Additive manufacturing of 3D-segmented plastic scintillator detectors for particle tracking and calorimetry

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on behalf of 3DET Collaboration

The 25th International Workshop on Neutrinos from Accelerators
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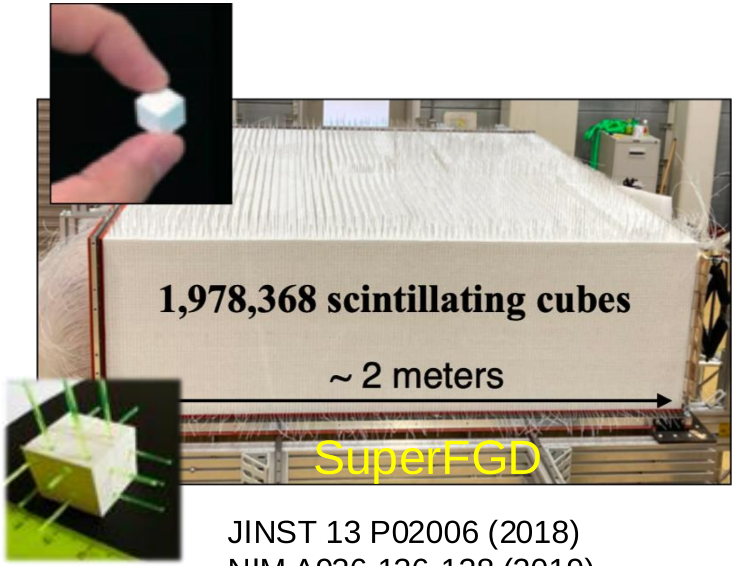
Why Additive Manufacturing?

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

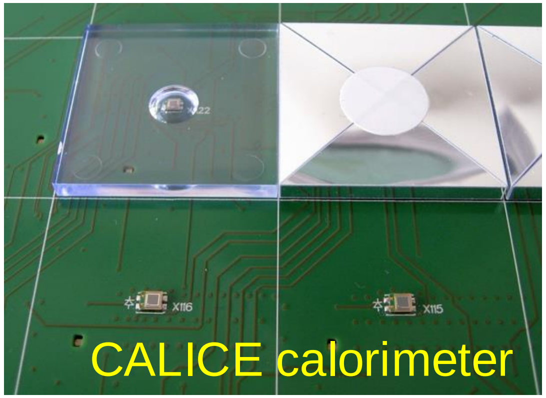
- Many experiments are incorporating or developing high granularity plastic scintillator detectors: <u>**larger volumes and finer segmentation**</u>.

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

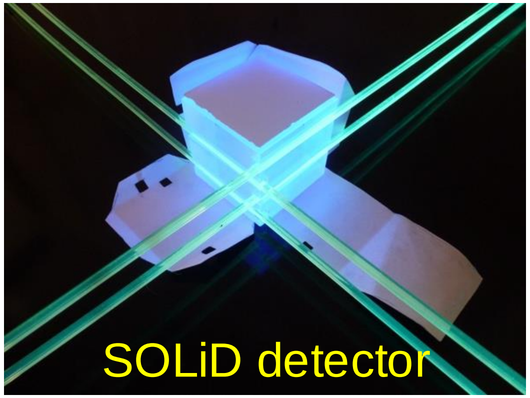
- **Additive Manufacturing may offer a solution**



JINST 13 P02006 (2018)
NIM A936 136-138 (2019)

