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Performance of optical pass-band interference filter for the Auger fluorescence detectors

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[1]**Abstract.** The present paper describes the characterization of an industrial production of a large number of pieces of UV optical filters proposed for the AUGER Fluorescence Detector. The filter pieces have been tested and they have nearly 92 % peak transmittance, between 320-400 nm, for an incidence angle range from 0 to 30 degrees, and typically 0.5 %, in average, in the range 400-700 nm, in the same range of angles. The filter pieces were also characterized in terms of the integrated signal yield in the air fluorescence radiation and also in the typical night sky background radiation (optical noise). The experimental results of the overall performance of these filters lead to the conclusion that they achieve an increased signal-to-noise ratio in comparison to that of absorption filters commercially available. We explain that the interference filters provide more flexibility and thus can be adjusted more easily to the needs of FD telescopes.

1 Introduction

This work deals with the issue of determining the optimum optical filter for the ground-based air Fluorescence Detector (FD) of the AUGER Observatory. We take as a main example the FD prototypes, the first of which has started successfully taking data in Malargue Argentina.

There are already more experiments which are using or are planning to use the technique of atmospheric fluorescence (Abu-Zayyad, 2000; TA Collaboration, 2000). The main objective when designing such optical filters is to reject much of the background of the night sky radiation and select, at the same time, as much as possible of the air fluorescence UV radiation produced by an Extensive Air Shower (EAS). As a result, the signal-to-noise ratio (SNR) of each pixel detector of the FD camera should be maximised for all the events of the Extreme High Energy Cosmic Rays. The SNR must be retained high enough, even in cases of events that are of very high energy but too distant, and if possible under less favourable night sky radiation rates. Therefore, we need an appropriate optical filter design, so that, we achieve the optimum spectral transmittance and consequently we obtain an improved signal detection sensitivity.

The existing commercial optical filters do not seem to be optimised, for the purposes of FD of AUGER, and thus an extensive R&D has been conducted in optical filters design (Fokitis, 8/2000) and production tests (Fokitis, 11/2000). Since then, the effort was focused in production of appropriate optical filter in industrial custom-made mode by Optical Coatings Japan (OCJ). We report on the evaluation of such optical filter production. In Section 2 the optical noise and the effect of the atmospheric conditions are described. In the Section 3 the characteristics of the optical filters, which were designed for the FD prototypes of AUGER, are discussed in comparison with other candidate filters, as well as a specific way for mounting the above filter array. The conclusions and prospects are given in Section 4.

2 The EAS detection in various atmospheric conditions and optical noise

2.1 The influence of the atmosphere

The noise in the UV region cannot be ignored but cannot also be avoided since it coincides with the optical filter pass-band. The only remedy against this noise is to increase the average filter transmittance in the UV region and thus increase the SNR. In conditions of increased optical noise, the EAS reconstruction and determination of the energy of the primary particle includes a significant error due to the low SNR in the signal detection. The use of a satisfactory optical filter is important in ensuring an optimum, i.e. increased SNR, under variable optical noise and atmospheric conditions, changing within certain limits. We give below a description of the expected form of the EAS signal, the optical noise, and its fluctuations.

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The EAS signal is caused mainly by the molecular, atomic and ionic de-excitations of atmospheric air caused by the electrons and positrons of the EAS. This spectrum is characterised by some strong groups of lines around 337, 357 and 392 nm. Details of this spectrum are given in (Elbert, 1993; Fokitis, 8/2000; Kakimoto, 1996). The air fluorescence radiation may be attenuated due to atmospheric absorption and scattering. This effect can be estimated using atmospheric conditions which include various levels of aerosol (Jakovides, 1997). The aerosol presence, and its fluctuations in concentration and height of the boundary layer, may produce a reduction of the signal at the pixel positions. In the experimental study below, we shall consider the performance parameters of the optical filter candidates in the presence of various degrees of atmospheric attenuation.

