CERN-PPE/92-207
CERN-LAA/92/SF/92-019
29 October 92

**PHOTOELECTRON COUNTING WITH SMALL DIAMETER
SCINTILLATING FIBRES***

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Abstract

We measured the attenuation losses and the corresponding number of photoelectrons in small diameter fibre bundles. Accordingly, two experimental set-ups have been developed for this purpose. The improvements in light yield of the last two years, due to better fibre production and to optimization of materials, concentrations and geometrical characteristics, are shown and discussed in detail. For 60 μm diameter fibre bundle, they amount to a factor 2 at the near end and to a factor 8 at 2 m distance from the light detecting photocathode.

To be submitted to Nucl. Instr. and Methods

* The work reported here is part of the LAA Project

1. INTRODUCTION

Applications of scintillating fibres are mainly restricted by the small fraction of excited light, which is trapped and finally guided to one fibre end for detection. This drawback arises from different sources: Firstly, from the low light trapping fraction caused by the small difference between the refractive indices of fibre core and its surrounding cladding, which selects a restricted light cone only to be kept within the fibre via total reflections. Secondly, only light rays traversing the fibre core within its meridional planes are guided with constant angular reflections, whereas skew rays, which spiral along helix paths, propagate always close to the core-cladding interface and therefore suffer from more reflections and are lost much faster. Thirdly, the transmitted light is attenuated in the fibre core due to absorption and reflection losses.

The trapping fraction can be improved by reducing the refractive index of the cladding material, if we consider a refractive index of 1.58 for the fibre core produced from polystyrene (PS). We have therefore replaced the standard PMMA* cladding of 1.49 refractive index by fluorinated** polymethacrylate of 1.42 refractive index, which should nearly double the trapped light fraction. The fraction of lost skew rays is related to the shape of the fibres and decreases slightly from circular over hexagonal to square cross-sections.

The reflection losses can be decreased by improving the quality of the core-cladding interface. This quality can be quantified by measuring the difference between the ideal value of unity and the real reflectivity q , as shown in ref.[1], where we achieved $1-q \leq 5 \times 10^{-5}$. Such small differences are essential, since in a 60 μm diameter fibre the light is reflected up to about 6000 times (normal cladding) or 8000 times (fluorinated cladding) within 1 m length.

Self-absorption is caused by the overlap of the dye-absorption band with its emission spectrum. Normally, plastic fibres are doped with two dyes. The first dye, e.g. p-terphenyl, emits in the opaque region of polystyrene (≈ 340 nm) and its light must be shifted by a second dye into the visible region (≈ 430 nm). Absorption and emission bands of the second dye overlaps to a large amount and therefore its concentration must be kept below some 0.03 weight %. This low concentration leads to rather long absorption lengths (≥ 100 μm) for the radiative light transfer between the two dyes. This causes unwanted cross-talk between small diameter (< 200 μm) fibres. We avoided this dilemma by doping the PS matrix with only one dye of large Stokes-shift***, which

* Polymethyl methacrylate

** H atoms in polymethacrylate are replaced by F atoms

*** Difference between the peak absorption and the peak emission wave numbers

spans all wavelengths between PS-emission (≈ 300 nm) and the transparent PS-region (≈ 430 nm) [2]. The required large Stokes-shift provides by itself already only a small overlap between absorption and emission bands and therefore a much higher dye concentration can be tolerated, which leads to non-radiative energy transfer and therefore to local light emission without cross-talk to neighbouring fibres.

This paper reports on light attenuation measurements and on photoelectron counting with scintillating fibres. Their light emission was stimulated by minimum ionizing electrons from a Sr-90 source at different distances from the photocathode of a multiplier tube. Our fibres of 60 μ m diameter contain different dyes, dye concentrations, and claddings. Their measured number of photoelectrons per millimetre is finally compared with that from fibres of larger diameter (≥ 1 mm) and different origin, but exposed to the same experimental procedure.

