Studies on Scintillating Fiber Response

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Abstract

Scintillating fibers of type BCF-12 with 2 mm $\times$ 2 mm cross section, up to 600 mm length, and PMMA cladding have been tested, in conjunction with the multi-anode photomultiplier HAMAMATSU R 4760, with minimum ionizing electrons. The impact of cladding, extramural absorbers and/or wrapping on the light attenuation and photoelectron yield is studied in detail. Fibers have been circularly bent with radii of 171 mm and arranged in two layers to bundles forming granulated scintillator rings. Their performance in the EDDA experiment at COSY for detection of high energy protons revealed typically more than 9 (6) photoelectrons per fiber from bundles with (without) mirror on the rear side, guaranteeing detection efficiencies $> 99\%$ and full compatibility with corresponding solid scintillator rings. The time resolution of 3.4 ns FWHM per fiber read out is essentially due to the R 4760.

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1 Introduction

Scintillating fibers and scintillator rods of small cross section attract growing attention in many fields of detector design, where a high granularity is of major importance as for instance in charged particle tracking devices. Their application is essentially aggravated by the well known restriction that only a rather small fraction of the primary light yield determined by the angular range for total reflection can be collected and transmitted to the photosensor, which therefore must be able to detect few photoelectron events quantitatively to ensure spectroscopic conditions.

Related problems of light guiding in fiber bundles, monofibers and liquid scintillator filled capillaries are discussed for instance in Refs. [1–5] and papers quoted therein. Noticable improvements could be achieved by a proper adjustment of the dye concentration in the scintillator in order to minimize self-absorption losses, by replacing standard cladding materials by ones with a lower refractive index in order to increase the acceptance angle for total reflection, and by using multiclad scintillating fibers.

In this paper, we report on some results obtained within R&D work on the EDDA detector system designed for studies on proton-proton interactions at energies up to 2.5 GeV and installed at the proton Cooler Synchrotron COSY of the Forschungszentrum J"ulich, Germany [6]. Because of spatial resolution requirements in the cms backward region six out of totally 46 half-ring shaped scintillator elements of the EDDA detector had to be equipped with scintillating fibers bundled to the geometric requirements discussed in Sect. 4.1. The properties of two suitable types of fibers, their response to ^{90}Sr β-particles and their performance within the fiber bundle including first results with energetic protons from COSY are analyzed here. The experimental program is outlined in Sect. 2; Sect. 3 focuses on monofibers, whereas Sect. 4 is devoted to fiber assemblies. Our results are summarized in Sect. 5.

2 Experimental program

2.1 Set up and materials

All fibers studied had a square 2×2 mm^2 cross section. The two types are

- fibers cut from blocks of BC-408 scintillator material[1] and carefully polished including the front and rear ends,

[1]Supplied by Bicron, Saint-Gobain/Norton Industries Ceramics Corporation

– commercially available BCF-12 fibers[1] with a cladding made of polymethylmethacrylate (PMMA). As quoted by the manufacturer their trapping efficiency for the primary light is typically 4%.

The scintillations were read out by a 16-channel photomultiplier (PM) of type HAMAMATSU R 4760. It comprises 16 separated ten-stage linear focused PM-systems. As all photocathodes and corresponding dynodes are interconnected within the tube, all channels are operated with only one common voltage divider. Thus individual gain adjustments to maintain a uniform response of all channels are impossible. Gain differences among the channels have to be corrected for off-line or by appropriate settings of external amplifiers.

Fig. 1 shows the set up in a schematic way and not to scale. Scintillations in the fiber F under test were excited locally by the β^--radiation from a ^{90}Sr source S collimated to a diameter of 1 mm. To minimize background contributions from bremsstrahlung, the collimator C was machined from aluminum. The fiber was pressed gently and reproducibly by a piece of soft rubber against the entrance window of the PM. d is the downstream distance from the PM. A trigger fiber TF of the same dimensions detected β^--particles traversing F and was read out by a second channel of the PM. It allowed to select events which deposit a fairly well defined energy in F (see Fig. 3). The signals from F were integrated and fed into a multichannel analyzer via a linear gate. This was activated by the signals from TF after passing a constant fraction discriminator. The recorded pulse height spectrum displays the distribution of the charges Q per PM output pulse. Their mean value $\overline{Q}$ for scintillation events is proportional to the mean light yield $\overline{L}$ at the PM entrance and was taken as a (relative) measure for $\overline{L}$.

