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CONCEPT STUDY OF UV FILTERS FOR EUSO

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Abstract

We report on the characteristics of existing UV absorption and interference filters as in literature and from studies related to the AUGER ground-based experiment in order to give some preliminary indication on the possible solution for the EUSO telescope. We discuss these data and we compare them with the EUSO specifications on the wavelength band-pass and on the minimum transmittance. Then, we discuss the crucial aspects to properly select the EUSO UV filters and we analyze the spectral response of the filter + MAPMT system to point out the best solution presently available. A deep analysis of the solution recently proposed by the team of the RIKEN for the BG3 filter/collector coupled to the new MAPMT with electrostatic focussing is also reported and extended to the case of a normal MAPMT. Finally, we suggest a new possible solution for accommodating a commercial UV filter glass and we discuss the advantages of such solution.

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Introduction

The detectors presently under study for the EUSO focal plane have a spectral window that covers all the fluorescence spectrum of the atmospheric Nitrogen (300 - 400 nm) (see Figure 1) and a good quantum efficiency in the same spectral region (see Figure 2).

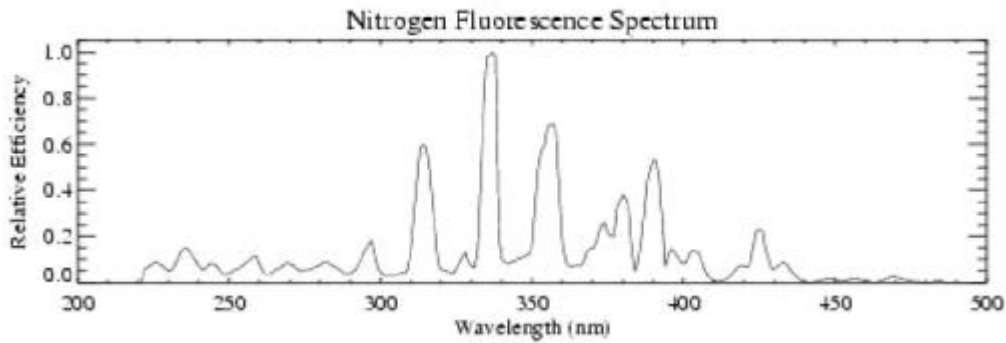


Figure 1. Atmospheric Nitrogen fluorescence spectrum.

Owing to the need for blocking out the radiation falling outside the spectral region of interest and the spectral response of the Multi Anode Photomultipliers (MAPMT), a suitable UV filter is a crucial optical component. The selection of a narrowband UV filter between 330 and 400 nm is not a trivial issue because it involves many different aspects like the choice of the best position into the optical system, the dependence of its transmittance on the incidence angle, the weight minimization, the coupling with other optical components, and so on. Therefore, the careful selection of some candidates must be made and it has to be followed by laboratory testing with a setup matching as best as possible the optical flight configuration.

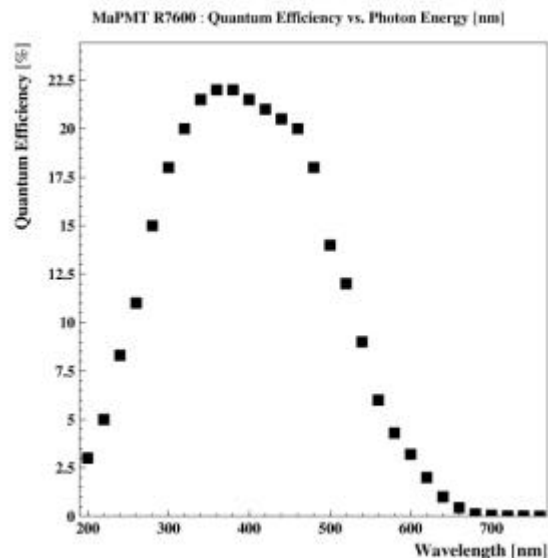


Figure 2. The quantum efficiency of the MAPMT R7600-03-M64 as a function of wavelength, as provided by the manufacturer [1].

In the following, the optical characteristics of several UV filters, with a band-pass fitting the spectral region of the EUSO experiment, are discussed on the basis of their transmittance curves. The aim of this report is to make a preliminary analysis of the currently available UV filters and their features. The request for the EUSO experiments is to find out filters that select the spectral band of interest with the largest transmission, avoiding contamination mainly from radiation at longer wavelengths. This last is a crucial point as MAPMT

are very sensitive to the visible portion of the spectrum, with a maximum at blue wavelengths, and ground-based and atmospheric sources emit mainly in that region. There are two possible ways to choose the most appropriate filter for EUSO: (a) to look for the best filter glass or interference filter that, once inserted in the optical system, fits the EUSO specifications or (b) to carry out a specific study to provide a new filter that better matches the instrument requirements.

Available filters

Most of the hereafter reported transmittance curves concerns UV filters that have been considered for the AUGER experiment [2] [3], which has the same spectral window of EUSO (see Figure 3).

- **Hi-Res**: absorption filter, from KOPP Glass Inc. (USA), used in the experiment Hi-Res, with size $57 \times 25 \text{ mm}^2$ and thickness 1.1 mm.
- **MUG-2**: commercial absorption filter, from Schott-Desag (Germany), with size $51 \times 51 \text{ mm}^2$ and thickness 3.2 mm.
- **ZC & R**: commercial interference filter, from ZC & R Coatings (USA), with size $51.5 \times 51.5 \text{ mm}^2$ and thickness 3.3 mm. This filter is a high quality standard product, but it has not been designed to have sufficiently large transmittance in the UV region of interest.
- **U-330**: commercial absorption filter, from Hoya (Japan), rather expensive.
- **OCJ**: simulated interference filter, from Optical Coating Japan (OCJ), designed according to the requested specifications. It seems to be a very promising UV filter.
- **IDEAL**: hypothetical ideal filter with $T = 0.96$ in the region from 280 nm to 400 nm and $T = 0$ above 400 nm. This has been included as a reference.

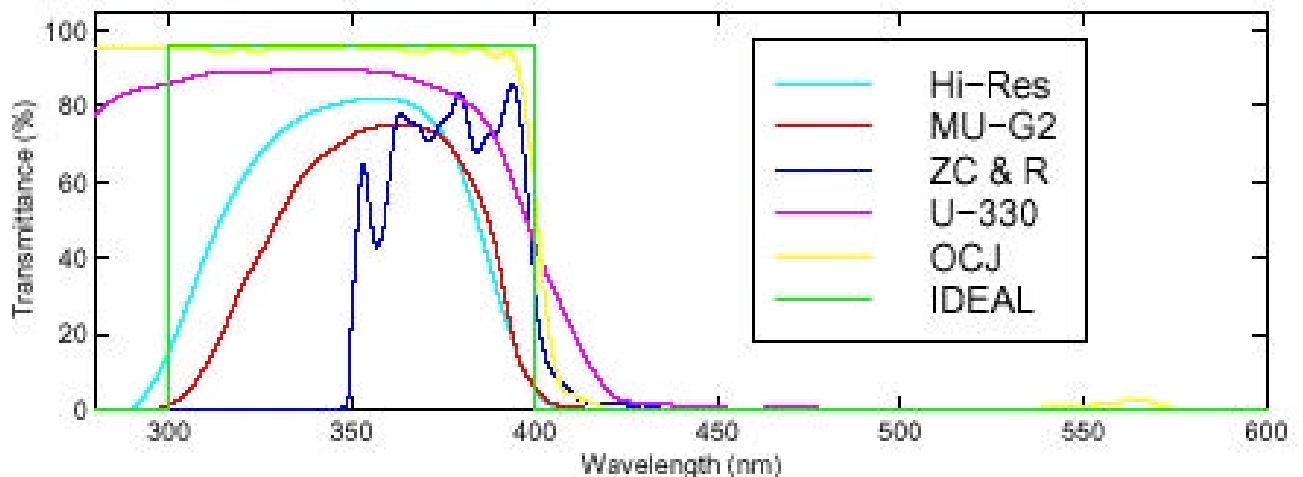


Figure 3. The transmittance curve of the UV filters for the AUGER experiment. The HiRes and ZC&R curves are the result of laboratory experimental measurements, the MUG-2 and U-330 curves are available from the manufacturers, and the OCJ is a simulation [2].

