PROCEEDINGS OF SCIENCE

Plastic scintillator production involving Additive Manufacturing

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Plastic scintillator detectors are widely used in high-energy physics. Often they are used as active neutrino target, both in long and short baseline neutrino oscillation experiments. They can provide 3D tracking with 4π coverage and calorimetry of the neutrino interaction final state combined with a very good particle identification, sub-nanosecond time resolution. Moreover, the large hydrogen content makes plastic scintillator detectors ideal for detecting neutrons. However, new experimental challenges and the need for enhanced performance require the construction of detector geometries that are complicated using the current production techniques. The solution can be given by additive manufacturing, able to quickly make plastic-based objects of any shape. The applicability of 3D-printing techniques to the manufacture of polystyrene-based scintillator will be discussed. We will report on the feasibility of 3D printing polystyrene-based scintillator with light output performances comparable with the one of standard production techniques. The latest advances on the R&D aim at combining the 3D printing of plastic scintillator with other materials such as optical reflector or absorber. The status of the R&D and the latest results will be presented.

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1. Introduction

Plastic scintillator is one of the most used active materials in high-energy physics. Recent applications aim at combining both three-dimensional particle tracking and calorimetry, hence they require relatively complex geometries, e.g. small optically-isolated active voxels, to achieve a fine mechanical as well as optical 3D segmentation of the active elements. Examples can be found in the latest-generation scintillator neutrino detectors [1] or sampling calorimeters. These detectors need to be massive, order of at least a few tonnes, thus they require relatively long manufacturing and detector assembly processes. Future evolutions may involve even finer granularity whilst maintaining a large mass, with obvious advantages for the detector performance.

Additive manufacturing opens a door to new automated processes that can drastically simplify the construction of plastic scintillator detectors. More commonly known as rapid prototyping or three-dimensional (3D) printing, additive manufacturing processes are used to design and create parts by adding material in a layer-wise fashion and produce complex internal geometries by simultaneously printing multi-materials. These processes potentially will allow cheaper and quicker operations compared to conventional techniques thanks to a tool-less operation.

Recently, the "3D printed Detector" (3DET) collaboration was formed with the goal of investigating and developing additive manufacturing as a new production technique for future scintillator-based particle detectors. The general purpose R&D aims at 3D printing scintillator detectors with performances comparable to the state of the art, obtained with traditional production methods.

The 3DET collaboration includes research institutes and universities based in Switzerland and Ukraine: CERN, ETH Zurich, the Haute Ecole d'Ingénierie et de Gestion du Canton de Vaud (HEIG-VD), and the Institute for Scintillation Materials in Ukraine (ISMA).

In this proceeding the latest R&D results obtained by the 3DET collaboration are reported.

2. Polystyrene-based 3D-printed scintillator

In a recent publication [2] the 3DET collaboration reported about the feasibility of 3D printing polystyrene-based scintillator using the fused deposition filament (FDM) technique. It consists of material deposition, performed line by line, that builds up many layers until the target volume is achieved. A thermoplastic filament in the form of thin wires is used as the base material which passes through a set of feeding rollers into the liquefier [3, 4].

The optimal composition was found to be polystyrene doped with pTP (2% by weight), POPOP (0.05% by weight) and an addition of 5% by weight of biphenyl, used as plasticiser to make the filament less brittle and overcome the challenge in the FDM filament production. In fact, the hardness of pure polystyrene can cause the 3D printer rollers to crush the filament when inserted or to produce cracks in the filament when positioning the 3D-printer extruder before starting the process. A clear advantage of this formula is that it does not require to invent a new chemical composition, since polystyrene is one of the most common polymers used in scintillator materials.

The first demonstration of the feasibility of 3D printing polystyrene-based scintillator with the FDM technique was obtained with performances similar to those of plastic scintillators produced with traditional techniques, such as cast or extrusion methods, as shown in fig. 1. It was also found that the printing parameters have to be carefully tuned to achieve the required transparency and

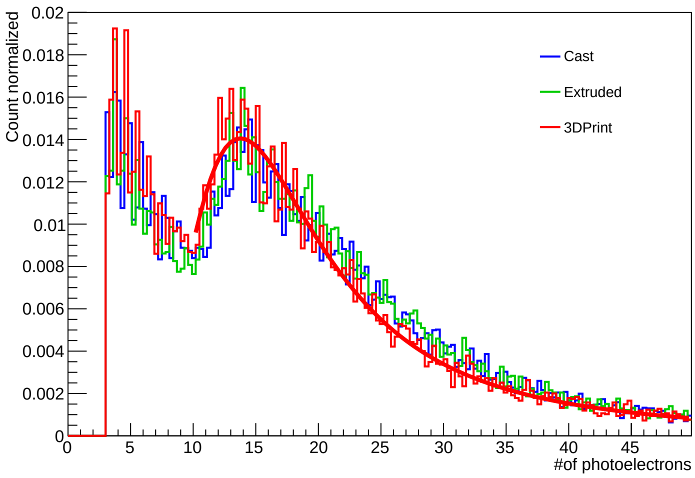

Figure 1: Light output of a 1 cm edge scintillator cube 3D printed with FDM (red) compared to scintillator produced with cast (blue) and extrusion (green) techniques. The results were obtaining from cosmic data.

light output. In fact, variations up to 50% of the light output were found before the parameter optimisation was completed.

