3DET

ETH zürich

Additive Manufacturing of 3D-Segmented Scintillator Particle Detector

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on behalf of 3DET Collaboration

The 26th International Workshop on Neutrinos from Accelerators
NuFact 2025, 01-07 September 2025, Liverpool, UK

ETH
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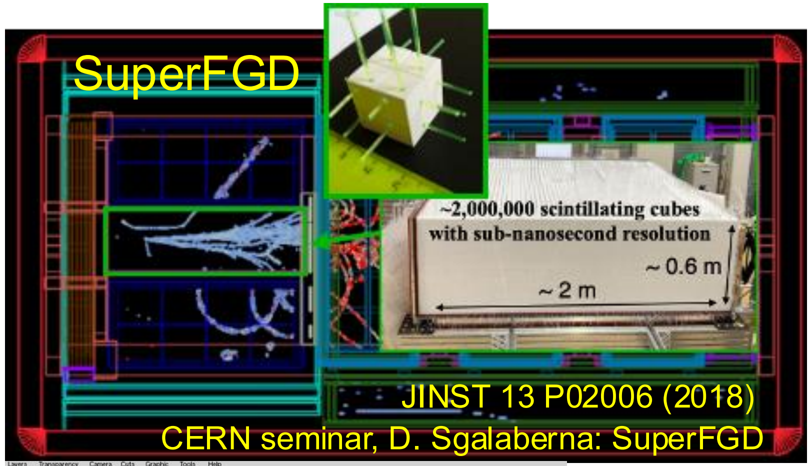
Motivation:

- **3D granularity** and **sub-nanosecond time resolution** of plastic scintillator detectors: **particle tracking**, **identification**, and **calorimetry**

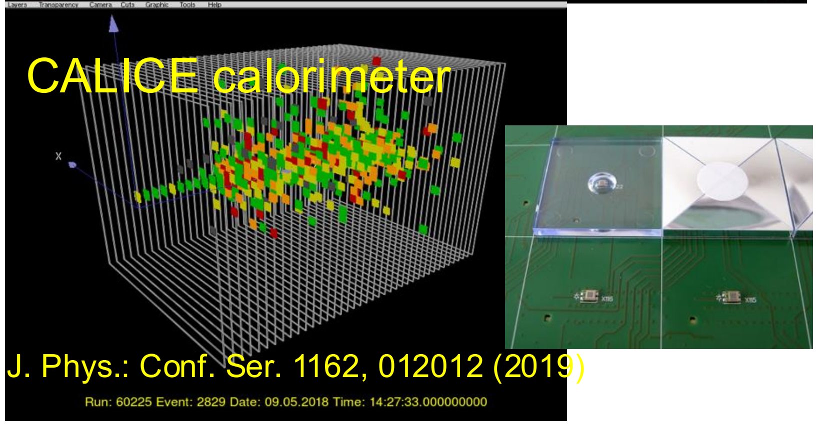
- Many experiments are incorporating or developing high granularity plastic scintillator detectors: **larger volumes and finer segmentation**.

- **Challenges** including high costs (production and assembly), long production time, and precision requirements of complex detector geometries, scalability.

- **Additive Manufacturing** is a promising solution to address the challenges: faster on prototyping the design, scalable, automated and cost-effective



JINST 13 P02006 (2018)
CERN seminar, D. Sgalaberna: SuperFGD



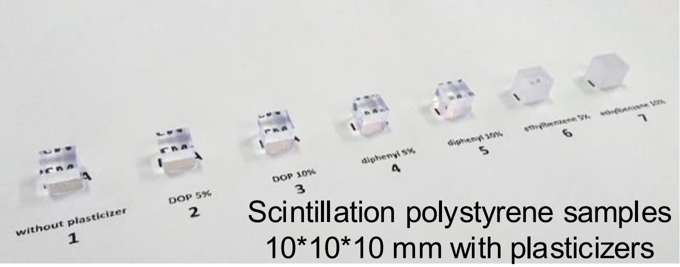
J. Phys.: Conf. Ser. 1162, 012012 (2019)

JINST 13 P05005 (2018)

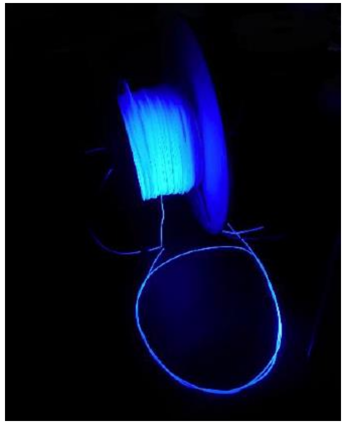
Toward Additive manufacturing of particle detector

- The **3D** printed **DET**ector R&D collaboration: the first 3D printed particle detector with performances comparable to the state of the art
- **Fused Deposition Modelling** as a promising solution
- **Scintillating filaments** developed based on Polystyrene + PTP + POPOP at the beginning plasticizers introduced for elasticity but then removed from the recipe
- **Reflector filaments** developed with 20% TiO_2 in weight mixed with PMMA
- **3D printing two material simultaneously:** scintillating and reflector filaments

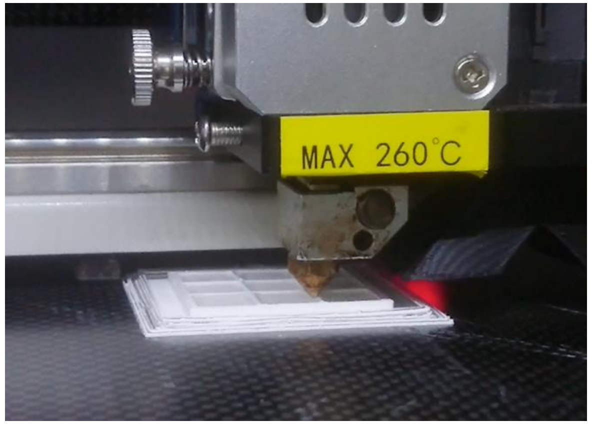
https://threedet.web.cern.ch



Scintillation polystyrene samples 10*10*10 mm with plasticizers

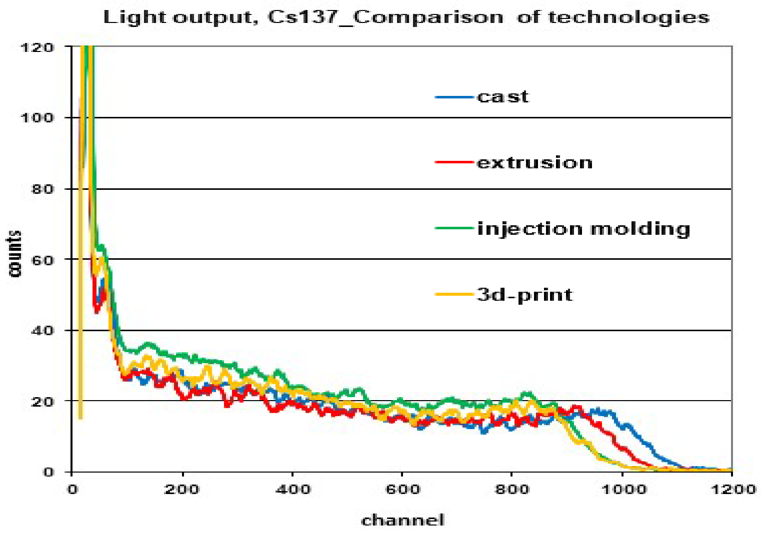


Polymer pellets
Reflective pigment TiO2 (or BaSO4, MgO...)
Reflective filament

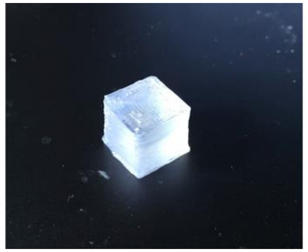


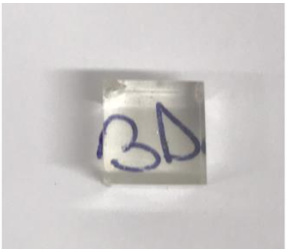
3DET, 2020 JINST 15 P10019

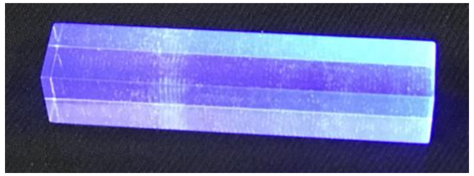
Proof-of-concept and characteristics of 3D printing scintillator cubes

