Design of a Base-Board for arrays of closely-packed Multi-Anode Photo-Multipliers


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Abstract

We describe the design of a Base-Board to house Multi-Anode Photo-Multipliers for use in large-area arrays of light sensors. The goals, the design, the results of tests on the prototypes and future developments are presented.

Key words: Photon Detectors, Multi-Anode Photo-Multipliers, Housing, Sensor Array, High-Energy Physics, Astro-Particle Physics.

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1 Introduction

Contemporary experiments in Nuclear, Particle and Astro-Particle physics often require the use of fast, large area and highly pixelized single photon detectors with limited dead-areas, featuring up to hundreds of thousands of channels with tight resource limitations. Among others, Ring Imaging Cherenkov detectors (RICH) (see HERAb [1], LHCb [2] and AMS [3]) and Space Telescopes for Ultra High energy Cosmic Rays observation (see EUSO [4], TUS/KLYPVE [5] and OWL [6]) belong to this category. Moreover Medical Imaging applications are often subject to very similar requirements. Multi-Anode Photo-Multipliers are often the preferred sensor for these applications.

In such cases one of the main problems is to assemble the whole detector, on the focal surface of the collecting optics, by closely packing the array of sensors, in such a way to keep an acceptable geometrical acceptance and avoid defocusing effects. With this goal in mind we have carried on the design, prototyping and testing of the housing (Base-Board) for a large array of closely-packed Multi-Anode Photo-Multipliers, with particular emphasis on possible Space applications. As Space applications have a number of tight additional requirements with respect to ordinary applications, the device described in this paper might have a broad range of applicability.

One should note that the geometrical acceptance of the sensor itself is a closely related issue, affecting the overall geometrical acceptance of the array of sensors. The usual way to deal with the geometrical acceptance of the sensor consists in either improving the geometrical acceptance of the bare sensor (like, for instance, in the R8520 and Flat Panel PMT series from Hamamatsu Corporation [7]) or using a suitable Light Collection System (either an imaging system or not) in front of the sensor [8,9,10]. This paper will not be concerned with this issue, and it will be assumed that the geometrical acceptance of the sensor itself has been already maximised in a suitable way. However, in the development of the Base-Board, we kept in mind that each sensor might be equipped with its own suitable Light Collection System.

The Base-Board which is the object of this paper was first developed in the framework of the development of the RICH detectors of the LHCb experiment [7]. Later on the design was improved to adapt it to the Space requirements of the EUSO mission [11].

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2 The Goals of the Design

A modular architecture is preferred when building large detectors made by assembling smaller units, because it has many advantages including: independence of the different modules, fault propagation limitation, easier spare modules management and procurement. Moreover a modular architecture makes the development, design, integration and testing phases easier.

Therefore the full apparatus shall consist of small independent functional units, named Elementary-Cells (EC), assembled into larger modules, named Photo-Detector Modules (PDM). The Elementary-Cell shall consist of a limited number of MAPMT, sharing some common resources and constituting a totally autonomous system.

The sharing of resources improves the economy and makes design, production and testing easier. Moreover when resources are limited, as it is the case in Space applications, saving on resources can be accomplished by combining functions, which is the approach implemented in the current design of the Base-Board.

The Elementary-Cell was conceived with the following guidelines and requirements in mind.

- The EC shall be an autonomous and compact module with different functionalities integrated onto a Printed Circuit Board (PCB) Base-Board.
- To EC shall allow to pack as closely as possible the MAPMT on the Base-Board and shall be built to allow to pack as closely as possible different EC, in both cases ensuring a precise relative positioning. The packing of both the sensors in the EC and the EC in the PDM has to be optimised to reduce losses in the geometrical acceptance, due to dead regions between the close packed elements, and defocusing effects, originating from a positioning of the elements at some distance from the ideal focal surface.
- To EC shall allow a sharing of different resources between different MAPMT:
  - there is one common mechanical supporting structure and common thermal dissipation capabilities;
  - the thick PCB is used as a mechanical supporting structure but it also acts as an electric board housing the electrical components and connections;
  - voltage dividers and HV/LV power connections may be common to different MAPMT (whenever this is desired);
  - common electro-thermo-mechanical components such as cables, connectors and heat bridges;
  - possibly common front-end electronic chips for more than one MAPMT.
- The EC shall include the front-end electronics chip for local processing of the signals, located as close as possible to the MAPMT in order to minimise
the length of the connections to preserve the fast signal from the MAPMT, with good signal to noise ratio. Due to the large number of channels and the tight space, speed and power requirements the development of an ASIC device is mandatory (see [12]).

- Finally the EC shall be a single, self-contained and autonomous system, designed as a general purpose instrument to be used in other applications too.