2. EXPERIMENTAL ARRANGEMENT

Light attenuations and photoelectron yields were measured on fused fibre bundles* [3] of 2 m length each and with square cross-section of 1 mm or 2.5 mm edges. Each of these bundles contains about 260 or 1600 fibres, respectively, with individual diameters of 60 μ m. These individual fibres are of hexagonal shape and share their cladding accordingly with their adjacent neighbours. Therefore, the cladding thickness of each fibre can be halved by still maintaining the required reflection quality. In contrast, circular shaped fibres or capillaries need their entire cladding to achieve the same result. Two kinds of cladding materials were used, PMMA of 1.49 refraction index and fluorinated polymethacrylate of 1.42 refraction index, surrounding the polystyrene (PS) fibre cores of 1.58 refraction index. The bundle end faces were machined with a diamond tool to achieve the required optical quality.

The arrangement for measuring light attenuations is shown in fig.1. The excited and transmitted light was detected with a photomultiplier**, which was coupled to the fibre bundle end via a 120 mm long and 40 mm diameter plexiglas light guide, in order to establish uniform light distribution across the 46 mm diameter bialkali-photocathode. Without light guide, we measured up to 60% more light at fibre excitations close to the photocathode. This result can be explained by the loss of skew rays, which are more attenuated by the non-cladded cylindrical light guide than from the fibres. In spite of these

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results, we measured in most cases with the light guide in place, since the results between different fibre installations were much more uniform, only scattering within $\pm 2\%$.

The scintillating light was excited with β^- particles from a Sr-90 source (400 MBq). The Sr-90 beta decay (half life : 28 years, maximum β -energy : 0.545 MeV) leads to Y-90, which decays again by β -emission (half life : 64.5 hours; maximum β -energy : 2.25 MeV) with almost 100% probability to the stable ground state of Zr-90. The source holder was driven by a computer controlled step-motor along the fibre bundle (fig.1a). This motor was programmed for stops every 25 mm or 50 mm. The fibre bundle was fixed in the groove of a bench and every 25 mm a 10 mm hole in this bench allowed for free passage of the β^- -particles, to avoid uncontrolled backscattering to the bundle. A collimator between source and fibre limited the particle beam to 4 mm diameter (fig.1b).

To establish well defined conditions for photoelectron counting, requires signals originating from minimum ionizing particles, which traverse a known pathlength within the material in question. Rather than to spend our time and efforts with exposures on particle beams, we opted for a measuring arrangement in our laboratory and checked the results with occasional beam tests.

The particles were again β^- -particles from a Sr-90 source of 37 MBq. This source is located in plexiglas (fig.2a) to avoid any noticeable bremsstrahlung contribution. The electrons were collimated through two slits of 1 mm and 0.6 mm width and 2.5 mm and 8 mm length, on the fibre bundle, which was again stretched along a groove in an aluminium bench. The beta source underneath and the coincidence detectors above this bench were positioned by a common support, which could be slid along the fibre bundle into the wanted positions. The coincidence arrangement consists of two photomultipliers* viewing via clear fibre light guides a common piece (5 mm $\times$ 10 mm) of plastic scintillator. The scintillating light reaching one end of the fibre bundle was detected with a quantacon**, the anode signals of which were gated with the coincidence pulses, as displayed in fig.2b.

3. MEASUREMENTS AND RESULTS

All measurements were performed in two steps for each fibre bundle. First we measured the light attenuation with our automatic arrangement, which provides 44 attenuation stops. At each of these stops, 50 dc-anode current values from the

* R 1635, Hamamatsu Photonics, Toyooka-village, Japan

** 8850, Burle Electron Tubes, Lancaster, PA, USA

photomultiplier were recorded and averaged by a Keithley* 1 s sampling nanoamperemeter. The strength of the Sr-90 source (400 MBq) provided enough anode current at the far distant end of the fibre bundle to keep the dark current to signal ratio below 2 %. The photomultiplier dark current amounted typically to 0.6 nA and was determined before and after each attenuation procedure, which took all together around 20 minutes. Fig.3 displays the attenuation curves of some different fibre bundles.

