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RELATIVE OPTICAL COUPLING EFFICIENCY OF WAVE LENGTH SHIFTING FIBER TO EXTRUDED SCINTILLATOR STRIPS

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ABSTRACT

We studied the relative optical coupling efficiency of 1.2 mm wavelength shifting fiber to a primary light of extruded scintillator strips with cross section 4.1×1 cm^2. The measurements have been made using cosmic rays and a ^{106}Ru β-source. The fiber was located inside a longitudinal 1.5-mm wide groove. We tested various fiber positions inside the groove and different amount of optical glue used for achieving good optical coupling, as well as different reflective groove covers. It was found that the light output does not depend directly on the groove depth but it does depend on how deep the fiber is secured inside the groove. We find a 20% enhancement in light collection efficiency when the fiber was secured deeper than 2.5 mm in the groove compare to fiber position by the surface of the strip. The best optical coupling was achieved when the fiber was covered with a thin layer of the optical glue. Complete filling of the groove with optical glue does not increase the light yield. The optical coupling efficiency of the fiber in the axial groove is 13% better than for a groove at the corner of the strip. The test of different reflecting coatings of the groove have showed that Bicron BC-620 paint in an optical coupling with hardened glue gives the best light yield. Aluminized Mylar gives 3% less light output. There are only minor differences between sticky and non-sticky aluminized Mylar tape provided they are optically coupled to hardened glue.

Introduction

In the current design of the MINOS detector [1] the light created by secondary particles from neutrino interactions in a 8-m long 4.1×1 cm^2 scintillating strips is read out with 1.2 mm Kuraray wavelength shifting (WLS) fibers, which are placed in axial longitudinal grooves. The WLS fiber is glued inside the groove with optical clear glue and covered by sticky aluminized Mylar. The light trapped in a fiber due to total internal reflection is transported to the photomultiplier tube (PMT). It is obvious that the light yield and response uniformity along the strip strongly depends on the light trapping efficiency of the WLS fiber inside a groove.

Unfortunately the design of the groove size and external reflecting coating can not be optimized by Monte Carlo simulations mainly due to lack of experimental information on the reflecting performance of the co-extruded cap (the ratio between specular and diffusion reflectivity is not completely understood). For example there are some indications that the light yield depends on fiber location inside the strip. In [2] it has been found that increasing the groove depth from 1 to 3.5 mm for 6 mm thick scintillating tile results in 18% rise in light yield. The comparison of the light output when 1 mm fiber was in 1×1 mm^2 groove at the surface of a 2×1 cm^2 extruded strip with fiber inside an extruded 1 mm in diameter axial hole gives 10% more light output for the axial hole configuration. A similar increase in light yield was obtained for 2×1 cm^2 strips made of parts cast by Vladimir Technoplast in Russia, when the fiber was in a 1×1 mm^2 groove in the center of the strip compared to when the fiber was inside a groove at the surface of the strip.

Moreover, it is well known that filling the groove with optical grease increases light output by almost a factor of 1.6, but there has been no information on the optimal amount of glue needed for filling the groove (from a light yield and cost estimate point of view).

The reflective performance of most technological materials (Tyvek, "Bicron paint", Al-Mylar, Teflon) are well known [3]. But the available data are more relevant to scintillator samples that have been wrapped in these materials and there was not optical contact between samples and reflectors. In the case of 8-m long strips of the MINOS detector it is better from a technology point of view to have an optical contact between hardened optical glue and an external groove coating.

In this note we summarize the experimental results obtained at Fermilab on studies of the light output from 4.1×1-cm^2 scintillating strips (Polysterine+2%PPO+0.15%POPOP) co-extruded with TiO_2 coating. Light yield has been measured versus depth of WLS fiber inside a 1.5-mm wide groove, the amount of optical glue inside groove and different possible (technically approved) reflective coatings of the groove. The measurements have been made using cosmic rays and a β-source. All results are relevant to the far end of the 8-m long strip.

Cosmic ray setup

The two -sided view of our cosmic ray stand is shown in Fig.1. The sample under test was placed in a light tight box between two layers of inner trigger scintillator counters. Each layer consisted of three 30-cm long, 1-cm wide, and 2-cm thick counters. The light produced by cosmic rays passing through an each individual counter was trapped and

guided to the PMT by three WLS fibers 1.2-mm in diameter, which were imbedded in each counter. To make the light yield of these trigger counters as high as possible the fiber length was only 60 cm and the far ends of these WLS fibers were polished and painted with Bicron BC-620 white paint. The 18 WLS fibers came to 6 pixels of Hamamatsu M-16 PMT, which were located inside a light tight box. Two external trigger counters (30-cm in length, 5-cm wide and 5-mm thick) defined a 5-cm test area along the sample. Under the dark box there was a 30×10×5 cm^3 lead block that was used to reduce triggers on low energy particles.