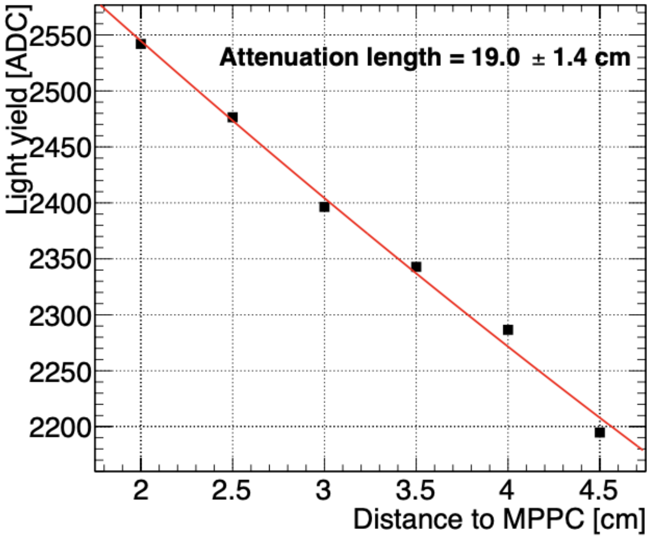


3DET, 2020 JINST 15 P10019







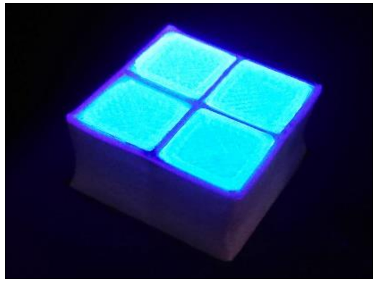


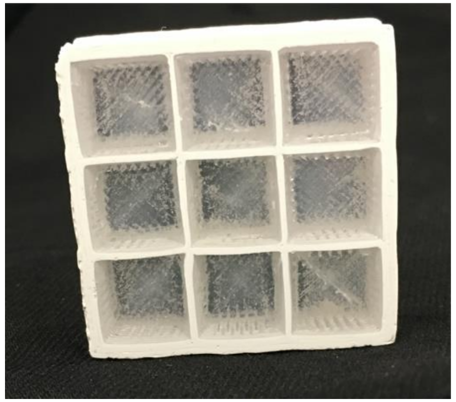
3DET, 2022 JINST 17 P10045

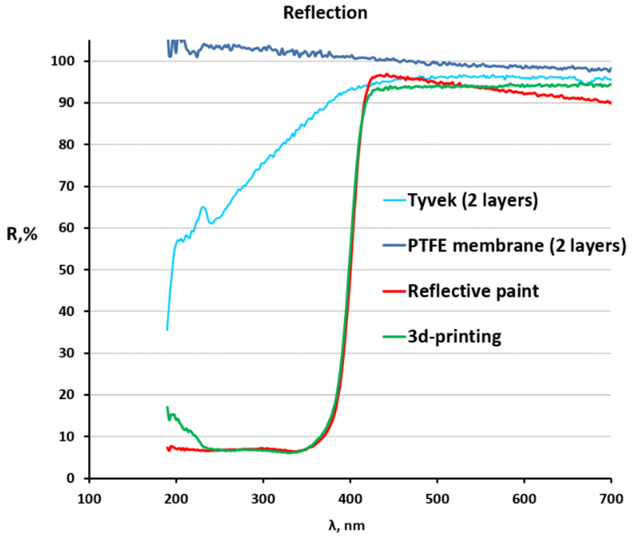
- 1 cm^3 cube samples produced via cast, extrusion, injection molding, and 3D printing with standard FDM printers.
- Exposed to ^{132}Cs, ^{90}Sr and cosmic muons for performance comparison.
- The scintillation light yield found to be comparable to cast and extruded scintillators.
- 3D-printed bar shows sufficient transparency → suitable for few-cm granularity detectors.

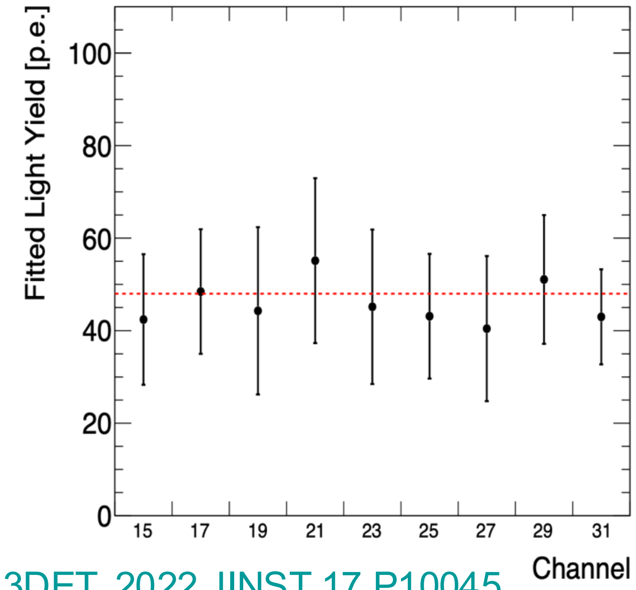
3D Printing Optically Isolated Scintillator Cubes layer

- **Successfully 3D print two material simultaneously** and produce a **matrix of optically isolated scintillator cubes**
  - Scintillating filament and PMMA+TiO_2 reflector filament
- 3x3 matrix layer with scintillator voxels of 10 mm cube and 1 mm thick reflector walls
  - **Caveats**: outermost surface not very precise due to the melting of the material at high temperatures and some reflector remnants in scintillator!
- Light output of ~45 photoelectrons (p.e.) and uniform among the cubes
- Cube-to-cube crosstalk of less than 2%.





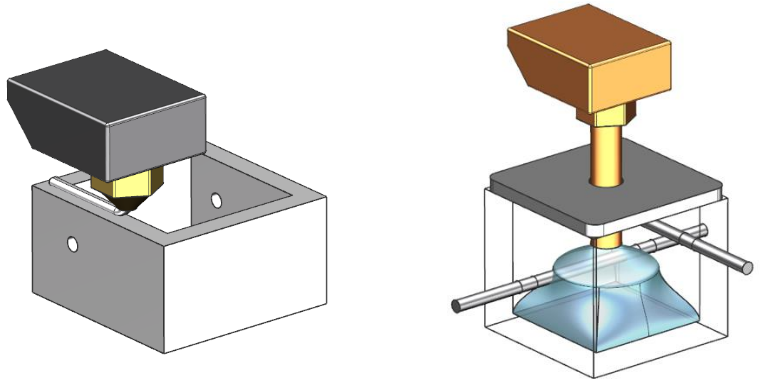




3DET, 2022 JINST 17 P10045

Fused Injection Modeling (FIM)

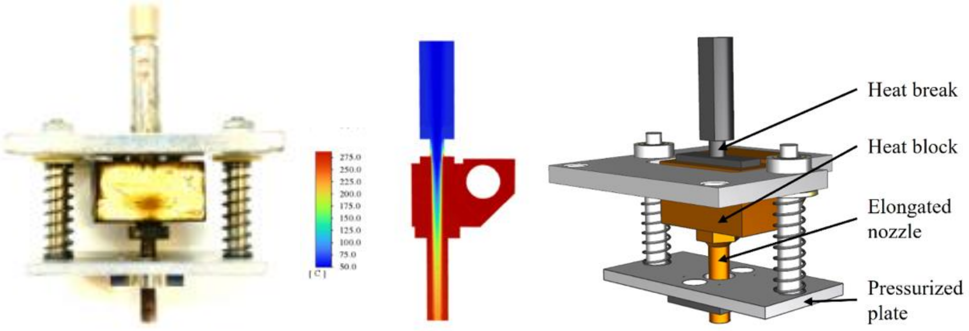
- Combination of **FDM (3D printing)** + **injection molding**.
- 3D-printed reflective frame (FDM) filled with molten scintillator (injection).
- Integrated cylindrical holes for WLS fibers → no post-processing.