As all channels of the PM used were able to resolve the single electron peak, it was possible to calibrate $\overline{Q}$ or $\overline{L}$ in average numbers $\overline{N}_{pe}$ of photoelectrons released from the photocathodes. From the mean charge $\overline{Q}_1$ corresponding to a *single* electron the gain could be estimated by $G = \overline{Q}_1/e_0$, where e_0 denotes the electron charge. To give an impression to what extent G may vary in a typical case, Fig. 2 shows the distribution of $\overline{Q}_1$ among all 16 channels. These data, however, was taken with fast light pulses from a green LED after appropriate attenuation.

The electron energy spectrum from the β^--decay cascade $^{90}\mathrm{Sr} \rightarrow\ ^{90}\mathrm{Y} \rightarrow\ ^{90}\mathrm{Zr}$ consists of two components extending up to 0.545 MeV and 2.25 MeV, respectively. As the minimum energy to cross 2 mm of fiber material is about 600 keV, only β^--particles from the second component above this value are registered in the triger fiber TF. Their energy loss distribution in F was calculated [1] and is shown in Fig. 3. The most probable energy loss is 360 keV, with a full width at half-maximum of 40 keV.

2.2 On the impact of extra mural absorbers

For a light beam starting within the scintillating core (refractive index n_1) and propagating towards the surface of the fiber through a cladding (n_2) into the surrounding medium (n_3) the conservation of the numerical aperture states

$$n_1 \cdot \cos\varphi_1 = n_2 \cdot \cos\varphi_2 = n_3 \cdot \cos\varphi_3, \tag{1}$$

where $\varphi_1, \varphi_2, \varphi_3$ denote the corresponding angles with respect to the fiber axis. The trapping efficiency of a fiber is given by $\varepsilon = (1 - \cos\phi)/2$. Here ϕ is half the angle of aperture for the light cone guided within the fiber by total reflection into one direction towards the photosensor. Total reflection at the fiber surface demands $n_3 < n_1$. The corresponding trapping angle is determined by $\phi = \varphi_1(\varphi_3 = 0°)$. According to eq. (1) this leads to $\cos\phi = n_3/n_1$ and $\varepsilon = (1 - n_3/n_1)/2$. Thus ε were **not affected** by the refractive index n_2 of the cladding, **if** the outer fiber surface would boarder on air. While this is highly desirable in terms of light output, it is not easily reconciled with avoiding cross talk between adjacent fibers, which requires some sort of wrapping or coating of the fibers.

For $n_1 > n_2 > n_3$, which is normally the case, ε separates into a core (ε_c) and a surface (ε_s) component. Starting from $\phi_c = \varphi_1(\varphi_2 = 0°)$ for the trapping angle of the first one, eq. (1) yields $\cos\phi_c = n_2/n_1$ and $\varepsilon_c = (1 - n_2/n_1)/2$. The surface component is the difference $\varepsilon_s = \varepsilon - \varepsilon_c = (n_2 - n_3)/2n_1$.