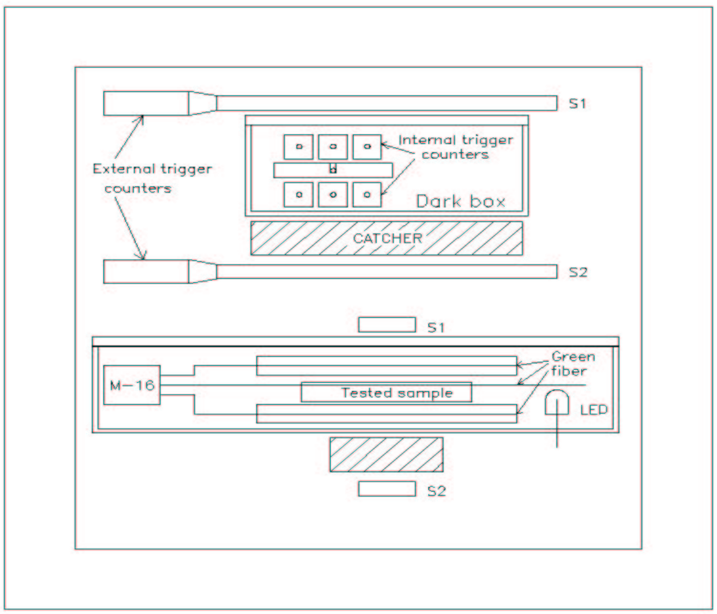

Figure 1: The two-side view of cosmic ray stand.

The light from the sample was guided to a PMT by 1.2 mm Kuraray WLS fiber 8.6 m in length. The fiber was coiled inside an additional light tight box. The far end of the fiber was polished and painted black. The fiber was optically coupled to one of the pixels of the same M-16 PMT inside the light tight box. To avoid possible cross talk between inner trigger counters and the sample, this pixel was as far as possible from the 6 pixels used for the inner trigger counters. There was a blue LED inside the dark box, which could illuminate the far end of WLS fiber. This LED was used for monitoring the gain of the M-16 PMT.

The block diagram of the cosmic ray trigger electronics is shown in Fig.2. The PMT signals were sent to LeCroy 620BL discriminators. The logic signals from the discriminators corresponding to each of the trigger counters of inner scintillator layers were summed by OR circuits and were sent to a coincidence unit (LeCroy 2341S), where final cosmic ray triggers were produced as four-fold coincidences of these signals and signals from external trigger counters. A 16-input coincidence unit (LeCroy 2341S) was used to

store a pattern of events for data analysis. The M-16 output was digitized by a LeCroy 2249A ADC. The 150-ns gate was common for the ADC and 16-input coincidence unit. Information about an event was readout by a PC using DSP (6002) CAMAC crate controller.

