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EUSO (Extreme Universe Space Observatory): The focal surface photo-detector

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Abstract. The design of a photo-detector to look from space to the Extensive Air Showers produced in the atmosphere by Extreme High Energy Cosmic Rays is a challenging task. The *EUSO* project, proposed to ESA for installation on the International Space Station, has been recently approved by ESA for a phase A study. In this paper the basic guidelines for the *EUSO* photo-detector design and the main results of the studies carried on so far will be summarized. The outcome of these studies can be used to estimate the performance of *EUSO* and to provide guidelines for further improvements of the present design. A realistic baseline scheme for the photo-detector, based on the presently known information and constraints, is proposed.

1 *EUSO* parameters

The *EUSO* experiment, designed to look from space to the Extensive Air Showers (EAS) produced in the atmosphere by Extreme High Energy Cosmic Rays, is described elsewhere in these proceedings. The present provisional *EUSO* parameters (O. Catalano, 2000), the ones most relevant to the photo-detector design, are summarized in table 1.

2 Requirements for the photo-detector

In this paper the word *photo-detector* will be taken to include the following systems:

- the focal surface structure, layout and engineering, its integration with the support structure and with the space vehicle;
- the optical interface to the sensors on the focal surface (the light collection system);
- the sensors;
- the front-end electronics;
- the ancillary systems required for the proper functioning and control of the photo-detector and for data acquisition.

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The choice of the best photo-detector for the observation from space of the EAS produced in the atmosphere by very high-energy cosmic rays is a very difficult challenge, due to the many requirements and constraints.

The photo-detector has to be able to detect the EAS by observing the nitrogen fluorescence light produced during the EAS development and the Cherenkov light diffused from the Earth surface. It must be able to determine the position of the arriving photons as a function of time, to be able to follow the space-time development of the EAS. The main requirements were reviewed in (AirWatch, 1997).

3 Sensors for the *EUSO* photo-detector

A number of possible sensors exist for use in the *EUSO* photo-detector which were evaluated during the past years (AirWatch, 1997). The use of commercial Multi-Anode Photo-Multipliers Tubes (MAPMT) (Hamamatsu Photonics K. K., R7600 MAPMTs) for the *EUSO* photo-detector (AirWatch, 1997) was finally proposed as the most viable option based on existing and reliable devices. In fact MAPMTs fulfill most of the requirements and they are a well-established technology, available from shelf, with a solid basis in industry and characteristics and a price which are easily quantified. The availability of devices different pixel sizes (and, correspondingly, different number of channels, namely 16 or 64) proves to be extremely useful to tune the photo-detector design to the requirements.

And $R\&D$ program was carried on to validate this choice and to find possible solutions to a few open items which might limit the usefulness of the device in *EUSO*, the most important of which appears to be the low overall geometrical acceptance of the bare device. Operational issues, such as power consumption, were also preliminarily investigated.

Desired pixel size at the Earth surface	$\Delta \approx 0.8$ km
ISS average orbit height	$H \simeq 380$ km
Overall atmospheric transmission (330 nm $\leq \lambda \leq 400$ nm)	$K_{atm} \simeq 0.4$
Background (330 nm $\leq \lambda \leq 400$ nm at ≈ 400 km height)	$B \approx 3{\cdot}10^{11}$photons m^{-2}s^{-1}str^{-1}
Observation duty cycle	$\eta \simeq 0.1 \div 0.2$
Orbital period	$T_0 \simeq 90$ min
Optics maximum diameter	$D_M = 2.5$ m
Optics aperture (entrance pupil diameter)	$D = 2$ m
Optics $f\#$	$f\# = 1.25$
Optics field of view (half-angle)	$FOV = 30^\circ \equiv \gamma$
Average transmission of the optics	$K_{opt} \simeq 0.5$
Provisional geometry of the focal surface	spherical, radius $= Df\# = 2.5$ m
Angular aperture of the focal surface	$\beta \simeq 30^\circ$
Overall photo-detector efficiency	$\varepsilon_{det} \simeq 0.15$

Table 1. The provisional *EUSO* parameters, assumed in the present study.

All the characteristics were found to be compatible with the presently known constraints and requirements.

These devices have been extensively tested, recently, by many groups. Among the others they have been used in the readout of a cluster of nine MAPMTs to detect Cherenkov light in a test-beam setup by the RICH-LHCb Collaboration at CERN (V. Gibson, 2001), in the framework of a RICH detector development and design. They have also successfully flown with the AMS detector on the Space Shuttle (B. Alpat et al., 2000).

Other interesting possibilities, namely the Flat Panel PMTs (Hamamatsu Photonics K. K., FPPMTs), do not seem to be compatible with the presently accepted *EUSO* time-schedule.

4 Recovery of the geometrical acceptance

The geometrical acceptance can be improved by means of a suitable light collector system (M. Ameri, 2001), to be placed in front of each device, and performing the required demagnification onto the MAPMT sensitive area. This system might consist of a lens system, a system made of a bundle of tapered light pipes (working either by normal reflection or by total internal reflection) or a fiber optic taper.