Developed a custom high-temp extrusion system:

- Copper heat block → fast heat transfer
- Stainless-steel heat break → strong thermal barrier
- PEEK feeding tube → heat resistant

Combined with a spring-loaded plate → Stabilized nozzle motion and constrained the melt pool



Process optimization:

- Temperature distribution from CFD: heat block temperature of 300C and extrusion speed of 15 mm/s
- Maintaining the PS temperature at 230°C at the nozzle orifice → preserves the scintillation properties.

3DET, Commun Eng **4**, 41 (2025)

Fully monolithic – no cutting, polishing, or post-processing required

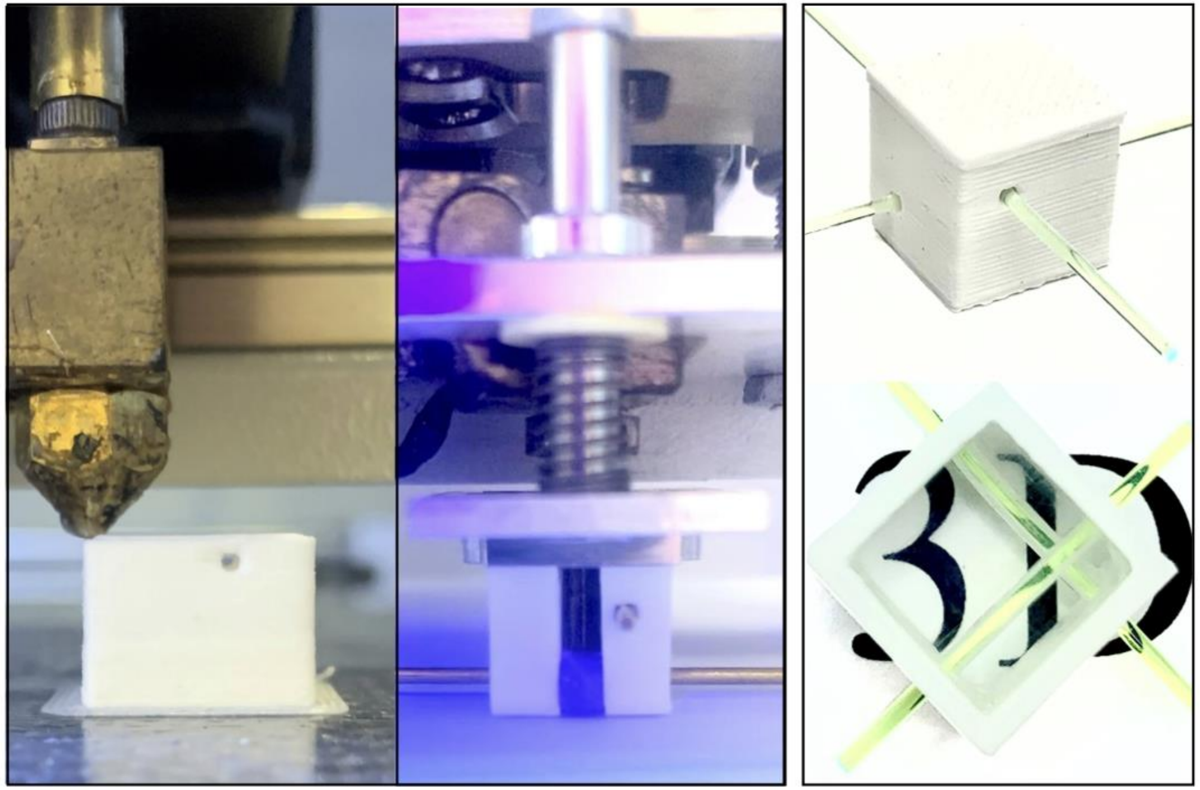
Fabrication of the First SuperCube

- **Material:** A commercial filament made of white polycarbonate + PTFE heat resistant (~300℃) was used to preserve geometrical shape
  - Transmission at 420 nm:
    - 1.2mm thickness (horizontal wall): ~13%
    - 1.5mm thickness (vertical wall): ~18%

- **Design:** Reflective frame with holes produced via FDM, then metal rods placed through the holes to create circular voids (1.1 mm) for WLS fibers (1 mm)

- **Filling process:** Voxel filled rapidly in a bottom-to-top motion

- **Speed**: 6 minutes per voxel, **~10x faster than FDM**



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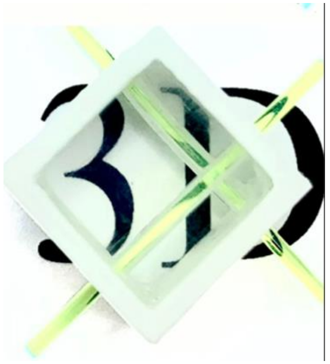
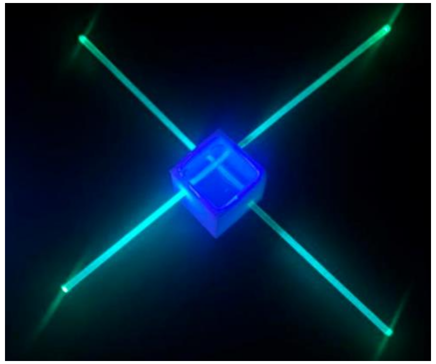
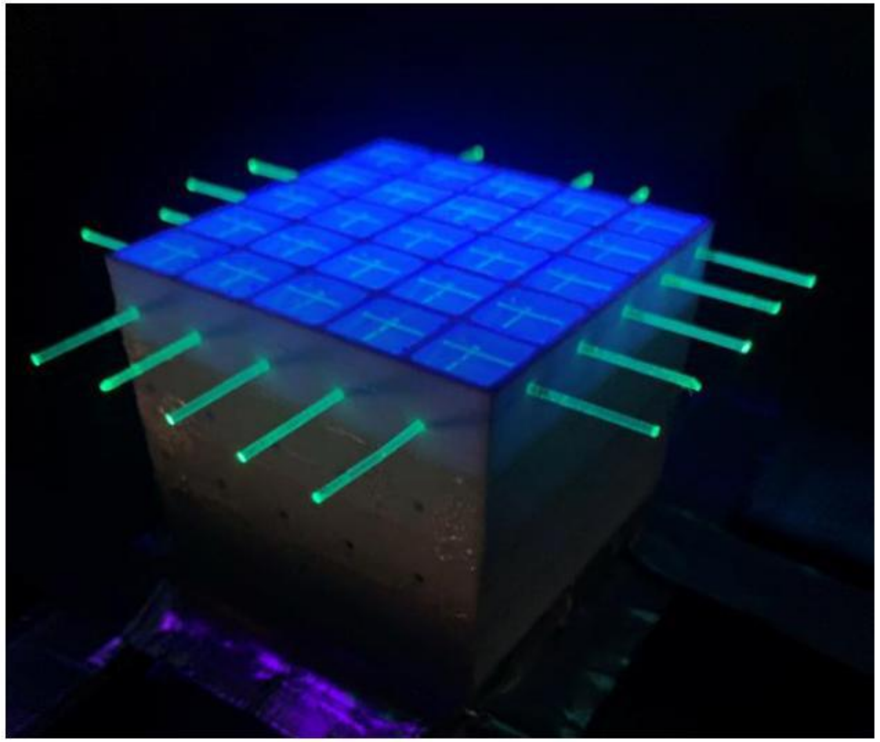
Monolithic SuperCube with FIM







