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Light collection study in scintillation strips with wave length shifting light guide

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The light collection process in a long polystyrene scintillator strip to a longitudinally placed wavelength shifting light guide is considered. By means of Monte Carlo method, the dependence of light yield on strip parameters: dimensions, bulk attenuation length (*BAL*), diffuse reflection coefficient have been calculated. The optimum number of light guides and their dimensions are estimated. The results are compared to theoretical estimations within the integrating sphere model. It is shown that in spite of the small strip transverse dimensions, the light yield depends substantially on the material transparency and attains its maximum value at BAL of about 1 m.

Рассмотрен процесс светособирания в длинном полистирольном сцинтилляционном стрипе на продольно размещенный спектросмещающий световод. Методом Монте Карло рассчитана зависимость светового выхода от параметров стрипа: его размеров, объемной длины ослабления света (*BAL*), коэффициента диффузного отражения. Получены оценки оптимального числа световодов и их размеров. Результаты сравниваются с теоретическими оценками в модели светомерного шара. Показано, что несмотря на малые поперечные размеры стрипа, световой выход существенно зависит от прозрачности материала и достигает максимального значения при *BAL* ~ 1 м.

In modern high energy physics experiments, in scintillator tracking detectors, cell hadron and electromagnetic calorimeters, plastic scintillators are often used where the light collection is provided by a wavelength shifting optical fiber (WLS) [1, 2]. In such detectors, light collection has some peculiarities [3, 4] even at a simplest geometry (cylinder, parallelepiped). This is especially pronounced when the light path length is small as compared to the bulk attenuation length (*BAL*) of the intrinsic luminescence light.

As an example, let us look at detecting device of the OPERA set [5]. Its main element is a long strip of scintillating polystyrene of 10×26×7000 mm^3 size, with a diffusely reflecting coating. The light collection is provided by a WLS fiber placed in a groove cut along the strip long side. Despite of the large strip length, the main transfer of the light energy occurs in the plane perpendicular to the fiber, which is more characteristic for short detectors. In this case, the most efficient light collection takes place with diffusely reflective surfaces, material transparency not playing such a great role. On this basis, it has been supposed [1] that scintillators with satisfactory operational characteristics could be made of technical polystyrene with relatively small light attenuation length (25 to 30 cm).

Since the information presented in literature is rather contradictory, it seems useful to carry out a complex theoretical study of light collection in detectors of such a type. In particular, it is necessary to answer the question whether is it necessary to increase scintillator transparency, and if yes, than to what extent.

To answer this question, let us try to apply the integrating sphere formula [3] to describe such a strip. Taking the light attenuation into account and neglecting the direct illuminating, this formula can be written as:

$$\tau = \frac{Q \cdot R \cdot \exp(-l/BAL)}{1 - (1 - Q) \cdot R\exp(-l/BAL)}, \qquad (1)$$
$$Q = \Sigma_{out}/\Sigma,$$

where Q is the output port relative area (Σ_{out} and Σ being areas of the output port (light guide) surfaces and scintillator total reflecting surface, respectively); R, the strip surface reflectance; l, the photon mean path before registration; BAL, the bulk attenuation length. It follows from consideration of (1) that light collection tends to increase with BAL, R and Q (Fig. 1).

It is known that, under some restrictions, equation (1) can be applied to scintillators of any arbitrary shape if their all three dimensions are of the same order of magnitude [3]. Its applicability to long strips is not evident. Therefore, theoretical estimations have been compared with direct Monte Carlo calculations. Having set the above strip parameters, with $R = 0.97$ and correction on difference in strip and fiber refracting indexes, we obtain from (1) the dependence presented by curve 1 (solid line) in Fig. 2. The Monte Carlo results are presented by curve 2. The curves agreement evidences the possibility to use the integrated sphere formula to describe light collection in the strip-fiber system. Equation (1) also shows that at R close to unity in the range of high transparency, the light collection value depends heavily on the diffuse reflection coefficient R. Indeed, with $BAL \to \infty$, $\tau \sim QR/(1 - R)$ and:

$$\frac{\tau_1}{\tau_2} \approx \frac{1 - R_2}{1 - R_1}. \qquad (2)$$

Thus, for example, the change from $R = 0.95$ to $R = 0.98$ corresponds to light collection increase by a factor of 2.5. A similar behavior is observed in low-absorbing diffuse light guides [3].

