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Time response simulation of a “shashlyk”-type calorimeter as applied to ECAL MPD / NICA

Time response simulation of a "shashlyk"-type calorimeter as applied to ECAL MPD / NICA

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Abstract. In the frame of the GEANT4 toolkit, a numerical simulation of light collection from the tower of the EMC MPD / NICA detector was carried out. The influence of reflective coatings of the scintillator surface, the propagation of light in fibers, taking into account their multilayer structure and light reflection from their ends, as well as the effects of joining a fiber bundle with an MPPC photodetector are considered. The temporal forms of the light signal at the MPPC input were obtained taking into account only geometric effects.

1. Introduction

At present, JINR, within the framework of the international project NICA [1], is developing a multipurpose detector (MPD) for a heavy ion collider operating in the $\sqrt{S_{NN}}$ energy range of 5-11 GeV. The aim of the project is to study hot and dense nuclear matter, and the process of transition of hadronic matter into quark-gluon plasma. One of the main probes for the formation of a quark-gluon plasma is electron-positron pairs and direct photons, which will be registered by a cylindrical electromagnetic calorimeter (ECAL) [2,3]. This sampling calorimeter occupies a cylindrical volume in the MPD detector with an inner (outer) diameter of 3.45 (4.6) m and a length of 6 m. ECAL contains 38400 shashlyk towers [4] with a total weight of 60 tons. The towers are composed of 210 alternating polystyrene scintillator plates with a thickness of 1.5 mm and 0.3 mm of lead and have the shape of a truncated pyramid with a base of 40×40 mm^2. Light collection on a silicon photodetector (MPPC Hamamatsu S13360-6025PE) with an area of 6x6 mm^2 is carried out using 16 WLS Kuraray Y-11 (200) wavelength-shifting fibers with 1.2 mm diameter which passing through holes in the plates.

An important stage in the creation of the EMC is its modeling and, first of all, its geometry and response to various particles. This work is dedicated to simulation of time response of ECAL. In total, this task consists of obtaining the distribution of energy deposition in the scintillators of the calorimeter, converting it into photons of visible blue light, collecting these photons by wavelength shifting fibers WLS, converting them into photons of green light and capturing them in fibers, that transport them to a photodetector, to register by a photodetector, shaping its output signal and register by digital electronics. Only part of this problem will be covered below. It includes only light collection from the calorimeter scintillators to the photodetector, taking into account only geometric factors, i.e. without taking into account the decay time of the scintillator and of the wavelength shifting time of the fibers.

2. Simulation model

Numerical modeling was done in the Geant4 environment [5]. We used G4OpticalPhycis package [6] which contains the main optical processes such as scintillation, Cherenkov radiation, wavelength shifting, transition radiation and physics of different optical surfaces. The model of the tower of the ECAL is shown in Figure 1a and consists of a polystyrene based scintillator with thickness of 1.5 mm and transverse dimensions of 40 × 40 mm. The absorption length of light in the scintillator is 210 cm, the refractive index is 1.58, and the density is 1.03 g/cm^3. Sixteen Kuraray Y-11 (200) WLS fibers pass through the scintillator, which convert the blue light of the scintillator into green light and transmit it to the photodetector installed at one of the ends of the fibers at a distance of 25 cm from the scintillator. The fiber model is shown in Figure 1b and will be described later. The Hamamatsu MPPC photodetector is simulated as an infinitely thin sensitive volume with transverse dimensions of 6 × 6 mm^2, divided into 240 × 240 Geiger cells. The distance between the detector and the end of the fibers was 0.3 mm. The source of initial photons is a flash with a wavelength of 440 nm, uniformly distributed over the entire volume of the scintillator. In this case, if this photon enters the fiber, it is reemitted at a wavelength of 470 nm. These values correspond to the maximum intensity wavelength in the emission of a given scintillator and the maximum intensity wavelength of wavelength shifting in the fibers respectively.