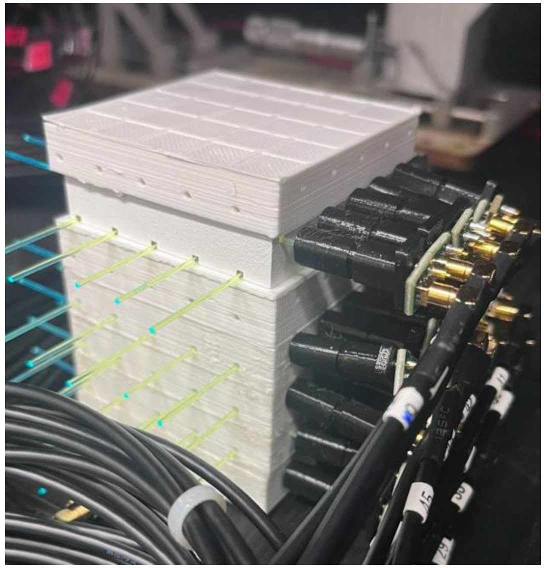
Complete 5th layer, UV-light exposed.

- 5 x 5 x 5 matrix of scintillating cubes were manufactured accurately with holes to place WLS fibers,
- Very good transparency and optical isolation
- No postprocessing was required
- As reflector commercial filament of polycarbonate + PTFE used

*3DET, Commun Eng **4**, 41 (2025)*

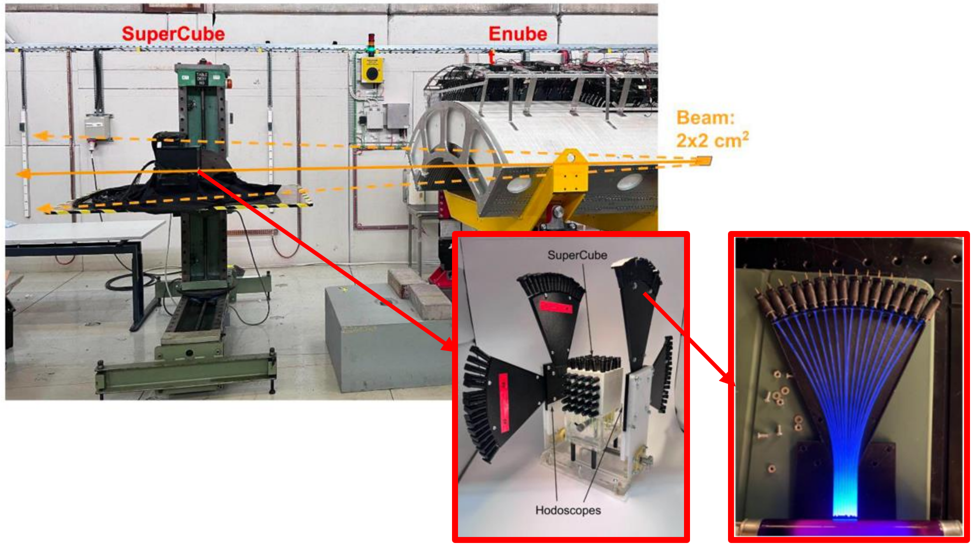
Characterization of Monolithic SuperCube

With Cosmic muons



- Compared with glued-cubes layers manufactured using standard cast polymerization method
  JINST 16 (2021) 12, P12010
- Vertical muons used to study light yield and cross-talk

Charged particle beam from CERN-PS T9

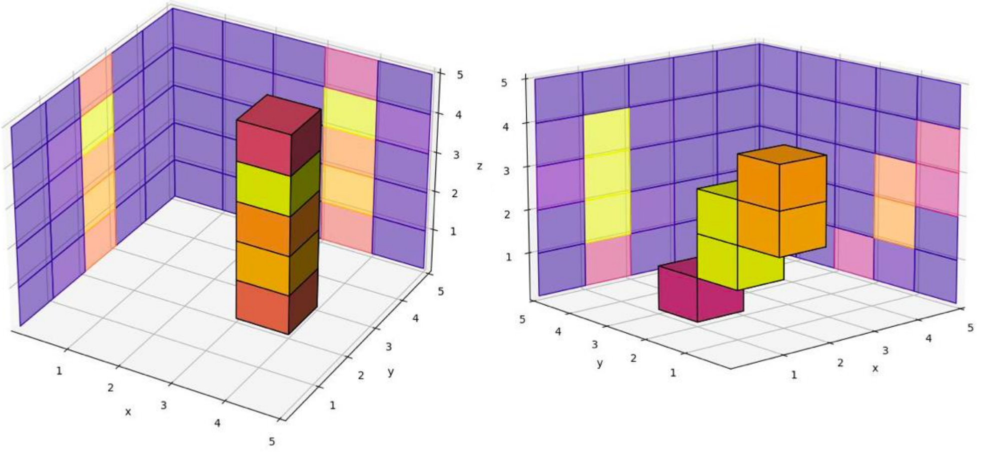


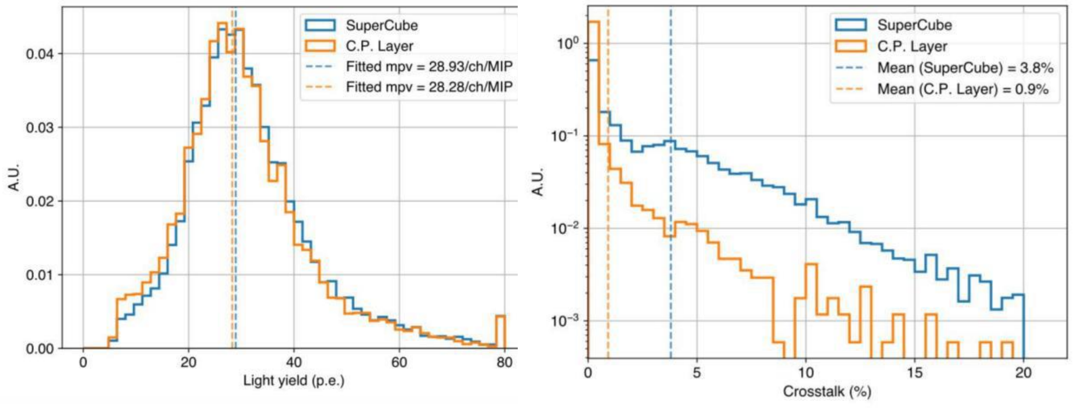
- Positioned downstream of ENUBET in the test beam
- Two hodoscopes (on each 16 x 1-mm square scintillating fibers) were assembled providing high spatial resolution particle tracking
  .3DET, *JINST* 20 (2025) 04, P04008

