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Additive manufacturing of plastic scintillator

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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 RD 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 have been widely used in scientific and industrial applications. Due to their low cost and ease fabrications, plastic scintillators provide an affordable approach to develop massive detector with complex geometries. Recent applications in high energy physics aim to combine both three-dimensional charged particle tracking and calorimetry; requiring optically separated 3D segments, i.e. voxels, of the active elements. This approach 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.

The "3D printed Detector" (3DET) collaboration was formed with the goal of investigating and developing additive manufacturing (AM) as a new production technique for the future scintillator particle detectors. 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 have been established with 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), exploiting the knowledge and expertise on particle detector development, scintillating materials and additive manufacturing.

In this proceeding the latest RD results obtained by the 3DET collaboration are reported.

2. 3D-printed polystyrene-based scintillator

The 3DET collaboration launched the R&D study with 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.

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 [4]. 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. The first phase of R&D study demonstrated the proof-of-concept, confirming the production of plastic scintillator process involving additive manufacturing techniques. Sample of scintillator cubes with dimensions of $10\times10\times10$ mm^3 were printed and scintillator quality was checked in terms of transparency and light output. The obtained results assessed the feasibility of 3D printing polystyrene-based scintillator with the FDM technique with performances similar to those of plastic scintillator produced with traditional techniques, such as cast or extrusion methods, as seen in Figure 1. The details can be found in elsewhere [4].

After obtaining the first proof-of-concept, the characterisation of 3D printed scintillator in terms of attenuation length have been studied. A scintillator bar sample with dimensions of $10\times10\times50$ mm^3 was printed. After polishing the outer surface, the attenuation length of the sample was measured by exposing a ^{90}Sr β source at several positions along the bar. The scintillating light

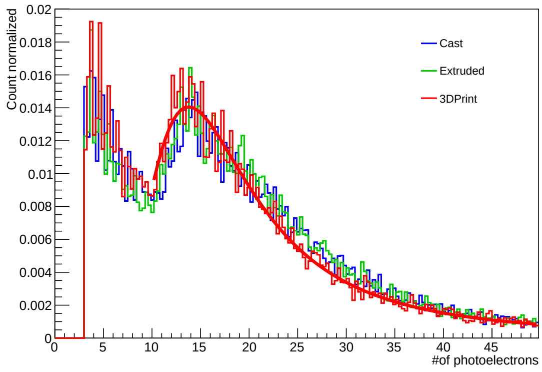

Figure 1: Light output of a 1 cm edge scintillator cube 3D printed with FDM (red) compared to scintillator produced with cast (blue) and extrusion (green) techniques. The results were obtaining from cosmic data.

output was measured with a silicon photomultiplier (SiPM) coupled directly to one edge of the bar. As shown on right panel of Figure 2, the attenuation length of the 3D printed plastic scintillator was found to be approximately 20 cm.

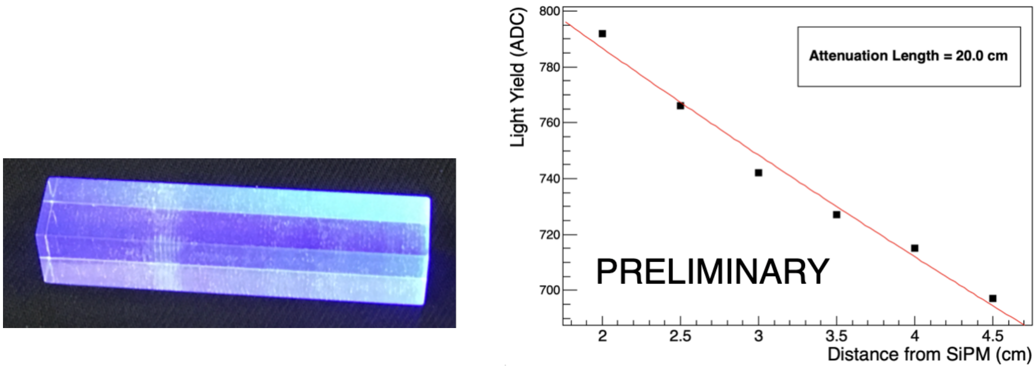

Figure 2: Left: the 3D printed scintillator bar with dimensions of 10×10×50 mm^3 exposed to UV light. This sample is used to evaluate the attenuation length of 3D printed scintillator. Right: Light output as a function of the ^{90}Sr β-source distance to SiPM.