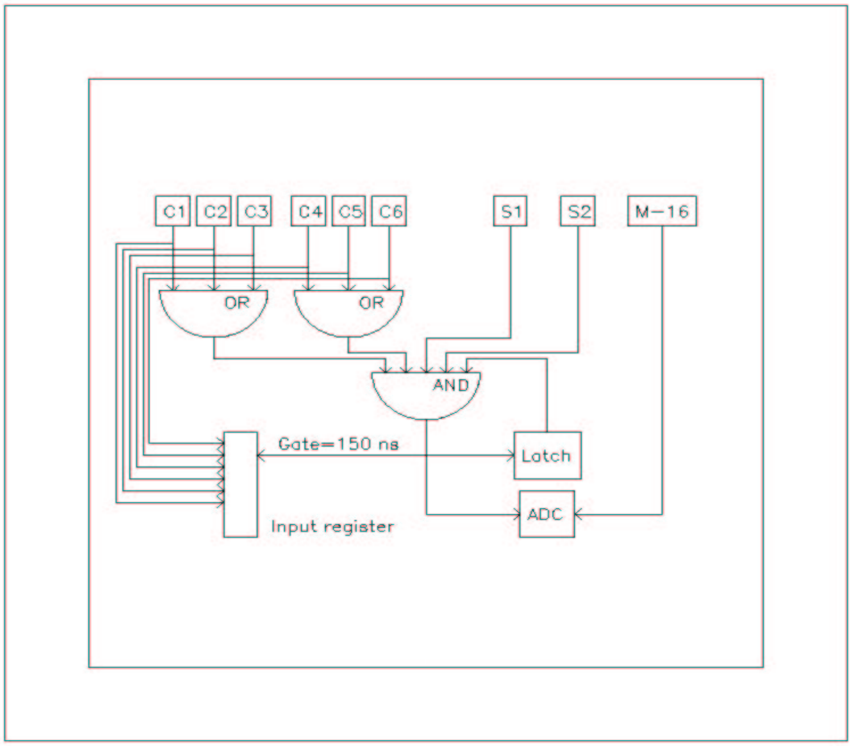

Figure 2: The block diagram of the cosmic ray trigger electronics.

The high voltage on the M-16 was set to 1000 V and the typical gain was about 2.3×10^7. Before and after each run, which took about 48 hours and contained around 2000 events, an LED calibration was done. Unfortunately, we found that during the measurements there was a small drift in the pedestal position, which could cause additional 3-4% error to the measured light output. Therefore, the final light yield was based on Poisson statistics and the number of zeros in the spectra. During the data analysis using information from inner trigger counters we reject events with multiple tracks and large angle tracks. The typical spectrum of the final selected events is shown in Fig.3. One can see good separation of pedestal from the first photoelectron peak.

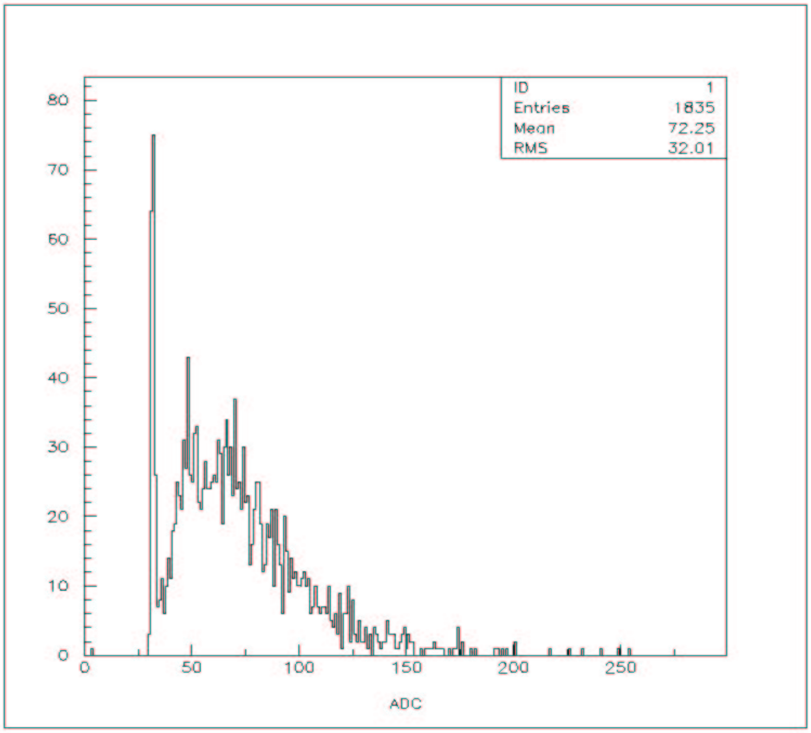

Figure 3: The typical M-16 response to cosmic rays selected by trigger.

The radioactive source setup

A schematic view of the radioactive source setup is shown in Fig.4. The sample to be tested was placed inside a 12 m long light tight box. The radioactive β-source (^{106}Ru, 270 μ-Ci) was located on a cart, which could move smoothly over the tested sample inside the light tight box by pulling the rope tied to the cart. The longitudinal position of the cart inside the box was reproducible to within 1 mm accuracy. The source location on the cart was shifted 1 cm away from the center, so it irradiated approximately one side of the sample. The light produced in the strip by β–particles was trapped by 1.2 mm Kuraray WLS fiber and guided to a Hamamatsu M-16 PMT. The total length of the green fiber was 9 m, but the distance from tested sample to the PMT was exactly 8 m. The far end of WLS was polished and painted black. The fiber was optical coupled to the PMT using clear optical grease. The current of the PMT, operated at 1000 V, was measured by a picoammeter, which was read

out by the PC using GPIB interface. The accuracy of individual current measurement was better than 1%. The main uncertainty came from the relative cart position against the tested strip and different thickness of reflective layers of samples. To decrease this uncertainty the light yield was measured in a few positions along the tested sample. Moreover the light yield was always measured twice for both halves of sample under test. The second measurement was taken when the sample was placed upside down inside the light tight box.

