

# Development of the Polystyrene Scintillator Technology and Particle Detectors on Their Base

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**Abstract:** The new designed at Institute for High Energy Physics (IHEP) technologies of polystyrene scintillators manufacturing, molding of polystyrene granules under pressure, melting of granules in forms with mirrors walls, production of scintillating granules and detectors on their basis are considered. The main characteristics of the polystyrene scintillators produced by a method of large-block polymerization and a method of extruding of scintillation strips from polymerized blocks are provided in this article also.

**Key words:** Polystyrene scintillators, melting technology, “bulk” type counters.

## Nomenclature

<i>E</i> :	Energy (GeV)
EM:	Electromagnetic
ph.e.:	Photoelectrons
PMT:	Photomultiplier
MIP:	Minimal ionization particle
SNM:	Special Nuclear Materials
WLS:	Wave Length Shifter
<i>TNF</i>	Tagged Neutrino Facility

## Greek Letter

$\sigma$ :	Resolution
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## 1. Introduction

The manufacture of polystyrene scintillators was started at IHEP about 30 years ago. The large scintillation block thermal polymerization technology followed by machining and polishing use at that time. The next step was the development and introduction of new technology, highly transparent scintillator strips extruded from large-block scintillators. The molding under pressure machines and the industrial extruder of the IHEP scintillator facility equipped with modern industrial machines, allows to produce scintillators commercially starts in early 2000s. Highly transparent

detectors on the base of this scintillation strips and plates manufactured by the technology of WLS-fibers light collection have been widely used in a number of experiments, both at the IHEP accelerator, and the physical facilities overseas centers. Others high-technology methods for scintillator manufacturing developed at the IHEP to date are briefly described in this article.

## 2. IHEP Polystyrene Scintillator Facility

### 2.1 Large Blocks of Scintillators Produced by Polymerizing

Scintillators production started in IHEP about 30 years ago. Initially, it was machining of large thermally polymerized blocks. Some characteristics of the developed scintillators are provided in Tables 1 and 2.

Some samples of the polymerized scintillators are shown in Fig. 1.

The extrusion technology of bars and rods up to 5 meters length from large-size polymerized scintillator blocks was developed afterwards [1]. High volume transparency (about 2 m) of extruded scintillator (cross-section up to  $10 \times 250 \text{ mm}^2$ ) allowed to use them in experiments at IHEP: in the hodoscope hadrons detector of general algebraic modeling system (GAMS) [2], in the Large Aperture Muon Hodoscopes

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**Table 1** The main characteristics of the developed scintillators.

Main characteristics	Forms and sizes
Base: polystyrene Density: 1.05 g/cm <sup>3</sup> Coefficient of refraction: 1.59 Ratio H/C: 1 Solution: dissolved in toluene, ethers ...	Scintillators can be produced as bars, sheets, blocks, rods. Bars can reach 4m length at width up to 250mm and thickness up to 25 mm. Blocks can reach 500 × 250 × 250mm <sup>3</sup>

**Table 2** Physical characteristics (bulk scintillators) (<http://exwww.ihep.ru/scint/bulk/product.htm>).

Type of a scintillator	Light output from anthracene (%)	Time decay (ns)	Maximum of irradiation spectra (nm)	Attenuation length (cm)*	Main applications
SC-201	55	3.0	420	200	$\beta, \gamma, \alpha$ , fast $n$
SC-202	52	4.6	465	200	$\beta, \gamma, \alpha$ , fast $n$
SC-203	52	4.5	480	>200	$\beta, \gamma, \alpha$ , fast $n$
SC-204	52	5.0	490	>200	$\beta, \gamma, \alpha$ , fast $n$
SC-205	66	2.4	420	200	$\beta, \gamma, \alpha$ , fast $n$
SC-206	67	1.8	430	200	$\beta, \gamma, \alpha$ , fast $n$
SC-207	44	1.8	380	50	For time of flight detectors
SC-221	32	2.4	430	50	1.7% Sn; for low energy $\gamma$
SC-222	59	2.4	430	50	1.7% Sn; for low energy $\gamma$
SC-223	52	2.4	430	50	2.4% Pb; for low energy $\gamma$
SC-231	56	2.4	430	100	0.6% <sup>10</sup> B; for $n$ of thermal energy

\* Attenuation length for samples of 1 × 20 × 200 cm<sup>3</sup> with polished surface.