One possible lens system consists of a plano-convex hemispherical lens located in front of the MAPMT with the curved face of the lens facing the incident rays and the plane face in optical contact (or separated by a small gap) with the MAPMT input window and coincident with the original focal surface. An array of such lenses, as shown in figure 4, would then provide the required mapping.

Alternatively a bundle of tapered light pipes, one per pixel, might be used in front of the MAPMT, exploiting either the total internal reflection inside a refractive and transparent light guide or normal reflection on the walls of an empty pipe. One possibility is to assemble a system made of square section tapered slanted light pipes, in such a way that each pipe has an exit face with the same dimensions of the MAPMT pixel, which is the demagnified mapping of the entrance face, thus creating a pixellation of the front face of the MAPMT.

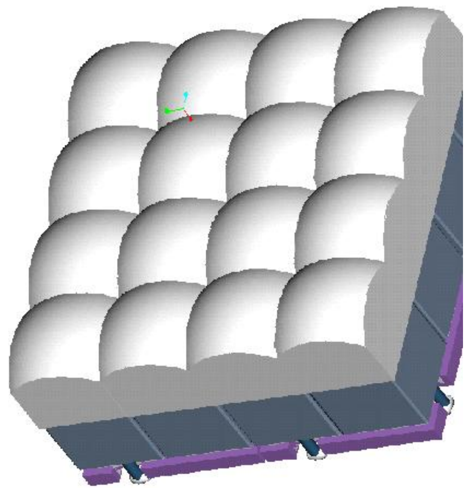

Fig. 1. The array of MAPMT plus hemi-spherical lenses.

A conceptual view of the system is shown in figure 4.

Fiber optic tapers might be finally used to demagnify the image from the focal surface onto the MAPMT sensitive area. Anyway the use of fiber optics tapers seems to be limited by the low sensitive to total area ratio at the entrance face.

4.1 Results of the simulations

Detailed simulations of the performance of the three systems were carried on with the conditions expected in *EUSO* and with assumptions based on the requirements and constraints known as of today (M. Ameri, 2001).

The results of the simulations of total internal reflection light pipes show that an overall efficiency up to $\approx 70\%$ can be reached with a 30 mm long pipe. This takes into account all the losses but those coming from the bulk absorption, which cannot be carefully estimated at present as it depends on the material. The same plastics used for the main Fresnel lenses can be considered as a good candidate material. It was assumed, conservatively, no anti-reflection coating on the en-

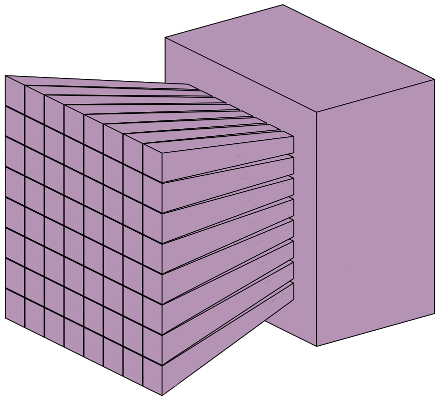

Fig. 2. Conceptual view of a tapered light pipes system, demagnifying the image onto the MAPMT sensitive area.

trance and exit faces and no optical coupling to the MAPMT input window.

In the simulations of reflective light pipes a constant reflectivity on the walls, equal to 0.9, was assumed, independent of the incidence angle and wavelength. The results show that an overall efficiency up to $\approx 55\%$ can be reached.

The results of the simulations of the hemi-spherical lens show that an overall efficiency of $\approx 70\%$ can be reached after the lens inclusion. This takes into account all the reflection losses and the inefficient inter-pixel region but ignores the bulk absorption, which depends on the material. It was assumed, conservatively, no anti-reflection coating and no optical coupling to the MAPMT input window. The lens introduces a degradation of the spatial resolution corresponding to about one pixel (for the 64 channel MAPMT) for about one third of the reconstructed rays.

5 The front-end electronics

The front-end electronics is needed to preamplify the signals from the sensors, to discriminate these signals with a programmable threshold, to mask noisy channels, to provide information to the trigger system, possibly performing a first level trigger, and to store the information until readout is done.

The most important and critical features are the optimal gain and input impedance to match the photo-detector signal, the double hit resolution (required to be of the order of $10\ \mathrm{ns}$), the time information (with precision of the order of $10\ \mathrm{ns}$) and the low power consumption allowed.

One should consider a highly integrated front-end chip for signal readout and possibly first level trigger. Required features are a very compact design with minimal distance between the MAPMT and the front-end electronics, a completely modular system with minimal cabling and self-triggering capabilities.

The design of a dedicated front-end chip is going on, carefully designed to comply with the *EUSO* requirements. A preliminary feasibility study shows that a design compatible with the *EUSO* requirements is possible. A preliminary design was carried on for the front-end section which matches the presently known constraints and requirements.

6 Focal surface design, construction and mechanical assembly

As the focal surface will be most probably curved, the packing of the devices has to be optimised to reduce losses in the geometrical acceptance, due to dead regions between the close packed devices, and defocusing effects, originating from a positioning of the sensor at some distance from the ideal focal surface. This makes the mechanical assembly difficult.