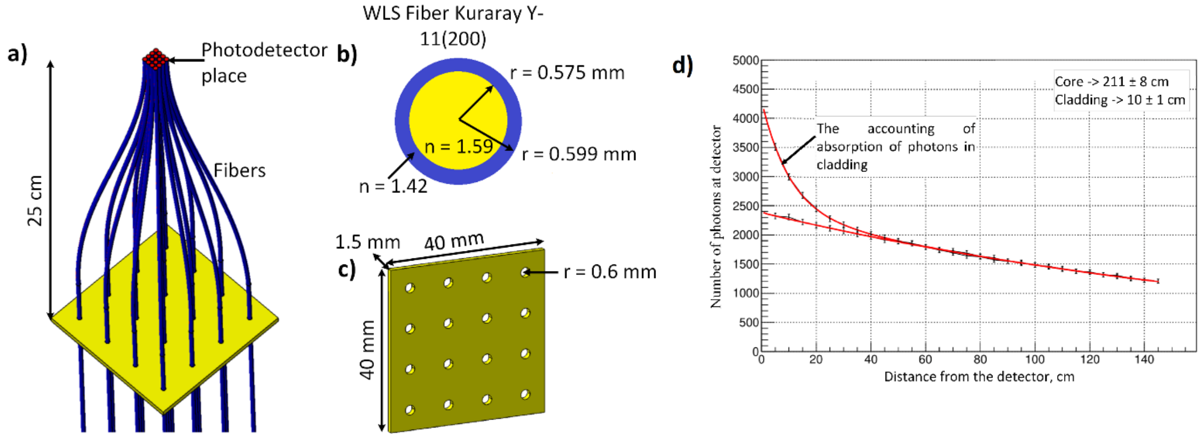

Figure 1. Tower model (a), model of the fiber geometry (b), model of the scintillator (c), number of photons at detector as function of distance between the scintillator and the detector (d).

The used fibers Kuraray Y-11 (200) contain a central fiber core made of high-purity polystyrene with a refractive index of 1.59, covered with two claddings with a refractive index of 1.49 and 1.42. Despite of the propagation of light in this fiber is simulated accurately, for simplicity we will assume that the fiber contains only a core and one cladding. In work [5], the lengths of light absorption in the core and the cladding were measured, that turned out to be about 217 cm and 10 cm, respectively. This value is noticeably less than more than 3.5 meters declared by the company. This is due to the fact that the company guarantees such a large value of the absorption length only at distances greater than one meter from the light source, while in [5] the testing of fibers was carried out in the region of significantly smaller distances, which are essential for our case. By varying the roughness of the outer surface of cladding and the absorption length of the core, it was possible to achieve the absorption length parameters in the model close to these experimental results. In this case, during the selection of these parameters, the fiber length was chosen equal to 1.5 m, and the far end was painted over with paint, which represents a surface with a zero reflection coefficient. A series of model experiments was carried out in which the scintillator was located at different distances from the detector on which the photons were counted. The results are shown in Figure 1d. The lower curve corresponds to the case realized in the calorimeter, when the fibers are tightly combined and fixed with epoxy glue immediately in front of the photodetector. The glue here plays the role of an absorber of light propagating along the cladding, which significantly increases the uniformity of light collection along the length of the fiber.

The scintillator model was "painted" with TiO_2 reflective paint, simulated as surfaces with a certain reflectivity. They imitate the real paint of the sides surfaces of the scintillator, as well as the painting of lead plates, which are pressed from both sides to the 40×40 mm^2 surfaces of the scintillator. In such case, both the possibility of creating an optical contact with the scintillator and the location of these planes surfaces at an infinitely small distance from the scintillator surface are realized, i.e. without optical contact.

3. Results of the simulation

Further, in each case, unless otherwise indicated explicitly, the number of initial photons in the scintillator was 10^7 the source of initial photons is distributed uniformly inside the volume of the scintillator. First of all, the reflection coefficient of the paint used was determined. For this task, the results of an experiment carried out by the JINR group were used. Different types of reflective paints were applied only to the 1.5×40 mm^2 sides of the scintillator, after which the intensity of the light signal on the fibers was measured when the scintillator was irradiated with a radioactive beta source. Before this, the intensity of the light signal on the fibers was measured in the case of a clear scintillator. The best results were obtained with TiO_2-based paint, which provided a signal increase by factor of 1.6 compared to the clear scintillator. In a similar way, during the simulation, the paint was "applied" only to the side edges of the scintillator with full optical contact. The optical contact means that each photon in the scintillator at first interacted with the surface of the paint without interaction with the surface of the scintillator itself. The reflection coefficient of the paint was varied and the ratio to the light yield from a clear scintillator was determined. The results are shown in Figure 2, from which the reflective coefficient of paint was determined, which provides an increase in the light yield by 1.6 times. This coefficient turned out to be 0.8 and was used in further simulation.

