency. ϵ_{MPPC} is equal to the MPPC fill factor, since electrons penetrating the MPPC are always detected.

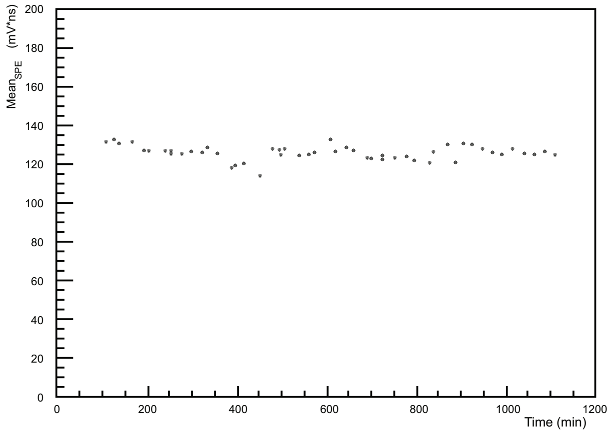

Fig. 6. – Results of the single photoelectron stability in time of the ZJ5025 prototype.

First of all the PDE of the devices has been tested. Each device has been lighted by very low-intensity laser beam (few photons per pulse) by using an optical fibre, during the test the laser beam intensity has been monitored by a power meter. By varying the photocathode power supply in step of 100 volts, a curve trend for the PDE has been obtained. As clear from fig. 7, the photon detection efficiency of the device becomes highly stable somewhere around -3 kV, showing a nice plateau region till -5 kV. This plateau region is due to the different gain-concept with respect to a HAPD (standard hybrid photodetector using an APD in substitution of the MPPC). Actually, in a HAPD high voltage is necessary to provide enough energy for the photoelectrons to bombard the APD and thus to obtain gain. In other words, the gain strictly depends on the high voltage. In the VSiPMT a new concept for the gain is exploited: it is obtained by electrons crossing the Geiger region of the MPPC and there is no connection between photoelectron energy and charge gain, since high voltage is required only for the photoelectron transfer. Thus there is no need for high-voltage stabilization, once the device is in the correct plateau.

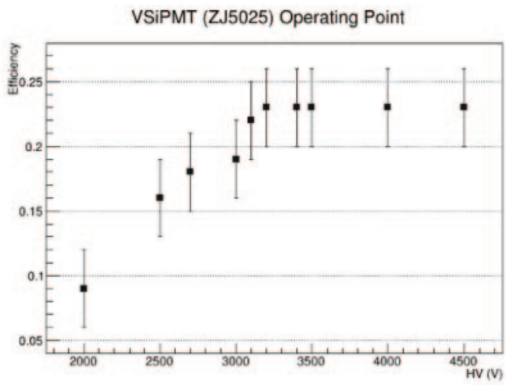

Fig. 7. – Results of the photon detection efficiency stability test on ZJ5025 prototype.

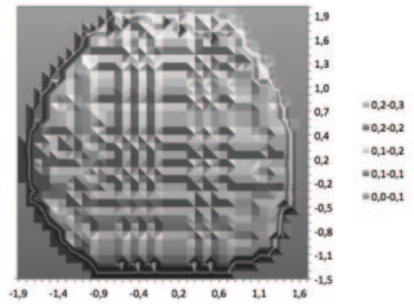

Fig. 8. – Results of the x-y scan of the photocathode of the ZJ5025 prototype.

The operating point for the high-voltage supply has been fixed to $-3.2\,\text{kV}$, corresponding to $\sim 23\%$ PDE value. Thanks to the different gain-concept an even lower operating point can be possible by simply reducing the thickness of the SiO_2 layer.

After testing the stability of the detection efficiency of the whole device (PDE), we perform x-y scan on the photocathode, to probe the uniformity of the PDE on the entire sensitive surface by estimating the local PDE. For this measurement, we used a micrometric x-y motorized pantograph integrated in an automatic DAQ system. Figure 8 shows the result of the x-y scan of the $3\,\text{mm}\ \varnothing$ GaAsP photocathode in a $7 \times 7\,\text{mm}^2$ entrance window. As evident from fig. 8 PDE is quite uniform (between 20 an 25%) almost on the overall photocathode surface, showing few boundary effects.

7. – Gain

As already introduced in the previous sections, in the VSiPMT the gain is obtained by the electrons crossing the geiger region of the MPPC. Thus, a standard current signal is given for each fired cell. On the basis of this working principle, we obtained a value of the gain as the ratio between the current output signal and the electron charge.

For this measurement, one needs a conversion of the output signal in the corresponding equivalent charge, and the contribution of the external amplifier must to be taken into account.

A measurement of the gain value with respect to the voltage supply has been carried out first by varying the HV (from -3 to $-4\,\text{kV}$) and keeping the MPPC bias voltage to $72.5\,\text{V}$, and then setting the HV to $-3.2\,\text{kV}$ and by varying the MPPC bias voltage from $72.1\,\text{V}$ to $73.0\,\text{V}$ in step of $0.1\,\text{V}$. As expected, there is no connection between HV and gain. Figure 9 highlights the linear trend of the gain on the MPPC power supply. The value for the gain at $72.5\,\text{V}$ is something around $4.3 \cdot 10^5$, that is the expected value for the MPPC.

8. – Transit Time Spread

A measurement of the TTS of the device has been carried out by using the experimental setup in fig. 10. The synch pulse of the laser is used as trigger, while the output signal of the VSiPMT is fed as stop signal via a discriminator. The time difference between the start and the stop signal has been measured. The TTS upper limit value measured is $0.5\,\text{ns}$.