A coating of the fiber surface with an extra mural absorber (EMA) paint to avoid cross talk between adjacent fibers in a bundle converts the directed (total) surface reflection into a diffuse scattering. If a nearly LAMBERTIAN angular distribution is assumed for the scattered light intensity, the contribution of this process to light guidance over distances long compared to the fiber diameter is negligible. Under these conditions the trapping efficiency ε should drop to zero for an uncladded fiber and to ε_c for a cladded one. The results presented in Fig. 4 support these arguments. They show for an uncladded fiber and a cladded one, both being partially EMA coated, the light yields $\overline{R}_1$ relative to the corresponding yields of the same uncoated samples as a function of the distance d from the PM. The coating extended from d_0 to the rear fiber end. The ratio $\overline{R}_1$ indeed decreases inside the EMA coated region within about 50 mm to almost zero for the (uncladded) BC-408 fiber and is reduced by $\Delta\overline{R}_1 = 30\%$ for the (cladded) BCF-12 fiber. This reduction, however, is much smaller than expected from the refractive indices $\big(n_1 = 1.60$ (BCF-12 core), $n_2 = 1.49$ (PMMA cladding) and $n_3 = 1$ (air)$\big)$, which lead to $\Delta\overline{R}_1 = \varepsilon_s/\varepsilon = (n_2 - n_3)/(n_1 - n_3) = 82\%$. This discrepancy is due to the poor optical quality of the outer cladding surface, which reduces the trapping efficiency in the uncoated part, but not in the EMA coated part. The fibers were used as supplied by the manufacturer and not treated in any way to attain optimal surface reflectivity. If an EMA coating is to be applied – as in the case in virtually all practical applications – the quality of the outer cladding surface is largely irrelevant. Then, the trapping efficiency is given by the refraction indices of core and cladding and the quality of the interface between them.

3 Results for monofibers

In a first step, several BC-408 fibers (400 mm long) and BCF-12 fibers (600 mm long), both without any additional coating or wrapping, were studied. We focused our attention on the response of the rear halves of the fiber length to get pronounced information about the light attenuation even in short run periods. Fig. 5 presents some of our results. The plots show the average charge $\overline{Q}$ (in channel numbers and on a logarithmic scale) taken directly from the pulse height spectrum of the integrated pulses versus the distance d from the PM. The straight lines are exponential fits to the data points yielding, the indicated values for the attenuation length, λ.

Although all six BC-408 fibers tested were cut and polished the same way as far as technically controllable, the results reveal significant variations of the response between individual samples. These certainly cannot be attributed exclusively to inhomogeneities in the bulk material. Thus it must be assumed that faint differences in the surface quality caused by the machining process are responsible for the observed deviations.

The corresponding results obtained for the BCF-12 fibers are more encouraging. Here four out of five samples studied behaved identically within the limits of experimental errors. Their common response is represented in Fig. 5 by one selected set of data (full circles). Obviously the integrated PMMA cladding guarantees a clean and homogeneous core-cladding interface. The response of the fifth fiber (open circles) deviated essentially. This is probably caused by local destructions (cracks) of the cladding.

In a second step, the influence of an external wrapping or coating on the light yield was studied. For this purpose, fibers of both types were loosely wrapped either in an aluminized plastic foil or in TYVEK[2], which is a white paper with a strongly structured surface, or they were coated with EMA. To pronounce the effects, the data were plotted as ratio

$$\overline{R}_2(d) = \frac{\overline{L}(d)}{\overline{L}_1(d)} = \frac{\overline{L}_0}{\overline{L}_{01}} \cdot e^{-d/\lambda_0} \qquad \text{with} \qquad \lambda_0 = \frac{\lambda_1 \cdot \lambda}{\lambda_1 - \lambda} \,,$$

where $\overline{L}_1(d) = \overline{L}_{01} \cdot e^{-d/\lambda_1}$ describes the responses of the bare fiber and $\overline{L}(d) = \overline{L}_0 \cdot e^{-d/\lambda}$ that of the same fiber after being wrapped or coated. $\overline{L}_{01}$ and $\overline{L}_0$ are the corresponding values extrapolated to $d = 0$. Fig. 6 shows the results. In all cases $\overline{R}_2 < 1$ holds, which

[2]Supplied by Du Pont Fibers, Wilmington, DE 19880, Canada

means that both wrapping and coating led to a reduction of the light yield at the entrance of the PM by up to 50%. Again the lines are fits to the data.

For the BC-408 fiber, the negative slope indicates a reduced attenuation length ($\lambda_0 < 0$ or $\lambda < \lambda_1$). The results for EMA coating are not shown, this coating pulled down the light yield almost completely because light guiding by total reflection is highly suppressed, cf. Fig. 4.