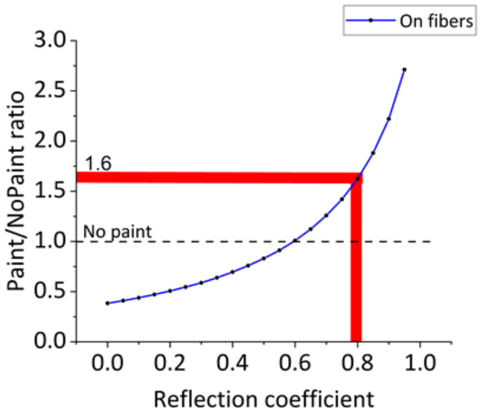

Figure 2. Paint/NoPaint ratio as a function of reflection coefficient of paint.

Also, several cases were considered to determine the effect of coating with reflective paint on the intensity of the light signal (Figure 3). In the first case, the clear scintillator was simulated and the relative number of hits into all 16 fibers (1) was measured to be 12%.

$$\mathrm{R} = \frac{\Sigma N(registed\ photons)}{\Sigma N(initial\ photons)} 100\% \tag{1}$$

In the second case, only the sides of the scintillator were painted, which resulted in an overall increase in the signal (Figure 3. upper, blue curve). In the third case, the entire scintillator was painted, and there was full optical contact between the scintillator surface and the paint. In this case, the light output drops significantly for all the reflectivity of the paint (Figure 3. lower, red curve). In the fourth

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case, the scintillator was also completely "painted", but without an optical contact between the scintillator surface and the paint on 40x40 mm^2 sides. Thus, in this case, each photon first interacted with the surface of the scintillator, and only then, if it did not have the total internal reflection, with the surface of the reflective paint. In this case, an insignificant, at the level of several fractions of a percent, increase in the relative output of the light signal is observed in comparison with the case when only the sides are painted. This makes it possible to ignore this case in the future. Figure 3b shows a histogram of the relative light output depending on the paint coating option with reflection coefficient of 0.8. This histogram shows that painting the sides of the scintillator can increase the light yield up to 19%. In the case of the formation of the optical contact between the scintillator and the painted lead plates, it will lead to a decrease in the light yield. This effect can introduce significant uncertainty into the calculations and requires experimental verification.

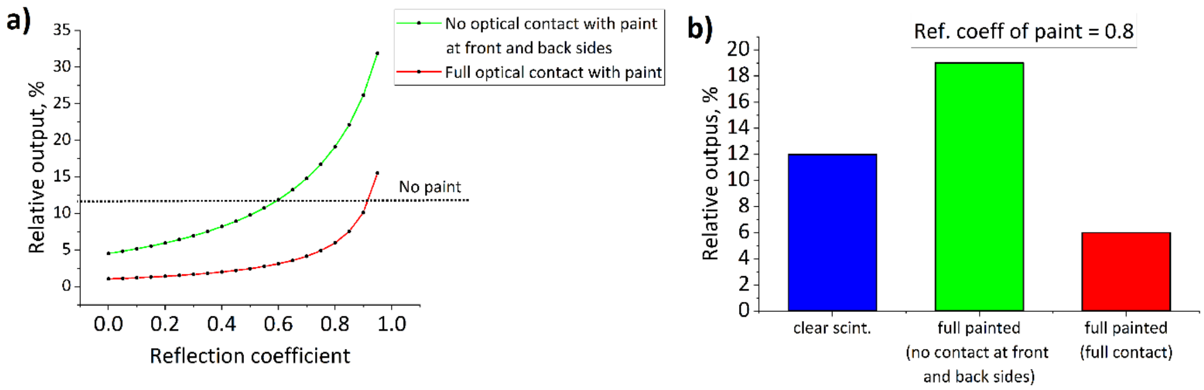

Figure 3. Relative light output as function of reflection coefficient of paint at 3 different cases (a) and histogram of relative light output as function of 3 different cases(b).