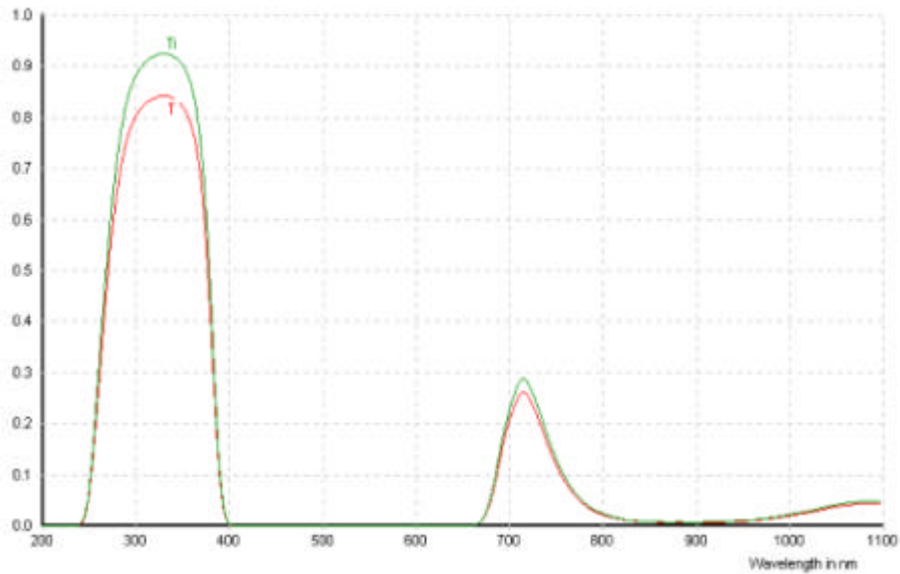


Figure 4. Transmittance curve of a 1-mm-thick UG11 filter. The green curve is the transmittance calculated for a single glass surface, while the red curve is the transmittance of the whole filter.

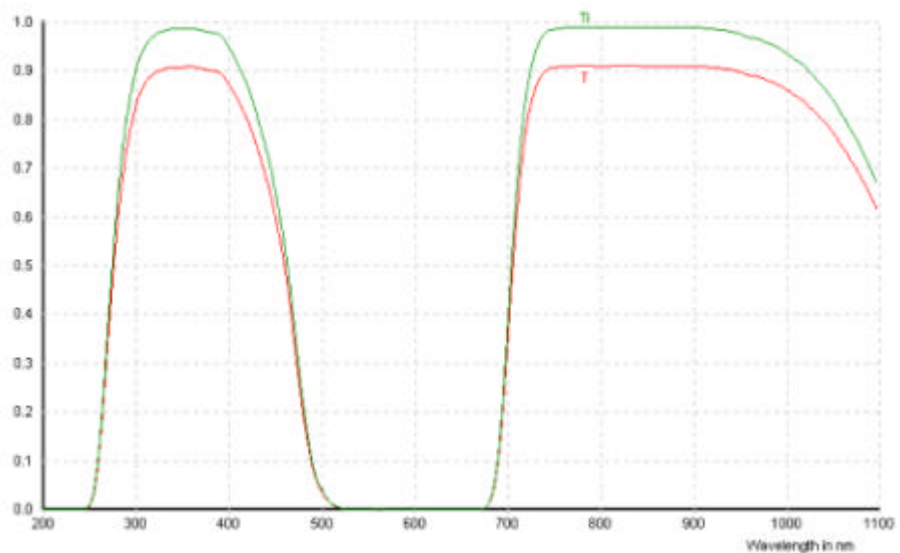


Figure 5. Transmittance curve of a 1-mm-thick BG3 filter. The green curve is the transmittance calculated for a single glass surface, while the red curve is the transmittance of the whole filter.

We also consider the transmittance curve of other two very interesting commercial filter glasses:

- **UG11**, from Schott Glass (Germany), is an ionically colored filter glass, i.e. a true solution of glass, ions of heavy metals or rare earths, which gives the typical glass coloration that making it opaque to the visible radiation. This filter has a transmission peak (80-85 %) between 300 nm and 350 nm and it goes to zero at 400 nm. Another transmission window is between 650 nm and 800 nm (about 25%) (Figure 4). An UG11 filter, having size $27.0 \times 27.0 \text{ mm}^2$ and thickness of 1.0 mm has a weight of about 2.13 g.
- **BG3**, from Schott Glass (Germany), is an ionically colored glass filter too. The BG3 transmission is about 90% between 330 nm and 400 nm, and it has a second window from 700 nm (about 40%) with a 'plateau' that extend from 750 nm (approximately 90%) up to 1000 nm where begin a steep decay

(Figure 5). A BG3 filter with dimensions $27.0 \times 27.0 \text{ mm}^2$ and thickness of 1.0 mm has a weight of about 1.87 g.

- **UAH filter.** The University of Alabama in Huntsville group has proposed an interference filter in the framework of the EUSO project. This filter consists of 44 layers of MgF_2 , ZrO_2 , and NaCl , each layer having a thickness ranging from 0.1 to 0.99 waves at 357 nm. The simulated performances show that this filter blocks approximately 80% of the flux in the spectral ranges 200-300 nm and 425-800 nm, with a 90% transmission in the intermediate region (Figure 6). This interference filter is fairly idealized, as the effects of the dispersion (change in the refraction index with wavelength) have not been included in its design. Furthermore, the materials that have been used in the filter design and simulation may not be structurally or optically optimized [4].

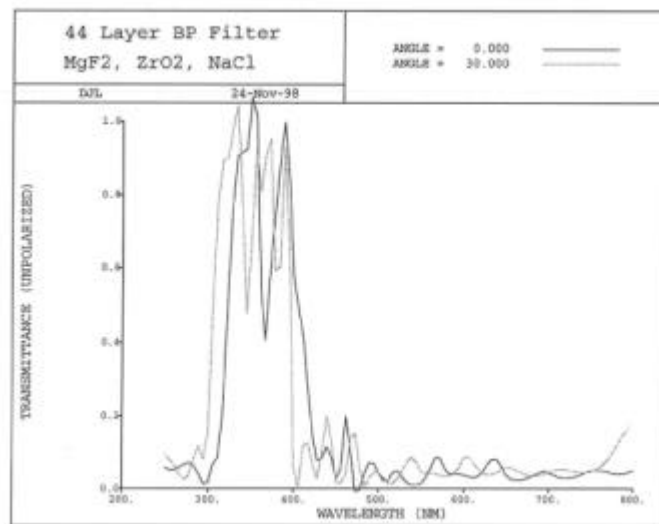


Figure 6. UAH interference filter transmittance curve [4].

Angular dependence

We report the results obtained by the AUGER team studying the transmittance of the ZC&R, MUG-2 and HiRes filters in function of an incidence angle ranging between 0° and 65° (Figures 7-9). Then, the results for a normal incidence angle have been compared with the principal Nitrogen fluorescence lines (Fig. 10).