3. Attenuation length

After obtaining the first proof of the concept, the 3DET collaboration is now focusing its efforts on the characterisation of the scintillator parameters and several samples with different geometries have been produced and tested. For instance, the attenuation length was tested. A 5 cm long bar of plastic scintillator with a cross section of 1×1 cm^2 was made. After polishing the outer surface, the attenuation length of the 3D printed scintillator was measured by exposing the bar to a Sr^{90} source along the bar length. The scintillation light output was measured with a silicon photomultiplier placed at one edge of the bar. As shown in fig. 2, the attenuation length of the 3D printed scintillator was found to be approximately 20 cm, which is acceptable for finely-segmented particle detectors. Future improvements aim at tuning the FDM parameters to increase the scintillator fill factor and, consequently, remove some very small air bubbles present in the scintillator sample.

4. Simultaneous printing of scintillator and optical reflector

The simultaneous printing of multi-material objects, i.e. both the plastic scintillator and the optical reflector, was also studied. A white optical reflector filament was made with an extruder by adding TiO_2 pigment to polymer pellets. In fig. 3 the scintillator and reflective filaments are shown. Reflectivity properties similar to TiO_2 paint or Tyvek were found for violet/blue ($\sim$ 420 nm) light, the typical emission range of plastic scintillators, as shown in tab. 1.

Then, we succeeded to 3D print several matrices of optically-isolated scintillator cubes, as shown in fig. 4. Each scintillator voxel corresponds to a 10mm-edge cube and the thickness of the

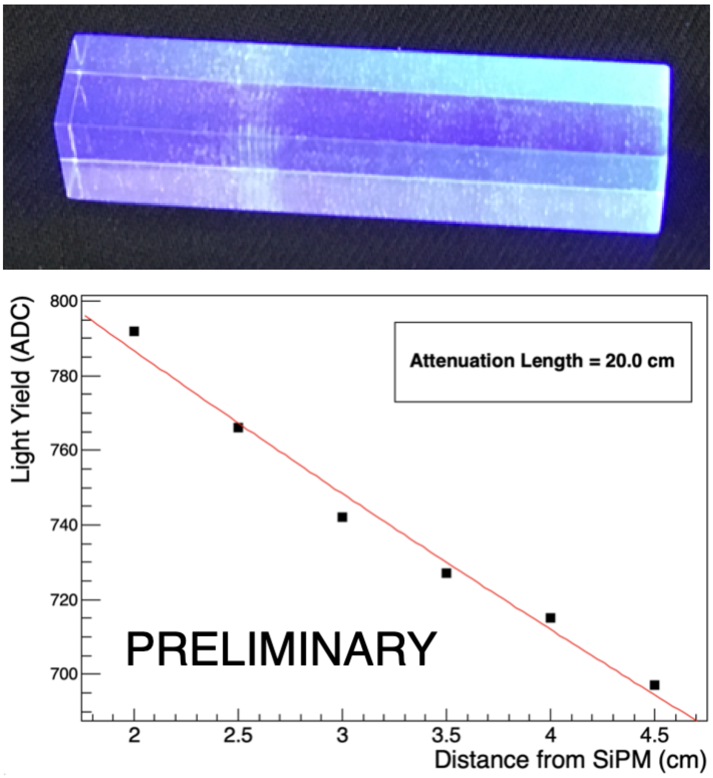

Figure 2: Top: picture of the 3D printed 5cm-long scintillator bar used to evaluate the scintillator attenuation length. Bottom: scintillator light output as a function of the Sr^{90} source to SiPM distance.

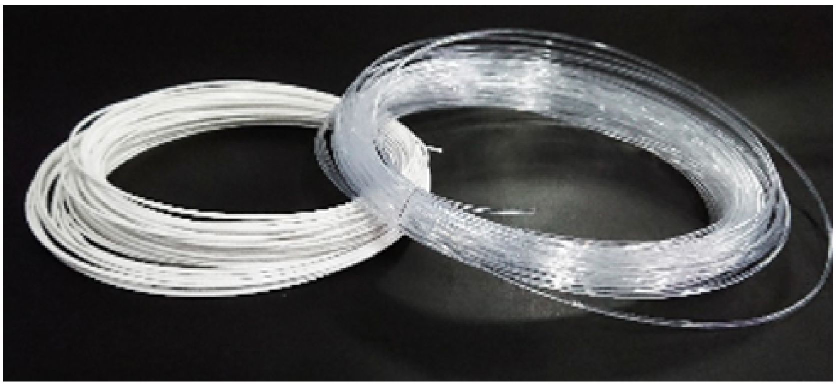

Figure 3: Scintillating and reflective filament used for 3D printing the cube matrix.

Sample	Reflectivity at 420 nm (%)
PTFE	100
Tyvek	94
TiO_2 paint	93
3D printed	91

Table 1: Reflectivity of FDM reflector filament compared to PTFE, Tyvek and TiO_2 paint.