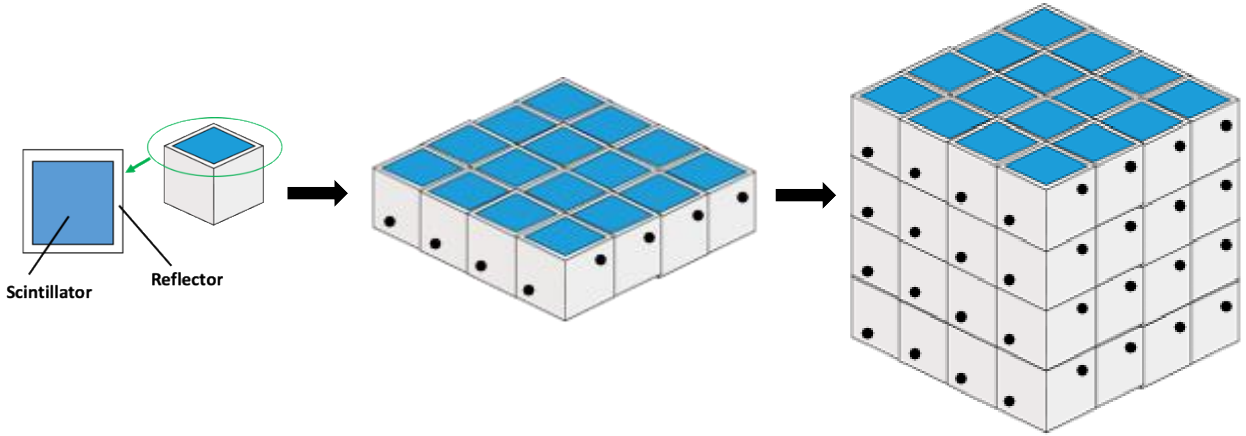


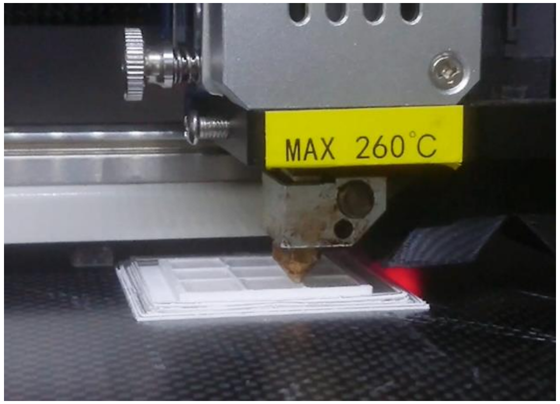
J. Phys.: Conf. Ser. 1162, 012012 (2019)



JINST 13 P05005 (2018)

Toward Additive Manufacturing of a SuperCube





- The **3D** printed **DET**ector R&D collaboration: the first 3D printed particle detector with performances comparable to the state of the art
  - 3D printing big volumes in relatively short time
  - Good scintillation performance and high transparency
  - 3D printing simultaneously multi-materials
  - Relatively fast and cheap

