

## 3D printing of heterogeneous detector elements for registering high-energy particles

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A new method for creating elements of a heterogeneous detector for sampling-calorimeters of the “Shashlik” type using FDM 3D-printing technology is proposed. An experimental sample was manufactured using the proposed method. The scintillation layers were printed with a filament made of a material consisting of polystyrene with the addition of 2 wt% paraterphenyl (p-TP), 0.05 wt% 2,2-p-phenylene-bis(5-phenyloxazole) (POPOP) and 0.2 wt% dioctyl phthalate. The absorption layers were printed with a filament made of a eutectic alloy (52% Bi, 32% Pb, 16% Sn). The light reflection function is implemented without additional reflective layers due to specular reflection from the metallic surfaces of the absorber. It has been experimentally shown that the proposed method ensures the formation of scintillator-absorber blocks in a single technological cycle. The amplitude spectrum of the response of the printed detector element was investigated. The proposed 3D-printing method may be useful in the development of sampling-detectors with improved energy resolution.

**Keywords:** 3D printing, sampling-detector, heterogeneous detector, “shashlik”, scintillator, absorber, light reflector, eutectic alloy, scintillation element, energy resolution.

**3D друк елементів гетерогенного детектору для реєстрації високоенергетичних часток.** *М.Л. Сибілев, О.В. Колесніков, В.О. Новгородцев, Т.Г. Сибілева*

Запропоновано новий спосіб створення елементів гетерогенного детектору для sampling-калориметрів типу «Шашлик» з використанням технології FDM 3D-друку. За запропонованим способом виготовлено дослідний зразок. Сцинтиляційні шари надруковано філаментом, виготовленим з матеріалу, який складається з полістиролу з додаванням 2% (за вагою) паратерфенілу (p-TP), 0,05% (за вагою) 2,2-р-фенілен-біс(5-фенілоксазолу) (POPOP) та 0,2% (за вагою) діоктилфталату. Абсорбційні шари надруковано філаментом, виготовленим з евтектичного сплаву (52% Bi, 32% Pb, 16% Sn). Функція відбивання світла реалізована без додаткових світловідбивних шарів за рахунок дзеркального відбиття від металевих поверхонь абсорберу. Експериментально показано, що запропонований спосіб забезпечує формування блоків сцинтилятор-абсорбер в єдиному технологічному циклі. Досліджено амплітудний спектр відгуку надрукованого елемента детектора. Запропонований метод 3D-друку може бути корисний при розробці гетерогенних (sampling) детекторів з покращеною енергетичною роздільною здатністю.

### 1. Introduction

Detectors of heterogeneous calorimeters of the “Shashlik” type (sampling-calorimeters), which are used in high-energy physics experiments [1, 2], have a layered structure and con-

sist of alternating layers of scintillator, light reflector, and absorber, strung on wavelength-shifting fibers for light collection (Fig. 1). Energy measurements using an electromagnetic calorimeter are based on the principle that the energy released in the detector material by

