PROCEEDINGS OF SCIENCE

Polystyrene-based scintillator production involving additive manufacturing

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Plastic scintillator detectors are widely used in high-energy physics, often 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 found in 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.

**** Particles and Nuclei International Conference - PANIC2021 ****
**** 5 - 10 September, 2021 ****
**** Online ****

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PoS(PANIC2021)086

1. Introduction

Plastic scintillator detectors can be found in a wide range of scientific and industrial applications. They are used for tracking and calorimetry in high energy physics, for diagnostic imaging in medicine, for beam monitoring on hadron therapy, and for many security applications. Plastic scintillators, due to their low cost and easy fabrications, provide an affordable approach to develop massive detector with complex geometries. Recent applications aim at combining both three-dimensional (3D) particle tracking and calorimetry by producing small optically isolated active voxels, allowing to achieve fine granularity as well as optical 3D segmentation of the active elements. Examples can be found in new generation scintillator neutrino detectors [1, 2] or in sampling calorimeters [3]. Such configurations require relatively long manufacturing and detector assembly processes. Development on Additive manufacturing technique may be a viable, cheap and fast solution to ease the production and assembly of such detectors.

In order to investigate and develop additive manufacturing (AM) as a new production technique for the future scintillator particle detectors, a 3D printed Detector (3DET) collaboration was formed. General purpose of the collaboration is to perform an R&D toward the first 3D printed particle detector with performances comparable to the state of the art. The 3DET collaboration composes of research institutes and universities based in Switzerland and Ukraine: CERN, ETH Zurich, Haute Ecole d'Ingénierie et de Gestion du Canton de Vaud (HEIG-VD), and Institute for Scintillation Materials in Ukraine (ISMA), profiting from the knowledge and expertise on particle detector development, scintillating materials and additive manufacturing.

In the following we will discuss the R&D results obtained by 3DET collaboration.

2. R&D program on 3D printed Detector

The 3DET collaboration aims to 3D print a plastic scintillator volume composed of many optically isolated scintillating cells as an example case study to apply AM techniques. The collaboration launched the R&D study with Fused Deposition Modelling (FDM) technology due to its versatility and cost effectiveness as well as rapid prototyping of specific shape and pattern. FDM technology requires scintillating filaments with a stable size and material properties for feed through the rollers and nozzle in order to achieve printing plastic scintillator. In the following we will summarize the R&D effort on the production of the scintillating and reflecting filaments.

2.1 Scintillating filament

The optimal composition of the scintillating filament was obtained to be polystyrene doped with 2% by weight of p-terphenyl (pTP) and 0.05% by weight of 2,2-p-phenilene-bis(5-pheniloxazole) (POPOP) and an addition of 5% by weight of byphenil used as plasticiser to make the filament less brittle and overcome the challange in the FDM filament production. This formula does not require to invent a new chemical composition, since the polystyrene is one of the most common polymers used in scintillator materials.

2.2 Optical reflector filament

A white optical reflector filament was made with an extruder by adding TiO_2 pigments to polymer pellets. The reflectivity has been studied as a function of wavelength together with different reflective materials, such as PTFE, Tyvek, and TiO_2 paint. Reflectivity properties of the 3D printed optical reflector were found similar to $Ti0_2$ paint or tyvek at 420 nm, typical emission range of plastic scintillator, as shown in Table 1.

Sample	Reflectivity at λ=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.

3. 3D printing of polystyrene-based scintillator

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 detailed in Reference [4]. This study represents a proof-of-concept for the production of plastic scintillator process involving AM techniques. On the other side, it was found that the printing parameters have to be carefully tuned in order to achieve the required transparency and light output. In fact, variations up to 50% of the light output were found before the printing parameter was optimised.