2.2 The night sky background considerations

The most significant component of the optical noise is the night sky background radiation (NSBR), which is a complicated function of time, within the night duration. The intensity of the NSBR depends on the viewing direction and the aerosol loading in the atmosphere. It has been observed that the presence of increased aerosol content, mainly in the Planetary Boundary Layer (PBL), increases the night sky background in the zenith angles 60-87 degrees, in which the Auger FDs will be observing. We also have the influence on it by the human artificial light. Some of these considerations have been described in (Maltezos, 2000).

We only describe briefly the conclusions of this work: As the night sky background increases, the threshold of the incident photon rate, s_{min} , of the EAS event, required to trigger the FD array, also increases. A necessary condition for triggering is that a certain sequence of pixels gives an SNR at least 5. In the next section we determine the above threshold by considering, as part of the FD apparatus, the optical filters under study.

3 Experimental methodology for evaluating the performance of various optical filters

3.1 The methodology and the experimental apparatus

Here we present the results of the performance of the optical filters, produced by a proprietary method of *plasma ion process* of OCJ by coating multilayers on Tempax, 2 mm thick, UV-glass substrate of Schott, Germany. These optical filters can have an essentially constant performance for over 20 years, according to manufacturer's specifications under normal laboratory conditions of low humidity.

We have given some more details for the method we used in (Maltezos, 2000). Below, we describe briefly the main points of this method. The performance of a pixel detector (a photomultiplier with an optical filter in front) in detecting the atmospheric fluorescence is expressed via the so-called "improvement factor", R, which has been initially introduced by (Elbert, 1993). This quantity is defined by the ratio of the SNR, using a filter, over the SNR without it. In our analysis we use more accurate expressions for the SNR determination (Hamamatsu, 1994; Hamamatsu, 1996). The SNR for these two cases is given by:

$$SNR' = \frac{S'}{\sqrt{S'+2B'}} \quad , \quad SNR = \frac{S}{\sqrt{S+2B}} \tag{1}$$

where S and B are the total photon rate of the air fluorescence (signal) and the total photon rate of the optical noise (background) detected by the pixel detector, respectively. The prime in the symbols means the use of the filter. It can be shown that the improvement factor is given by:

$$R = \frac{SNR'}{SNR} = E_s \Big/ \sqrt{\frac{(S/2B)E_s + E_b}{(S/2B)+1}} \tag{2}$$

where the quantities $E_s = S'/S$ and $E_b = B'/B$ are the detection efficiencies for the signal and the background, respectively, which are also called "performance parameters" of the filter.

As we see, the factor *R* depends on the performance parameters as well as on the ratio S/B. If the latter ratio is much less than 1 (low signal level compared to background), *R* can be approximated by the expression:

$$R_b = \frac{E_s}{\sqrt{E_b}} \tag{3}$$

This quantity can be used to evaluate the performance of an optical filter, under the condition that the signal *S* is large enough to provide a trigger. Such cases are typical when we are near the detection limit, where SNR approaches the threshold value 5. The determination of R_b can be done by measuring the S', *S* in the Laboratory, by using the air fluorescence discharged lamp, and by measuring B', *B* in the natural night sky environment.

To compute the s_{min} we consider that SNR≥*n* (the trigger threshold), specified by using the particular filter. The latter condition, after some calculations, leads to the expression:

$$s_{\min} = \frac{n^2}{2SE_s}\left(1+\sqrt{1+\frac{8bBE_b}{n^2}}\right) \tag{4}$$

where b is the absolute NSBR photon rate incident to each pixel detector and the quantities *S* and *B* must be used after normalisation to 1.

Below we present the main parts and characteristics of the experimental set-up for these tests: A schematic diagram of the apparatus is seen in Fig. 1. This apparatus can accommodate large filter pieces for characterisation, and is using a low-pressure air-fluorescence lamp and photon counting method based in bi-alkaly photocathode. This apparatus is portable and has been transported outside Athens, at a darker place 5 km away from the city of Eretria in Evia. There we evaluated the capability of the filters in rejecting the NSBR .We proceed to present the obtained results.