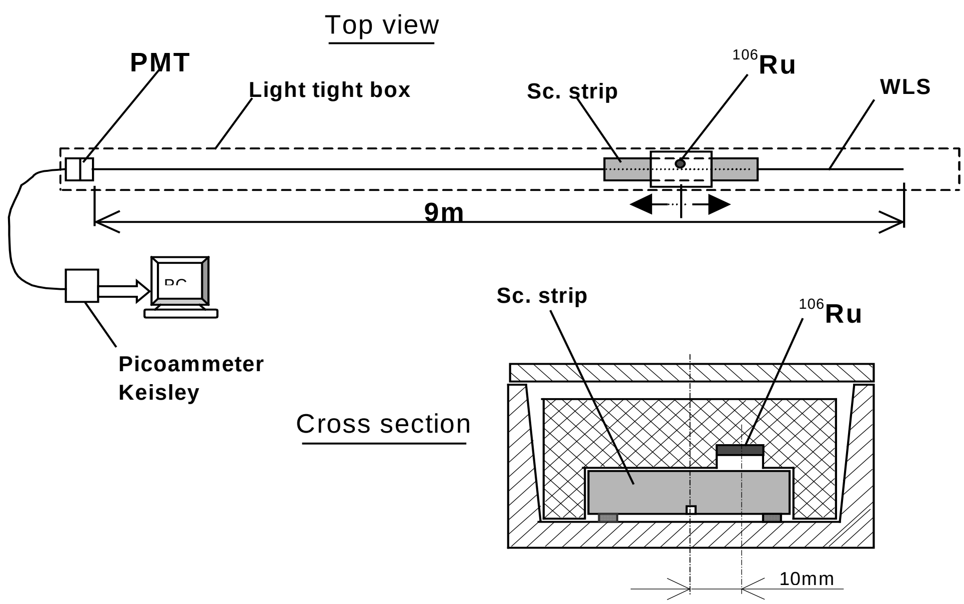

Figure 4: The scheme of the radioactive source setup.

Fiber handling

The typical length of the scintillator samples was 20 cm. To avoid the influence of the groove shape on the results of the light yield dependence on groove depth, the original extruded groove was filled with clear adhesive epoxy and after hardening was painted with BC-620 white paint. A new 1.5-mm wide groove was made on the other side of the strip. Each time after the measurements were made the fiber was removed from the sample and the groove was made deeper. Then the fiber was placed inside the groove which was filled with a clear resin optical epoxy BC-600 compound and covered with sticky aluminized Mylar.

We have solved the problem of keeping the fiber at the bottom of the groove. Just after the groove had been filled with clear optical glue, the buoyant force was pushing the fiber out of the groove. Care was taken to be sure the fiber stayed in place at a certain depth inside the groove. We used short pieces of clear fiber to support the fiber in place, as is shown in Fig.5. These pieces of clear fiber were placed at three points near the ends and in

the middle of the strip exactly within our working area. Since these pieces of clear fiber were very short (5-6 mm) and their refractive indexes were pretty close to the refractive index of the optical epoxy compound, we believe that their effect on measurements was negligible.

During the test of different reflecting groove covers the WLS fiber was glued inside the groove. Measurements were taken for the reflectors were with and without optical coupling to the hardened glue. The optical coupling was achieved using clear optical grease.

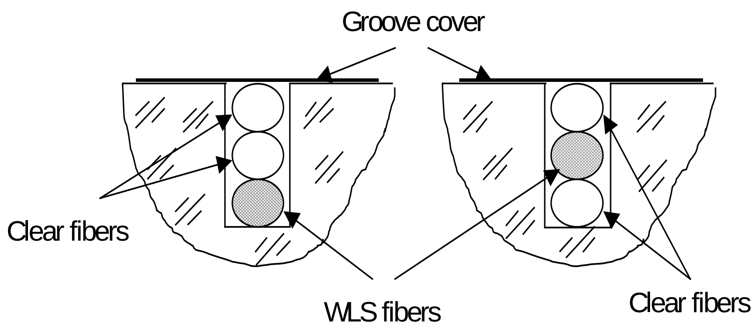

Figure 5: Keeping the fiber in place at a certain depth inside the groove.