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.

2.1 Simultaneous printing of scintillator and optical reflector

The simultaneous printing of multi-material, i.e. plastic scintillator and optical reflector, have been studied in detail. 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: PTFE 100%, Tyvek 94%, TiO_2 paint 93% and 3D printed 91%.

Once the scintillating and reflecting filaments were produced, the 3DET collaboration have succeeded to 3D print matrix of optically isolated scintillator cubes. Figure 3 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 since 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.

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 a minimum ionizing particles, cosmic muons, are crossed vertically, as seen on the left panel of Figure 4. 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 4. 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.

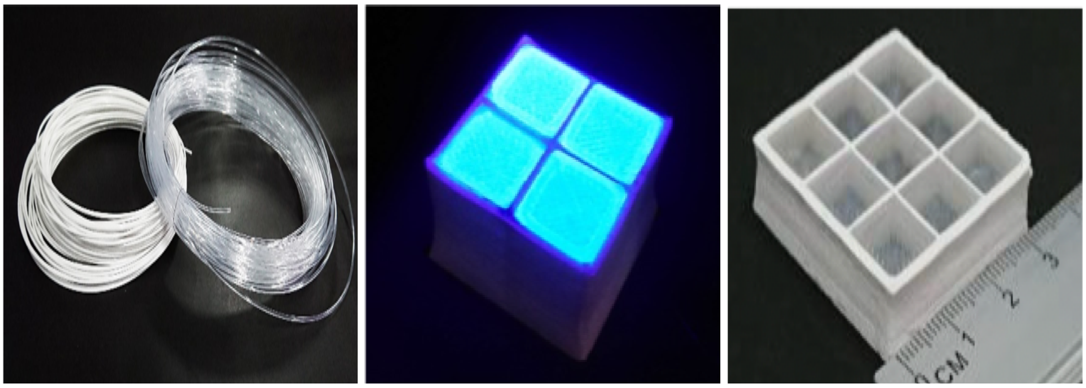

Figure 3: Left: scintillating and reflecting filament used for 3D printing the cube matrix, Middle: 2×2 cube matrix layer exposed to UV light and Right: 3×3 cube matrix layer. The plastic scintillator cubes are optically separated by 1 mm thick reflector.

3. 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.

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.

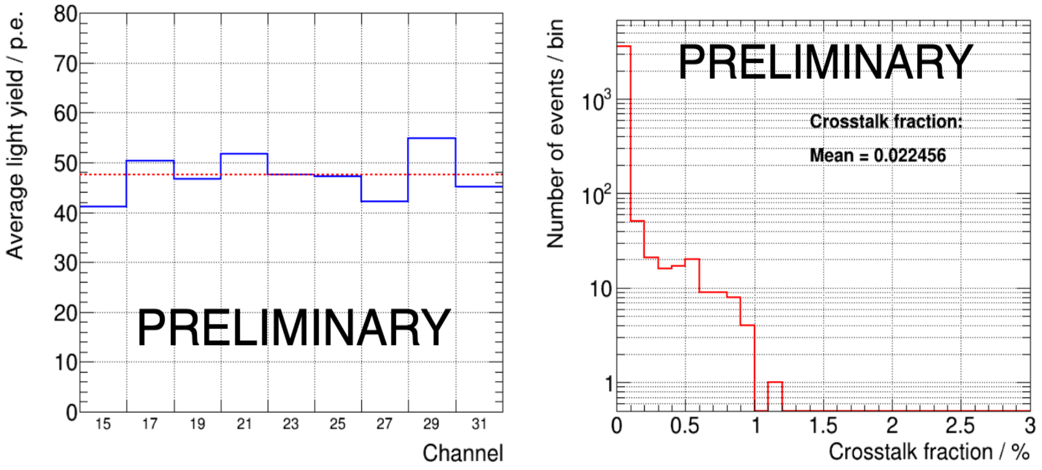

Figure 4: Left: average light output obtained by exposing the nine cubes of the 3D printed matrix to cosmics (vertical muons). Right: light cross talk between adjacent cubes from cosmic data taking.

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

References

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