(a)



(b)

**Fig. 1** (a) Scintillating plates and parallelepiped; (b) scintillating counter with the scintillator of 10 × 500 × 2,000 mm<sup>3</sup> sizes for scintillating detector planes without empty gaps.

of TNF [3] and at CERN: in the Large Aperture Hodoscopes of NA-12 [4], in the Forward Muon Hodoscope and Shower Maximum Detector of DELPHI [5, 6], in the Muon Hodoscope of DIRAC [7].

## 2.2 Application of the Industrial Methods of Scintillators Manufacture

The manufacturing process of scintillators on the base of a molding under pressure was used at IHEP in the late 1980s at IHEP [8, 9]. It was proposed for the first time to use commercial polystyrene granules powdered by scintillation additives for the producing of scintillators using a molding under pressure. They have been designed for use with WLS-fiber readout. That made the requirement for a long attenuation in scintillator less important.

Plates and short strips manufacturing at IHEP with molding under pressure technology are the highest demand now. These plates are using in several detectors in high energy physics (HEP) experimental setups on particle accelerators (electromagnetic and hadron calorimeters, guard counters) and for detecting

cosmic showers (large area detectors with a fiber readout).

The molding under pressure machines and the industrial extruder of the IHEP scintillator facility put into operation in early 2000s are shown at Fig. 2.

This large-tonnage technology has provided the possibility to create cellular wide aperture electromagnetic [10] and hadron calorimeters [11-14]. Cells were fabricated as metal-scintillator “sandwich” modules. The thickness of the scintillator variation 1-15 mm and the transverse dimensions of a square are 40-200 mm. The production of injection moldings plates with different configurations including grooves and holes for WLS-fibers (Figs. 3-5) was setting up in IHEP for the mass production of a wide range of scintillator plates.

The physical characteristics of the developed scintillators are provided in Table 3.

The total number of counters with more than  $1 \times 1$  m<sup>2</sup> square [15], assembled from the injection moldingscintillators with the dimensions  $200 \times 200 \times 5$  mm<sup>3</sup> manufactured for different laboratories is about 500. 1.5 tons of similar elements, but with the element dimensions ( $120 \times 100 \times 5$  mm<sup>3</sup>), shown in Fig. 3, have been used in guard systems (SNM monitors) [16]. Typical number of PMT photoelectrons for the assembly of two plates (10 mm thick) is 40 ph.e./MeV.

Electromagnetic calorimeter of “Shashlyk” type with optimal configuration on the base of injection molding scintillator was designed at IHEP in the early 2000s and tested jointly with INR RAS group is shown in Figs. 4 and 5 [17-20]. After that, “Shashlyk” began to be widely used [21-23].

The modules with a record for this type of calorimeter energy resolution  $\sigma(E)/E = 4\% / \sqrt{E}$  are presented in Fig. 6. Module size is  $110 \times 110 \times 650$  mm<sup>3</sup> and sampling structure is about 300 layers of 1.5 mm scintillator plates and 0.275 mm lead.



(a)



(b)

Fig. 2 (a) IHEP molding under pressure machines; (b) industrial extruder for production of scintillating bars and strips.

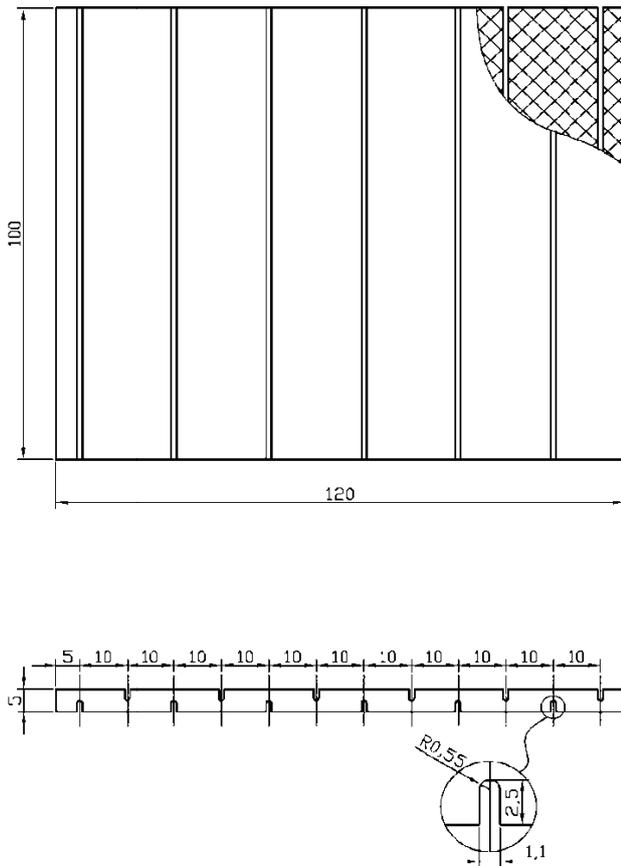


Fig. 3 Scintillating element of large sizes counters with WLS light collection.