Also, the dependences of the relative output of the light signal were obtained depending on the time collection of light on the fibers at different reflective coefficients of the paint for the case of optical contact (Figure 4a), and in its lack (Figure 4b). It can be seen that in the lack of the optical contact, the relative light yield is approximately 3 times higher, but the collection time is also approximately 3 times longer. The fitting was carried out using function (2), where the collected light yield reaches 97% during the time τ = 3t.

$$y = y_0 + A \times e^{-\frac{t}{\tau}} \tag{2}$$

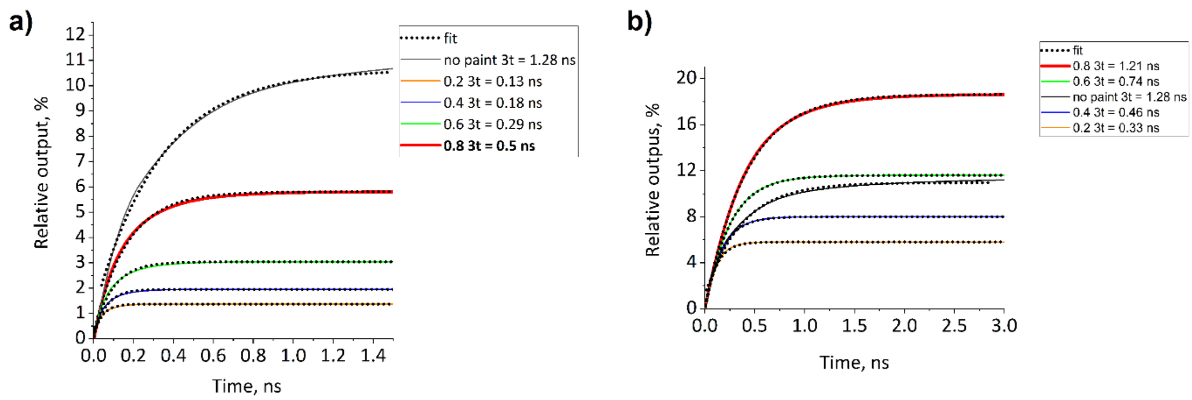

Figure 4. Relative light output as a function of time collection for different reflection coefficients in optical contact case (a) and in no optical contact case (b).

The same data were obtained for light collection on a photodetector located at a distance of 25 cm from the scintillator, which are shown in Figure 5. In this case, the reflective coefficient of the paint was 0.8, and the far end of the fiber was "painted" with a reflective paint with a reflective coefficient of 0.5. In this case, the increase in the relative light yield was three times greater in the lack of optical contact.

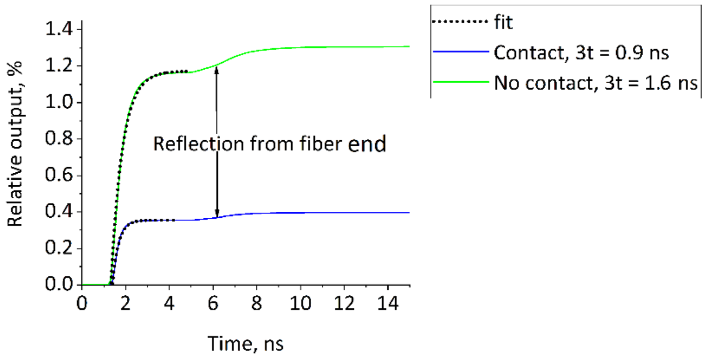

Figure 5. Relative light output as function of time collection in optical contact case and no optical contact case.