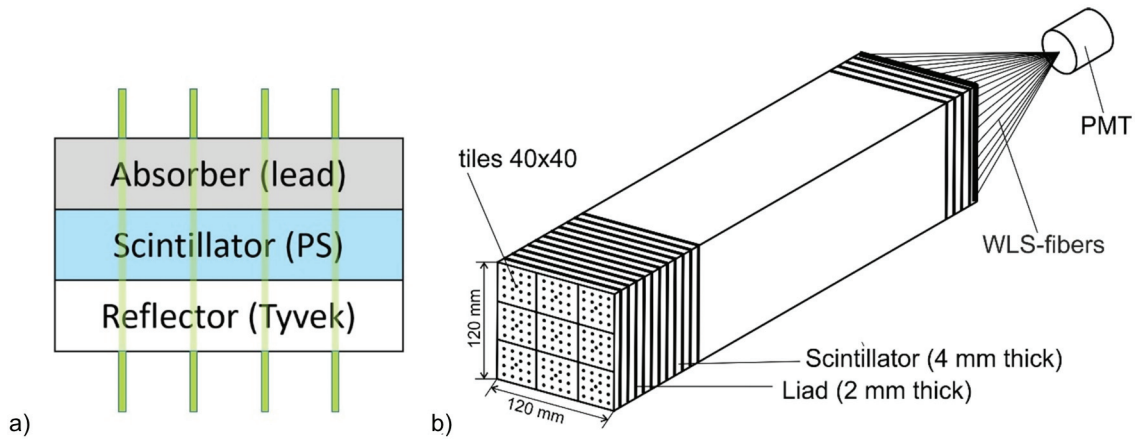


Figure 1. Schematic depiction of a “Shashlik” type detector: a) fragment of the detector; b) general configuration of the detector

charged particles in the shower, mainly through ionization and excitation, is proportional to the energy of the incident particle. The scintillation layers in sampling-detectors are almost always made of plastic scintillators (PlS). The absorber is a layer of material with high density ( $\rho$ ) and high effective atomic number ( $Z_{\text{eff}}$ ), in which the main part of the interactions of incident particles occurs. It serves to initiate and develop electromagnetic or hadronic showers, converting the energy of the primary particle into a cascade of secondary, lower-energy particles. Heavy absorbing materials are traditionally used to create absorbers for sampling-detectors. The most common absorber is lead [3, 4], as it has a very high density  $\rho$  (11.34 g/cm<sup>3</sup>), a large atomic number  $Z$  (82), and a short radiation length  $X_0$  (0.556 cm) [5].

### 1.1. Scintillation/absorber layer thickness parameters

Although sampling-calorimeters have been used for several decades, they continue to be improved. In particular, their energy resolution can be improved by reducing the sampling through the use of thinner absorber layers with a corresponding increase in the number of detecting scintillation layers [6, 7]. The most common thickness of the lead absorber layer is from 2 to 3 mm (Table 1).

In sampling-calorimeters, the absorber determines the depth, structure, and dynamics of the shower, while the active (scintillation) layers only provide registration of part of the released energy. The choice of absorber material and thickness determines the energy resolution of the detector.

The energy resolution ( $\frac{\sigma_E}{E}$ ) of a calorimeter directly depends on the thickness of the absorption layers ( $t$ ) [12]. The smaller the thickness  $t$ , the more times the active layers sample the shower data (i.e., the sampling frequency) and the greater the number of detected particles, and the better the energy resolution. Thus, in principle, the energy resolution of a sampling-calorimeter can be improved by reducing the thickness of the absorber layers.

At the same time, virtually all main characteristics of electromagnetic showers (e.g., their longitudinal and transverse sizes) depend on one parameter – the radiation length  $X_0$ , which depends on the material characteristics [12]. Therefore, other basic parameters of the absorber that affect the energy resolution are high density ( $\rho$ ) and short radiation length ( $X_0$ ), which depends on the large value of the atomic number  $Z$  (or  $Z_{\text{eff}}$  for compounds and mixtures) [13].

### 1.2. Requirement for light reflection in scintillator layers

One of the problems that limits the energy resolution of sampling-calorimeters of the “Shashlik” type and leads to nonlinearity of the response is the problem of light leakage and uncontrolled propagation of scintillation light between adjacent layers (crosstalk) [14]. A modern solution to this issue is the individual coating of each tile with reflective paint (which, given hundreds of layers of tiles in each detector, is a technologically difficult procedure), or the use of diffuse wrapping of each plate with reflective materials with a thickness of 100–200  $\mu\text{m}$ . For example in [14], Tyvek with a thickness of 150  $\mu\text{m}$  was used between lead plates and scintillators for diffuse light reflection. Overall, this

Table 1. Characteristics of scintillator and absorber layers in “Shashlik” type calorimeters.