The characterisation of 3D printed scintillator in terms of attenuation length has been studied. A scintillator bar sample with dimensions of 10×10×50 mm^3 was printed. After polishing the outer surface, the attenuation length of the sample was measured by exposing a ^{90}Sr β source along the bar. The scintillating light output was measured with a silicon photomultiplier (SiPM) coupled directly to one edge of the bar. As shown on right panel of Figure 1, the attenuation length of the 3D printed plastic scintillator was found to be approximately 20 cm. As shown on the left panel of

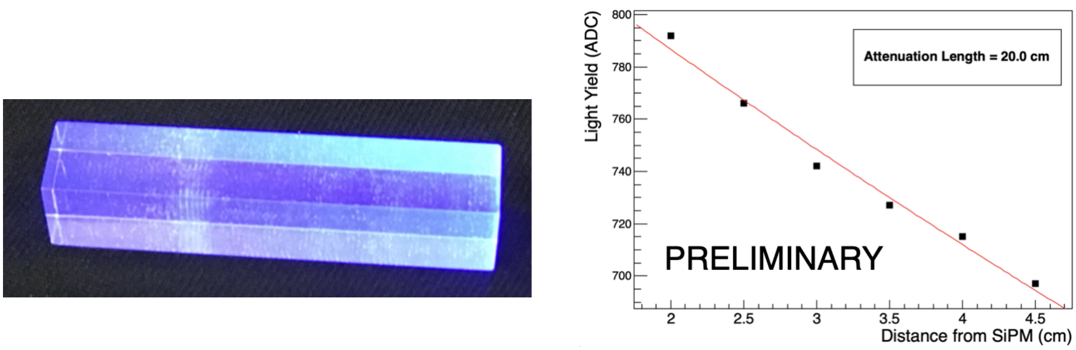

Figure 1: Left: the 3D printed scintillator bar with dimensions of 10×10×50 mm^3 exposed to UV light. This sample is used to evaluate the attenuation length of 3D printed scintillator. Right: Light output as a function of the ^{90}Sr β-source distance to SiPM.

Figure 1, whilst very small air bubbles present in the printed scintillator bar, it is pretty transparent.

Future improvements may be achieved by fine tuning the printing parameters in order to obtain a higher fill factor and, consequently, get rid of small air bubbles seen in the printed sample.

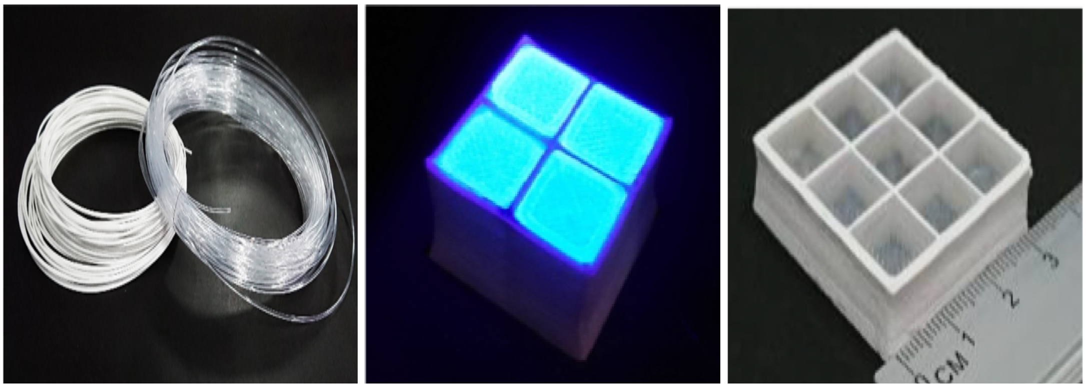

Figure 2: Left: scintillating and reflecting filament used for 3D printing the cube matrix, Middle: 2×2 cube matrix layer exposed to UV light and Right: 3×3 cube matrix layer. The plastic scintillator cubes are optically separated by 1 mm thick reflector.