For the BCF-12 fiber, TYVEK and aluminum wrapping leave λ unchanged ($\lambda = \lambda_1$). EMA-coating seems to increase λ beyond λ_1 and diminishes the light yield by about a factor of two (see Fig. 6 for two fiber samples). This affirms that not only the core-cladding interface but also the outer cladding surface contributes appreciably to the fraction of light trapped in the fiber, unless coated with EMA.

4 Fiber assemblies for the EDDA detector

Groups of 24 fibers forming half-rings have been studied in detail with ^{90}Sr electrons (Sect. 4.2) and high energy protons (Sect. 4.3). The particular shape was chosen to meet the requirements of the EDDA detector; it will be discussed shortly as an example for a set up that takes advantage of the fiber technology.

4.1 The EDDA detector

EDDA is an internal target experiment at the Proton Cooler Synchrotron COSY in J"ulich, Germany; it is designed to study the elastic *pp*-scattering in the projectile energy range 300 MeV $\leq T_p \leq$ 2500 MeV. The detector concept is based on a fast triggering of coplanar binary events that fulfill the kinematic relation for elasticity between the proton scattering angles in the laboratory frame, namely $\tan\Theta_{lab}^{p1} \cdot \tan\Theta_{lab}^{p2} = 2m_pc^2/(T_p + 2m_pc^2)$, where m_p is the proton rest mass. For this purpose, the detector is equipped with a cylinder of beam-concentric plastic scintillator rings of rectangular cross sections. They surround the thin walled beam pipe downstream the internal target in the angular range $10° \leq \Theta_{lab} \leq 72°$ [7]. Each ring is subdivided into two half-rings with an inner radius of 171 mm and thickness 23 mm; the widths of the rings are designed to allow an angular resolution $\Delta\Theta_{cm} < 1°$ in the center-of-mass system through analysis of the amounts of scintillation light created in the two adjacent rings [7] traversed by each reaction proton. For angles $\Theta_{lab} < 52°$ this requirement could be met with rings of widths $\geq$ 14 mm and read out via light guides by individual photomultipliers HAMAMATSU R 1450 [8].

For angles $\Theta_{lab} > 52°$, however, this concept would require very small rings yielding geometrical problems as well as excessive angular straggling. The requirement $\Delta\Theta_{cm} < 1°$

must therefore be fulfilled by mere detector granularity. This lead to half-rings of a discrete fiber structure.

Each 24 fibers of cross section 2 mm $\times$ 2 mm and 544 mm length (BCF-12) were bent at room temperature to semi circles of radius $r = 171$ mm and 173 mm, respectively. Two layers of 12 fibers each were glued inside a massive support half-ring of inner radius 175 mm and width 26.4 mm. The layers were arranged to avoid cracks reaction protons might escape through. The structure was manufactured[3] with differential deviations of less than 0.1 mm. In order to suppress cross talk, the fibers were coated with TiO_2 based EMA; loose wrapping would have yielded more light (cf. Sect. 3) at the expense of technical complications and was therefore disregarded. Readout was accomplished with inactive BCF-98 fibers as flexible light guides.

4.2 Tests with ^{90}Sr electrons

The performance of these fiberrings was studied as before with the ^{90}Sr source mentioned above. The fibers of the outer layer served as trigger counters. Representative results from three selected fibers of the same bundle are presented in Fig. 7. Here the average number of photoelectrons, $\overline{N}_{pe}$, for a deposited energy $\overline{\Delta E} = 360$ keV (cf. Fig. 3) and calibrated with the single-electron-response, is plotted (logarithmic scale) versus the angle $\varphi = d/r$, where d is the distance from the front end of the (circular bent) fiber and r the bending radius. Within the angular range considered, the response $\overline{N}_{pe}(\varphi)$ for roughly 30% of all fibers tested could be fitted by a single (decaying) exponential – although with differing values λ for the attenuation length – with a quality that is evident from Fig. 7 for fiber samples #5 and #9. A critical survey, however, over all the data collected within our experimental program, including those for the monofibers supports the general experience [4,5,9] that light transport in bare or cladded fibers is obviously not a simple exponential process (see Fig. 7, fiber #4). Quantitative predictions are tedious to obtain from fundamental optical principles. As analyzed for instance by Hawkes et al. [5], light guiding by the core on one hand and by the cladding on the other contribute in clearly different ways to the total attenuation. To explain further peculiarities of the response $\overline{N}_{pe}(d)$, Hawkes et al. take into account spiraling off-axis photons and crosstalk between core and cladding.