Axial groove versus groove in the strip corner

According to results of Monte-Carlo simulation of the light yield in a long 4.1×1 cm^2 scintillator strip with WLS fiber readout, the highest light yield with a specular reflecting scintillator surface is achieved when the fiber is located in a corner of the strip [4]. The comparison of the two light yields when fiber was inside the groove in the corner of the strip and when it was in an axial groove was made using sample of Kuraray extrusion 20 cm long. Before the new 1.5×1.35 mm^2 groove in the corner of the sample was made, the light output was measured in the original extruded groove. Then the axial groove was filled with clear optical glue and after the glue had hardened the surface was painted with Bicron BC-620 white paint. The cosmic ray stand allowed uniform irradiation of the sample, but the radioactive source configuration caused a light yield variance across the sample. Therefore the measurements were taken at four points, as it is shown in Fig.6.

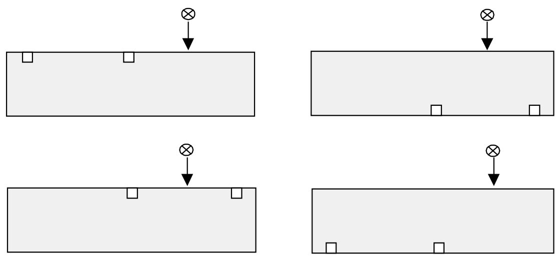

Figure 6: The scheme of different sample orientation relative to the ^{106}Ru-radioactive source.

The cosmic ray stand results and the average of the data from radioactive source set up are shown in Table 1. The data are in a good agreement with each other. The light yield for axial groove was a 14% bigger than the light yield when fiber was in the corner of the strip.

Table 1. Light yield for different groove locations in the scintillator strip.

	Axial groove	Groove in the corner
Cosmic rays	2.29±0.08 pe	1.96±0.06 pe
^{106}Ru	250±2 nA	217±2 nA

Light yield versus fiber depth inside scintillator strip

The absolute light yield of the strip with WLS fiber readout under irradiation by cosmic rays is shown in Fig.7 as a function of the groove depth. The fiber was held at the

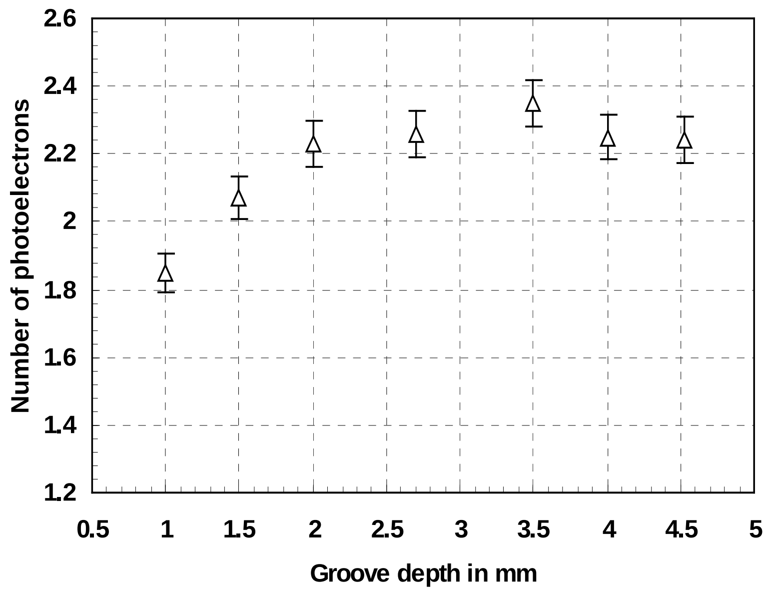

Figure 7: The absolute light yield versus the groove depth.

bottom of the groove during the measurements. The measured light yield was slightly higher than two photoelectrons. This relatively high light yield was observed because there was not any light lost in optical connectors or clear fibers.

The relative light yield measured with cosmic rays and with a radioactive source is shown in Fig.8. Both light outputs were normalized to groove depth 1.5 mm.