4. Simultaneous printing of scintillator and optical reflector

In order to reach the final goal on printing scintillator volume with many optically isolated cubes, the simultaneous printing of plastic scintillator and optical reflector have been studied in detail. As discussed in Section 2 and shown on the left panel of Figure 2, scintillating and reflecting filaments were produced. The 3DET collaboration have succeeded to 3D print a matrix of optically-isolated scintillator cubes. Middle and right panel of Figure 2 show 3D printed cube matrices: 2×2 cube matrix layer under UV light and 3×3 cube matrix layer. Each scintillator voxel corresponds to a 10 mm edge cube and ~1 mm thick reflector. The geometrical precision was found to be acceptable for the inner part of the matrix. Tolerance of the reflector thickness and cube shape were found to be ~0.5 mm, while the outermost part of the matrix does not show a perfect rectangular shape. This is mainly due to the fact that the material needs to be melted to achieve an acceptable transparency and the outermost part is not mechanically constrained at the required position. However, this issue can be solved by post-processing the outermost surface if the required geometrical precision is not achieved already at the 3D printing stage. Moreover, some reflector remnants in scintillator were observed since the extruder could not move up and down before changing the material. All this can be improved after some tuning and possible modifications on 3D printer.

Preliminary measurements of the scintillation light output and light uniformity of the matrix layer were performed by coupling nine SiPMs directly to the plastic scintillator cubes. The light output was found uniform among the cubes and about 45 photoelectrons in a cube when minimum ionizing particles, cosmic muons, are crossed vertically, as seen on the left panel of Figure 3. The optical cross talk between adjacent cubes, i.e. the probability for a scintillation photon crossing the optical reflector, was found to be about 2% , as shown on the right panel of Figure 3. Complementary tests with ^{137}Cs γ source confirmed the light output similar to the one obtained from scintillation produced with injection molding and $Ti0_2$ reflector.

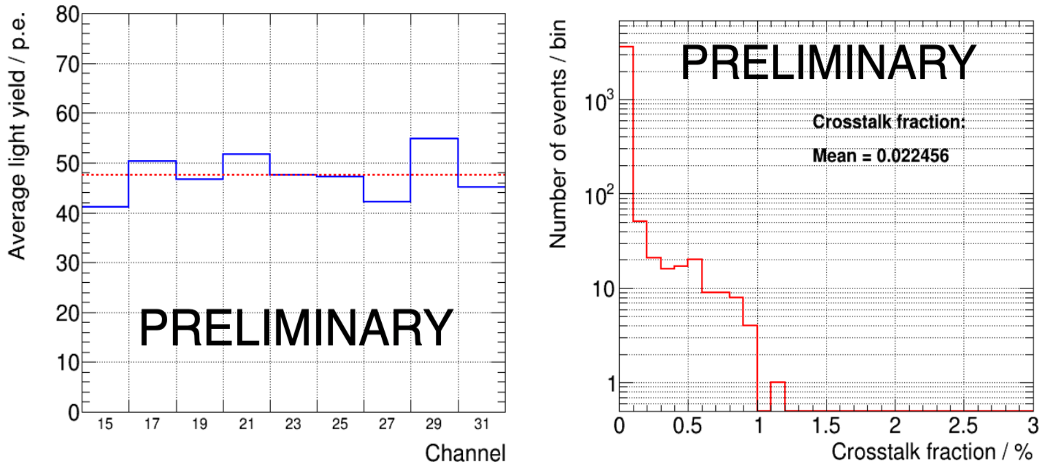

Figure 3: Left: average light output obtained by exposing the nine cubes of the 3D printed matrix to cosmics (vertical muons). Right: light cross talk between adjacent cubes from cosmic data taking.

5. Conclusions

The 3DET collaboration demonstrated the feasibility of 3D printing plastic scintillator detectors 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 improving the multi material printing and testing the matrix reproducibility and the stability of the printing performances. In order to obtain a full characterization of the printed scintillator, the decay time as well as the potential ageing effects will be studied. In parallel, some work is ongoing also on 3D printing of inorganic materials.

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

References

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