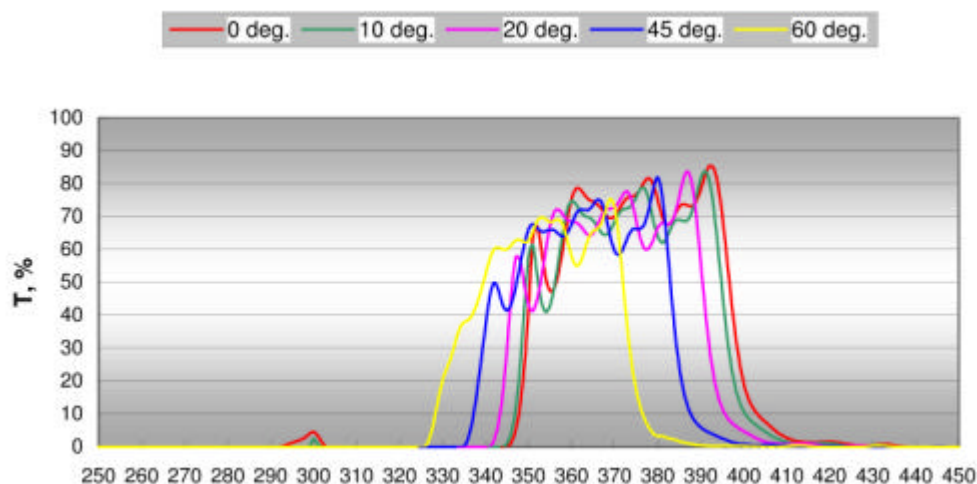


Figure 7. ZR&C filter transmission curve vs. wavelength (nm) for different incidence angles [3].

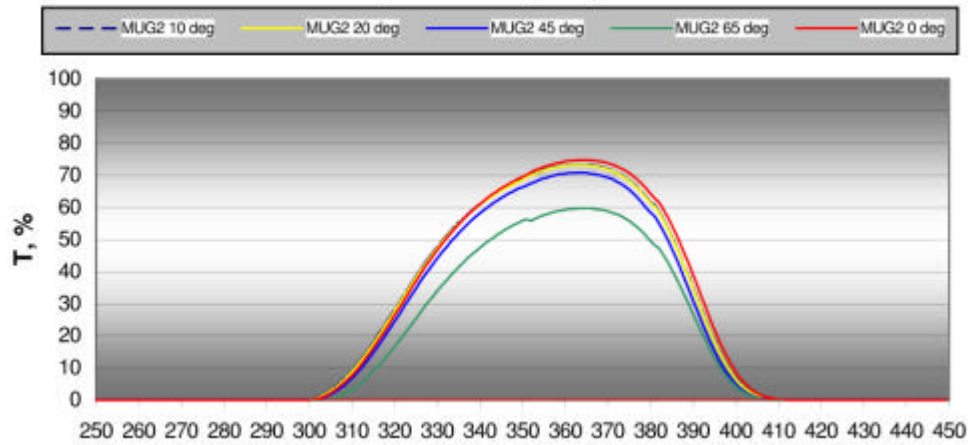


Figure 8. MUG-2 filter transmission curve for different incidence angles [3].

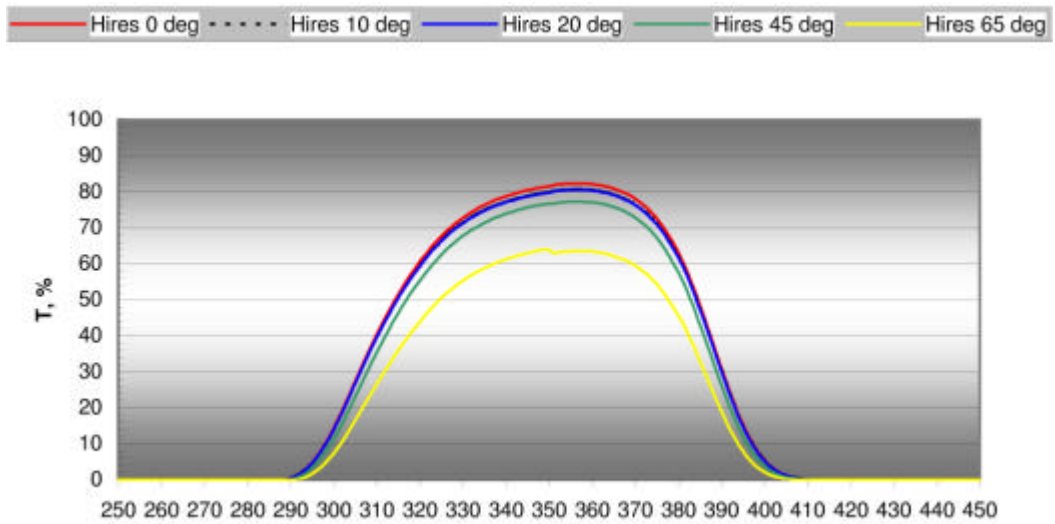


Figure 9. HiRes filter transmission curve for different incidence angles [3].

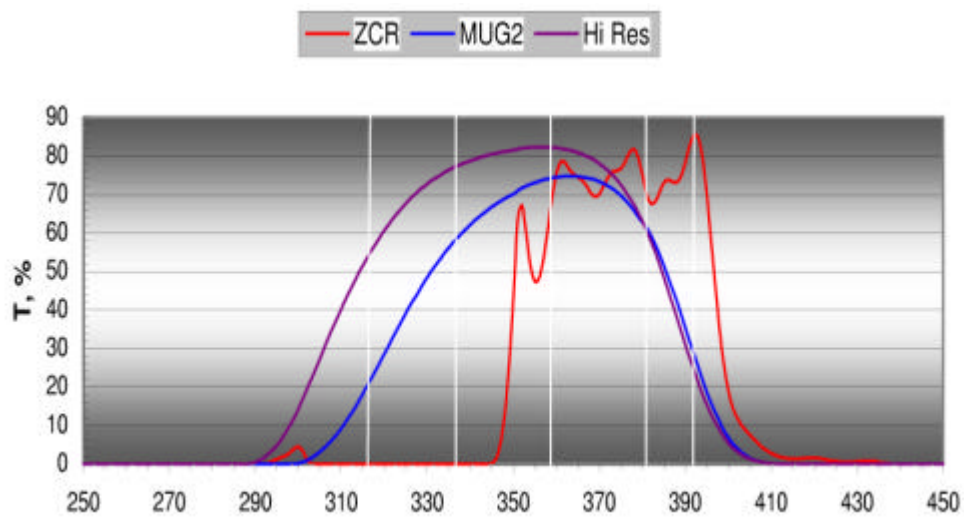


Figure 10. Comparison between the transmission curves of the ZCR, MUG-2, and HiRes filters [3]. The vertical lines represent the principal atmospheric Nitrogen fluorescence lines.

General considerations

Some general considerations about UV absorption filters and interference filters have to be done in order to point out some remarks on the properties of such filters and on how these can match the EUSO specifications. However, it must be reminded that the final selection can be done after an overall field-testing of the proposed solutions, as the optical properties are strongly dependent on the characteristics of actual, and not ideal, filters. The spectral properties of the ionically colored filter glasses are nearly constant within the individual melts. Based on slight deviations in the properties and pureness of the raw materials and batch composition, there can be deviations from melt to melt. Therefore, if a filter glass is the final choice for the EUSO optical system, further selection is necessary to select the filter matching at best the specifications on the wavelength band-pass. Through selection and reservation of suitable melts and through variation in the filter glass thickness, closer tolerances than normally listed in the manufacturer specifications can usually be achieved. The INFN/University of Florence experimental team has planned a program including the UV optical testing of the proposed filters.

