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Recent development on the realization of a 1-inch VSiPMT prototype

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Abstract. The VSiPMT (Vacuum Silicon PhotoMultiplier Tube) is an innovative design for a revolutionary hybrid photodetector. The idea, born with the purpose to use a SiPM for large detection volumes, consists in replacing the classical dynode chain with a SiPM. In this configuration, we match the large sensitive area of a photocathode with the performances of the SiPM technology, which therefore acts like an electron detector and so like a current amplifier. The excellent photon counting capability, fast response, low power consumption and great stability are among the most attractive features of the VSiPMT. In order to realize such a device we first studied the feasibility of this detector both from theoretical and experimental point of view, by implementing a Geant4-based simulation and studying the response of a special non-windowed MPPC by Hamamatsu with an electron beam. Thanks to this result Hamamatsu realized two VSiPMT industrial prototypes with a photocathode of 3mm diameter. We present the progress on the realization of a 1-inch prototype and the preliminary tests we are performing on it.

1 Introduction

We propose an innovative photodetector for the astroparticle physics experiments: the VSiPMT. In this scenario the Vacuum Silicon PhotoMultiplier Tube represents an appealing solution to use SiPMs from large detection area or volumes, a current big challenge.
This new device is based on the combination of a SiPM with a PMT standard envelope, see fig. 1. In this device, invented in Naples in 2007 [1], the multiplication stage is provided by a special SiPM designed for electrons detection, called SiEM (Silicon Electron Multiplier). The SiEM acts as electron detector and so as current amplifier.
Using a SiEM allows to reach a very high gain totally provided by the pixels working in geiger mode. This has many advantages:

- Excellent photon counting. The photocathode is only a passive intermediary, so the device shows an exellent resolution of the single electron allowing an easy photon counting.

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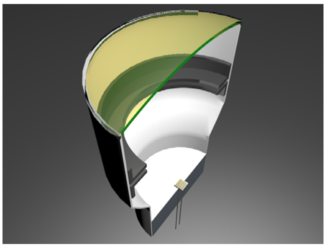

Figure 1. *A cutaway of the VSiPMT showing the interior composition of the device. On the top there is the light entrance window, then a photocathode for the photons conversion into electrons. In the middle there is a focusing ring producing an electric field which accelerates and focuses the photoelectrons on the SiEM surface. Finally, on the bottom there is a special SiPM whose structure is modified to act as an electron detector and current amplifier. Everything is assembled into and hermetically sealed container.*

- High gain with low voltage. Differently from a classical HPD, in this case the high gain is totally realized by the SiEM pixels operating in geiger mode. The average voltage supplied to the photocathode in a VSiPMT is commonly $\sim 3\ kV$.
- Negligible power consumption thanks to the absence of the voltage divider;
- High speed. The absence of a dynode chain means that a sistematical reduction of the VSiPMT TTS with respect to a classical PMT TTS is expected.
- Compactness and simplicity. Only 3 output connection are required.

2 Realization of a 1-inch prototype

The characterization of the first industrial prototype gave results beyond expectation [2]. Anyway an optimization of the focusing was necessary in order to optimize both the dynamic range and the PDE. With this aim we studied an optimized design for a 1-inch prototype.

2.1 The focusing

Since the SiEM is a pixelated device if the focusing is too weak, the photoelectron spot exceeds the size of the SiEM, in this case a fraction of the photoelectrons misses the target and is systematically lost, thus decreasing the overall PDE of the device.
On the other side, a too strong focusing produces a too much squeezed photoelectron beam, therefore the photoelectron spot intercepts only a fraction of the active surface of the SiEM, with a consequent reduction of the linearity.
In order to fully and correctly exploit the VSiPMT features the photoelectrons coming from the photocathode should: have a spot size comparable with that of the SiEM and be uniformely distributed on the SiEM surface.
SimION 8.0-based simulations have been implemented in order to find a configuration that meets this requirements.
The proposed solution is preliminary and consists of a single stage focusing system. Therefore, the device can be schematized as follows:

- flat 25 mm ∅ photocathode;

- focusing ring 25 mm in external diameter, 10 mm in height and 1.5 mm in thickness;
- $3 \times 3\ mm^2$ SiEM target.

The photocathode and the focusing ring are kept at the same voltage HV, while the SieM is at its nominal operating voltage, i.e. 67.2V.
A mesh of $3 \times 3\ mm^2$ with a $50\mu m$ pixel size is used to simulate the SiEM surface. In the simulations we first set HV to -3kV and then we varied the SiEM distance from the photocathode. The distance that better meets the requirements for the focusing is 16mm, see fig. 2.