In a second step we counted the electrons released by the photons of the excited fibre bundle from the photocathode of the quantacon. The layout of the coincidence detectors (fig.2b) was designed to count only photoelectrons arising from the passage of minimum ionizing β^- -particles through the fibre bundle. Such particles span a kinetic energy range between approximately 0.8 MeV and 2.8 MeV [4]. We therefore inserted in front of the plastic scintillator an inert plastic filter of 1 mm thickness, corresponding to 0.2 MeV energy loss and absorbing all β^- -particles leaving the bundle with less than 0.34 MeV kinetic energy. The 3 mm thick plastic scintillator absorbs all β^- -particles passing this filter with less than 0.75 MeV energy and causes 0.6 MeV energy loss to still minimum ionizing ones. With 0.6 MeV threshold settings for the coincidence signals we selected in this way from the continuous Y-90 β^- -spectrum only β^- -particles leaving the fibre bundles with more than 0.8 MeV kinetic energy. Multiple scattering of such electrons could increase their path through the fibre bundle by some 4% to 8%. Large scatterers are excluded by the geometrical cross-section of the coincidence scintillator.

The probability to observe n photoelectrons follows a Poisson distribution :

$$P(n, ht) = \frac{1}{n!} e^{-ht} (ht)^n \quad (1)$$

where h means the average density of photoelectrons (hits) (mm^{-1}), and t the particle's path (mm) through the fibre bundle. This distribution (1) leads to different evaluations of the hit density from the measured values and we selected and applied mainly two methods out of them. The first one, evolves directly from relation (1) and describes the difference between probability one and the measured ratio of quantacon efficiency ($Q \cap H$) and the coincidence rate H from the two phototubes $H1$ and $H2$ viewing the coincidence scintillator (fig.2b) :

$$P(0, ht) = e^{-ht} = 1 - \frac{Q \cap H}{H} \quad (2)$$

* Model 485, Keithley Instrument Inc, Cleveland, OH, USA

With increasing quantacon efficiency, $Q \cap H$ approaches the count rate H and relation (2) tends to become zero. Therefore, this method can be applied only at fibre distances from the quantacon, where the count rate Q stays smaller than the coincidence rate H .

The second method of evaluation is based on the mean ADC-channel content :

$$ht = \frac{1}{\Delta} \left(\frac{\sum_{i=0}^{1024} C_i N_i}{\sum_{i=0}^{1024} N_i} - N_{ped} \right) \quad (3)$$

with C_i meaning the counts within the N_i -th ADC-channel, N_{ped} the pedestal channel number, and Δ the difference between the pedestal channel number N_{ped} and that of the first photoelectron peak. This method works over the whole bundle length, once the channel number of the first photoelectron peak has been established at several convenient source distances from the quantacon. Fig.4 shows such distributions observed with the coincidence arrangement (fig.2) at different β -source distances from the quantacon photocathode. The indicated average number of photoelectrons was evaluated with relation (3) and controlled by relation (2).

These measurements of hit densities took between half and 1 hour per source position, depending on its distance from the quantacon. Therefore, we measured each fibre bundle at about ten different source positions only and determined from each measurement the quotient between the dc-anode current from the light attenuation and the photoelectron (hit)-density. Table 1 shows an example. The quotient remains fairly constant and we can use our quasi-continuous attenuation curves, displayed in fig.3, to normalize their ordinate coordinates to the number of photoelectrons per millimetre. From each fibre type we measured light attenuation and hit density of five bundles and averaged the results, which are listed in table 2.