Absorption filter glasses are heavier than interference filters and in addition they require a mechanical support for accommodation in the final arrangement of the optical system. This means that the total mass of the system is slightly increased. On the other hand, interference filters are more attractive because they can be deposited directly on the lenses (it may be not a trivial issue to deposit such coatings on the plastic Fresnel lenses) with a negligible impact on the mass budget of the system, but their transmittance is strongly dependent on the incidence angle and this can limit the use of the interference filters in EUSO (see Fig.7). The arrangement on the focal plane implies that the design should vary with the transverse position on the focal plane for regions experiencing greater incidence angles. This can lead to a more complex system.

A common advantage of the filters described in this report is that they are commercially available, the techniques to obtain high quality glasses or coatings are well known and it is possible to get any shape or size of the filter glass, even diameters up to 2.5 m. A feasibility study on new filters can be an alternative productive, but longer, way to achieve optimized filters.

Particular attention must be paid in filter glass positioning in the optical system. Filter glasses are largely ionically colored glasses. Ions of heavy metals or rare earths can influence the coloration of glasses when in true solution. This coloration depends on the nature and quantity of the coloring substances, on the oxidation state of the coloring substances, and on the base glass composition. UV irradiation of these filters produces fluorescence due to the ionic species. This fluorescence is mainly in the red region of the spectrum, where the MAPMT are still sensitive. This effect can increase the background and produce unwanted signals if the filters are positioned nearby the MAPMT. On the other hand, if the filters are far from the MAPMT the weak fluorescence signal is highly dispersed and therefore it may be lower than the detection limit of the MAPMT.

Transmittance and spectral response evaluation

A better evaluation of the filter of choice can be based on the UV transmittance of the filters combined with the transmission of the detector window. Three different UV filters have been selected and compared, i.e., BG3, UG11, and UG5 (from the Schott Product Catalog). The UG5 filter has been considered because it has a transmittance curve very similar to the Hoya UV filter U-330 previously discussed and these values are easily available. The transmittance curves in Fig.11 refer to the filters coupled to a borosilicate glass (similar to the WG 305 from Schott), and to a UV transmitting glass (similar to the WG 225 from Schott). The resulting transmittance curve is reported for an optical coupling with the components in contact (cemented) and having an air (or vacuum) gap between the components (non-cemented). The thickness of the filters is 1.0 mm while the window glass thickness is 0.8 mm.

Looking at the transmittance plots, the BG3 and UG5 filters coupled to the UV glass appear to be the best solutions for the spectral range of interest. The main difference between these two filters concerns the transmittance of the filters in the blue-green spectral region that is between 400 nm and 500 nm. The UG5 filter has a lower transmittance than the BG3 filter at 400 nm (about 30%), but the BG3 red wing extends down to 500 nm letting in an unwanted red leak. This may cause an increased background, as there are many ground-based sources that strongly emit in that region. A careful evaluation of fluxes arriving from the ground, combined with the spectral response of a system supporting the BG3 film, should be done if this filter is selected. UG5 can solve this problem.

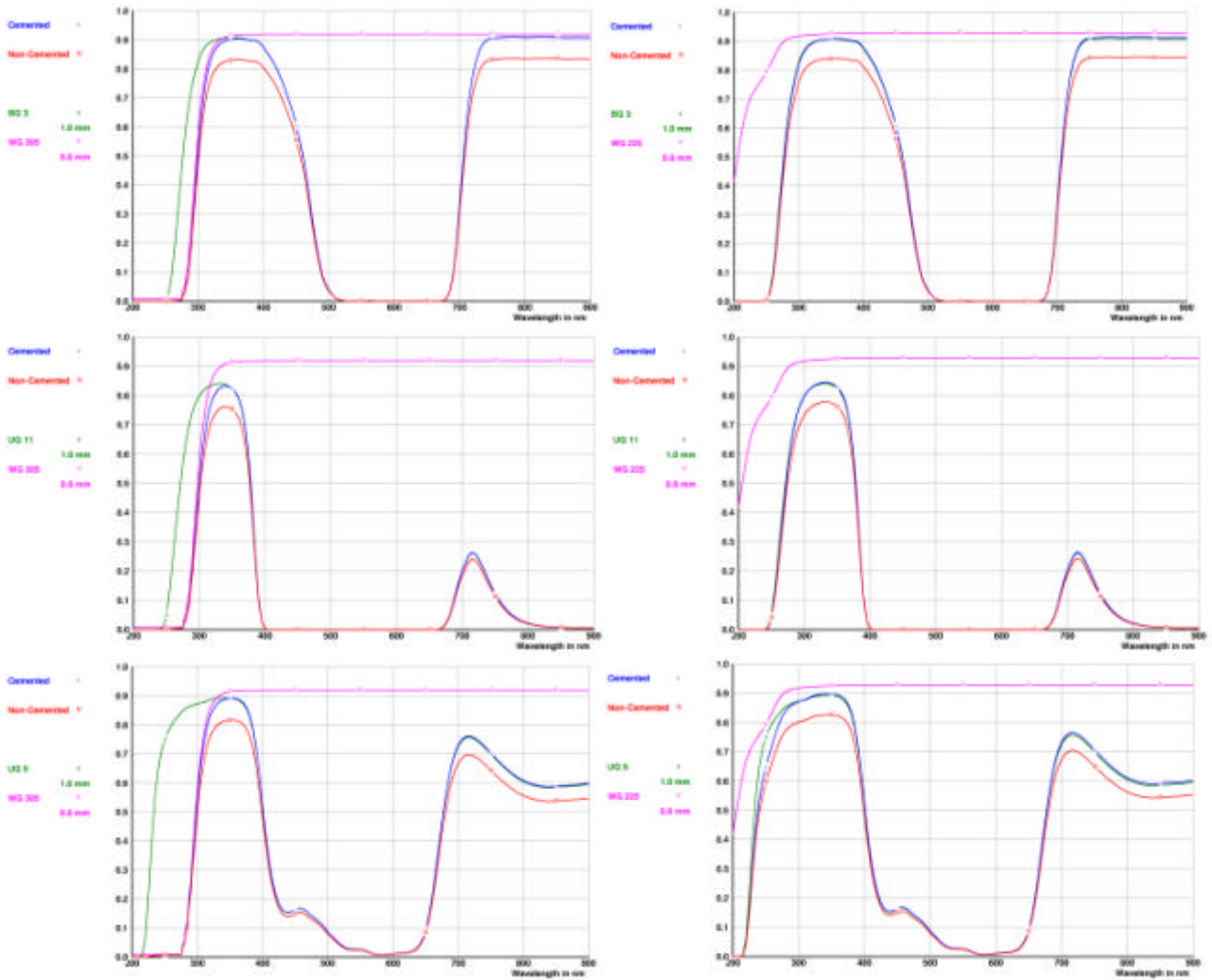


Figure 11. Transmittance curves for the BG3, UG11, and UG5 UV filters coupled to a borosilicate glass (WG 305) (left column) and a UV transmitting glass (WG 225) (right column). The filter thickness is 1.0 mm and the glass window thickness is 0.8 mm. The curves in each plot are related to the filter (green), the window glass (violet), the filter and the window glass in optical contact (blue), the filter and the window glass with an air gap (red).