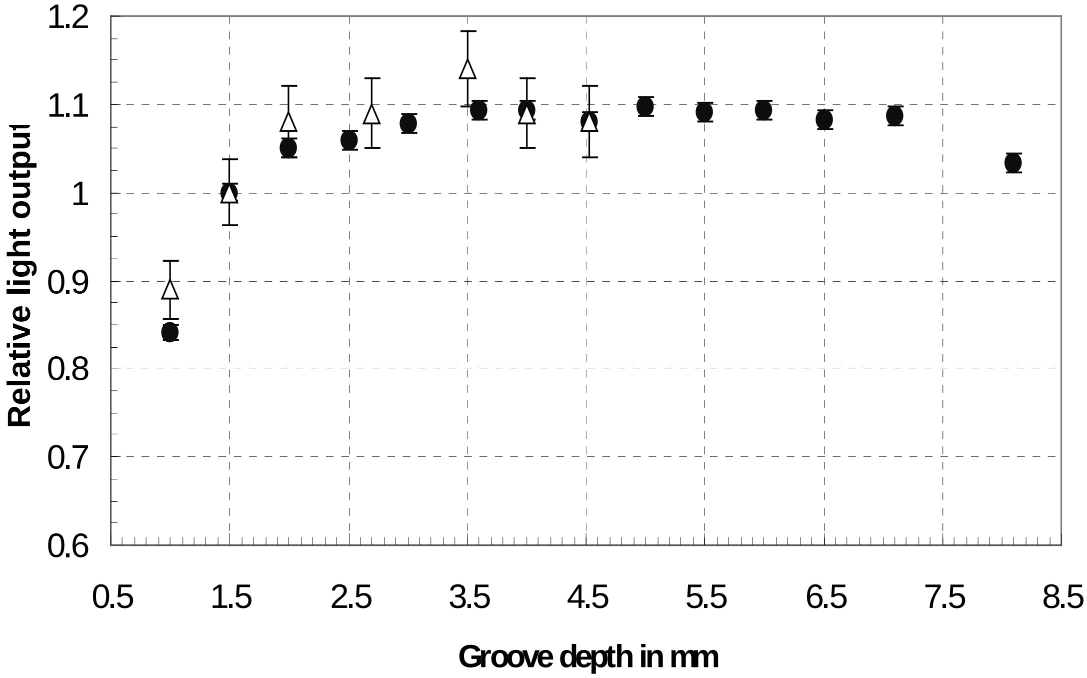

Figure 8: The relative light output versus the groove depth.
| - cosmic rays, =- radioactive source.

It is obvious that for these particular measurements the radioactive source method has better statistical errors. There is good agreement between both sets of data. Starting from a shallow groove the light yield increases with depth of the groove but after about 3 mm it remains constant. There is a 20% increase in light output compared with fiber at the surface of the strip. Recently our colleagues from Tufts University have seen similar effects in their measurement [5].

After these measurements had been made it was obvious that depth of the groove is not a relevant parameter. There is only one crucial factor, the depth of the fiber inside the groove. Refractive indexes of the optical glue and polystyrene are quite close, and replacement of the polystyrene with optical glue should not make big impact on photon absorption or scattering inside the scintillator.

In Fig.9 the relative light output is shown versus the depth of the WLS fiber inside a 4.53-mm groove. The data show exactly the same dependence as one can see in Fig.8. Again there is a 20% increase in light yield if the fiber was placed deeper than 3 mm inside the scintillator strip.