The Monte Carlo calculated light collection dependence on bulk transparency is shown in Fig. 3. The calculation has been made for the following initial conditions: 18000 photons/MIP; PMT cathode efficiency 12 %; WLS fiber Y11 of Kuraray Co., 1.1 mm diameter; the light conversion coefficient in WLS 0.95; the coefficient of converted light capture in WLS fiber 0.063; the WLS fiber transmission coefficient 0.4; the reflection on the strip walls is diffuse with cosine distribution like $\pi^{-1}\cos\theta$.

It is seen from the Figure that the light yield dependences on bulk transparency have a specific shape with saturation (plateau). The value of this plateau, that is, the maximum light yield value, is easy to obtain from (1) letting BAL approach infinity, that is, supposing the absence of bulk attenuation. As a result, we obtain:

$$\tau_\infty = \frac{Q \cdot R}{1 - (1 - Q) \cdot R} < 1, \qquad (3)$$

because even for the large BAL, light collection is restricted by surface losses. As the critical BAL value, which it is inexpedient to exceed, one can take the one at which light collection equals to a specified fraction, D, of its possible maximum, that is,

$$\tau(BAL_{crit})/\tau_\infty \le D. \qquad (4)$$

It follows from (1)–(4) that

$$BAL_{crit} = \frac{l}{\ln\left[\dfrac{D}{1 - R(1 - Q - D + DQ)}\right]}. \qquad (5)$$

Critical values of the bulk transparency for different diffuse reflection coefficients calculated according to (5) are presented in Table.

The enhance of light collection seems to be due to increase of distance $<l>$ passed by a photon before its absorption and, therefore, by increase of its capture probability by the light guide. Monte Carlo calculated results for $<l>$ are presented in Fig. 4. The number of reflections which photon under-

Table. Critical values of bulk transparency

R	BAL_{crit}, cm		
	$D = 0.9$	$D = 0.8$	$D = 0.75$
1	271.5	121.0	90.9
0.98	194.2	86.7	65.2
0.97	170.0	75.9	57.1
0.95	136.1	60.9	45.8
0.85	68.4	30.8	23.2
0.83	62.3	28.0	21.4
0.8	54.9	24.8	18.7
0.6	30.8	14.0	10.7
0.5	25.0	11.6	8.9

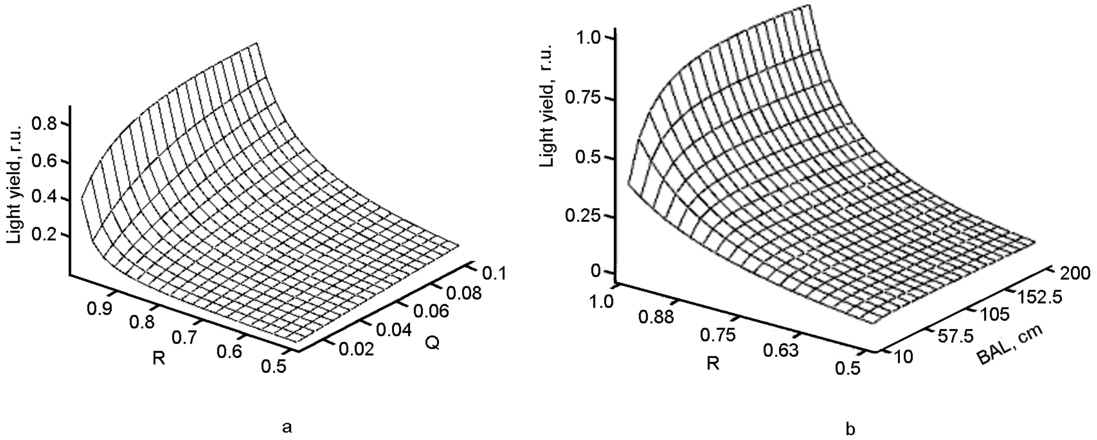

Fig. 1. Light yield theoretical dependence on diffusion reflection coefficient R, relative area of output port Q and bulk transparency BAL.

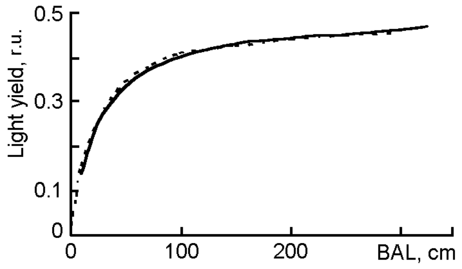

Fig. 2. Dependence of light yield dimensions on bulk attenuation length for a $10\times26\times500$ mm^3 strip. Solid line, calculations by integration sphere formula (*1*); dashed line, Monte Carlo calculations.