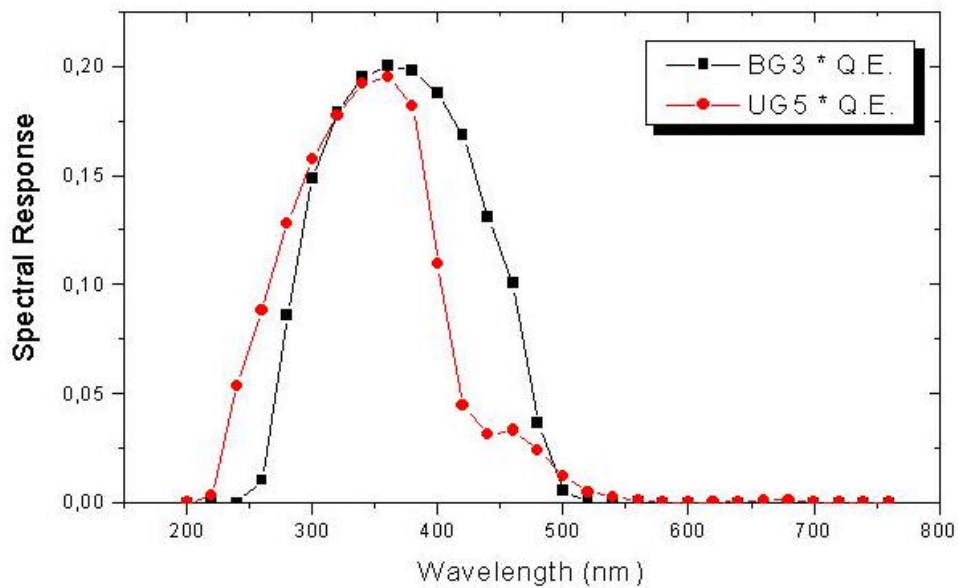


Figure 12. Spectral response of the BG3 and UG5 filter glass combined with the MAPMT R7600-04-M64.

To investigate thoroughly the difference between these filters, we have analyzed the spectral response of the filter + MAPMT system, calculating the product between each filter transmittance and the quantum efficiency for the MAPMT R7600-04-M64 (see Figure 2), as provided by the manufacturer. The result is plotted in Fig.12 and it shows that the spectral response in the 300-370 nm region is comparable for the two solutions. At longer wavelengths, the UG5 has a sharper cut-off providing a reduction of 30% of the spectral response at 400 nm, but a considerable rejection of the band 400-500 nm. The spectral region beyond 500 nm is highly suppressed owing to the MAPMT spectral response.

It must be emphasized that if the blue-green wing of the UG5 transmittance is still a problem, the U-330 Hoya filter has a better suppression at 500 nm than the UG5 filter (see Fig.13), keeping the same transmittance in the band 300-400 nm. Therefore, it can be a more suitable choice than the UG5 filter.

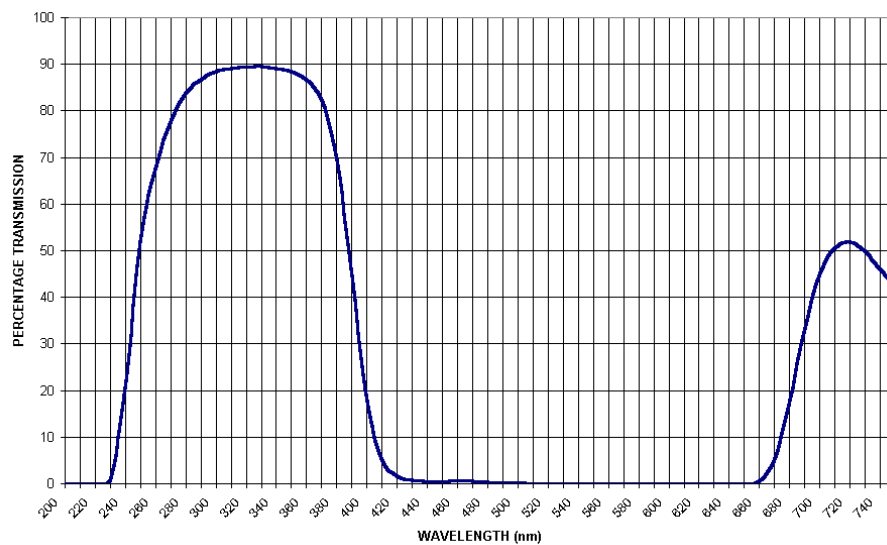


Figure 13. Transmittance curve of the U-330 Hoya UV filter.

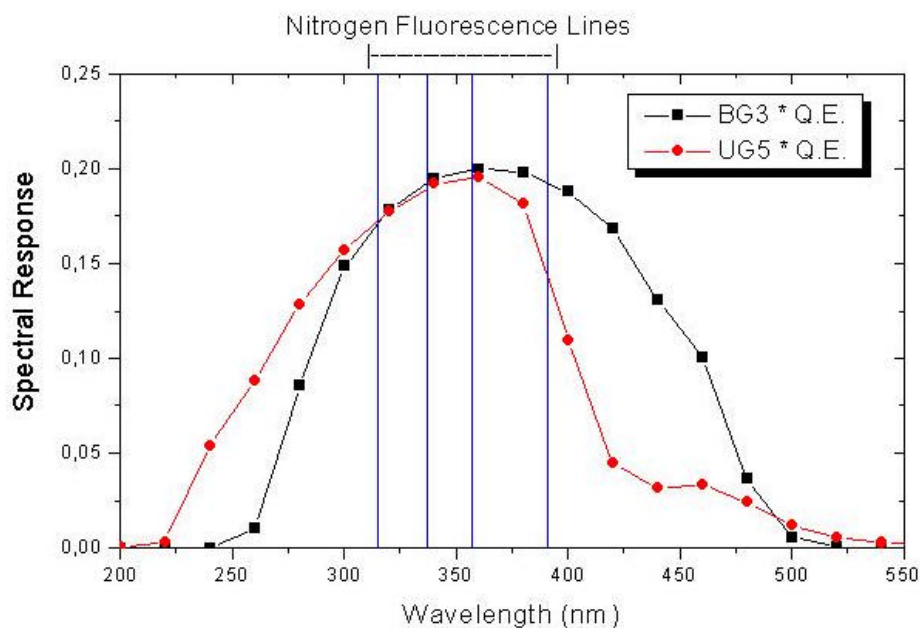


Figure 14. Spectral response for the BG3 and UG5 UV filters superimposed to the principal Nitrogen atmospheric fluorescence lines represented with the blue vertical lines.

Fig.14 shows the Nitrogen lines of interest for the EUSO program superimposed to the estimated spectral responses in order to evaluate the impact of these different configurations on the detection of these lines. It is evident that the main difference between the transmission of the two absorption filters is a 30% reduction of the detected flux of the 391 nm line, because for the other three lines (315 nm, 337 nm, and 357 nm) the performances are comparable. The question is whether the good transmission at 400 nm is a requirement overwhelming the rejection of the blue-green radiation between 400 nm and 500 nm.

Finally, Fig.14 shows also that the choice of a UV transmitting glass as detector entrance window can be relaxed, since the borosilicate glass can suppress the spectral region below 300 nm, without affecting considerably the transmittance of the spectral lines of interest. In this way the source of background radiation can be further limited.

Evaluation of a BG3 filter/collector coupled to a MAPMT

The group at RIKEN Japan has recently proposed a possible compact solution for the UV filters coupled to a MAPMT with electrostatic focusing [5]. We have analyzed this optical configuration through ray tracing simulations to assess it quantitatively and to evaluate its performances also in the case of a normal MAPMT. The optical coupling of a BG3 filter glass to the entrance window of a new generation MAPMT (Mod. R8520 with electrostatic focusing) presents some interesting aspects but also drawbacks. The proposed assembly concerns a custom shaped (truncated pyramid) BG3 filter optically glued (Epotek 301-2) that cements the filter to the MAPMT entrance window (see Fig.16).