Fibers readout with MPPC S13360-1325 and signals digitized with CAEN FERS DT5202

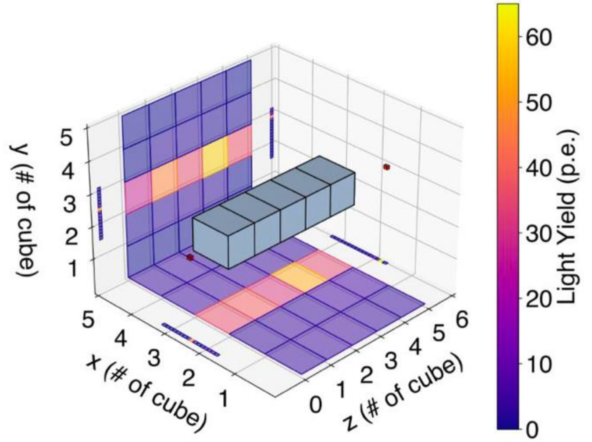
Characterization of Monolithic SuperCube

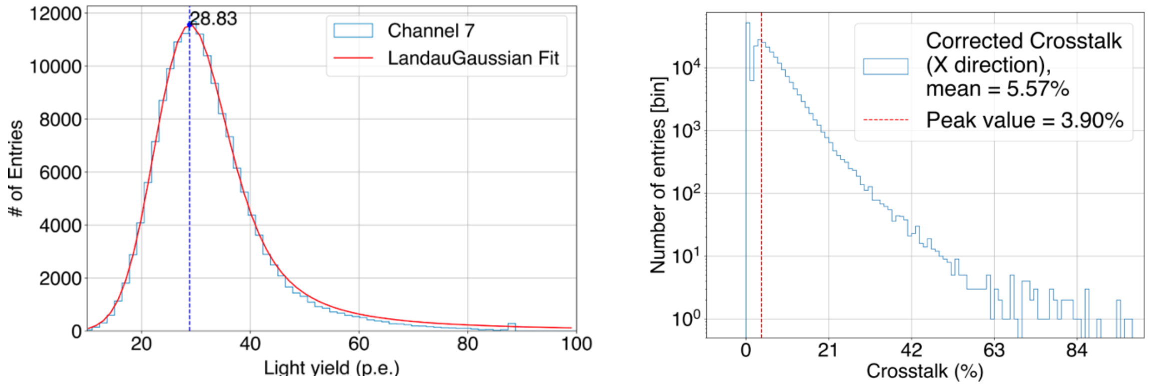
With Cosmic muons





Charged particle beam from CERN-PS T9





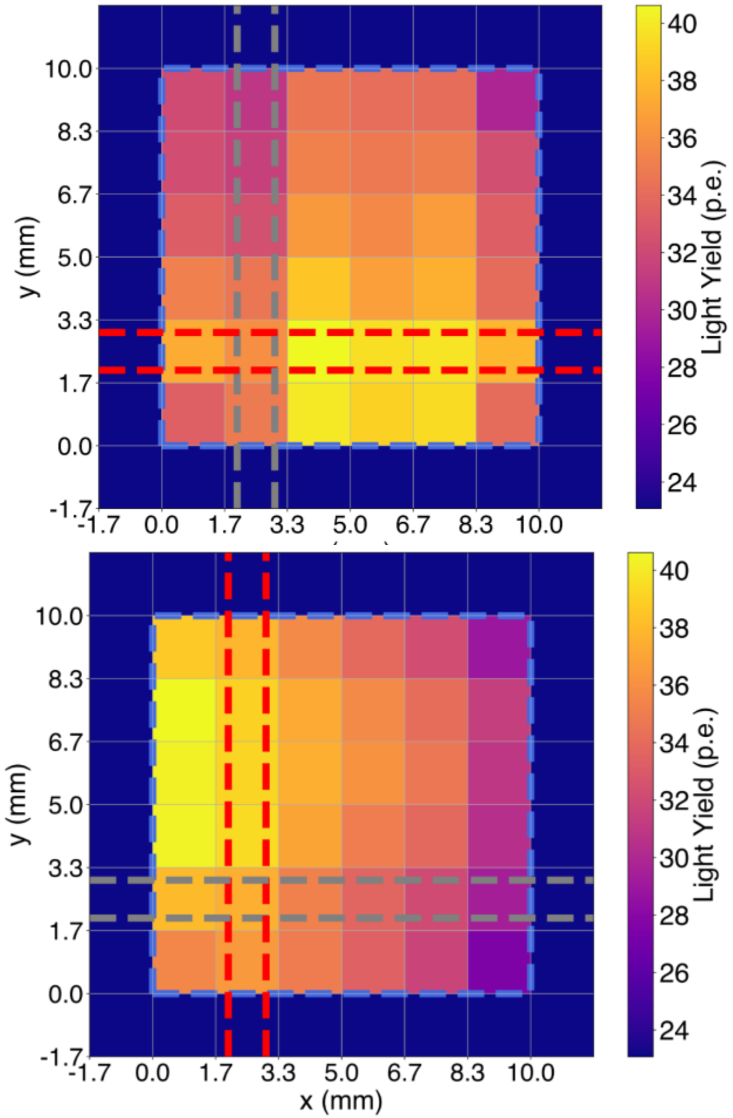
Light yield: 29 p.e./channel
Cross-talk: 3.8%/face

3DET, Commun Eng **4**, 41 (2025)

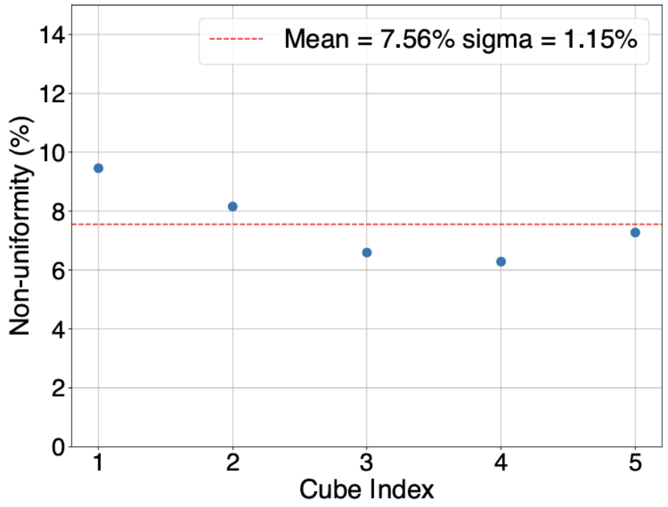
Light yield: 28 p.e./channel
Cross-talk: 3.5% for X fibers, 3.9% for Y fibers

3DET, *JINST* 20 (2025) 04, P04008

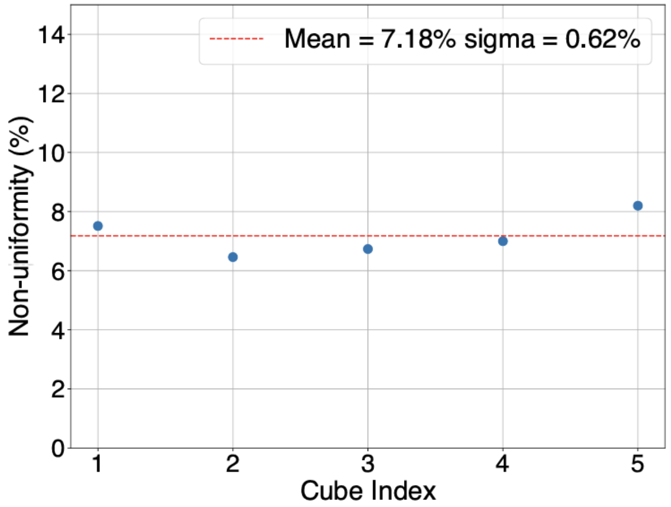
Non-Uniformity in the light response



X-fiber



Y-fiber



Light yield as a function of particle incident position in a single cube

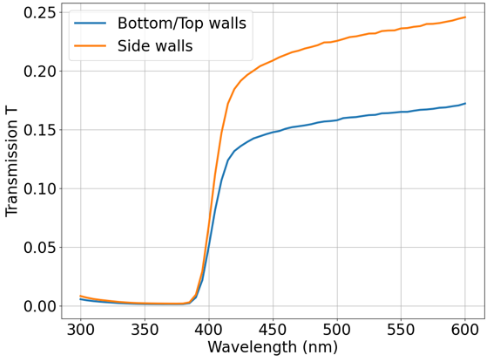
Non-uniformity within a single cube measured to be approximately 7%

.3DET, *JINST* 20 (2025) 04, P04008

New diffuse reflector filament: Why?