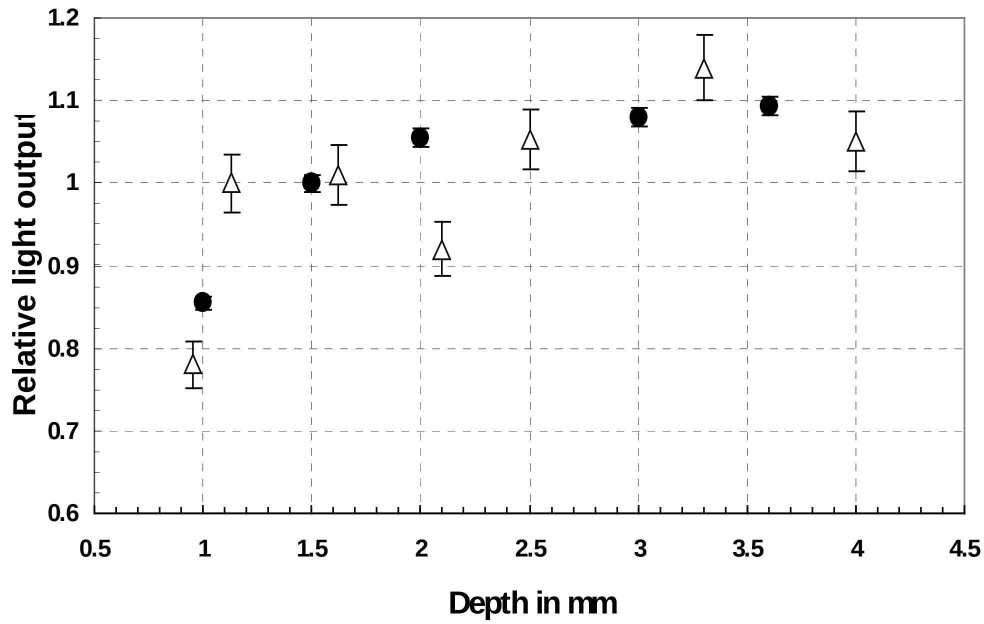

Figure 9: The relative light output versus the depth of WLS fiber inside a 4.53-mm groove. | - cosmic rays, = - radioactive source.

Effect of the glue thickness on light yield

The results described above have shown that for obtaining the best light yield the WLS fiber has to be secured at the bottom of a relatively deep groove. At the same time to get good optical coupling of fiber with a strip, the groove should be filled with relatively expensive optical glue. For the MINOS detector, where there are a great number of 8-m long scintillator strips, the total cost of the detector might increase inadmissibly. To optimize the amount of optical glue in the groove we have studied the light yield as a function of thickness of the glue layer. In Fig.10 the relative light yield of the tested sample for different groove depth is shown versus thickness of the glue layer. All data were normalized to light yield when there was not any glue in the grooves. One can see that the light yields increase faster by increasing the amount of glue and has its maximum at a glue thickness around 1.5 -1.6 mm. The measured increase in light output is 1.6 times and is in a

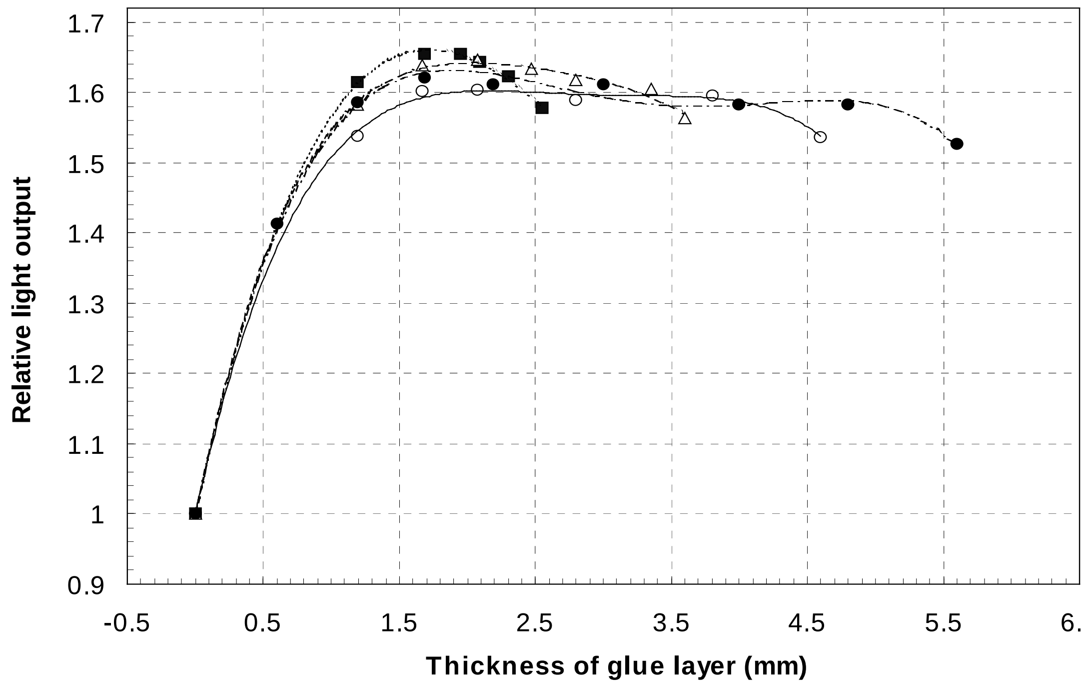

Figure 10: Relative light yield for different groove depth versus thickness of the glue layer. The groove depth in mm : <- 2.95; | - 4.0; O - 5.0; =- 6.0.

good agreement with previous observations. Further filling the groove with the optical glue does not give any increase in the light output, in fact a small degradation in light yield is observed when the grooves are filled completely with the glue.