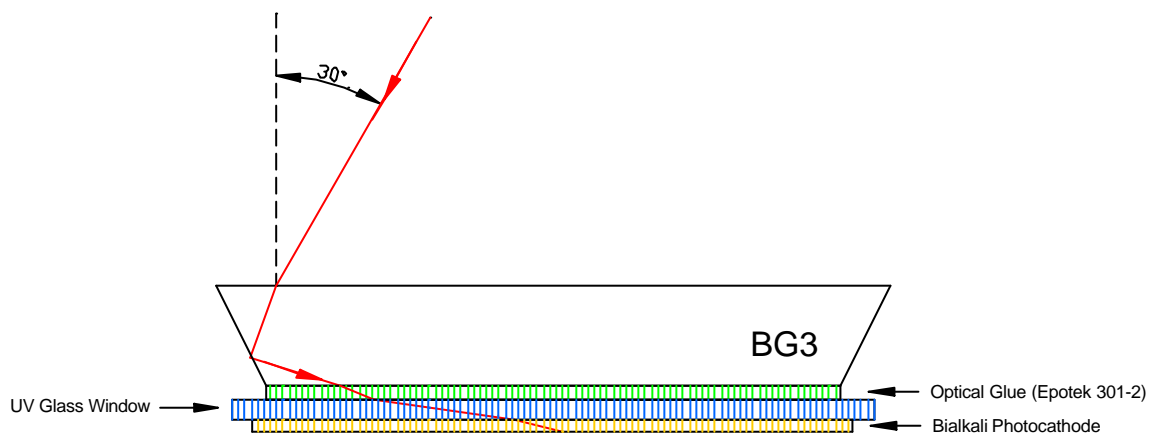


Figure 16. Sketch of the optical layout of the assembly for the MAPMT R8520.

The optical performances of this assembly have been simulated using a ray tracing software (Zemax 9.0) to better understand its peculiar characteristics. The parameters used in the simulation are reported in Table 1.

Table 1 Parameter values considered for the simulation.

Component	Thickness (mm)	Index of Refraction
Filter (BG3)	4.0	1.540
Optical Glue (Epotek 301-2)	0.005	1.564
MAPMT Window (UV Glass)	0.8	1.483
Photocathode (Bialkali)	3E-5	1.517*

*Arbitrary value being the ray tracing unaffected by it

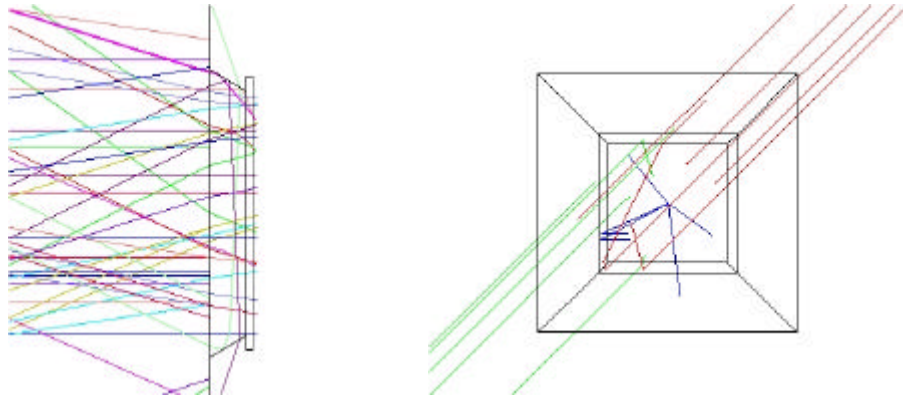


Figure 17. Ray tracing: side (left) and top (right) view. The large square represents the front stop, which prevents lateral ray incidence on the external walls. For sake of clarity, only some of the rays and directions of incidence have been reported.

The simulation has been performed by illuminating the optical assembly with an array of 25 collimated sources, uniformly distributed in space, with the incidence angle ranging between 0° and 30° . The results of the simulation are reported in Fig.17 for the wavelength 357 nm.

It is possible to see that there are lost rays (violet and green rays in the side view and a red ray in the top view), due to the ray incidence nearby the filter corner that produces a double reflection changing the next angles of incidence on the other surfaces. A map of the photon distribution as they escape from the window of the MAPMT ($25.7 \text{ mm} \times 25.7 \text{ mm}$) without and with the BG3 filter is shown in Fig.18.

The internal highlighted square in Fig.18 refers to the photocathode area ($24 \text{ mm} \times 24 \text{ mm}$). These two images show that the photon distribution is uniform without the filter and several photons, falling outside the photocathode, are lost, whilst the BG3 collects all photons impinging on the MAPMT window on the photocathode. Note the different values of total rays collected after a beam size larger than the MAPMT overall dimensions: 470355 rays without the filter against 504575 rays with the filter. This is due to the combined effect of a thick and larger glass ($27 \text{ mm} \times 27 \text{ mm}$) and an incidence angle up to 30° : some of the photons that without filter should be collected by the nearby MAPMT's are deviated on the considered MAPMT.

In addition, the number of lost photons using the BG3 filter has been calculated and it results in a 1% of the number of total rays. It must be underlined that this is a good results but it is not linear with the number of total rays: the number of photons used for this simulation is much larger than the realistic number from a EAS event, if the number of photons decreases the percentage of lost photons could be greater than 1%, depending on each event.

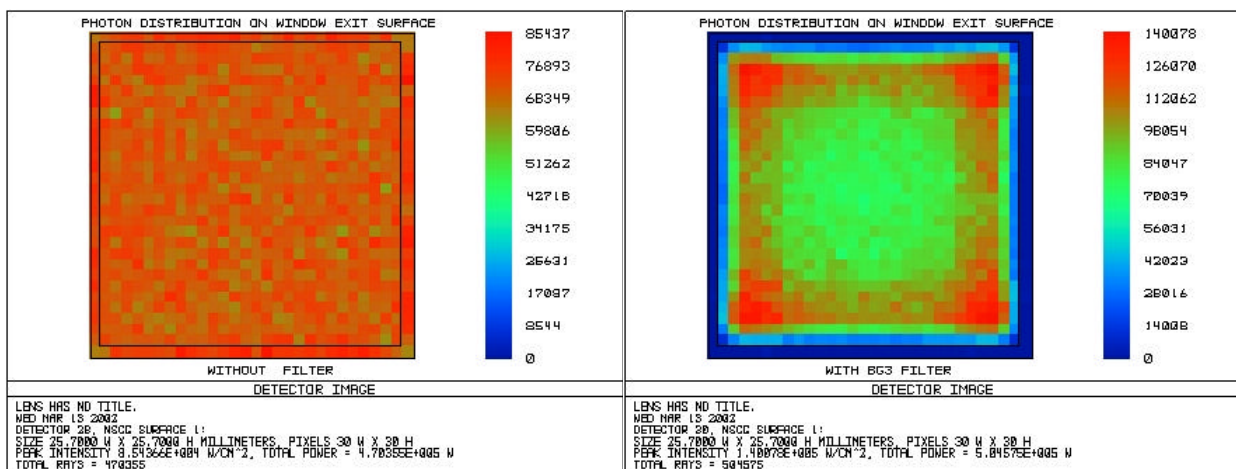


Figure 18. Photon distribution at the internal surface of the MAPMT window without (left) and with the BG3 filter (right). Note the different scales for the two maps. The frame format is 30×30 pixels.