Promising solution: **Fused Deposition Modeling (FDM)**

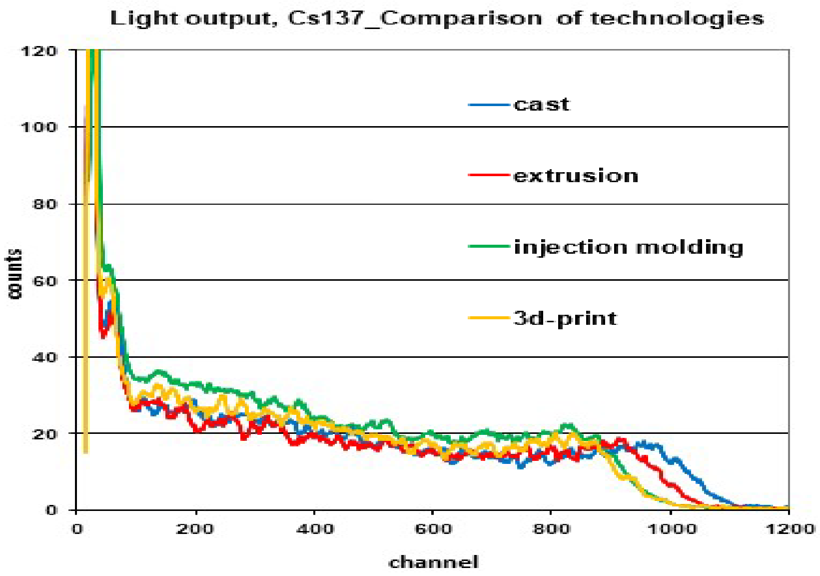
https://threedet.web.cern.ch

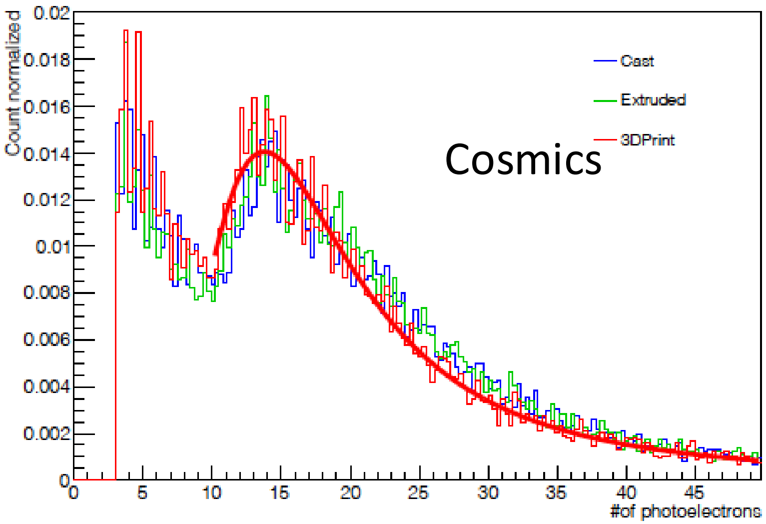
Proof of Concept: 3D printing of plastic scintillator

3DET, 2020 JINST 15 P10019

Optimal composition is Polystyrene + pTP + POPOP

Scintillation polystyrene samples 10*10*10 mm with plasticizers

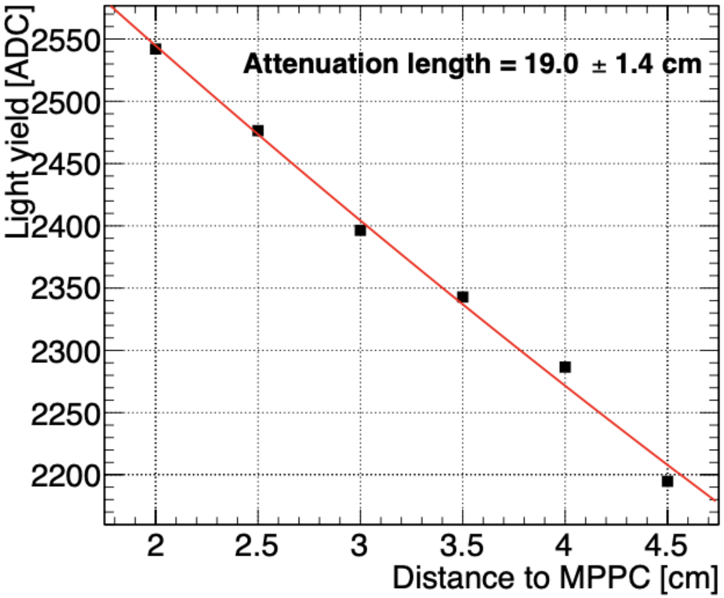




Attenuation length with 3D printing

3DET, 2022 JINST 17 P10045

- The 3D-printed sample (10 mm x 10 mm x 50 mm) was polished on the outermost surface and wrapped with white teflon
- The scintillator is pretty transparent
- Sparse presence of small air bubbles
- The line-by-line deposition of FDM is also visible
- SiPM directly coupled on one end and Sr^{90} source moving at different positions



The scintillator transparency was found to be sufficiently good for few-cm granularity detectors