Through each of the attenuation curves we fitted a straight line to evaluate an average attenuation length over 2 m fibre bundle (fig.3). This least square-fit was part of the computer programme for the attenuation measurements and is therefore decoupled from any subjective bias. These attenuation lengths are listed together with the hit densities obtained for different source positions in table 2. As can be seen, there is a continuous improvement which is due to the application of fluorinated cladding, reduction of cladding thickness, decreased dye concentration, and also a non negligible better

production performance, which reflects mostly on the quality of the core-cladding interface. The improvements are illustrated by table 3, which lists the relevant ratios. All results displayed in figs 3 and 4 as well as in tables 1 through 3 have been obtained with plexiglas light guides between the fibre bundles and the EMI-or the quantacon-photocathode. Therefore, most of the skew rays have been suppressed. Several bundles were, however, measured without light guide and the relevant ratios without/with are listed in table 3, which shows also the improvement achieved with a mirror at the end-face opposite to the photocathode.

4. DISCUSSION

The improvements on light output and hit densities are documented in tables 2 and 3. In particular, the ratios listed in table 3 show clearly the expected ameliorations. The second column indicates the ratio of hit densities between fluorinated (1.42 refractive index) and normal polymethacrylate (1.49 refractive index) cladding. The theoretical light capture ratio amounts to 1.78 for these claddings. Obviously, we achieved these ratios and even better ones at the far bundle ends, mainly because of production improvement.

The third column in table 3 shows the ratio of hit densities for different cladding thicknesses. With $1.7 \mu\text{m}$ cladding thickness per individual fibre, the packing fraction* amounts to 90% and with $3.4 \mu\text{m}$ to 80% only. Again, we clearly achieved the theoretical ratio of 1.13 and even better ones, due to production improvement.

Reduction of the dye concentration from 0.7% wt (bundles G) down to 0.5% wt (bundles L) leads to higher hit densities in particular at the far fibre end where an improvement is strongly desired. This is shown in the fourth column of table 3, which indicates a considerable improvement obviously due to the decreased light absorption caused by the reduced overlap between absorption and emission band of the dye. Further reduction of the dye concentration down to 0.3% wt (bundles I) drops the light emission at zero distance from the photocathode down by $I/G=0.84$ which is only compensated by the reduced self-absorption after 1 m distance. However, for longer fibres ($>2 \text{ m}$) a dye concentration of 0.3% wt might be advantageous.

The fifth column in table 3 shows the gain in hit densities by mirroring the far distant end faces of fibre bundles. We achieved 75% reflectivity and increased largely the hit densities at far distances from the photocathode, where improvements are particularly important. Near the photocathode end of the fibre, this advantage disappears, since the

* Packing fraction means the ratio between the fibre-core and the core + cladding cross-section

light emitted into the opposite direction has to travel large distances up to 4 m, to reach the photocathode after reflection.

The next column in table 3 lists the ratios for measurements without and with plexiglas-lightguide between fibre bundle and photocathode. The improvement occurs mainly in the bundle-region close to the photocathode. This is due to skew rays, which are gradually lost during their reflections on the cladding. Therefore, at long distances these rays do not survive the multiple reflections. The light guide, however, does not transmit the surviving skew rays from shorter fibre distances to the photocathode. This behaviour explains the ratios in column 6 of table 3.

Finally, the last column lists the ratio of hit densities, if we consider a fibre arrangement within a particle tracker in a collider experiment (e.g. LHC or SSC). For these ratios, we assumed fibre bundles arranged at 1 m radial distance from the collider beams, which is traversed by ionizing particles originating at the collision point. The real path lengths of the particles change with their polar angles. Therefore, with polar angles θ decreasing from 90° (location of the fibre end close to the photocathode and perpendicular incidence of the particles) the particle pathlength increases with $t / \sin\theta$ within the same fibre thickness t . Again, this improves considerably the hit density per mm thickness at the far bundle end.