Relative light output for different reflective coatings

In Fig.11 the relative light yield of the test sample is shown for different groove cover materials. The best light output was obtained when the groove was covered with Tyvek. All data were normalized to this light yield. The results obtained, when black paper was in optical contact with cured glue, show how important it is to have good reflection in this relatively small area of the strip. One can lose almost 45% of light yield. On the other hand, without any coating relying only on total internal reflection the glue surface one can get 80% of the maximum light output. Apart from Bicron white paint, all materials lost their reflectivity when in optical contact with cured glue. After about forty minutes the light output measured for Tyvek decreased by 15%. The light yield for Al-Mylar decreased by 8% and was almost equal to the light output of sticky Al-Mylar. So the Bicron white paint (BC-620) showed the highest light yield when in an optical contact with glue in the groove.

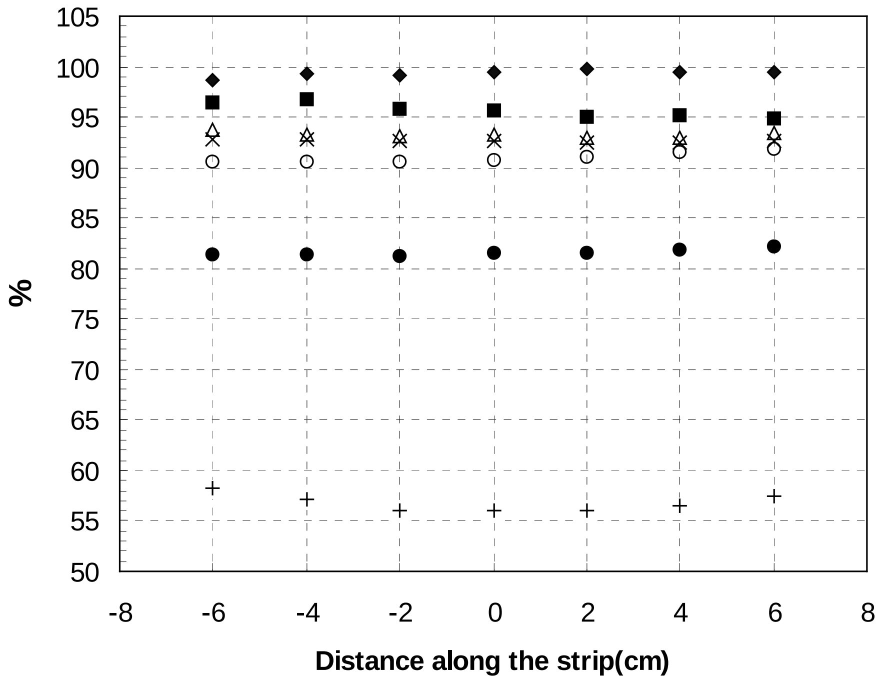

Figure 11: Relative light output for different reflective coating materials of the groove: ◆ - Al/Mylar without optical contact, < - Bicron white paint (BC-620), | - Al/Mylar imbedded in the glue before it hardened, ρ - sticky Al/Mylar, O - Al/Mylar in optical contact, = - black paper without optical contact, ✦ - black paper in optical contact.

Summary

In this note we have presented the detailed data on relative light yield of WLS fiber embedded in a long 4.1×1 cm^2 in cross section co-extruded scintillating strip. It was confirmed in details that the light output depends on fiber depth inside the strip. One can get 20% increase in the light yield fixing the fiber deeper than 2.5 mm comparing to fiber on the surface of the strip. From the other hand it was found that owing to the fiber floating inside the optical glue before it gets solid one can expect at least 20% non-uniformity in the strip response, unless measures will be taken to keep the fiber at the bottom of the groove. The axial longitudinal groove gives a 15% higher light yield than the groove in a corner of the strip. Testing different reflecting coating in the region of the groove we have found almost the same light output for few most common used reflectors, including sticky Al-mylar tape. So our study approves using of this tape as a reliable, feasible from economical point of view reflector, which would meet MINOS light output requirement.

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