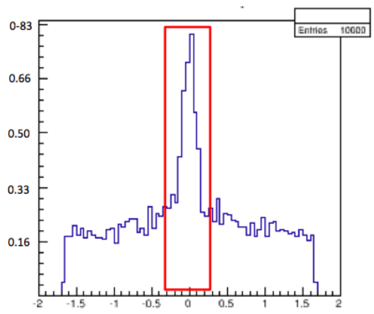

Figure 2. *Electrons distribution on the SiEM surface. The distribution in this position results to be flat in the 99% of the surface and only 1% of the SiEM has an higher probability to be fired by electrons.*

2.2 The photocathode

We chose the CsI as photocathode material since it is not sensitive to the oxigen in the air and thus allows an easy handling in the assembly phase. Since it is an insulating material, we needed a conductive layer to supply voltage. We performed a dedicated study in order to find a material that is conductive as well as transparent, in order to maximize the quantum efficiency of the photocathode. Between all the deposited materials we found the best solution to be a substrate made of Carbon and Nichel that will ensure a high quantum efficiency. We then deposited the CsI photocathode obtaining a QE = 15% with a MgF_2 window and QE = 11% with a quartz window at $\lambda = 170\ nm$,[3][4].

2.3 The SiEM

The selected SiEM is a custom MPPC S10943-3360(X) realized for us by Hamamatsu upon request. It is without epoxy resin and with a p-over-n internal structure. The surface is $3 \times 3\ mm^2$ with a $50\mu m$ pixel size. It has been fully characterized with a light source before being used in the VSiPMT.

3 The preliminary results

Once the several parts that composes the VSiPMT have been chosen, an intermediate phase between the preparation of the parts and the final assembly is necessary.
In view of the final assembly of the VSiPMT, we set up a test bench in the DAFNE Light facility available at Frascati National Laboratories (LNF) aimed at testing the focusing.
The SiEM is mounted on a movable support, the photocathode is lighted by a deuterium lamp. We

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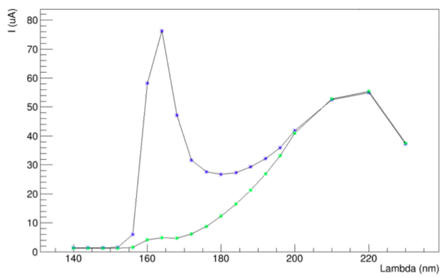

Figure 3. *Output current with HV off (green dots) and HV on (blue dots).*

first measured the output current with HV off and on, in such a way to check the proper operation of the device, see fig. 3. This is a very important result since the difference between the two states of the photocathode (on and off) concentrates in the region of sensitivity of the CsI photocathode, this means that the exceeding current is due to photoelectrons coming from the photocathode.
We finally tested the focusing by varying the SiEM distance from the photocathode. In fig. 4 the SiEM readout current is plotted with respect to the SiEM distance from the photocathode. The results

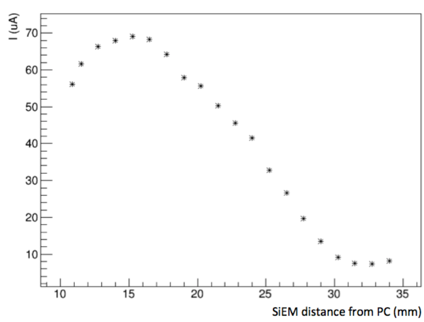

Figure 4. *Plot of the SiEM output current with respect to the distance from the photocathode.*

of the test were good in terms of focusing. It's easy to observe that the position that maximize the readout current (i.e. the number of fired pixels) correspond to the position where the photoelectron distribution on the SiEM surface is expected to be mainly flat from the simulations. These two plots combined together represent a significative milestone in the project since it means that for the first time the sensitive surface of the SiEM has been enlarged of more than 50 times.
In addition, the dark counts rate remains that typical of a single SiEM. This is equivalent to reduce the dark-rate/mm2, that up to now has been one of the main issue for the SiPM manufacturers.

4 Conclusions

The VSiPMT is an innovative hybrid photodetector which combines a photocathode with the SiPM technology. Simulations for an optimized focusing have been done. A 1-inch pre-prototype has been realized in Naples and Bari laboratories and tested at LNF. The results of the tests were in agreement

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with the simulations. A 1-inch prototype realized by Hamamatsu is currently under test in Naples laboratories.

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