| Experiment / Project                 | Tile area, mm <sup>2</sup> | Scintillator |                     | Absorber |                     | Source |
|--------------------------------------|----------------------------|--------------|---------------------|----------|---------------------|--------|
|                                      |                            | Material     | Layer thickness, mm | Material | Layer thickness, mm |        |
| RD36 Shashlik Calorimeter (CERN)     | 47 x 47                    | PIS          | 4                   | Pb       | 2                   | [8]    |
| Shashlik INFN SCENTT R&D project     | 30 x 30                    | PIS          | 3.3                 | Pb       | 3.3                 | [9]    |
| The LHCb electromagnetic calorimeter | 40 x 40                    | PIS          | 4                   | Pb       | 2                   | [10]   |
| ALICE EMCAL Shashlik                 | 60 x 60                    | PIS          | 1.77                | Pb       | 1.44                | [10]   |
| FASER calorimeter (on LHCb ECAL)     | -                          | PIS          | 4                   | Pb       | 2                   | [11]   |

solves the crosstalk problem, but it is a complex process to manufacture and results in the loss of several centimeters of active working space in the detector volume.

Instead, in this work, we propose not to use an additional reflective layer. Since the layered structure is created by fusing a metal layer directly onto the polymer without gaps between them, the mirror surface of the metal layer performs the light reflection function instead of diffuse reflector layers and prevents light leakage and uncontrolled propagation of scintillation light between adjacent layers (crosstalk). The light reflector has a low density and does not participate in shower absorption; it is also not a scintillation material, so it does not participate in the formation of the scintillation signal. Therefore, eliminating the use of separate reflective layers not only simplifies the detector design but also frees up the extra space they occupy to increase the number of active layers in each detector.

### 1.3. Statement of the problem

The main difficulties in the production of sampling-detectors of the “Shashlik” type are the high complexity of the technological process of assembling the finished module. The scintillation and absorption layers consist of small-sized tiles with holes (Table 1), which are manufactured separately at a third-party production facility. The layered structure includes hundreds of layers of such tiles, strung on dozens of WLS-fibers, which requires a labor-intensive assembly process and precise positioning of each layer. The mass of such detectors, which can reach tens of kilograms (for example, “Shashlik” type detectors used in LHCb ECAL experiments weigh 30 kg [15]), significantly complicates the produc-

tion process. Considering that the detectors are assembled manually, the labor intensity of the process increases significantly.

An alternative method of manufacturing detectors – 3D-printing – is promising for eliminating the complexities of multi-stage labor-intensive production of detectors with complex configurations. Our previous studies [16, 17] showed that plastic scintillation detectors with a reflective layer, manufactured by 3D-printing in a single technological cycle, are competitive with detectors manufactured using traditional technologies of bulk polymerization, injection molding, or extrusion. The methodology of 3D-printing the absorber with a metal alloy on a polymer base is presented in our work [18]. In the future, such elements, consisting of dozens of layers, can be used in the creation of large-sized sampling-detectors by large-scale assembly, which will reduce the time, cost, and labor intensity of calorimeter production processes.

This work aims to develop a technological method for optimizing the creation of elements of a multilayer sampling-detector, which reduces the complexity of production through the use of additive technologies. An additional result of the use of automated 3D printing may be the improvement of the energy resolution of the detector due to the precise printing of thinner absorber/scintillator layers. This work presents results on the development of a methodology for creating elements (blocks) of a sampling-detector for the “Shashlik” type calorimeters, consisting of scintillation and absorption layers, using FDM 3D-printing technology, as well as the results of experimental studies of the registration of cosmic muons by the obtained element.