The interdependence between the average number $\overline{N}_{ph}$ of scintillation photons per pulse reaching the photocathode and its relative variance, $v^2_{N_{ph}}$, can be used to check how far our results are in accordance with simple theoretical predictions. It was analyzed for the 12 fibers of the inner layer of one selected bundle with restriction to the data observed at $\varphi = 90°$, that is half-way between the fiber ends.

[3]Gesellschaft f"ur Meß- und Systemtechnik mbH (GMT), Rudower Chaussee 5, D-12489 Berlin (Germany)

According to [10,11] a photomultiplier responds to a scintillation pulse emitting N_{ph} photons onto its cathode with a relative variance

$$v_Q^2 = v_{N_{ph}}^2 - \frac{1}{\overline{N}_{ph}} + \frac{v_{Q_1}^2 + 1}{\overline{N}_{pe}} \tag{2}$$

of the pulse charge distribution at its output, where $v_{Q_1}^2$ is the relative variance for the *single* electron peak. If $\overline{q} = \overline{N}_{pe}/\overline{N}_{ph}$ denotes the mean quantum efficiency of the PM, eq. (2) can be written as

$$v_{N_{ph}}^2 = v_Q^2 - \frac{v_{Q_1}^2 - \overline{q} + 1}{\overline{q} \cdot \overline{N}_{ph}} \tag{3}$$

For photon numbers N_{ph} that are POISSON distributed ($v_{N_{ph}}^2 = 1/\overline{N}_{ph}$), the equations reduce to

$$v_Q^2 = \frac{v_{Q_1}^2 + 1}{\overline{N}_{pe}} \qquad \text{or} \qquad v_Q^2 \cdot \overline{N}_{pe} = v_{Q_1}^2 + 1 \tag{4}$$

All our measured charge distributions showed nearly GAUSSIAN shapes. Therefore the relative variance v_Q^2 could be calculated from the observed full width at half-maximum ΔQ by the simple relation $v_Q^2 = 0.18 \cdot (\Delta Q/\overline{Q})^2$. In a corresponding way $v_{Q_1}^2$ was extracted. The average photon numbers were determined as $\overline{N}_{ph} = \overline{Q}/\overline{q}$ from the mean charges $\overline{Q}$ and as well for $\overline{Q}_1$. The value for $\overline{q}$ was taken from the PM data sheet.

The results of the analysis are presented by Fig. 8. The fibers are numbered according to falling $\overline{N}_{ph}$ values, and $v_{N_{ph}}^2$ was calculated from eq. (3). Consistently, a decrease in $\overline{N}_{ph}$ is associated with an overall increase in $v_{N_{ph}}^2$. Furthermore, the product $v_{N_{ph}}^2 \cdot \overline{N}_{ph}$ is plotted in Fig. 8. If POISSON statistics would strictly be applicable it should be constant and equal to one. Our data shows this constancy, but scatters around an average value three times higher; it was checked and verified for a total of 108 fibers tested. This fact is attributed to $v_{N_{ph}}^2$ and supports the presumption that the additional spread of the N_{ph}-distribution is mainly due to the process of light guidance within the fiber suffering from local inhomogeneities of the surface reflectivity. Other effects taken into account – such as systematic uncertainties in reading $\overline{Q}, \overline{Q}_1, \Delta Q$ and ΔQ_1 from the recorded data – did not contribute significantly. This is also true for the spread arising from the energy loss distribution (see Fig. 3). Its relative variance was calculated to be $v_{\Delta E}^2 = 0,009$ which is negligibly small compared to the average values $v_Q^2 = 0,25$ and $v_{Q_1}^2 = 0,30$.