3D Printing Optically Isolated Scintillator Cubes layer

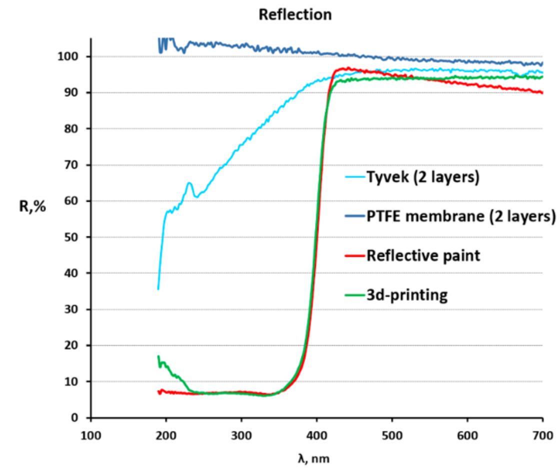
[3DET, 2022 JINST 17 P10045](#)

Polymer pellets

\+

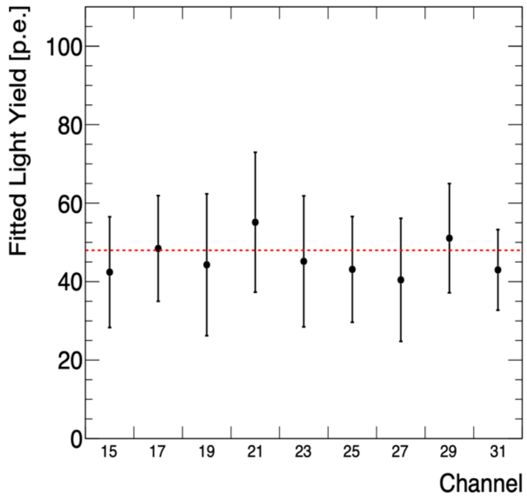
Reflective pigment TiO2
(or BaSO4, MgO...)

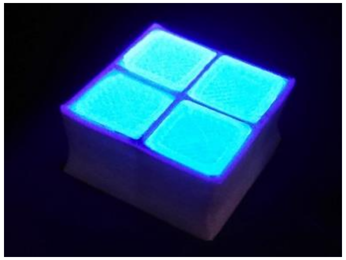
Reflective filament

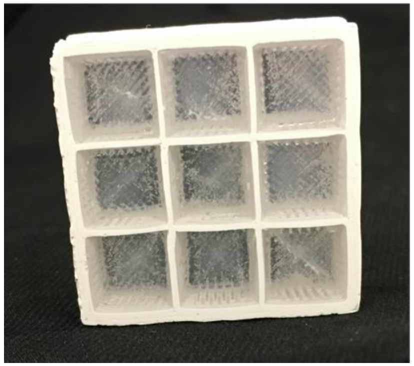


Reflector filament: 20% Ti02 in weight mixed with PMMA

- We could **successfully 3D print two material simultaneously** and produce a **matrix of optically isolated scintillator cubes**
- **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!