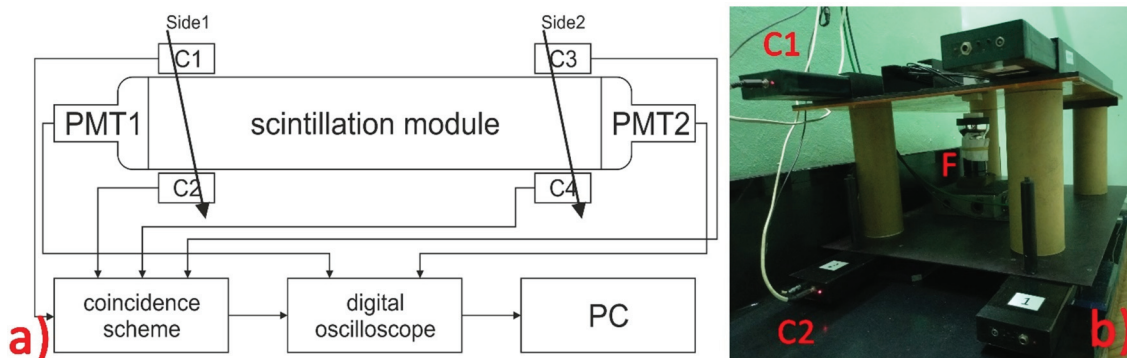


Figure 2. Assembling equipment for detecting cosmic muons: a) diagram of the equipment structure for studying “Shashlik” type detectors; C1, C2, C3, C4 are coincidence scheme counters; b) measurement of the printed element. F is the photomultiplier tube, on which the scintillation element under study is placed.

## 2. Experimental

### 2.1. Materials and methods

For additive manufacturing of parts, FDM (Fused Deposition Modeling) 3D-printing technology is used, which is based on the layer-by-layer application of molten material onto a working platform. A filament of low-melting material is fed into a heated extruder, melted, and extruded onto the platform. The extruder moves along a specified trajectory, creating a part of a given shape.

In classical sampling-detectors of the “Shashlik” type, layers of three different functional purposes (scintillator, light reflector, and absorber) are used. The printing of our prototypes of sampling-detector elements involves the sequential creation of a structure consisting of two layers: scintillator and absorber in one technological process.

The scintillation layer was printed with a standard diameter filament of  $1.75 \pm 0.05$  mm, manufactured by a previously developed method [16, 17] from a material based on polystyrene with the addition of 2 wt% paraterphenyl (pTP), 0.05 wt% 2,2-p-phenylene-bis(5-phenyloxazole) (POPOP), and 0.2 wt% dioctyl phthalate.

The absorption layer was printed with a standard diameter filament of  $1.75 \pm 0.05$  mm, which was manufactured by a previously developed method [18] from a eutectic alloy (52% Bi, 32% Pb, 16% Sn). The eutectic point ensures rapid crystallization of the melt and, as a result, uniform distribution of elements in the solid solution. This ensures uniformity of absorption properties.

The Noztek Pro HT extruder [19] was used for filament production. The CREATBOT F430 3D-printer [20] was used for printing samples.

### 2.2. 3D-Printing of a sampling-detector element

The samples were printed in the following order. The first layer was printed from scintillation polystyrene, measuring  $41 \times 41 \times 0.8$  mm. To prevent the melt of the metal alloy from leaking out of the printing zone, an additional edge 0.5 mm high was printed around the perimeter. Scintillation layer printing parameters: printing layer height per extruder pass ( $h_m$ ) = 0.1 mm, extruder nozzle temperature ( $T_0$ ) = 240 °C, printer bed temperature ( $T_{base}$ ) = 110 °C, extrusion multiplier (Flow) = 110%.

The absorbing layer was printed as the second layer. Printing parameters of the absorption layer: printing layer height of one extruder pass ( $h_m$ ) = 0.1 mm, extruder nozzle temperature ( $T_0$ ) = 120 °C, printer bed temperature ( $T_{base}$ ) = 110 °C, extrusion multiplier (Flow) = 125%. The metal was distributed in a manner similar to ordinary FDM printing, but the entire metal layer was in a molten state during printing.

### 2.3. Method of detecting cosmic muons

Verification of the possibility of detecting high-energy charged particles by the printed scintillation element was performed on equipment developed for testing industrial samples of “Shashlik” type detectors during production at the ISMA NASU base (Fig. 2).