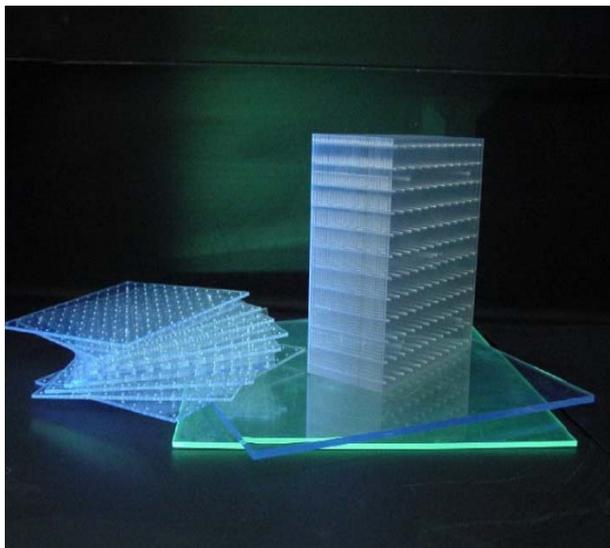


Fig. 4 Photos of scintillation plates of different sizes and different configuration producing by the injection molding.

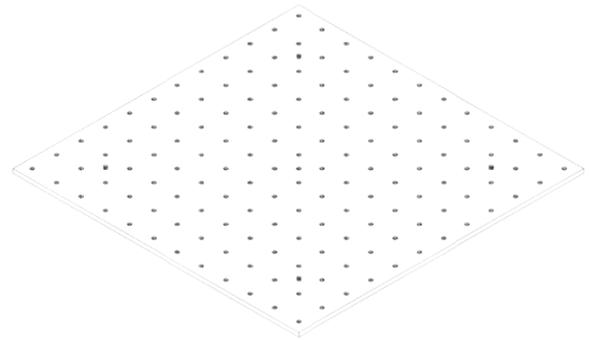


Fig. 5 Scintillating element of electromagnetic calorimeter (Shashlyk type) with WLS light collection.

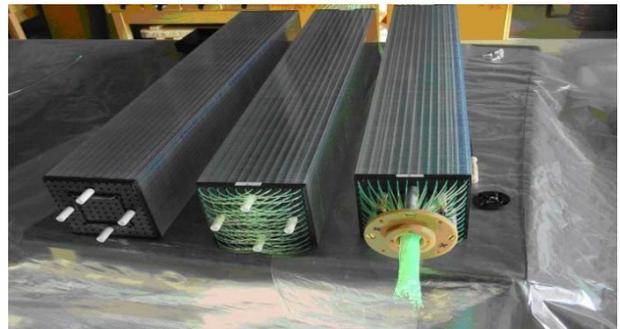


Fig. 6 General view of an improved calorimeter modules “Shashlyk” type and their constituent elements.

### 3. Development of New Technologies

#### 3.1 The Technology of Melting of the Polystyrene Granules, Powdered with Scintillation Dopants in the Forms with Mirrors Walls

The design of mirror forms is very simple, it is a box with sides made of mirror-polished stainless steel plates. Scintillator manufactured in such form does not require machining and polishing. Several forms are manufactured for each scintillator dimension-type.

It was manufactured by this technology around 1,500 lengthy scintillation strips with dimensions of  $15 \times 100 \times 2,000 \text{ mm}^3$  and  $10 \times 60 \times 2,600 \text{ mm}^3$  (Fig. 7) for Ghent University (Belgium), Universite Catholique De Louvain (Belgium) and University of Mainz (Germany). Four Y-11 type 1 mm diameter WLS-fibers assure 10 and 13 of PMT photoelectrons for MIP from the far end of the scintillator, respectively.