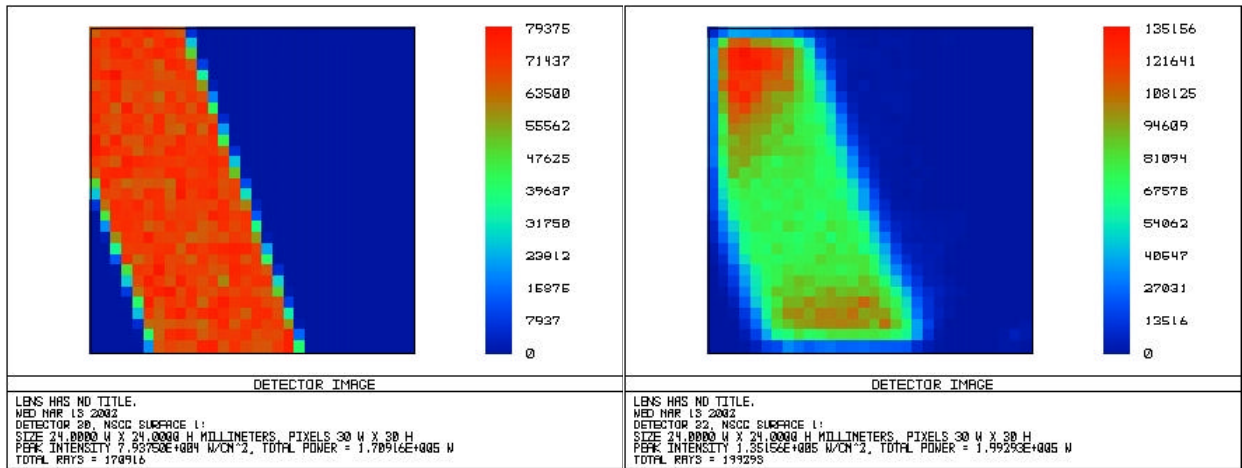


Figure 19. Simulation of a uniform track (6 mm wide) on the photocathode surface without (left) and with the BG3 filter (right). The frame format is 30×30 pixels.

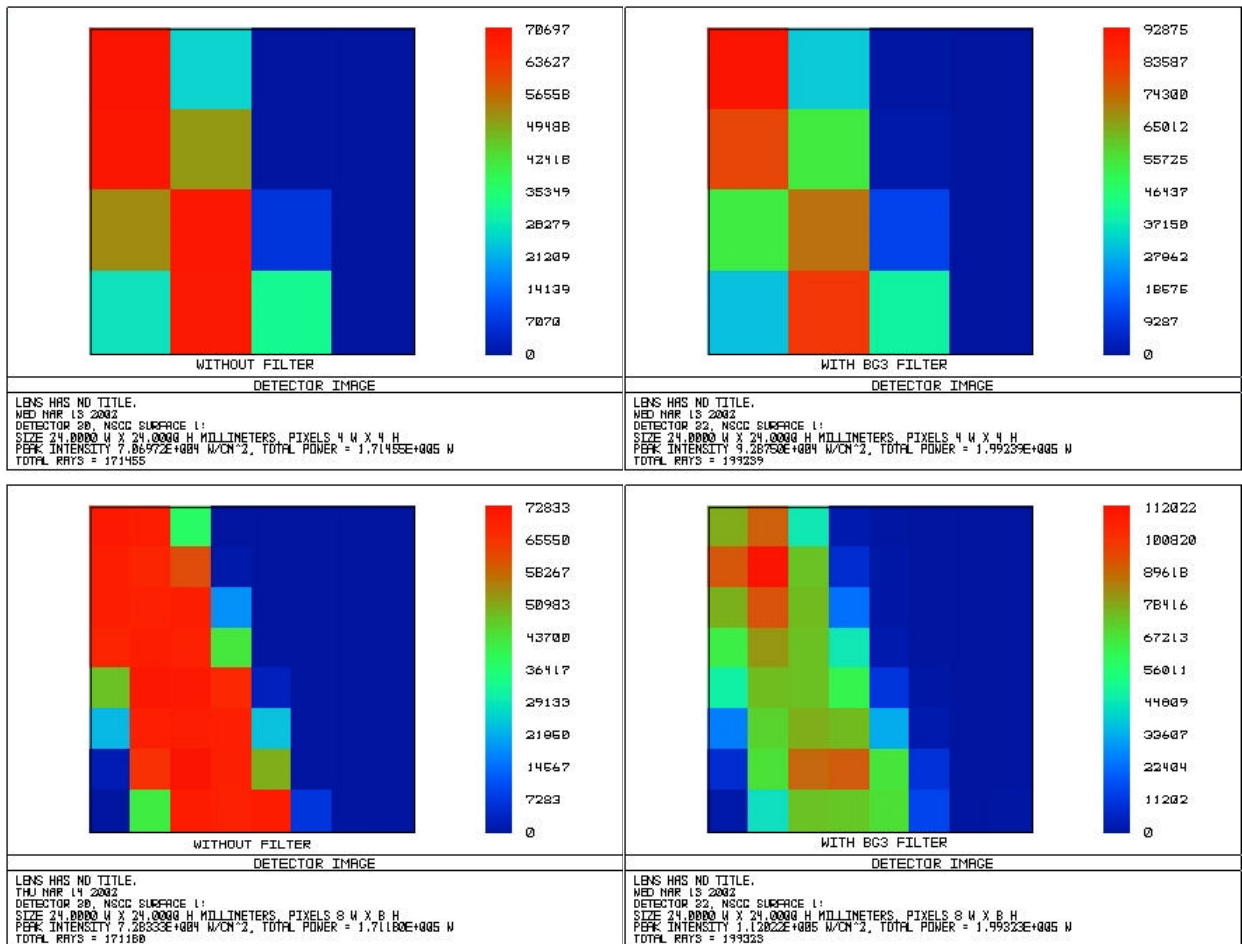


Figure 20. Simulation of a uniform track (6 mm wide) on the photocathode surface without (left column) and with the BG3 filter (right column), for a 16-pixels MAPMT (upper) and for a 64 channel MAPMT (lower).

Owing to the shape of the BG3 filter-collector, the corners and the edges of the photocathode are the regions collecting more photons. This feature represents an important drawback, since the spatial information is lost in order to improve the overall collection efficiency of the MAPMT.

This is also evident if we simulate a uniform intense track, 6 mm wide (considering the expected PSF of the EUSO main optics), impinging on the MAPMT (see Fig.19). The track is simulated by illuminating a

rectangular shaped mask, on the first surface of the optical system, with the previously described array of collimated sources uniformly distributed. In this case, the uniform track is detected more efficiently at the edges and at the corners with the BG3 filter. This effect can contribute to loose or incorrectly identify the track peak and therefore the following data analysis can be affected.

To show a more realistic case, we reports in Fig.20 the photon distribution just before the photocathode for the same track as in Fig.19, but for a detector with 4×4 pixels (as the R8520) and, for comparison, with an hypothetical detector with 8×8 pixels (as the R7600-03-M64 size, presently unavailable for the R8520). Fig.20 shows that the track direction for a 16-channels detector is not so clearly defined as for a 64-channels detector.

Another realistic simulation is a track provided by a single collimated source with incidence angle of 30° (see Fig.21) to point out the effects of the BG3 insertion in the most critical case. The number of rays that fall on the detector is adjusted to match the expected flux in the case of the maximum of a track, i.e. about 100 ph/px for a typical 10- μ s track on a 64 channels MAPMT, that gives a total of about 2400 photons on the MAPMT assuming a track focused on 24 pixels (3×8).