Table 1 shows the summary results for the relative light output and collection time for fibers and for the photodetector. The highest light yield per photodetector, 1.3%, is achieved when only the sides of the scintillator are painted and there is no optical contact between the painted plates of the lead and the scintillator surface. The light collection time turns out to be not negligible compared to the decay time of a polystyrene based scintillator, which is about 2.5 ns.

Table 1. Results for the relative light output and collection time for fibers and for the photodetector

	At fibers		At detector	
	Collection time	Relative output	Collection time	Relative output
Optical contact	0.5 ns	6 %	0.9 ns	0.4 %
No optical contact	1.2 ns	19 %	1.6 ns	1.3 %

4. Simulation of signal at the detector

Also, images of the light output signals on the detector were obtained for the case when the light flash is set at the center of the scintillator (Figure 6a), and when the light flash is uniformly distributed in the volume (Figure 6b).

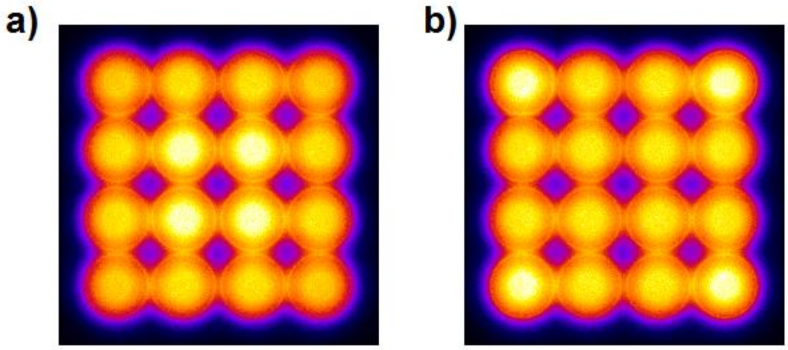

Figure 6. Light signal at the detector. Source at the center of the scintillator (a) and source is distributed uniformly in the volume of the scintillator (b).

At the stage of the simulation 2×10^9 initial photons were used for both cases. In the case of the point source, the intensity on the 4 central fibers is on average 15% higher than on the rest of, and in the case of a volume source, the intensity is 15% higher on the 4 corner fibers. On average, it turns out that for 2×10^9 initial photons, about 10^3 photons hit into one detector cell. In case of rough estimation of realistic experiment, when 3 GeV electron produce up to 10^7 photons in scintillators of 9 towers, since the Moliere radius for ECAL / MPD is 6 cm. Taking into account this factor and the efficiency of the MPPC photocathode equal to 25% the probability to trigger MPPC cell is 13%. This means that the probability to have unregistered photons is high. This can result in nonlinearity of energy response of the calorimeter at high energies. Of cause, accurate calculations can be performed with the simultaneous simulation of light collection and electromagnetic shower development.

5. Conclusion
The program that simulates light collection in shashlyk-type calorimeters was developed by means of Geant4 toolkit. Quantitative results were obtained for the electromagnetic calorimeter of the MPD / NICA detector. The light collection efficiency is at the level of 1%.

The importance of ensuring the lack of optical contact between the scintillator plates and painted lead plates, as well as the possibility of nonlinearity of the energy response when registering light with multi-cell Geiger detectors, are pointed out.

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References
[1] Kekelidze V D 2018 *Phys.Part.Nucl.* **49** 457
[2] URL http://mpd.jinr.ru/doc/mpd-tdr/
[3] Kulikov V V *et al.* 2020 *JINST* **15** 09 C09017
[4] Atoian G S *et al.* 2008 *Nucl.Instrum.Meth.* A **584** 291
[5] Geant4 Collaboration 2019 *Book for application developers* URL http://geant4-userdoc.web.cern.ch/geant4-userdoc/UsersGuides/ForApplicationDeveloper/BackupVersions/V10.5-2.0/fo/BookForApplicationDevelopers.pdf
[6] Geant4 Collaboration 2019 *Guide for Physics Lists* URL http://geant4-userdoc.web.cern.ch/geant4-userdoc/UsersGuides/PhysicsListGuide/fo/PhysicsListGuide.pdf
[7] David M *et al.* 1994 *Comparative Measurements of WLS Fibers* Tech. Rep. ATL-TILECAL 94-034