The EC can be built as a thick multi-layered Printed Circuit Boards (PCB). A number of these modules, each one making an essentially autonomous system, are then put together to make a PDM. These are independent assemblies tied to each other by a common supporting structure and having a shape determined by the layout of the focal surface. In fact a modular structure made of small elements is well suited to fit any focal surface shape, as it is required by some of the applications, featuring a highly curved focal surface.

In the current work MAPMT are assumed to be packed into a \((2 \times 2)\) EC. A realistic (and possibly conservative) MAPMT pitch is assumed to be 27.0 mm to account also for the large tolerances on the MAPMT dimensions provided by the manufacturer: \((25.7 \pm 0.5)\) mm.

It will be assumed that a PDM is made of an array of close-packed EC with a suitable layout and shape, possibly surrounded by a border of variable thickness running all around the MAPMT, to leave space for the mechanical assembly of the PDM. Obviously the detailed design of the PDM geometry depends on the specific application and it will not be discussed in this paper.

3 Design, production and assembly of the Base-Board

The MAPMT used in this design is the R7600-M64 Multi-Anode Photo-Multipliers from Hamamatsu Corporation [13]. The sensor has a square input window with \(L = 25.7\) mm side and about 35 mm height. Its mass is about 30 g.

The current prototype has been designed and manufactured without the front-end chip, due to the parallel development of the ASIC chip itself. In place of the front-end chip two high-density connectors per MAPMT, with 0.5 mm pitch, were installed. The signals are then taken away from the EC by means of a flex-cable to be processed by a suitable electronics.
3.1 The Elementary-Cell

The EC, in the current design and configuration, consists of:

- the sensors (currently four R7600-M64 Multi-Anode Photo-Multipliers);
- the Light Collector System;
- the HV dividers (currently one for each MAPMT);
- the front-end electronics chip;
- the connectors for HV/LV, signals and controls;
- the Base-Board, a thick PCB housing all the other components and carrying the electrical connections;
- a copper layer, buried inside the PCB, to help heat transfers away from the EC;
- mechanical elements;
- a potting resin;
- any other required structural or functional element (if any).

A resistive voltage divider was chosen for maximum reliability. MAPMT are powered in negative polarity, that is with anode grounded, in order to avoid using decoupling capacitors at the anodes, thus saving space and increasing the reliability.

In order to keep the linearity of the response, under the expected photon rates, suitable capacitors were inserted in parallel to the last three dynodes. Moreover, in order to save power while keeping an acceptable linearity of the response, three different HV inputs were provided to the MAPMT at the level of the cathode and the last two dynodes.

3.1.1 The Base-Board

Any EC is totally autonomous and it is individually fixed to the PD module supporting back-planes. This approach allows a large flexibility in the choice of the shape of the PD module, including, possibly, allowance for a curved shape.

The Base-Board acts as the structural element, housing the MAPMT, the front-end electronics and all the other necessary components. It includes the traces to carry the signals from the MAPMT to the front-end electronics and to the outside of the Base-Board as well as the traces carrying the power and control signals to the components.

The MAPMT side of the Base-Board also houses the components of the voltage dividers to power the dynode chain. Up to one voltage divider per MAPMT (that is four in total) can be housed onto the Base-Board (as it is in the
prototype). Alternatively, one might install only one or two voltage dividers (trade-off). In the current base-line one voltage divider per MAPMT is used in order to decouple as much as possible the four MAPMT. This approach increases the reliability and reduces the interactions among the MAPMT, while testing the design in its most challenging configuration.

3.2 The Mechanical and Thermal design

The following assumptions have been made:

- standard printed circuit board manufacturing accuracy (0.1 mm);
- maximum MAPMT side length limited to 25.7 mm;
- minimum installation clearance between neighbouring MAPMT: 0.5 mm.

The mechanical drawing of the current Base-Board design is shown in figure 1.

![Mechanical drawing of the current Base-Board design.](image)

The Base-Board is a 4 mm thick flame retardant FR4 glass epoxy laminate. It integrates a copper layer, 0.5 mm thick, to help to convey the heat produced on the Base-Board to the screws and dowel pins as well as improving the structural properties. The Base-Board is secured to the back-standing support by four M2.5 stainless steel screws and, if necessary, by up to four φ2.0 dowel pins. This allows a precise relative positioning of the different EC onto the PD-module and redundant support.
Screws and dowel pins fit into metallized holes drilled into the PCB. Screws are equipped with cylindrical hollow aluminium spacers, so that enough space to allow the routing of the services is available between the Base-Board and the back-standing support. The spacers also allow to improve the structural performance of the fastening system. The location of the holes is a trade-off between the structural requirements and the electrical layout. High accuracy, conventionally available in PCB manufacturing, should allow the precise positioning of the EC, so that the design characteristics can be kept without any interference during assembly and dismounting operation.

