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Test on VSiPMT prototypes

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Vacuum Silicon PhotoMultiplier Tube (VSiPMT) is an innovative photodetector based on the combination of SiPM and PMT technologies. The basic idea consists in replacing the classical dynode chain of a PhotoMultiplier Tube with a SiPM.

Such a design was proposed by our group in order to match the goal of a large photocathode sensitive area with the unrivalled photon counting performances of SiPMs. Moreover, much more improvements with respect to the standard PMT technology are expected to be obtained by VSiPMTs. First of all, the absence of the standard dynode chain will lead to avoid using voltage dividers and, hence, to a much lower power consumption. Transit Time Spread is expected to be sensibly reduced, since there will be no dynode chain spread, while Single Photoelectron resolution and gain stability will be much improved.

In the proposed configuration, the SiPM acts as an electron multiplying detector. Therefore, the proof of feasibility of VSiPMT has required a thorough study both from a theoretical and experimental point of view.

The extremely encouraging results obtained by our group led us to a new, advanced phase, consisting in the test of some VSiPMT prototypes realized by Hamamatsu.

Our results show that VSiPMT prototypes performances go far beyond our expectations, thus charting the course for the development of an unrivalled innovative photon detection technology.

In the present work we will describe accurately the results of our tests on Hamamatsu prototypes and we will show our studies and our purposes for the optimization of the device.

Summary

The detection of (single) photons is an essential experimental tool for a wide range of research areas. To date, in astroparticle physics experiments based on Cherenkov detectors a crucial role has been played by photomultiplier tubes. PMT technology has been improved continuously in the last years: the quantum efficiency of the photocathode has now reached a level of 40%, close to the theoretical maximum; single photon sensitivity and time resolution have been improved by a careful design of electrostatic focusing on the 1st dynode; with new coatings the secondary electron yield of dynodes has greatly improved, reducing the required number of dynodes and their size. Nevertheless standard photomultiplier tubes suffer the following drawbacks:

- fluctuations in the first dynode gain make single photon counting difficult;
- linearity is strongly related to the gain and decreases as the latter increases;
- transit time spreads over large fluctuations;
- mechanical structure is complex, voluminous, rather massive and expensive;
- they are sensitive to magnetic fields.

Moreover, in low background experiments the radioactivity of the photomultiplier components is a key concern. In fact, in many applications PMTs can dominate the total radioactivity of the detector. A significant effort is being made by manufacturers and research teams in order to reduce the background from photomultiplier tubes by rigorous choice of the raw materials used for all components. However, significant traces of radioactive nuclei are encountered in the metal and ceramic parts of the electron multiplication system.

Hybrid photodetectors, not using dynode structures for amplification, are an attractive solution. In fact, in this type of device photoelectrons emerging from the photocathode are focused onto a silicon detector. As

silicon is virtually free of radioactivity and the mass of the photodiode can be very small, the background from the inner part of the tube can be significantly reduced.

The Vacuum Silicon PhotoMultiplier Tube (VSiPMT) is an innovative photodetector based on the combination of SiPM and PMT technologies. The basic idea consists in replacing the classical dynode chain of a PhotoMultiplier Tube with a SiPM.

Such a design was proposed by our group in order to match the goal of a large photocathode sensitive area with the unrivalled photon counting performances of SiPMs.

Moreover, much more improvements with respect to the standard PMT technology are expected to be obtained by VSiPMTs. First of all, the absence of the standard dynode chain will lead to avoid using voltage dividers and, hence, to a much lower power consumption. Transit Time Spread is expected to be sensibly reduced, since there will be no dynode chain spread, while Single Photoelectron resolution and gain stability will be much improved.

Differently from standard hybrids based on APDs, in the VSiPMT the HV between the photocathode and the silicon device is limited to 2-4 kV. Moreover, this HV is needed for the transportation of the photoelectrons and to make them overcome the SiO₂ coating layer covering the SiPM. Therefore, the photoelectrons need a much lower voltage to be detected by a SiPM. The multiplication given by the SiPM is independent of the kinetic energy of the photoelectrons, as the output signal of a SiPM is independent of the number of electrons/holes created by the photoelectron in the same cell and is instead proportional to the number of cells fired.

Several studies have been performed in last years by the INFN Napoli group on this subject. On the base of the very encouraging results obtained by our group, a first prototype of the VSiPMT has been developed in collaboration with Hamamatsu and tested in our labs.

The measured performances are extremely encouraging. The work function of the VSiPMT has been evaluated showing a good linearity with satisfactory gain output $G=(3\div 6)\cdot 10^5$. This prototype showed extremely good photon counting capabilities thanks to the very good performance in terms of SPE resolution ($<17\%$), peak-to-valley ratio (> 60) and Transit Time Spread (< 0.5 ns).

With an optimized design, the VSiPMT will exhibit several attractive features such as:

- excellent single photon detection;
- high gain;
- small electron amplification system size;
- negligible power consumption;
- low radioactivity background;
- weak dependence on magnetic fields;
- small price with respect to PMTs;
- good performance at low temperature.

In this work we will provide an accurate description of the prototypes and of the extremely encouraging results of our tests. Moreover, we will show our studies and our purposes for the optimization of the device.

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