The diagram of the equipment structure for studying “Shashlik” type detectors is shown in Fig. 2, a). The detector is placed directly between the coincidence scheme counters (C1–C4). The collection system registers signals from two pairs of counters (C1–C2 and C3–C4) and two photomultiplier tubes (PMT1, PMT2), which receive the signal from both sides of the “Shashlik” type detector. The program sepa-

rates and registers those pulses that coincide in time of occurrence in both counters and in the photomultipliers of the detector. The fact of simultaneous passage of a charged particle through two counter volumes and the detector without significant energy loss determines a high-energy particle (cosmic muons).

To verify the registration of muons by the element created using FDM 3D-printing, the measuring equipment was expanded, and a PMT (F) with the printed element was placed in the vertical plane in the space between two coincidence scheme counters (C1 and C2) (Fig. 2, b). The scintillation light from the 3D-printed element was collected via WLS fibers (see Fig. 4b), which extend onto the surface of the horizontal plane of the detector. The program similarly registered signals from the two counters and the PMT located between them with the element under test. The obtained data is used to build graphs of the amplitude spectrum of the scintillation element response and the averaged response pulse. It should be noted that this measurement method has a certain drawback: the equipment is designed to work with signals from a large-sized “Shashlik” type detector, which occupies the entire space between the coincidence scheme counters, while the measured printed element occupies only a small part of the working space. This leads to the program registering a large number of events that occur when charged particles pass through the coincidence scheme counters but not through the area of the printed detector. These events are recognized as background and are reflected on the amplitude spectrum graphs of the response (Fig. 5, a) as a large “pedestal” value. Despite this, such a measurement method allows evaluating the overall operability of the printed detector.

### 3. Results and discussion

The design of the layers of the printed element (Fig. 3) was based on the samples of “Shashlik” type detector tiles produced by ISMA NAS of Ukraine with sizes: for scintillation layers – 40x40x2 mm, for absorption layers – 40x40x1 mm. To improve the energy resolution of the printed element, the final layer sizes were adopted as 40x40x0.8 mm for scintillation layers and 40x40x0.4 mm for absorption layers.

The entire metal layer of the absorber during printing was in a molten state at the glass transition temperature of polystyrene (110°C).

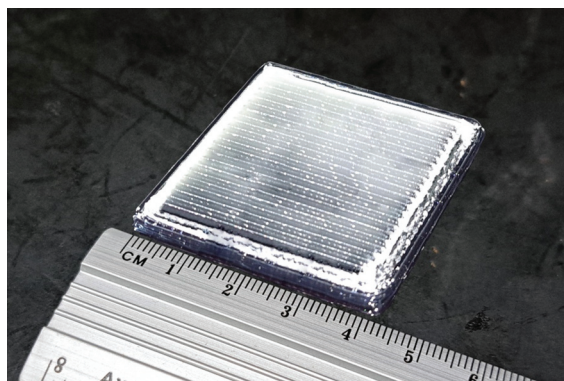


Figure 3. Printed sample 41x41 mm of a two-layer structure plastic scintillator + metal absorber.

This allows the absorbing material to be evenly distributed over the entire surface of the part. At the same time, the metal layer firmly bonds with the plastic layer by fusion. No air gaps were observed between the layers.

Using the developed method, ten pairs of blocks were printed, each consisting of two layers: an absorber layer (based on scintillation polystyrene, similar in composition to UPS-923A), on top of which a layer of metal absorber from the eutectic alloy (Bi-Pb-Sn) was printed. After that, the surfaces were processed for geometric accuracy, joined using optically transparent epoxy resin, and brought to the design dimensions (40x40x15 mm). The obtained multilayer module consists of 11 absorber layers, between which 10 scintillator layers are located according to the construction principle similar to the “Shashlik” type detector (Fig. 4, a).