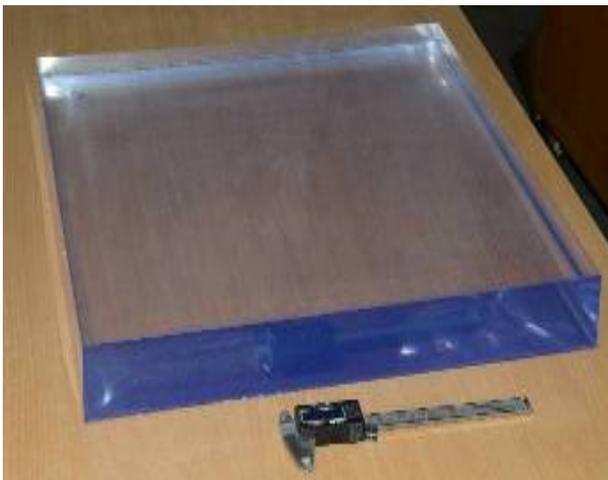
**Table 3 Physical characteristics (mold scintillators) (<http://exwww.ihep.ru/scint/mold/product.htm>).**

Type of a scintillator	Light output from anthracene (%)	Time decay (ns)	Maximum of irradiation spectra (nm)	Main applications
SC-301	55	2.4	420	$\beta, \gamma, \alpha$ , fast $n$
SC-302	57	2.3	430	$\beta, \gamma, \alpha$ , fast $n$
SC-303	55	4.6	490	$\beta, \gamma, \alpha$ , fast $n$
SC-304	57	2.5	420	$\beta, \gamma, \alpha$ , fast $n$
SC-305	59	1.9	430	For time of flight detectors
SC-306	66	2.3	418	$\beta, \gamma, \alpha$ , fast $n$
SC-307	69	2.2	416	$\beta, \gamma, \alpha$ , fast $n$
SC-308	69	2.2	416	$\beta, \gamma, \alpha$ , fast $n$
SC-309	61	2.0	404	$\beta, \gamma, \alpha$ , fast $n$
SC-321	46	2.5	430	4% Sn <sup>**</sup> ; for low energy $\gamma$
SC-322	40	2.5	430	7% Pb <sup>**</sup> ; for low energy $\gamma$
SC-331	52	2.5	420	0.6% B <sup>10**</sup> ; for $n$ of thermal energy

\*\*The concentration of the dopes can be increased by request: Sn, up to 8% weight fraction, Pb, upto 12% weight fraction, B<sup>10</sup>, up to 5% weight fraction.



**Fig. 7** The lengthy scintillation counters with dimensions  $10 \times 60 \times 2,600 \text{ mm}^3$  and grooves for WLS-fibers.



**Fig. 8** The scintillation block with dimensions  $50 \times 500 \times 500 \text{ mm}^3$ .

More than 1,000 scintillator blocks with dimensions  $50 \times 500 \times 500 \text{ mm}^3$  (Fig. 8) were supplied to the Baksan Neutrino Observatory. The light yield through the large face of the block from cosmic muon is 90% of the yield for polystyrene plastic scintillators, but 3 times lower cost.

As an example, Fig. 9 shows a solid scintillation counter with dimensions  $30 \times 300 \times 1,500 \text{ mm}^3$ , made with the described technologies. For the light collection, the new manufactured at IHEP photomultiplier FEU-KS (Section 4) with the lengthy photocathode ( $15 \times 200 \text{ mm}^2$ ), is used.

The new PMT construction allows capturing without fiber scintillation light at the counter center with all its width. To improve the uniformity of the light collection along the length of the scintillation counter concentration of dopes varied from center to its ends. Number of photoelectrons (for MIP) from the ends was about 30.

### 3.2 The Scintillating Granules as Material for Ultra-Large Counters Manufacturing

The conception of the new technology is to use WLS-fibers for light-collection system, run through the volume of the counter filled with scintillation granules (“bulk” counter) [24]. WLS-fibers of light collection system arranged periodically with optimal step.



**Fig. 9** The massive scintillation counter with dimensions  $30 \times 300 \times 1,500 \text{ mm}^3$  made with the discussed technology. The light collection on photomultiplier FEU-KS with the lengthy photocathode.

Comparative measurements were made for light output from the scintillation counter with dimensions of  $10 \times 140 \times 260 \text{ mm}^3$  produced by polymerization (Fig. 10), and “bulk” type counter with the dimensions  $20 \times 200 \times 200 \text{ mm}^3$  (Fig. 11). In the last, one single row of periodically arranged WLS-fibers with 10mm gap between them was used.

Scintillation counter volume was filled with  $\text{Ø } 3 \times 3 \text{ mm}$  granules, which ensures the effective density  $0.65 \text{ g/cm}^2$ . Measurements show that the PMT light output in the counter is about 40 ph.e./MeV.