Screws, dowel pins and spacers also act as thermal bridges to convey the heat generated on the Base-Board, by the voltage dividers and front-end electronics, away from it, to the back-plane supporting structure. This is accomplished by conduction, and dedicated heat bridges, whenever necessary.

3.2.1 Structural analysis

A finite elements structural simulation has been performed, modelling the Base-Board with its links to the back-standing structure and simulating the MAPMT as added masses. The modal analysis of a 5 mm thick Base-Board, fastened through four $M2.5 \times 15$ stainless steel screws, with an overall mass of 0.2 kg, has determined the following first modal frequencies: 716 Hz, 872 Hz, 1259 Hz, 1801 Hz, 1878 Hz. Afterwards a random vibration analysis has been performed with the input spectrum suggested by NASA for acceptance of items whose mass at launch is below 23 Kg ([14]). Such spectrum of acceleration is equivalent to 6.9 G RMS. A standard damping ratio of 0.025 has been assumed, constant throughout the frequency range. The calculated response of the system, when the excitation is parallel to the Base-Board plane, showed a sharp peak in correspondence of the first modal frequency, with an integral value of 25 G RMS. The calculated response of the system, when the excitation is orthogonal to the Base-Board plane, showed a sharp peak in correspondence of the fifth modal frequency, with an integral value of 39 G RMS. The result is consistent with the fifth modal shape.

The static analysis performed with the above acceleration combined in a load vector showed the screws working as fully constrained beams, as expected, with the most stressed points at their ends. Calculated Von Mises’ equivalent stress in those points was well below the allowed limits.

3.2.2 Thermal analysis

A finite elements analysis has been performed on a simplified model, where the EC was thermally linked, through its fastenings, to a cold pit at $T = 13^\circ\text{C}$. Heat is supposed to be drained away by means of conduction only. An
uniformly distributed power of 0.3 W, as expected in real operation, has been assumed. The results of the analysis showed that the copper layer works well: the PCB hot side temperature becomes uniform to within one degree and a temperature drop of $\Delta T = 6^\circ C$ is generated with respect to the cold pit.

3.3 The Electrical design

The routing of the electric connections is hard, due to the high number of channels and components and the limited available space. However, thanks to the regular geometry of the MAPMT anode connections and of the connectors, it was easy to manually route the connections in such a way that no intermediate layer was necessary in the PCB for the routing the signal paths.

The four voltage dividers (made of resistors, capacitors and the three HV inputs per MAPMT) are made of surface-mount devices and installed on the side of the MAPMT.

The signal connections starts from the MAPMT side and are routed to the back-side of the Base-Board through via holes, where either a front-end chip or suitable connectors are housed.

The signal connectors on the back-side are located at the centre of the corresponding MAPMT. The HV connector is located at the centre of the Base-Board and the three voltages are routed to the four voltage dividers.

The PCB layout was done following the standard design rules.

3.3.1 Mounting of the MAPMT

By using a surface-mount technique for the MAPMT the thickness of the Base-Board can be kept relatively small, compatibly with the mechanical requirements, thus saving mass. The optimal thickness will result from a trade-off with the structural requirements.

If one wants to avoid direct soldering of the MAPMT one needs a suitable socket. A dedicated surface-mount socket was produced [15], as shown in figure 2.

3.4 The Elementary-Cell assembly

A possible assembly procedure can be carried on via the following steps.
(1) Mounting of the passive components on the Base-Board: voltage-dividers components, surface-mount socket for the MAPMT and connectors. Test of the passive components. An X-ray scan can be performed at this stage to check the soldering joints.

(2) Installation and test of the front-end electronics.

(3) Installation and test of the MAPMT.

(4) Potting of the whole EC.

A suitable potting between the MAPMT and the Base-Board and all around the four MAPMT with a suitable resin will ensure electrical and mechanical insulation, mechanical damping, structural strength, containment and good protection of the components, long-lasting mechanical resistance and good electrical contacts, and, possibly, light tightness and good thermal conduction. Dow Corning DC-93500, a commonly used potting resin for space application, has been assumed as base-line potting compound.

The impossibility to perform a complete visual inspection of the EC can be overcome by X-ray inspection techniques and/or by defining a suitable alternative testing functional procedure, either for the MAPMT connections and for the front-end ASIC.