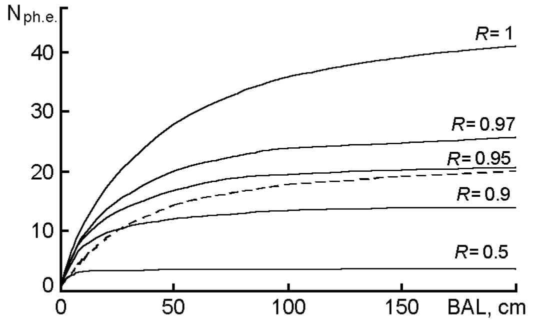

Fig. 3. Monte Carlo calculations of light yield dependence on bulk attenuation length for different diffuse reflection coefficients R for a $10\times26\times500$ mm^3 strip. Dashed line corresponds to ideal mirror reflecting (Fresnel) surface.

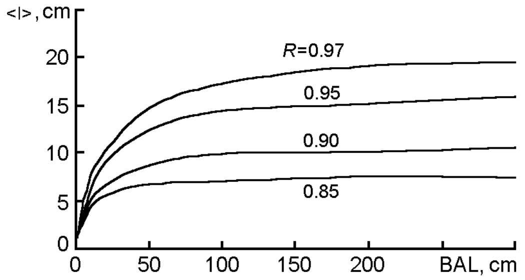

Fig. 4. The dependence of photon mean path prior to registration on bulk attenuation length for different R.

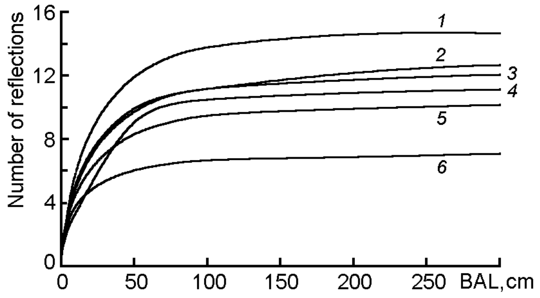

Fig. 5. Dependence of reflections number on bulk attenuation length and strip surface quality. $R = 1$ (*1*), 0.97 (*2*), 0.95 (*5*), 0.90 (*6*). Curves 3 and 4 correspond to mirror reflection from surface obtained by polymerization between glasses and from polished surface, respectively.

goes before detection is presented in Fig. 5. It is seen in the Figure that the number of reflections is increased with BAL and R and also tends to a maximum value. It is to note that mirror reflection gives nearly the same result as the diffusion one at high reflection coefficient $R = 0.97$.

It follows from Fig. 4 that at high surface reflectance, the mean path exceeds significantly the strip characteristic dimensions (1 and 2.6 cm). But comparison with

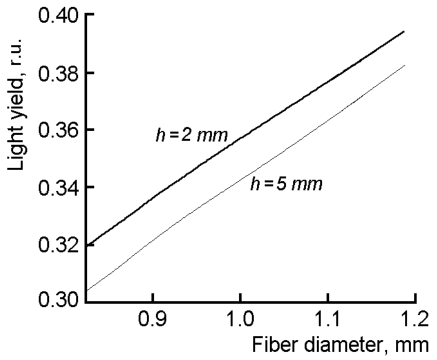

Fig. 6. The dependence of strip light yield on WLS fiber diameter at its different locations, *h*.

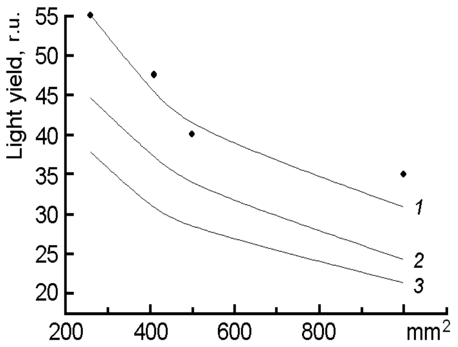

Fig. 7. Dependence of light yield of long strips on cross section area. Dots, experiment (R = 0.96). Curves, Monte Carlo calculations. R = 0.96 (*1*), 0.95 (*2*), 0.90 (*3*).

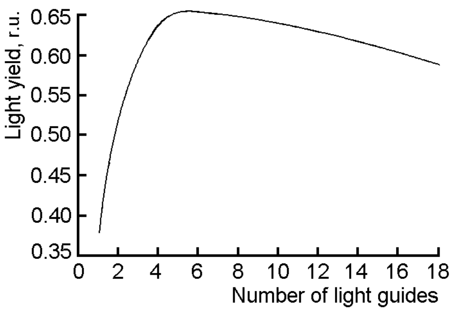

Fig. 8. Dependence of light yield for on the number of WLS fibers for 26×10×500 mm^3 strip.