- For finely segmented 3D scintillator, **high reflectivity and low transmittance** are crucial

- **Limitations of previous reflectors**:
  - **PMMA+TiO_2** → high reflectivity, but low heat resistance
    - the material could not maintain its structural integrity during printing/injection of scintillating filament due to the similar heat resistance of the reflector to the PS
  - **Commercial filament PC+PTFE** →heat resistant, good to preserve geometrical shape but has high transmittance (13% horizontal - 18% vertical wall)



- Challenge to find a reflector that is both optically and mechanically optimal:
  - Developed new high-performance reflector filament compatible with FIM fabrication
  - Polycarbonate (PC) or PMMA base with various fraction of additives of TiO_2 + PTFE
  - Produced via extrusion → diameter ~1.75 mm (FDM standard)

- Tested reflectivity and transmittance from 200 to 800 nm at various thicknesses

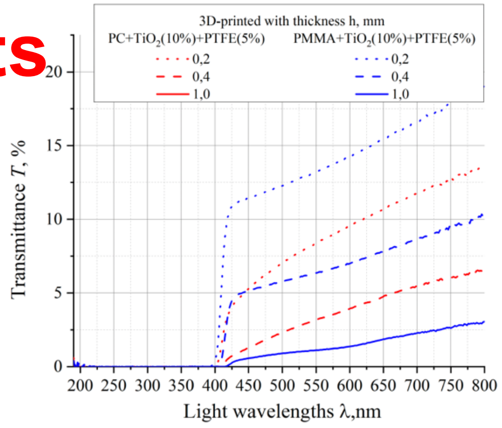
- Validation by manufacturing 4 x 4 x 1 cm^3 SuperLayers and performed cosmic muon test,

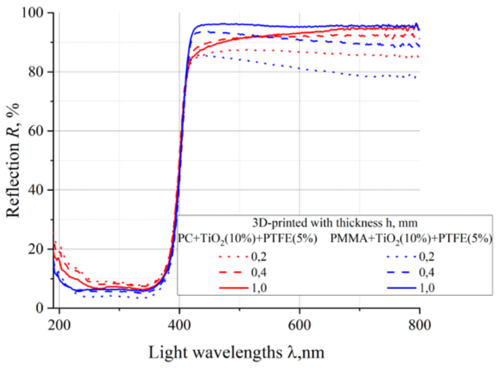
3DET, arXiv: 2509.01247

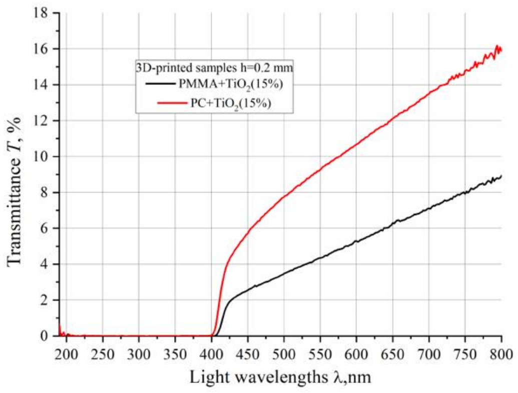
Optical Results of new reflector filaments

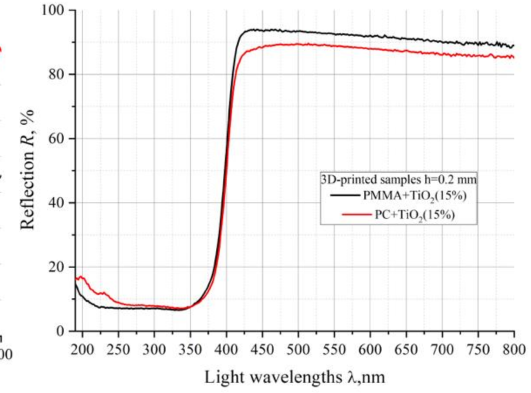
Sample Composition	Reflectivity R (%) 0.2 mm	0.4 mm	1.0 mm	Transmittance T (%) 0.2 mm	0.4 mm	1.0 mm
PC + TiO_2 (15%)	81.38	82.96	83.36	3.81	0.55	0
PC + TiO_2 (10%) + PTFE (5%)	83.35	86.22	84.47	3.60	0.55	0.01
PC + TiO_2 (20%)	77.23	78.55	71.70	0.35	0.32	0
PC + PTFE Nanovia [8]	–	–	68.69	–	–	18.67
PMMA + TiO_2 (10%) + PTFE (5%)	84.73	90.53	92.07	10.36	3.69	0.1
PMMA + TiO_2 (15%)	91.95	92.53	91.1	1.57	1.69	0.01

R: Measured light reflectivity at $\lambda = 420$ nm (%)
T: Measured light transmittance at $\lambda = 420$ nm (%)
Each sample was printed at the indicated thickness and characterized optically.







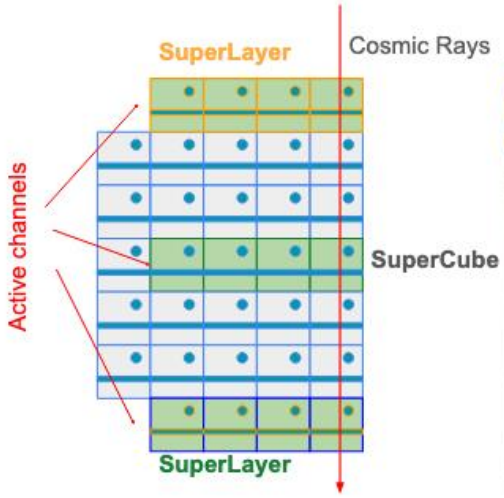


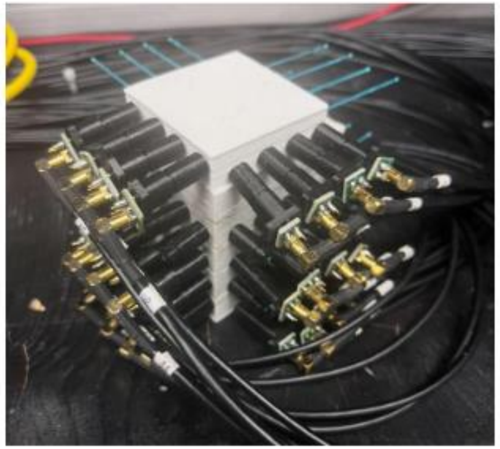
- PMMA + 15% TiO2 → best reflectivity but lower softening temperature
- PC + 10% TiO2 + 5% PTFE → best compromise between reflectivity and transmittance