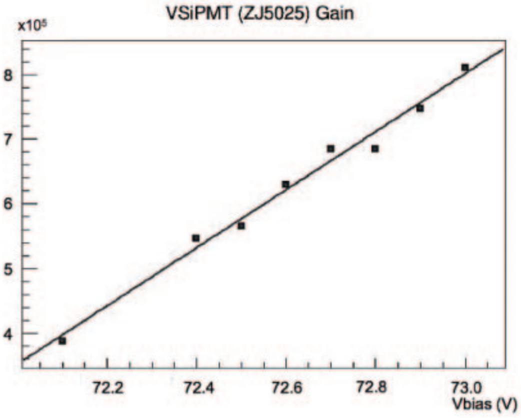

Fig. 9. – Gain work function of the ZJ5025 prototype.

9. – Dark counts rate

Like the gain, we expect that the rate of the dark counts is related only to the MPPC. The MPPC dark count rate is known to be strongly dependent on the bias voltage and on the pe threshold. For this reason, measurements of the dark counts rate at different bias voltage and different thresholds (respectively, 0.5, 1.5 and 2.5 pe) have been done.

Figure 11 shows the results of the dark counts rate of the ZJ5025 prototype. We performed these measurements in two different configurations: with HV set to the operating point and with no photocathode power supply too. No differences have been found between the two configurations, thus demonstrating that the dark counts rate depends only on the MPPC.

10. – Afterpulses

The VSiPMT suffers of two different classes of afterpulses: the MPPC internal afterpulses and the vacuum afterpulses.

The former are known to be due to silicon purity and are characterized by a small-amplitude signal (up to 3 pe) and higher frequency: their contribution has been measured to be less than 10%. The latters are characterized by a high-amplitude signal (up to

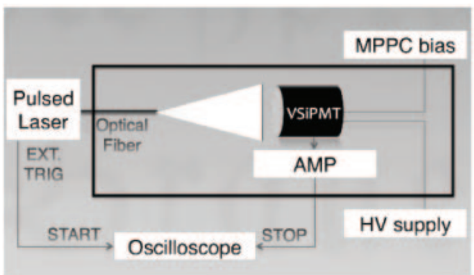

Fig. 10. – Experimental setup scheme for the ZJ5025 TTS measurement.

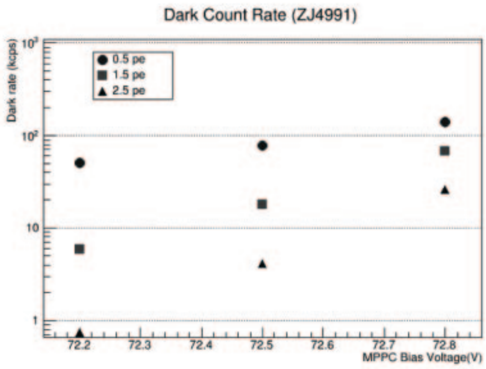

Fig. 11. – Dark count rate of the ZJ5025 prototype at 0.5, 1.5 and 2.5 value threshold.

10 pe) but a very low occurrence frequency. The arrival time distribution of afterpulses indicates they are generated by the interaction of electrons with the residual gases or desorbed materials present in the tube after evacuation. The residual gas contribution (spread out points in fig. 12) is very low $< 0.02\%$.

11. – Conclusions

Both the VSiPMT prototypes show excellent performances beyond expectations as unrivalled photon-counting capability, no power consumption (thanks to the absence of the voltage divider), a very easy stabilization due to a new high gain concept and a very fast response (TTS < 0.5 ns).

On the other side, these devices also suffer of some drawbacks as high dark counts rate and dynamic range, all related to the number of pixels. Both the problems are object of current studies. The former can be partially overcome by using the new generation

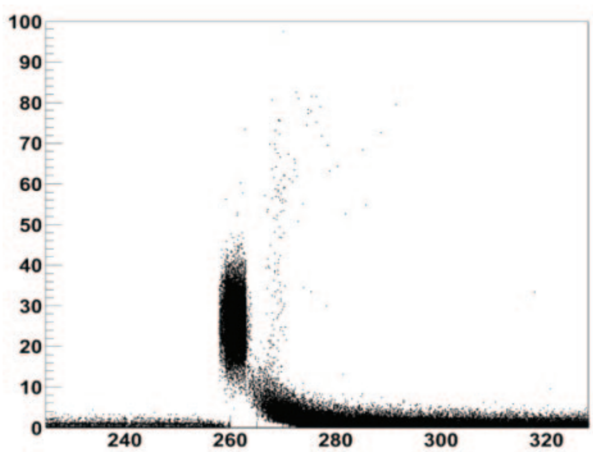

Fig. 12. – Signal amplitude distribution *vs.* arrival time of the ZJ5025 prototype.

of MPPC by Hamamatsu, for which the dark counts rate has been reduced of a factor 10. The dynamic range of this device strongly depend on the number of pixels of the MPPC used, the greater the number of pixels the wider the dynamic range. For these reasons, a SiPM with new, optimized shape and a new focusing technique are currently under study.

However, these first results lead us to believe that the proposed device has the potential to fulfill the requirements of the next generation of astroparticle physics experiments.

* * *

I would like to kindly thank Prof. Giancarlo Barbarino, the inventor of the VSiPMT, since both his original idea and his enthusiasm have been foundamental in steering our group to obtain the results presented.

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