For practical reasons, the effect of mirroring the rear fiber ends to raise the light yield [2,12] was studied. Two types of mirrors covering all 24 fiber ends were tested, namely an aluminized plastic foil and a high quality silver surface mirror with a reflectivity of 99.8%. Optical contact to the polished bundle end was accomplished by silicon grease. Fig. 9

shows the average light yield $\overline{R}_3$ for the 12 inner fibers of the bundle relative to the yield for EMA coated fiber ends. The average increase amounts to 33% (44%) for the Al (Ag) mirror. Mirroring also clearly improves the attenuation length. Fig. 10 presents results for one representative fiber. Here, the yield $\overline{N}_{pe}$ measured is plotted on a logarithmic scale versus the angle φ; it can be seen that the mirror roughly doubles the attenuation length λ.

4.3 Response to high energy protons

After completion of the tests with ^{90}Sr electrons, six of the fiber half-rings were installed in the EDDA detector and exposed to protons from elastic *pp* scattering. Their energies T'_p varied kinematically between 50 MeV and 500 MeV, and therefore the numbers N_{PE} of photoelectrons were expected to be at least 50% higher than those observed with minimum ionizing electrons (cf. Fig. 10). In this application, pairs of fibers were attached to one channel of the photomultiplier (HAMAMATSU R 4760) for read-out.

Examples of pulse height spectra from fibers residing in different angular positions Θ_{lab} and from different projectile energies (T_p = 793 MeV and 2205 MeV, respectively), are shown in Fig. 11. The widths of the peaks result from the straggling of the deposited energies about the average values ΔE indicated, the light attenuation along the fiber depending on the point of incidence, the photoelectron statistics and the pulse height resolution of the individual photomultiplier. Estimates based on POISSON statistics for the photoelectrons predict a detection inefficiency due to pulse height discrimination at typically 15–20 mV of less than 1%. As expected, the most probable pulse heights scale fairly linearly with the proton energy deposit ΔE, and the relative widths decrease with increasing ΔE.

Proton detection for angles $\Theta_{lab} < 52°$ occurs in the EDDA experiments with conventional scintillators; therefore the angular distributions receive contributions from events with and without fiberrings being involved. Fig. 12 shows that there is a smooth transition between these regions and no indication of systematic deviations in the detection of intermediate energy protons. Scintillating fiber arrays seem to present no efficiency problems for intermediate energy proton detection, provided proper care is taken in their geometric positioning (see 4.1).

4.4 Timing properties

The time resolution capabilities of fibers in conjunction with the PM R 4760 were tested (representatively) for PM-channel # 6 (cf. Fig. 2). Its cathode was directly illuminated with short light pulses from a green LED driven by a fast pulse generator [13]. For $\overline{N}_{pe} = 5$

the anode pulses had a scintillation-like shape with a rise time of 6 ns and a fall time of 19 ns. The pulses were fed into the stop input of a CAMAC TDC via a constant fraction discriminator. The start signals were taken from the pulse generator.

The time resolution Δt obtained as a function of $\overline{N}_{pe}$ and expressed by the full width at half-maximum (FWHM) of the recorded time peaks is presented by Fig. 14. The curve is a fit to the data according to the frequently used expression

$$\Delta t = \sqrt{\alpha^2 + \beta^2/\overline{N}_{pe}}.$$

The fit parameters are $\alpha = 0.89$ ns and $\beta = 5.92$ ns. Obviously, for $\overline{N}_{pe} \lesssim 50$ the second term begins to dominate. It describes the influence of photoelectron statistics on the time resolution. The first term contains noise contributions from the PM and the electronics.