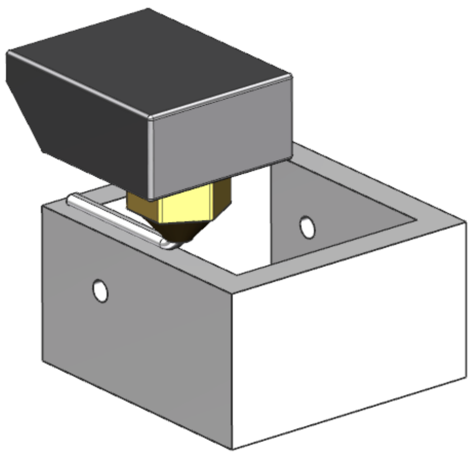


Light output of ~45 p.e.
PMMA+TiO2:
cube-to-cube crosstalk < 2%

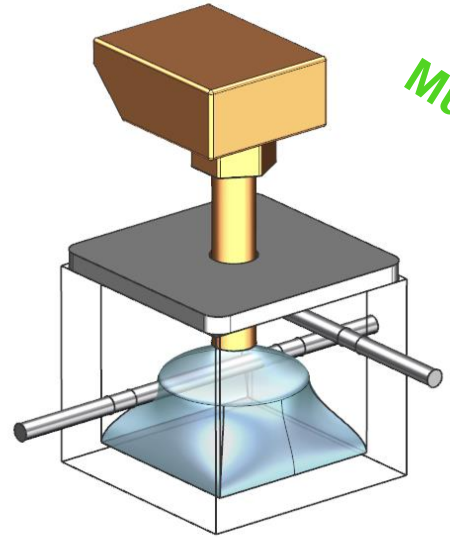
Innovative Progress in 3D printing: Fused Injection Modeling

3DET, arXiv:2312.04672

Method:



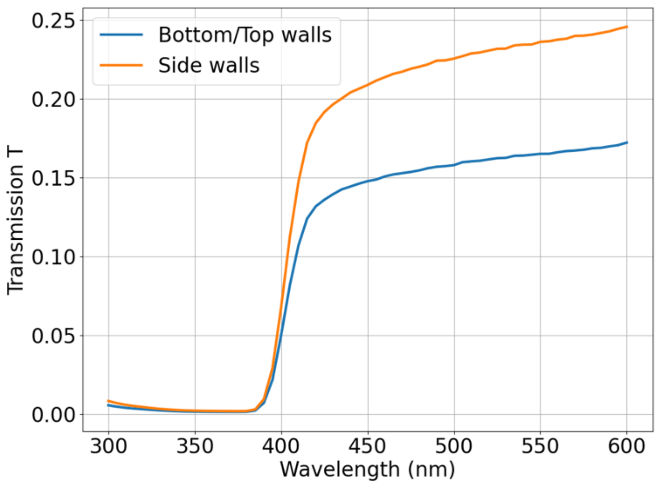
3D print the mold with FDM



Inject melted plastic scintillator

Much faster than standard FDM !

- The desired geometrical shape is preserved by a commercial filament made of white polycarbonate + PTFE heat resistant (~300℃)
- Transmission at 420 nm:
  - 1.2mm thickness (horizontal wall*): ~13%
  - 1.5mm thickness (vertical wall*): ~18%



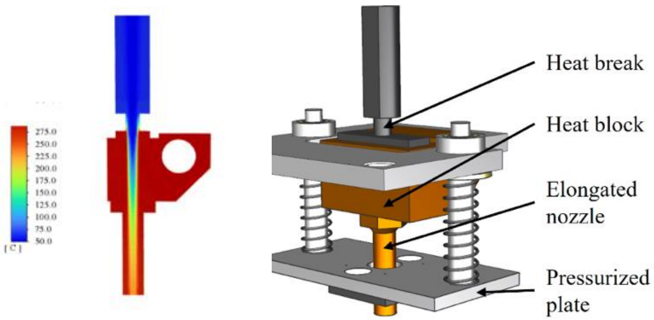
* Different in filling factors, defined thickness allows to obtain a uniform cube-to-cube light xtalk,