The scheme of the mounting is shown in figure 3.
4 Prototype tests

A batch of Base-Board prototypes has been manufactured to be used in laboratory tests, and equipped with BGA sockets and dummy, expendable, MAPMT. This prototype is reasonably close to the designed EC as far as the thermomechanical properties are concerned. Moreover one prototype was installed including real MAPMT.

Pictures of the prototype EC with some of the MAPMT installed, without Light Collector Systems and no potting, are shown in Figure 4 and 5.

4.1 Functional tests

The EC prototype was submitted to functional tests. The behaviour of the MAPMT was as expected and no effect due to the specific housing on the EC was noticed.
Fig. 4. Front-view of the prototype EC, with three of the MAPMT installed but without Light Collector Systems and no potting.

4.2 Structural tests

Effectiveness and reliability of $M2.5$ screws, a forced choice because of the tight layout constraints, have been checked through an extensive test campaign. An $M2.5$ stainless steel screw has been tightened on a 5 mm thick FR4 board and submitted to approximately six times the maximum expected equivalent static stress. After eight months, there was no evidence of damage either of the Base-Board, or of the screw. Then, $M2.5$ stainless steel screws have been tightened to rupture onto a 4.5 mm thick G10 board (including a 0.5 mm thick copper layer inside): all the five screws tested broke at a torque in the range from $(60 \div 65)$ cNm.
Mechanical tests have then been performed on a vibrating table.

A EC sub-assembly, complete with dummy MAPMT and potting resin, has been set up. Its measured mass, including stainless steel screws and aluminium spacers, was measured to be 0.16 kg, that is much lighter than assumed in the simulations.

The EC assembly has been installed, in horizontal position, equipped with an accelerometer, and submitted to a sine sweep. The first resonances were found at 1.0 kHz and 1.3 kHz. Afterwards a Random Vibration Test was started, submitting the assembly to white noise in the frequency range from 20 Hz ÷ 2000 Hz. The load was gradually stepped, from 4 G RMS to 9 G, and each step lasted 60 seconds. As a last step, the spectrum measured by the accelerometer on the support bracket (input) was equivalent to 8.3 G. After the Random Vibration Test campaign, a sine sweep has been performed again, and resonances have been found at almost the same frequencies, showing that no significant changes happened.

The same test campaign has been repeated with the EC assembly installed in vertical position. The first resonances were found at 0.6 Hz and 0.8 Hz. The system has been submitted to the same Random Vibration Test with white
noise and up to 9 G in input was measured. The location of the resonances showed no significant change after the test.

At the end, the assembly in horizontal position has been submitted to a sine burst, where a sinusoidal excitation at 35 Hz and amplitude equivalent to 11 G entered the system for 10 seconds. The sine sweep again found almost the same resonances after the test. The EC response was about the same as the input, showing a rather ineffective damping at 35 Hz.

After all the tests, the whole assembly has been inspected, and electrical continuity checked. No damage has been noticed.

The preliminary tests performed on the prototypes proved that the mechanical design solutions chosen are reliable, including the choice of the stainless steel screws holding directly on a thread machined on the glass-epoxy EC Base-Board.

4.3 Thermal tests

A group of three EC, equipped with heaters to simulate the power dissipation of the on-board electronics and instrumented with PT100 temperature probes, has been installed in a test set-up, with a geometry that kept at negligible level the convective heat exchange.

All the parameters have been set to reproduce the boundary and load conditions, as assumed in the simulations. Measured Base-Boards surface temperatures were around 22 °C, slightly above room temperature, while the temperature drop measured across the mechanical links of the EC was in the range 4.5 °C ÷ 5.8 °C. Results are in good agreement with the simulations. The heat balance confirmed that 0.95 of the power was flowing through the EC mechanical fasteners, as desired.

The good agreement between estimates and measurements confirms the good thermal conduction at the metallized holes.

The preliminary tests performed on the prototypes proved that the thermal design solutions chosen are reliable, including the choice of including a copper layer inside the EC Base-Board to reduce both temperature peaks and temperature non-uniformities.
5 Conclusions

The design, construction and tests of the prototype of a Base-Board for arrays of closely-packed Multi-Anode Photo-Multipliers was presented. The design was carried on taking into account the tight requirements of space applications and it is, therefore, of wide applicability.

The EC Base-Board design proved to be robust enough to withstand the severe environmental conditions expected during a space mission.

The next and final step of prototyping foresees a Base-Board with the front-end electronics ASIC installed on the back-side. It is planned to use the device as the sensitive element of the Photo-Detector for applications including: measurement of the background to Ultra-High-Energy Cosmic Rays observations from space, test measurements of Ultra-High-Energy Cosmic Rays either from the Earth surface or from balloons and measurements of the air scintillation yield (a basic information for Ultra-High-Energy Cosmic Rays experiments).

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