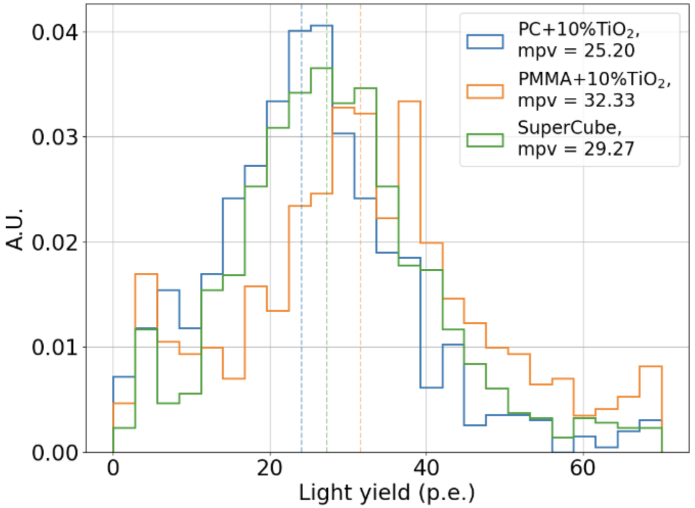
3DET, arXiv: 2509.01247

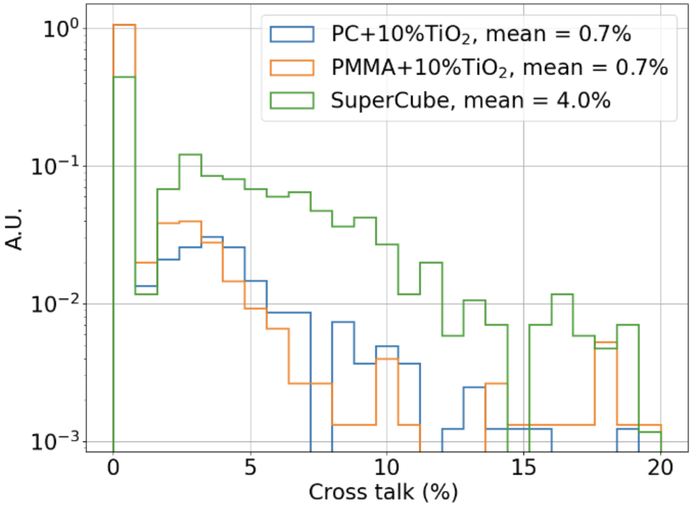
Validation of new reflector filaments

- Two SuperLayers (SL), 4x4x1 cm3 were manufactured, using:
  - PC + 10% TiO_2 + 5% PTFE
  - PMMA + 10% TiO_2 + 5% PTFE
- 1 mm thick reflective walls
- For test, SuperCube used as a reference (with commercial white reflector filament)
- Each SL read out by 8 WLS fibers and MPPC S13360-1325
- CAEN FERS FEB DT5202









	Light Yield (p.e./MIP/channel)	Cross talk (%)
SuperCube	29	4.0
PMMA based SL	32	0.7
PC based SL	25	0.7

3DET, arXiv: 2509.01247

Conclusions:

- Successfully demonstrated the **first fully 3D-printed**, **monolithic**, **optically segmented scintillator detector**
  - Capable of particle tracking, energy loss measurement and calorimetry
  - Fused Injection Molding enables fast, scalable, automated production of detectors with fine 3D granularity,
  - Manufacturing a single monolithic block
  - Without the need for any subtractive processes → ready-to-use

- **Performance comparable** to detectors with similar geometries produced using traditional manufacturing processes: cast, extrusion: both cosmic and beam test results confirm

- Moreover, **new diffuse reflector filaments** developed and validated, providing good optical and mechanical properties, to improve light yield and reduce cross talk among voxels.

- We are currently **designing a fully automated 3D printer** capable of creating holes along all three axes

One of the final goal to 3D print a neutrino detector (see talk by D. Sgalaberna, NuFact2025)

- More 3D printed particle detectors:
  - Developed 3D printing inorganic scintillator detector T. Sibilieva et al., JINST 18 (2023) 03, P03007
  - Additionally, we developed neutron sensitive scintillating filaments (with Boron). As a reference samples with standard manufacturing prepared (1cm3 cube, bar, 3x3x1 voxels layer). 3D printed samples will be prepared soon using FIM method

Thank you!

References:

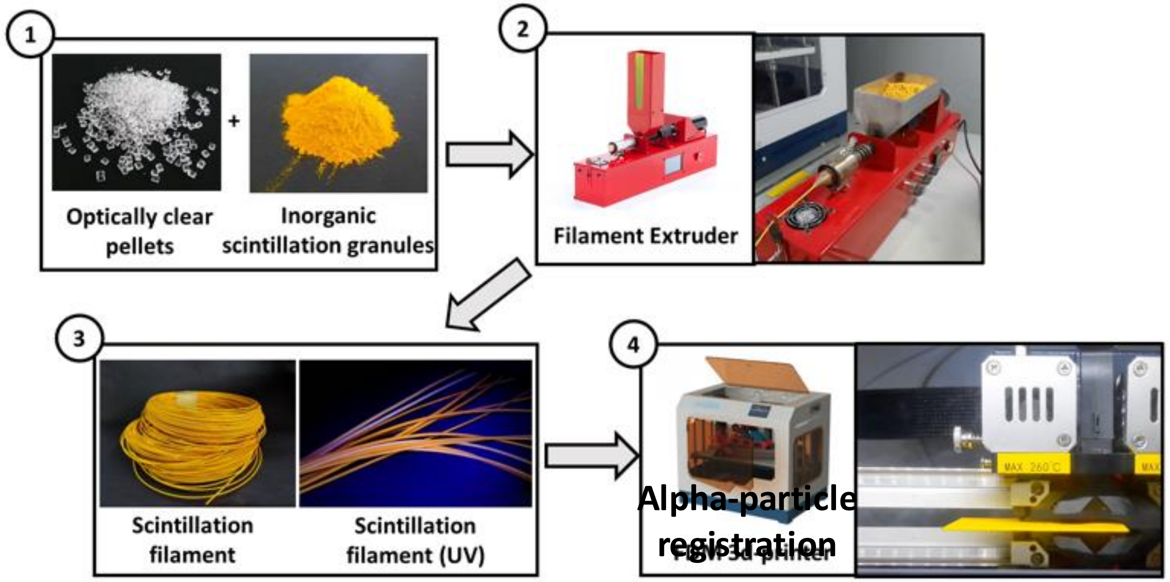
[1] The 3D printed DETector Project:
https://threedet.web.cern.ch/
[2] Additive manufacturing of a 3D-segmented plastic scintillator detector for tracking and calorimetry of elementary particles,
3DET Collaboration, T. Weber et al. arXiv:2312.04672
[3] Additive manufacturing of fine-granularity optically-isolated plastic scintillator elements
3DET Collaboration, S. Berns et al. JINST 17 (2022) 10, P10045
[4] A novel polystyrene-based scintillator production process involving additive manufacturing,
3DET Coll., S. Berns et al. *INST* 15 (2020) 10, 10
[5] Demonstrating a single-block 3D-segmented plastic-scintillator detector,
A. Boyarintsev et al., *JINST* 16 (2021) 12, P12010
[6] 3D printing of inorganic scintillator-based particle detectors
T. Sibilieva et al., JINST 18 (2023) 03, P03007
[7] Additive manufacturing of a 3D-segmented plastic scintillator detector for tracking and calorimetry of elementary particles
T. Weber et al., Commun.Eng. 4 (2025) 41
[8] Beam test results of a fully 3D-printed plastic scintillator particle detector prototype
B. Li.et al., *JINST* 20 (2025) 04, P04008
[9] A new diffuse reflector filament for additive manufacturing of 3D printing finely-segmented plastic scintillator
3DET Coll., S. Berns et al., arXiv:2509.01247

Backup

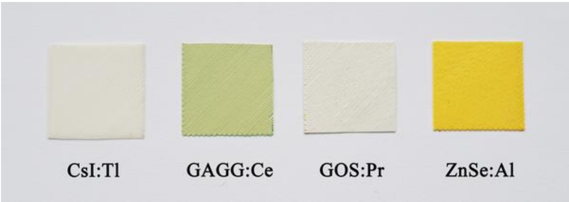
Additive Manufacturing Inorganic Scintillator-based Particle Detector