3.2 First results on large area interference filters

The OCJ Company has measured the transmittance of some pieces of large area filters (170 mm x 170 mm), under normal incidence, and two typical curves are seen in Fig. 2, while results from HiRes filter and the expectation from the Telescope Array Project filter are seen for comparison.

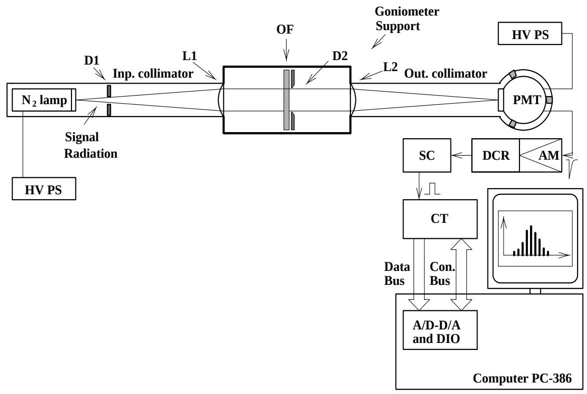

Fig. 1 A top view of the experimental set-up for measuring the integrated signal yields of the filter pieces.

We observe a steeper slope in the cut-off region in the case of OCJ filter, and an average UV transmittance larger than the HiRes type filter. Also, the OCJ filter rejects better the optical noise in the range 410-460 nm than the TAP filter. The results of detection efficiency for various incidence angles are also seen in Fig. 3. It can be seen that up to about 25 degrees angles of incidence the response is rather constant. For higher angles, up to 35 degrees, the detection efficiency and the sensitivity in the optical noise is reduced. In Fig. 4 we present the experimentally determined improvement factor, R_b , as a function of the incidence angle for two OCJ filter samples. In the same figure the corresponding improvement factor for the absorption filters from (Abu-Zayyad, 2000), is also shown. The-OCJ filters tend to have systematically higher improvement factors up to incidence angles 32 degrees. Near 20 degrees, the best performance is achieved by the OCJ filter, due to the strong suppression of NSBR.

We should also note that the improvement factor must be measured under very typical night sky noise levels. Our results, in natural background radiation, included some low level of artificial light coming from Eretria. This fact corresponds to conditions of increased optical noise in UV region, mainly from the lines 365 nm and 405 nm of mercury lamps and lesser to the presence of lines from sodium lamp spectrum. These conditions of optical noise flux correspond to nearly 6 times more than that expected for very dark night sky sites; they give roughly the same radiation with 1/4 of moon phase, a case where the FD could retain data taking. We plan to do measurements in darker areas so that we study the improvement factor in lower level of night sky radiation fluxes.

Considering a typical NSBR spectrum and the Eq. (4), we can deduce the required value of s_{min} for each specific optical filter type considered. For example for an expected low background rate, b=108.5 ph/μs per pixel detector, we obtain for OCJ filters s_{min}=147, and 149 ph/μs respectively. For b 5 times larger, that is 542.5 ph/μs we get 191.9 and 192.7 respectively. The corresponding values for an ideal optical filter are 141 for the low value of b and 181 for the higher value, respectively. These results indicate that these filters approach well the expected performance of the ideal filter.

Furthermore, the atmospheric absorption and various acceptable deviations from what we call U.S. standard atmosphere should be considered when we present improvement factors. By using absorbing liquids with detection efficiency of 21 % and 18 % in the air-fluorescence signal, we have obtained the improvement factors of the OCJ filter samples at normal incidence angle. The resulting values of R_b are 1.74 and 1.66 respectively. The average value of R_b without absorption is 1.74. We observe that even at high levels of atmospheric absorption, these filters retain high improvement factors.