The next stage was to coat the external surfaces of the module with reflective paint based on epoxy resin and titanium dioxide (33% by mass). After that, 17 holes with a diameter of 1.3 mm for wavelength-shifting WLS-fibers (diameter 1.2 mm) were drilled in the obtained element in the vertical plane, similar to the arrangement of holes in the tiles of the industrial sample of the “Shashlik” type detector. Segments of fibers were inserted into the holes and painted with reflective paint from one end. The opposite side of the sandwich with open light-conducting channels was polished to create an end surface of the WLS-fibers from which light could pass freely. This side of the scintillation element is installed on the photomultiplier tube (PMT) during experiments on radiation registration (4, b).

The obtained prototype of a layered combined scintillation element was investigated under conditions of registering high-energy

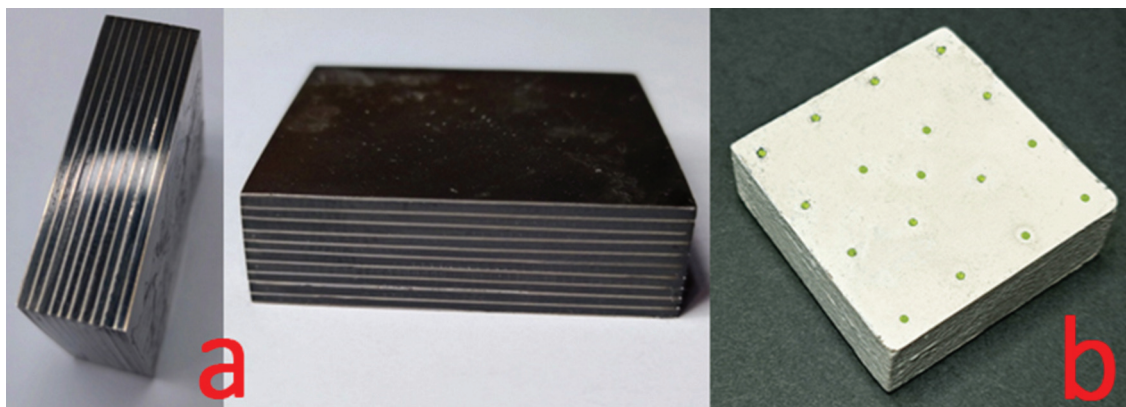


Figure 4. Prototype of a scintillation element for muon registration: a) without holes for wavelength-shifting fibers and reflective coating after post-processing; b) with holes, WLS fibers, and reflective coating.

particles (cosmic muons) for 72 hours according to the methodology presented in section 2.3. The research results were compared with the indicators of the industrial sample of the “Shashlik” type detector produced by ISMA NAS of Ukraine (accumulation time – 22 hours). The dimensions of the industrial prototype detector are 120x120x420 mm, which consists of 120 scintillation and 120 absorber layers. The comparison results (Fig. 5) confirm the possibility of using FDM 3D-printing technology in the production of combined elements of sampling-detectors with metal absorber layers.

It should be noted that at this stage of research, the comparison of measurement results of a 3D printed sample and an industrial detector is purely for demonstration purposes. As a result of the measurements for the printed sample, a “muon peak” was obtained, the parameters of which correlate with the indicators of the standard sample; this indicates the fundamental ability of using additive technologies in the production of such heterogeneous detectors.

This experiment also showed that when using FDM 3D printing, it is possible to avoid using additional layers of reflector. The layered structure is created by welding the metal layer directly onto the polymer layer without the presence of gaps between them, since the metal printing temperature slightly exceeds the glass transition temperature of polystyrene. It is the absence of an air gap between the transparent polystyrene layer and the mirror surface of the metal absorber that creates the conditions for light reflection. Thus, the mirror surface of the metal layer performs the function of reflecting light instead of the diffuse reflector layers used in a number of industrial detectors of the “Shashlik” type. This prevents light leakage and uncontrolled propagation of scintillation

light between adjacent layers (crosstalk). This not only simplifies the detector design but also provides additional space occupied by the reflective layers for increasing the number of active layers in each detector.

#### 4. Conclusions

The principal possibility of 3D-printing using the FDM method of scalable modules of a sampling-detector for the subsequent creation of large-sized sampling-detectors by large-scale assembly has been demonstrated, which will increase the degree of production automation, reduce the time, cost, and labor intensity of calorimeter manufacturing processes.