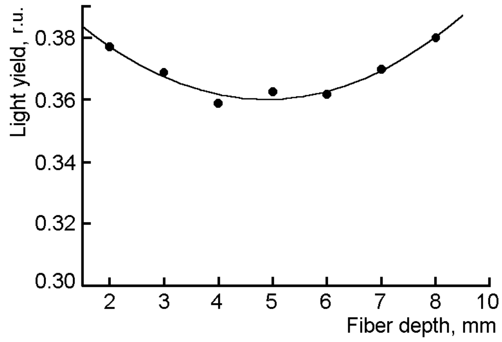

Fig. 9. Dependence of light yield on the WLS fiber depth for 26×10×500 mm^3 strip.

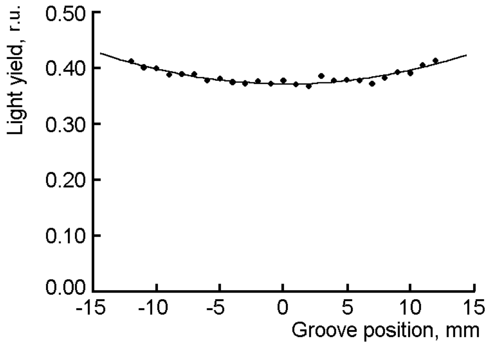

Fig. 10. Dependence of light yield on WLS fiber position (*depth* = 2 mm from surface) for 26×10×500 mm^3 strip.

Fig. 5 shows that the mean path between reflections changes only slowly, approximately from 0.8 to 1.5 cm. This is essentially the same as the mean path calculated by standard expression:

$$l = 4V/\Sigma, \qquad (6)$$

where V is the strip volume. It follows from (6) that l = 1.49 cm, that agrees with Fig. 4.

It follows from (1) and Fig. 1 that the light collection increases with Q, that is, with the output port area. To check to what extent this conclusion is valid in the case of a strip, the Monte Carlo light yield calculations have been made with light guides of different diameters. The calculation results are presented in Fig. 6. One can see in the Figure that dependence on diameter is essentially linear. The light guide diameter being the same, the output port relative area is changed with strip dimensions. In Fig. 7, the calculated light collection values are presented in strips of different dimensions. It is seen in the Figure that the strip cross section increase (which is equivalent to output port area reduction) results in the light yield decrease, as is predicted by integrated sphere formula. Let us note a good agreement between experimental and calculated results obtained for OPERA strip with R = 0.96.

The output port area and thus the light yield can be increased by means of adding additional light guides-collectors. In Fig. 8, the light yield dependence of OPERA strip on the number of light guides is presented. It is supposed that light guides are uniformly distributed over the strip width at 2 mm depth. It is seen in the Figure that the curve has a maximum at $n \approx 5$. Further increase of light guide number results in their mutual shielding and therefore is not advisable. However, it is to note that the shielding effect could be reduced to some extent by appropriate arrangement of light guides (Shashlyk) [2]. The light yield dependence on the output port position is not included in the integrated sphere formula. This dependence has been studied by means of Monte Carlo calculations for different positions of light guide. The calculation results are presented in Figs. 9 and 10. It is seen in the Figures that the light guide position does not affect essentially the light yield value.

Thus, it is found in the study that the maximum light yield in a strip - WLS fiber system is attained with diffuse type of surface reflection. The light yield is influenced by the strip material transparency (up to 1 m), its dimensions, the diffuse reflection coefficient, WLS diameter, and number of these fibers. The mean number of reflections which photon undergoes before capturing by WLS depends on transparency and attains about 11 when $BAL > 100$ cm and $R = 0.97$. An optimum number of WLS-fibers exists (about 5 for the systems considered), which provides the maximum light yield. The dynamics of light collection in long strip - WLS fiber system can be satisfactory described by integrated sphere formula.

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Дослідження світлозбирання у сцинтиляційних стрипах зі спектрозміщуючим світловодом

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Розглянуто процес світлозбирання у довгому полістирольному сцинтиляційному стрипі на поздовжньо розташований спектрозміщуючий світловод. Методом Монте Карло обчислено залежність світлового виходу від параметрів стрипу: його розмірів, об'ємної довжини послаблення світла (*BAL*), коефіцієнта дифузного відбиття. Отримано оцінки оптимальної кількості світловодів та їхніх розмірів. Результати порівнюються з теоретичними оцінками у моделі світломірної кулі. Показано, що незважаючи на малі поперечні розміри стрипу, світловий вихід суттєво залежить від прозорості матеріалу і досягає максимального значення при $BAL \sim 1$ м.