Table 4 shows the hit densities of different monofibres measured with our equipment. An outstanding result was obtained for the 1mm diameter fibre 99-02 from Bicron*, which produced 1.45 photoelectrons at 2 m distance from the photocathode. The other monofibres stay within the values, we have finally also achieved for our 60 μm diameter fibres (table 2). It is particularly interesting to compare our results measured with an Optectron** fibre, which was a sample from the UA2-tracker at the Sp $\bar{p}$ S collider in CERN. The same type of fibre has been also measured in a previous beam exposure at CERN [5] and a comparison with the hit densities evaluated from that run shows an excess of hits by a factor 1.6 in favour of ref.[5]. Some 15% can be explained by the 5 GeV pions used, which show already some relativistic rise in their energy loss. But about 45% of excess in hit densities remain still unexplained.

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ACKNOWLEDGEMENTS

We wish to thank Prof. A. Zichichi for his continuous interest and generous support of our work. We also acknowledge substantial support from Y. Okabayashi, Kuraray Co. Ltd, Tokyo.

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FIGURE CAPTIONS

Fig. 1 Arrangement to measure light attenuations

- a) longitudinal cross-section
- b) transverse cross-section

Fig. 2 a) Arrangement of β -source (1), fibre bundle (5) and coincidence counters with (7) meaning scintillator, (6) light guides, (9) PM R1635, (8) inactive plastic filter. (2) are collimator slits in plexiglas, (3) the common support structure for source and coincidence units, and (4) the bench guiding it and housing the fibre in its groove.

b) Electronic bloc diagramme of the coincidence signals gating the quantacon exit pulses.

Fig. 3 Light attenuation for fibres of different characteristics. The straight lines indicate χ^2 -fits to obtain the attenuation lengths indicated in table 2 .

- a) different claddings : G) fluorinated, A) non fluorinated PMMA
- b) different dye concentrations : L) 0.5% wt and G) 0.7% wt
- c) production improvement

Fig. 4 Distribution of photoelectron peaks for different average numbers of photoelectrons. Note the different scales.

Table 1 : PM-anode current to photoelectron (hit density) ratios for 0.7%wt PMP420 (bundle H) at 14 source positions. The average value of 159 ± 6 was applied to normalize the attenuation measurements to the number of photoelectrons per mm particle path in the fibre bundle.

Position	Number of	Anode current	Ratio
[mm]	photoelectrons[p.e]	[nA]	nA/p.e
0	5.78	962	166
50	5.08	780	153
100	4.40	668	152
200	3.35	519	155
300	2.75	430	156
400	2.40	367	153
500	2.04	315	154
800	1.30	219	168
1000	1.03	168	163
1200	0.81	137	169
1400	0.63	105	167
1600	0.56	87	155
1800	0.48	76	158
2000	0.42	68	162

Table 2: Comparison of hit densities (photoelectrons·mm⁻¹) and attenuation lengths for different bundles with 60 µm individual fibres. Each quoted value represents the average of five measurements on five different bundles. All bundles were produced by Kuraray.

pos. [mm]	A	C	G	H	I	I *	L	L *	L **
0	3.50	6.02	7.05	5.78	5.94	6.05	6.85	6.97	6.97
50	3.18	5.00	5.70	5.08	5.20	5.51	5.62	5.72	5.72
100	2.75	4.25	4.90	4.40	4.56	4.88	5.00	5.10	5.15
200	2.20	3.12	3.75	3.35	3.68	3.94	4.02	4.14	4.22
300	1.75	2.40	3.08	2.75	3.15	3.39	3.48	3.65	3.80
400	1.44	2.09	2.60	2.40	2.81	3.03	3.19	3.35	3.62
500	1.20	1.70	2.01	2.04	2.48	2.68	2.71	2.87	3.36
800	0.63	0.90	1.35	1.30	1.76	1.97	1.83	1.98	2.53
1000	0.51	0.65	1.02	1.03	1.44	1.68	1.50	1.71	2.41
1200	0.38	0.51	0.80	0.81	1.20	1.50	1.22	1.48	2.31
1400	0.30	0.37	0.61	0.63	1.05	1.38	1.05	1.38	2.37
1600	0.21	0.30	0.54	0.56	0.84	1.18	0.84	1.18	2.23
1800	0.17	0.24	0.46	0.48	0.75	1.17	0.75	1.13	2.33
2000	0.13	0.18	0.40	0.42	0.65	1.14	0.65	1.10	2.46
att length	634	629	742	802	980	1178	913	1112	2172