A sampling-detector module created using the FDM 3D-printing method, consists of 10 absorber layers printed with filament from a eutectic alloy (52% Bi, 32% Pb, 16% Sn) on top of a scintillation layer printed with filament made from a material similar in composition to UPS-923A.

The functional performance of the printed module in registering high-energy particles were compared with the characteristics of the industrial detector of the “Shashlyk” type. The comparison results showed the effectiveness of using the proposed method for printing sampling-detector modules.

The proposed method may be useful in creating sampling detectors with improved energy resolution due to printing modules with thinner scintillator/absorber layers without the need for additional diffuse reflective layers, since the reflective function is performed by the mirror surface of the metal absorber. More detailed studies based on additional experimental data, quantitative performance indicators, and modeling of printed detector operation processes may be a task for future research.

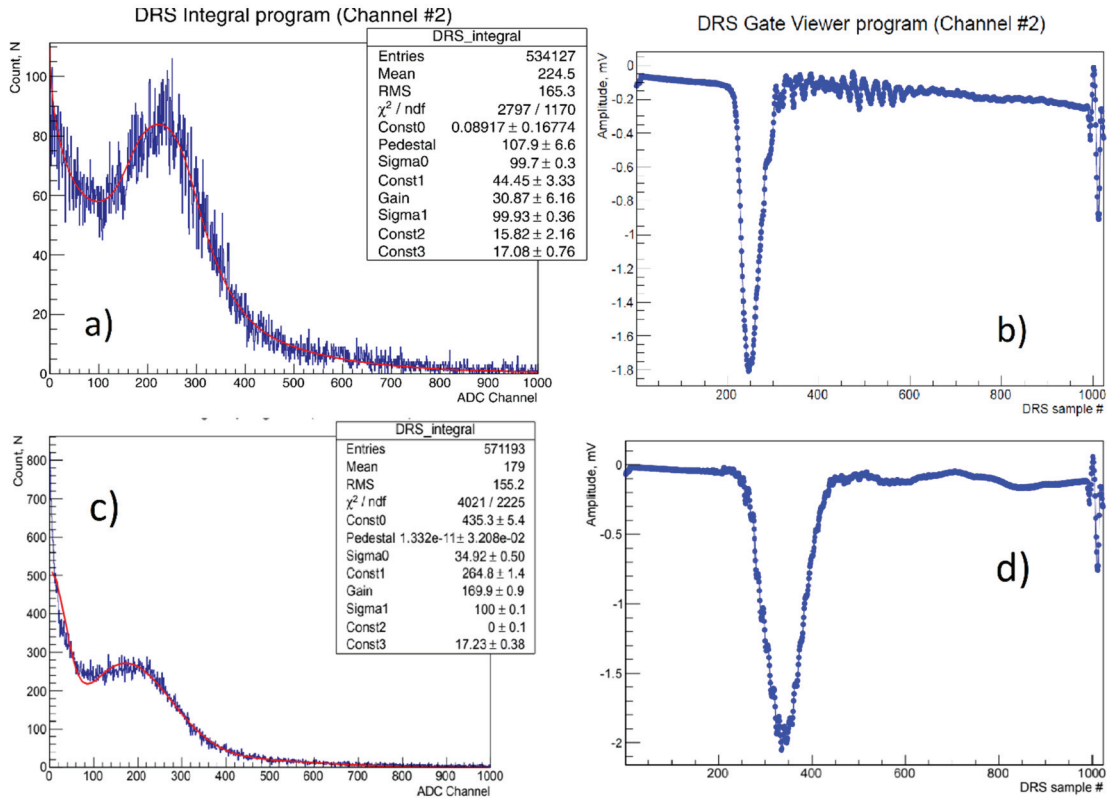


Figure 5. Comparison of the amplitude spectrum of the detector response and the averaged response pulse of the prototype created using 3D-printing technology (a, b) and the industrial “Shashlik” type detector (c, d).

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