T. Sibilieva *et al* 2023 *JINST* **18** P03007

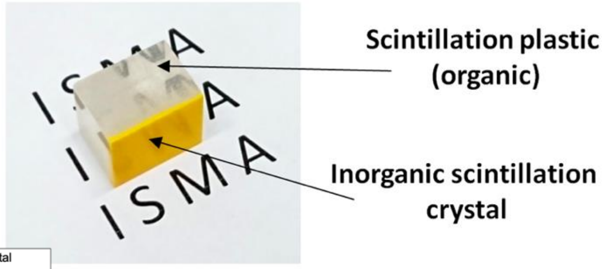
- Inorganic scintillators widely used in HEP, medical, and industrial detectors.
- Extend **3D printing (FDM)** to inorganic scintillators → fast prototyping & cost-effective large-area detectors.
- For alpha, beta, gamma and X-ray radiation
- 3D printed and tested samples from ZnSe:Al, GOS:Pr, GAGG:Ce, CsI:Tl



Alpha-particle registration

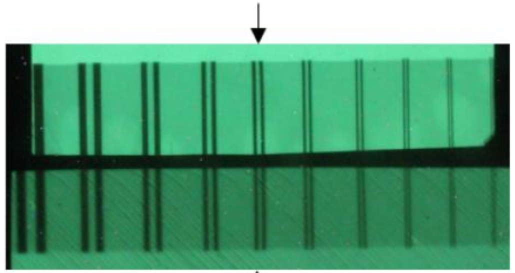


3D printing multi-material scintillators

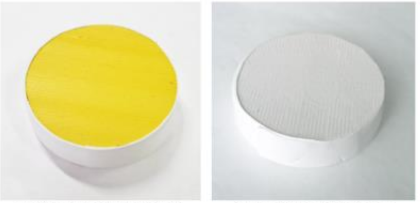


X-ray imaging screen

Reference GOS:Pr

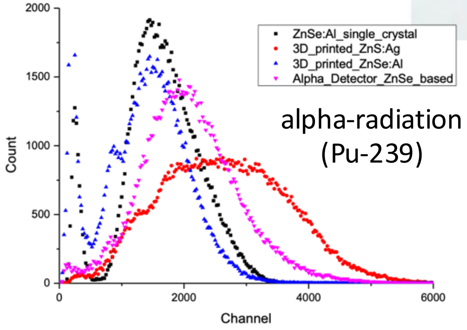


3D printed GOS:Pr



3D printed ZnSe:Al with PS

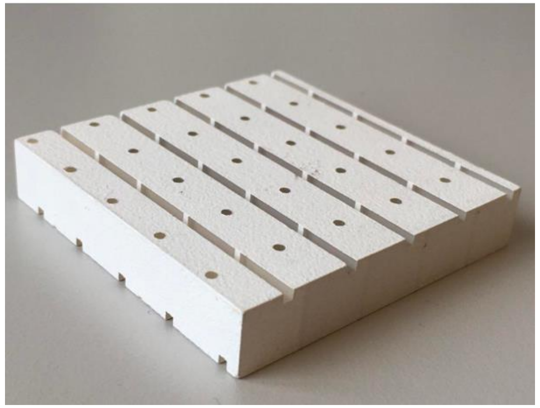
3D printed ZnS:Ag with PS

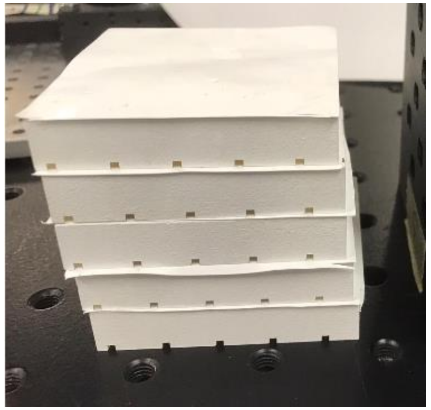


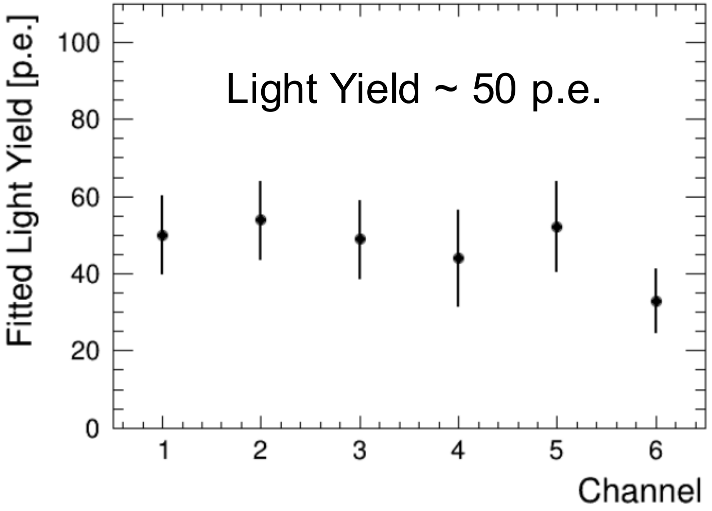
alpha-radiation (Pu-239)

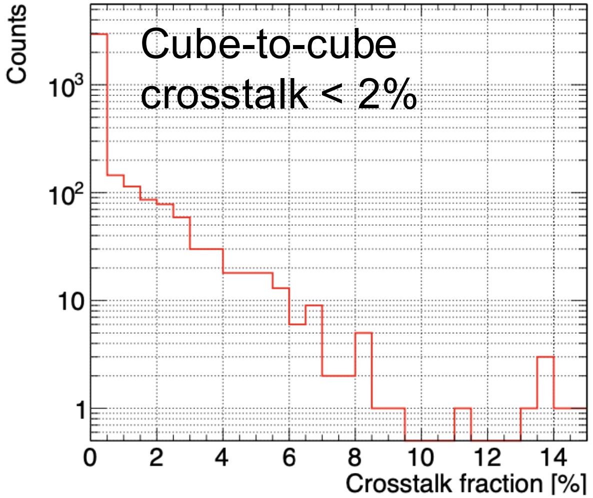
A single-block 3D-segmented plastic-scintillator detector

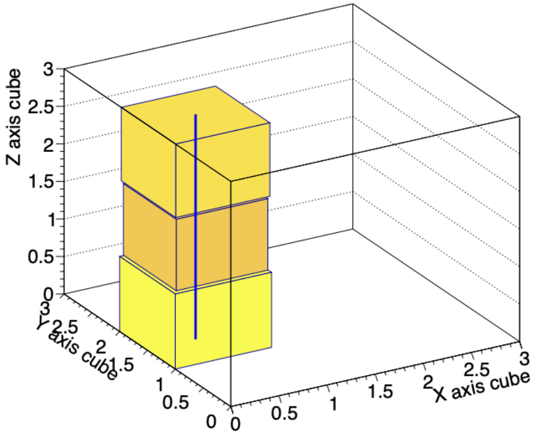
- A plastic scintillator is produced
- 1 mm gaps are created in the layer using CNC machining to form a matrix of cubes.
- Gaps are then filled with a white reflective epoxy resin
- Groves along X-Y and hole along Z
- Performance test: three 2D readout view and tyvek sheets to isolate layers; single cladding WLS fibers read out by Hamamatsu S13360-1350CS











Such technique can be scaled up to at least 50x100cm^2, a single block layer of 5000 optically isolated 1cm^3 cubes.