A) PMP420,0.7%wt,cladding thickness:1.7 µm

C) PMP420,0.7%wt,fluor.,cladding thickness:3.4 µm

G) PMP420,0.7%wt,fluor.,cladding thickness:1.7 µm

H) PMP420,0.7%wt,fluor.,cladding thickness:3.4 µm

I) PMP420,0.3%wt,fluor.,cladding thickness:1.7 µm

I *) I aluminised at opposite end face

L) PMP420,0.5%wt,fluor.,cladding thickness:1.7 µm

L *) L aluminised (mirrored)

L **) Taking into account the particle paths p at different polar angles θ in a fibre bundle of thickness t placed in a tracker shell at 1 m distance from the collider axis : $p = t / \sin\theta$

Table 3: Ratio of hit densities for variations in cladding material (G/A) cladding thickness (L/H), dye-concentration (L/G), with/without mirrored endface of the bundle (L*/L), without/with light guide (*) and taking into account the particle paths at different polar angles, in a fibre bundle placed in a tracker shell at 1 m distance from the collider axis (L**/L*).

pos. [mm]	G/A	L/H	L/G	L*/L	*	L**/L*
0	2.01	1.18	0.97	1.02	1.95	1.00
50	1.79	1.11	0.98	1.06	1.60	1.00
100	1.78	1.14	1.02	1.07	1.40	1.01
200	1.70	1.20	1.07	1.07	1.25	1.02
300	1.76	1.26	1.13	1.08	1.20	1.04
400	1.81	1.33	1.23	1.08	1.15	1.08
500	1.67	1.33	1.35	1.08	1.13	1.17
800	2.14	1.41	1.36	1.12	1.10	1.28
1000	2.00	1.46	1.47	1.18	1.10	1.41
1200	2.10	1.51	1.52	1.25	1.10	1.56
1400	2.03	1.67	1.72	1.31	1.10	1.72
1600	2.57	1.50	1.56	1.40	1.10	1.89
1800	2.71	1.56	1.63	1.56	1.10	2.06
2000	3.08	1.55	1.63	1.75	1.10	2.24

Table 4 : Comparison of Hit densities per mm for different monofibres measured with our equipment.

pos. [mm]	M	N	O	P
0	6.88	4.78	3.27	3.55
50	6.07*	4.51	3.05	3.18
100	5.24	4.16	2.78	2.69
200	3.97	3.82	2.31	2.34
300	3.44	3.58	2.02	2.09
400	3.03	3.31	1.78	1.88
500	2.86	3.07	1.63	1.70
800	2.25*	2.59	1.29	1.41
1000	1.88	2.34	1.07	1.23
1200	1.70	2.10	0.94	1.12
1400	1.43	1.94	0.77	0.98
1600	1.27	1.77	0.67	0.86
1800	1.15	1.60	0.58	0.78
2000	1.00	1.45	0.54	0.69
att length	1181	1767	1149	1333

M) Optectron aluminised monofibre, ϕ 1 mm

N) Bicron 99-02, ϕ 1 mm

O) Bicron BCF10, 2×2 mm²

P) Kuraray SCSF81, ϕ 1 mm

*10 and 3.3 photoelectrons resp. were measured in [5]

Fig.1

a)

b)

Fig.2

number of photoelectrons per mm

fig. 3

Fig.4