Scintillating polystyrene granules can be produced on an industrial scale with a capacity of tens of thousands of tons per year, by using as a feedstock “powdered” granules of commercial transparent polystyrene.

The production output of a single industrial set-up for the production of polystyrene granules from styrene with scintillation dopes dissolved in the styrene can be

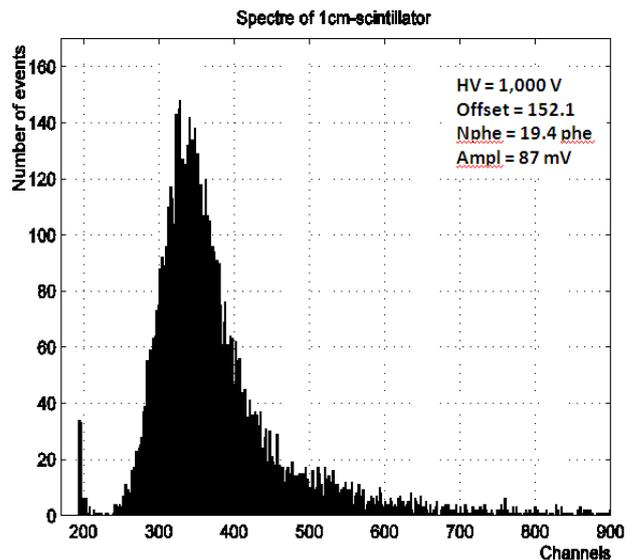
hundreds of thousands tons per year. Scintillation dopants do not affect the manufacturing process.

#### 4. Thin Scintillation Counters Based on FEU-KS

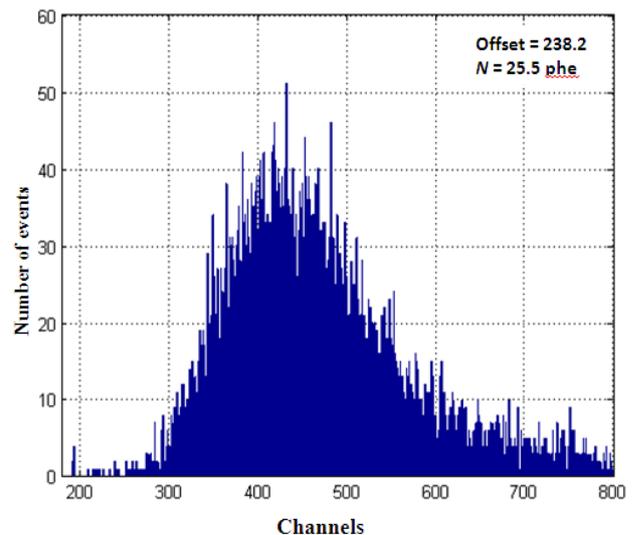
Several scintillation super-thin counters without light guide based on FEU-KS are presented in Fig. 12 (references above and Fig. 13).

Design of the new PMT allows to collect the scintillation light from the counters without light guide.

The PMT gain is more than  $10^6$ . The photocathode



**Fig. 10** Amplitude spectra from MIP from polymerized type scintillator with dimensions  $10 \times 140 \times 260 \text{ mm}^3$ .



**Fig. 11** Amplitude spectra from MIP from the “bulk” type counter with dimensions of  $20 \times 200 \times 200 \text{ mm}^3$ .



**Fig. 12** Family of scintillation counters without light-guides based on FEU-KS with extended photocathode.



**Fig. 13** New photomultiplier FEU-KS with an extended photocathode ( $15 \times 200 \text{ mm}^2$ ), produced at IHEP.

blue sensitivity is up to 70 mA/W. The photoelectron number of thin polystyrene scintillators with sizes  $1 \times 200 \times 200 \text{ mm}^3$  and  $0.5 \times 100 \times 100 \text{ mm}^3$  are 20 and 12 per MIP, respectively.

## 5. Conclusions

In the near future, we are planning the following lines of investigation:

(1) Increasing the length of attenuation of light in the scintillators manufactured by extrusion, high-pressure molding under pressure and melting in the mirror forms to replace too expensive polymerized polystyrene scintillators;

(2) Investigation and optimization of scintillation granules manufacture and detectors on their basis;

(3) Development of “thin” counters for experiments at low energies and ion beams;

(4) Increasing of radiation hardness of polystyrene

scintillators.

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