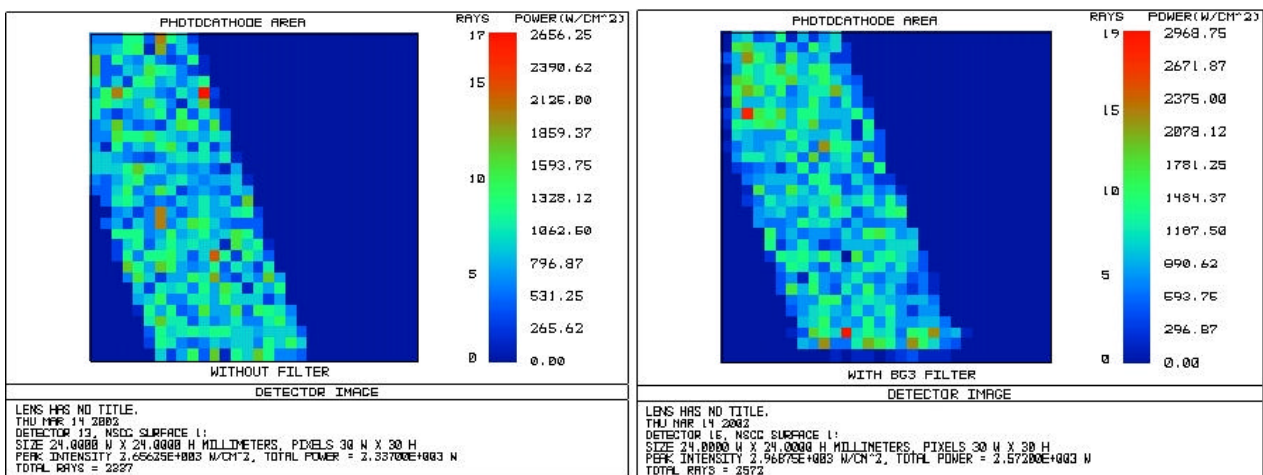


Figure 21. Simulation of a track with off-axis radiation at 30° . The total number of rays in the simulation is adjusted to match the expected number of photons falling on the detector (about 2400) at the track maximum.

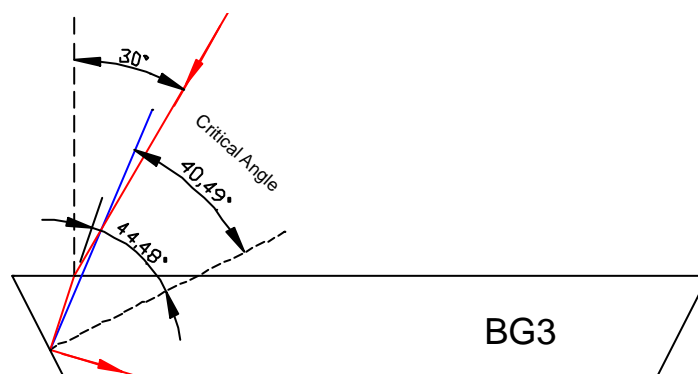


Figure 22. Critical angle for the BG3 walls.

The images reported in Figure 21 show that the difference between the two configurations is not as large as in the previous simulations; moreover the BG3 filter improves only a little bit the track detection with respect to the case without filter, still having some photons falling outside the photocathode.

Furthermore, it is important to remind that this solution has been applied to the new MAPMT R8520. In fact, this new detector has a sensitive area of $24 \text{ mm} \times 24 \text{ mm}$, and then the required demagnification is 1.125 (from 27 mm to 24 mm). The present MAPMT (R7600-03-M64) instead requires a greater demagnification factor, from 27 mm to 18.1 mm. This factor implies that the BG3 filter must be thicker, then the filter transmission in the UV region is lower, since the filter walls have a fixed angle defined by the fact that the rays impinging at 30° are already near to the critical angle for the total reflection on the walls (see Fig.22). This implies also that the rays impinging on the BG3 wall are reflected on the opposite wall with an incidence angle lower than the total reflection angle, being lost. These rays impinge on the edges with incidence angle between 30° and about 24° (see Fig.23). In conclusion, the use of a custom shape BG3 filter-collector cemented to the MAPMT entrance window is possible, with the implications discussed, only with the new MAPMT R8520 that, at present, is not available on the market and whose performances have not yet been extensively tested and assessed.

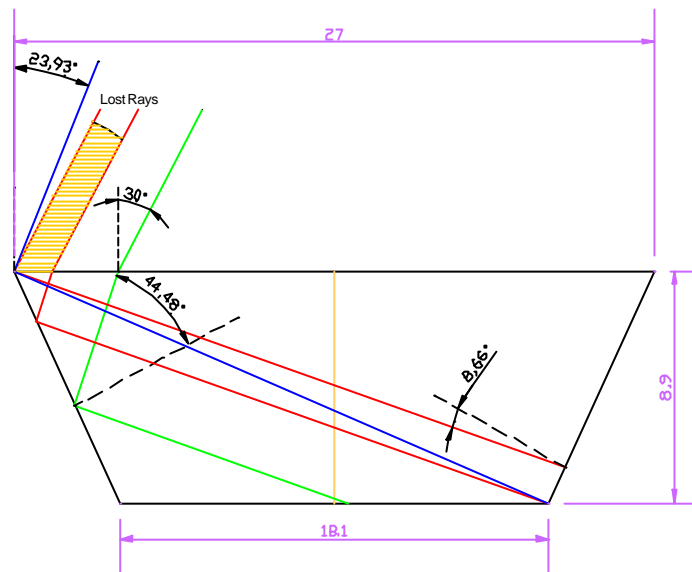


Figure 23. BG3 filter shape for coupling to the MAPMT R7600-03-M64.

Our proposal

The conclusion of this analysis, based on the presently available material and products, suggests that the U-330 filter glass can be a good choice, because coupled to the other optical components allows a better selection of the wavelength of interest. In addition, no angular dependence is expected against the interference filters.

Our proposal is to accommodate a 2.5 m filter at the entrance pupil (see Fig.15) of the EUSO optical system. The advantages of this solution over other proposed solution using filter glasses, is that the light entering the system has a spectral distribution limited to the band of interest, preventing unwanted reflected, refracted or diffused visible light on the detector. In addition, this solution solves the problem concerning the previously discussed scintillation of the UV absorption filters, because it is reduced at levels below the detection limit of the MAPMT.

If the filter is optically coupled to the MAPMT (with epoxy), the scintillation increases the background, but the transmission is further reduced as the epoxy can be considered an added filter. Moreover, visible light entering the system can be diffused or reflected in such a way that it may arrive on the MAPMT for example through small apertures in the mechanical accommodation of the focal plane detector. This is not a safe solution.

The fabrication and mounting of the proposed filter is technologically feasible. Such large filters have been already produced, for example for the Auger experiment, even assembling smaller filters.

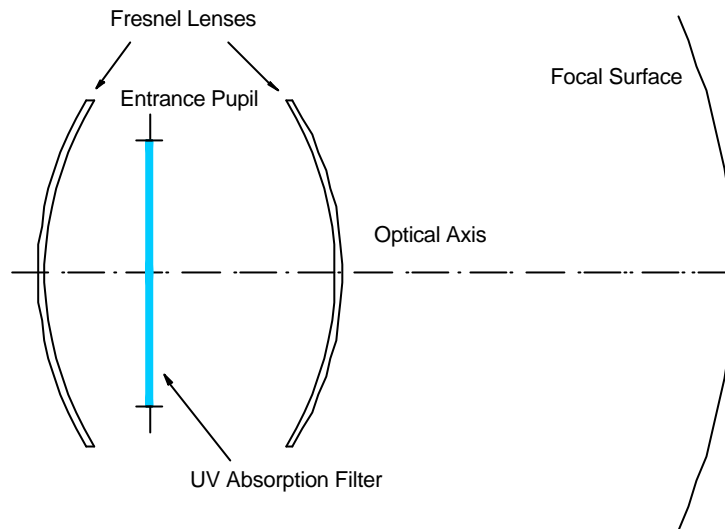


Figure 15. UV absorption filter position in the EUSO optical layout.

References

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