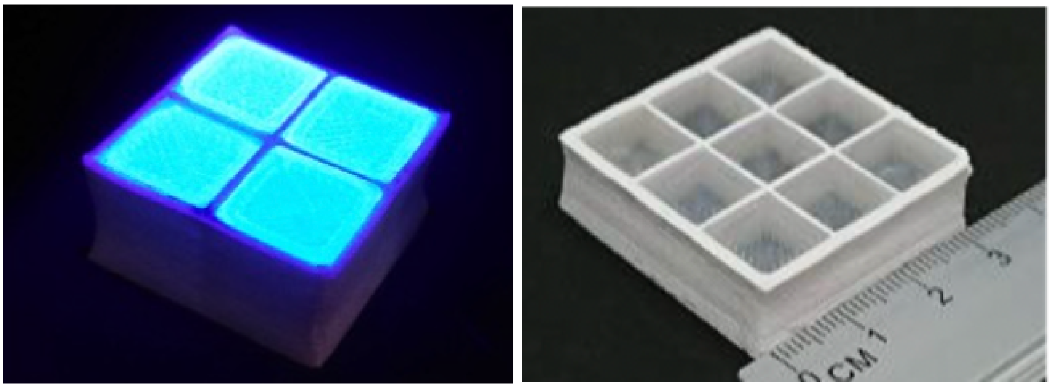

Figure 4: 2×2 cube matrix exposed to UV light (left) and 3×3 cube matrix (right). The plastic scintillator cubes are optically separated by 1 mm thick reflector.

white diffuser is approximately 1 mm. The geometrical precision was found to be acceptable for the inner part of the matrix. As shown in the picture above, whilst the inner part of the matrix has a quite good geometrical tolerance quantifiable as about 0.5 mm, the outermost part (about half centimeter) of the matrix does not show a perfect rectangular shape. This is due to the fact that the material needs to be melted in order to achieve an acceptable transparency and the outermost part is not mechanically constrained at the required position. However, one can deal with this issue by post-processing the outermost surface if the required geometrical precision is not achieved already at the 3D printing stage.

Preliminary measurements of the scintillation light output were performed by coupling nine silicon photomultipliers directly to plastic scintillator. About 45 photoelectrons (p.e.) are produced in a cube when crossed from top to bottom by minimum ionizing particles, i.e. cosmics. The optical cross talk between adjacent cubes, i.e. the probability for a scintillation photon to cross the optical reflector, was found to be about 2%. The results are shown in fig. 5. Complementary tests with Cs^{137} confirmed a light output similar to the one obtained from scintillation produced with injection moulding and TiO_2.

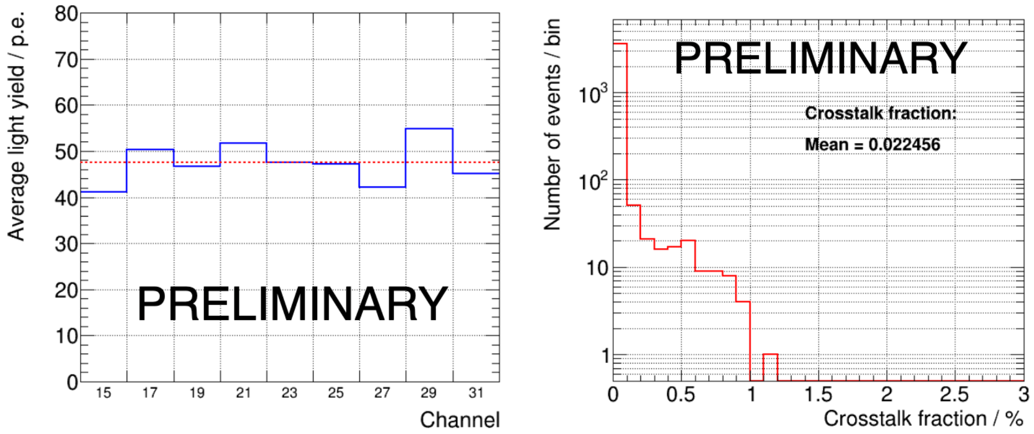

Figure 5: Left: average light output obtained by exposing the nine cubes of the 3D printed matrix to cosmics. Right: light cross talk between adjacent cubes from cosmic data taking.

5. Conclusions

The 3DET collaboration demonstrated the feasibility of 3D printing plastic scintillator detectors (both the scintillator and the optical reflector) with the Fused Deposition Modelling, achieving the goal of realisation a 3D matrix of optically-isolated scintillator voxels.

However, more R&D is foreseen to improve the geometrical tolerance and the transparency of the 3D printed scintillator. Future steps will aim at optimizing the attenuation length of the scintillator, improving the multimaterial printing and testing the matrix reproducibility and the stability of the printing performances. In order to obtain a full characterization of the scintillator the decay time as well as the potential ageing effects will be studied. Work is ongoing also on 3D printing of inorganic materials (not reported here).

Finally, we plan to investigate other additive manufacturing technologies complementary to the fused deposition modelling technique.

References

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