Due to the relatively high cost, at present, of the multilayer filters, it is proposed that these should be placed just in front of the camera at a safe distance from it. A possible configuration is based on plane hexagon filter pieces, approximating the spherical surface of the camera, can be found in (Fokitis, 11/2000). It is obvious that the distribution of the angles of incidence on the filter array is quite similar to that on the window of the respective PMTs. Since the filter pieces are somewhat thin, a special procedure had to be established for carrying out water-jet cutting, to obtain hexagon shape. It can now be successfully done with small risk of breaking or damaging the filter. We are still working to complete the optimisation of the mounting of such a filter array to ensure good mechanical stability and minimum obscuration .

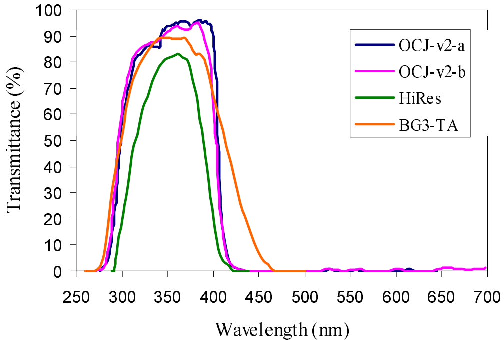

Fig. 2. The transmittance curves of OCJ (a,b), HiRes and Telescope Array filters, at normal incidence, are seen for comparison.

4 Conclusions and prospects

We have studied the first large area OCJ filters, obtaining the performance for various incidence angles. Although, this optical filter is more expensive than equal size absorption filter, it could make a low cost filter if it is placed near the camera of the Auger FD.

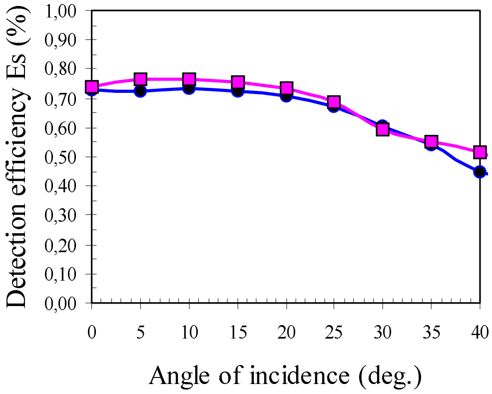

Fig. 3. The detection efficiency of air fluorescence for two filters samples as a function of angle of incidence.

One may envisage the possibility that such an optical filter may be used as alternate filter in cases where the atmospheric conditions are characterised by high level of turbidity. It has been tested under laboratory conditions with varying degrees of atmospheric absorption and has been displayed, within the range studied

a slower rate of decrease of the improvement factor than the commercially available absorption filters. The method of using the interference filters provides great flexibility and can be adapted in the geometrical characteristics of the FD telescope, such as the F/number, use of corrector disc, placement of the filters on the diaphragm or in front of the camera.

Systematic characterisation of the full production of around 80 filter pieces in terms of improvement factors and actual testing at the Auger FD site, under varying atmospheric and night sky noise conditions, can give more definitive evaluation for the merits of the optical filters presented.

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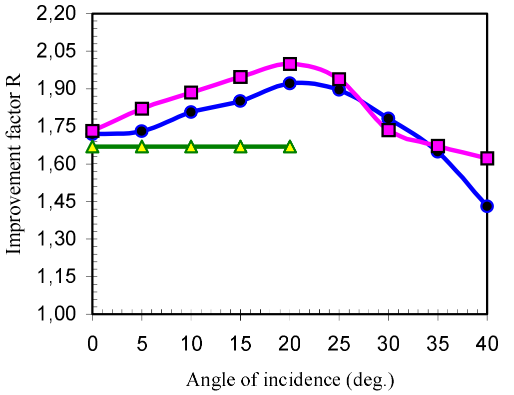

Fig. 4. The improvement factor obtained using two filters samples from OCJ (circles and square points respectively) as a function of angle of incidence. The horizontal line refers to the filter used in the HiRes experiment.

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