A curved focal surface requires a modular structure. The overall structure should consist of small functional units (*elementary cells*) assembled in super-modules. The elementary module consists of a limited number of MAPMTs sharing some common resource like being installed on the same Printed Circuit Boards (PCB) base-board, having one common HV power supply and/or voltage divider, a common magnetic or electric screen (whenever required), common heat dissipation facilities and all of the front-end electronics plus as much as possible of the following readout electronics integrated in the module.

The elementary cells can be thick multi-layered PCB, as described in section 6.1. A number of these modules, each one making an essentially autonomous system, are then assembled to make a super-module. These are independent structures tied to each other by the support structure and having a shape determined by the layout of the focal surface.

6.1 MAPMT base-board

A base-board was designed and prototyped for 2×2 MAPMTs (M. Ameri, 2001). This constitutes the elementary unit, with one single HV connection and one resistive bleeder circuit per MAPMT. It was attempted to close-pack the MAPMTs with a $1\ \mathrm{mm}$ pitch between adjacent MAPMTs. It was avoided to use any additional space along the edges of the board to allow close packing of different boards, again with $1\ \mathrm{mm}$ clearance. The removal of the heat produced by the bleeder circuit was accomplished by inserting a copper layer inside the PCB to be thermally connected to the cooling system. The board allows for mounting of the front-end chip on the same board as the voltage divider, on the opposite side with respect to the MAPMT. In this way the front-end electronics is close to the photo-detector in a compact structure which minimize cabling. Preliminary tests show that it is working as expected. A view of the assembly of the elementary cell is shown in figure 3.

6.2 Layout of the curved focal surface

A few different approaches have been investigated for the layout of the focal surface (M. Ameri, 2001). The most promising one seems to be the one based on fitting by means of

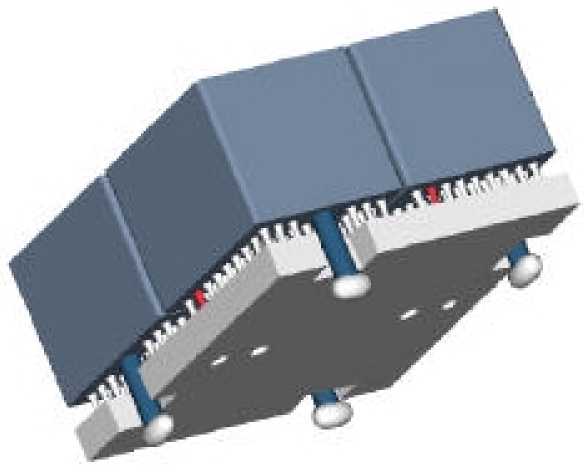

Fig. 3. View of the elementary cell with one board housing four MAPMT.

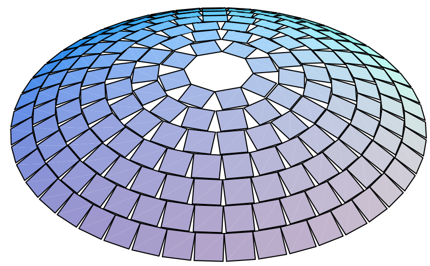

Fig. 4. Focal surface layout based on a segmentation in polar angle and square super-modules.

square flat panels, which can be applied to any surface with cylindrical symmetry. This can be built by a segmentation in polar angle, producing circular coronas, filled with square (or rectangular) flat panels. This arrangement, shown in figure 4, can make use of identical rectangular super-modules only, thus greatly simplifying the geometry, the logic and structure of the trigger and readout electronics. Note that the surface cannot be filled exactly with rectangular shapes, but holes will unavoidably remain because the curved surface cannot be tessellated exactly by means of squares.

The focal surface dimensions are limited by the maximum dimensions allowed by the space mission and ISS environment, about 2.5 m diameter. The focal surface dimensions are therefore fixed by the obvious requirements to have as large as possible aperture and field of view of the optics. Note that the focal surface diameter is equal to the optics diameter, D_M. On the other hand the sensor dimensions are fixed, and these are the same for both the 64 channels version and the 16 channels version. As the focal surface dimensions are fixed, and the same applies to the sensor and pixel size dimensions, the obvious requirement to fill as much as possible with sensors the focal surface unambiguously fixes the number of sensors. As a consequence the number of channels is also fixed, once the number of channels per sensor has been chosen according to the required angular sensitivity of the instrument and the desired pixel size at the Earth surface. One might use different MAPMT pixel sizes on different regions of the focal surface, to match the PSF of the main optics.

Different solutions, based on different choices, can be proposed following this scheme and the optimization of the layout is going on. All the solutions result in a number of MAPMTs of the order of six thousands with a filling factor of the focal surface of about 0.8. The resulting number of channels depends on the choice of the MAPMT pixel size, which is mainly driven by the physics requirements. A number of channels of $\approx 2 \cdot 10^5$ is presently foreseen.

7 Conclusions

A lot of work remains to be done during the phase A study of the *EUSO* experiment but a realistic baseline design for the photo-detector, based on the presently known information and constraints, was developed. The most critical issues, related to the photo-detector design, were preliminarily investigated. Possible solutions to some open issues were studied and proposed.

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