The timing properties of the fibers within the bundle were studied with the set up given in Fig. 1. Here, F and TF were the corresponding fibers of the inner and the outer layer of the bundle, respectively. The PM anode pulses from TF and F passed constant fraction discriminators and were fed into the start and stop inputs of a time-to-pulse height converter. Time calibration was performed by controlled delaying of the F-signal. The results for the full width at half-maximum Δt of the observed time peaks are displayed in Fig. 14 (full circles) together with those for $\overline{N}_{pe}$ (open circles) obtained for fiber # 10 at various angles φ. The observed time resolution Δt is essentially constant at 4.8 ns. From Fig. 13, a time resolution of about $\Delta t = 2.5$ ns is expected for $5 < \overline{N}_{pe} < 8$ and per PM-channel. Quadratic addition for two identical channels leads to $\Delta t = 3.5$ ns. These figures refer to the detection of artificial light pulses with a rather small dynamic range and thus represent a lower limit for Δt when detecting scintillations covering a larger range of light yields. In this respect the measured time resolution of about 4.8 ns (i.e. 3.4 ns per read out) throughout the whole fiber length is in accordance with the result of Fig. 13.

5 Summary

Square cross section (2 mm $\times$ 2 mm) scintillating fibers (BCF-12) were tested for suitability in a high granularity section of the EDDA detector [6–8]. As in most applications, avoiding cross talk between fiber channels without compromising granularity required a paint-type extramural absorber (EMA), which comes at the price of strongly reducing the potential for light collection (Sect. 2.2). Under such circumstances, the all important light collection efficiency is determined by the refractive indices of fiber core and cladding, and by the quality of the core-cladding interface. Measured light collection efficiencies can differ considerably from those predicted by simple optics. Differences observed from individual fiber to individual fiber suggest that rather minute deficiencies – such as cracks in the cladding or defects in the core-cladding interface – can make a significant difference. With reasonable care and extension testing it is, however, possible to assemble arrays of mm size fibers with essentially 100% efficient detection even of minimum ionizing particles. After low fiber-to-fiber cross talk has been "bought" at the expense of light collection efficiency, multi-channel PMTs employed should afford correspondingly low cross talk, such as the R 4760 manufactured by HAMAMATSU. The timing properties observed in commercially available scintillating fibers allow for resolutions of a few nanoseconds FWHM.

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Figure Captions

Fig. 1: Schematic experimental set up of fiber F, trigger fiber TF, ^{90}Sr source S and collimator C.

Fig. 2: Distribution of the gain G among all 16 channels of a R-4760 photomultiplier as determined from the single electron peak. The values are given relative to that of channel 7 (G_0). The horizontal line indicates the mean value.

Fig. 3: Calculated energy loss distribution in 2 mm scintillator material for ^{90}Sr-electrons reaching the trigger fiber.

Fig. 4: Influence of an EMA-coating on the light transport in an uncladded (BC-408) and a cladded (BCF-12) 2×2 mm^2 fiber.

Fig. 5: Light attenuation in various samples of uncladded (BC-408) and cladded (BCF-12) 2×2 mm^2 fibers.

Fig. 6: Light guiding in uncladded (BC-408) and cladded (BCF-12) 2×2 mm^2 fibers after wrapping in TYVEK-paper (TYV) or Aluminum-foil (ALU) or after coating with EMA.

Fig. 7: Light attenuation in three representative EMA-coated 2×2 mm^2 BCF-12 fibers bent to a radius of 171 mm and integrated into a fiber bundle.

Fig. 8: Systematic analysis of the response of 12 EMA-coated BCF-12 fibers forming the inner layer of a bundle. The lines are to guide the eye.

Fig. 9: Improvement in light yield of fibers by mirroring the rear bundle end.

Fig. 10: Effect of mirroring on the light transport for a representative fiber of a bundle.

Fig. 11: Response of two selected fiber pairs (shadowed) to protons under real experimental conditions of the EDDA experiment.

Fig. 12: Proton angular distribution at 793 MeV projectile energy. The regions covered by the fiber bundles are indicated.

Fig. 13: Time resolution versus number of photoelectrons for one selected channel of the PM R 4760.

Fig. 14: Light yield and time resolution (solid dots) for one selected fiber of a bundle.