ETH Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

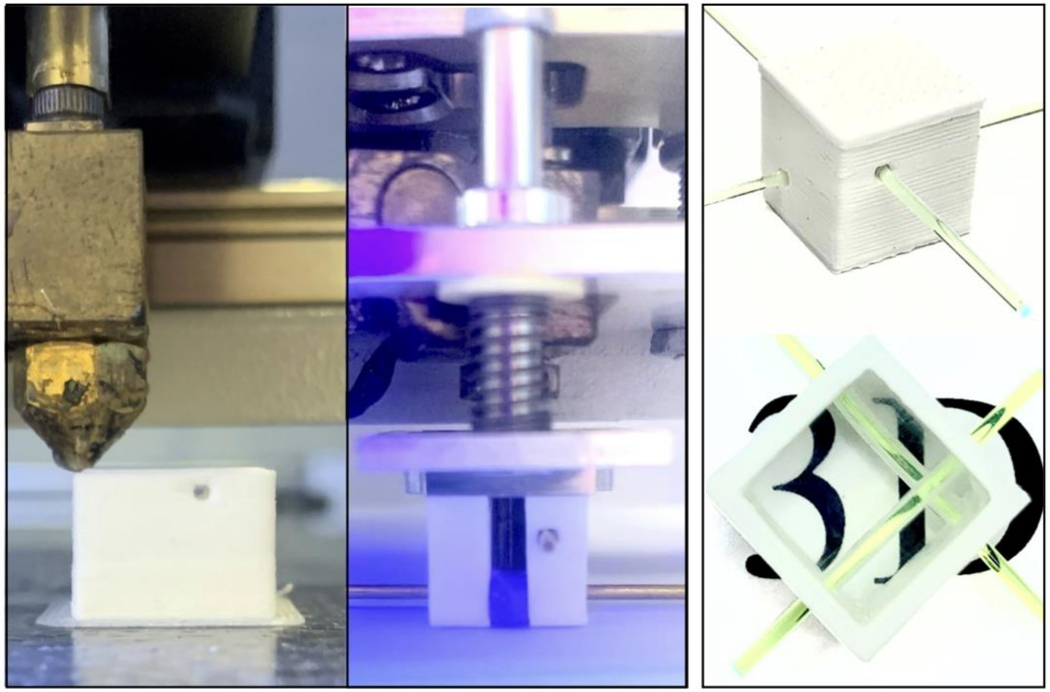
Implementation of Fused Injection Modeling

3DET, arXiv:2312.04672

Custom design of the extrusion system
(T. Weber, ETH-Z)



- Melting components, heat block and nozzle
- Temperature distribution from CFD: heat block temperature of 300 C, extrusion speed of 15 mm/s

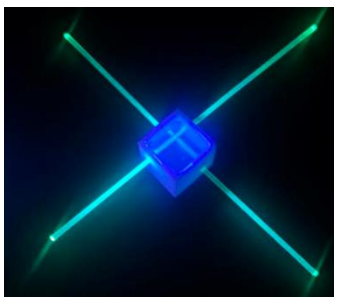


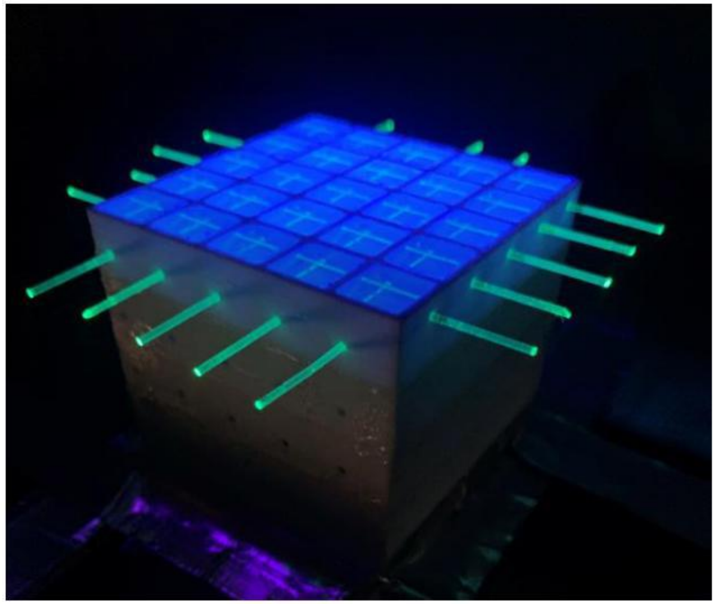
- Plastic scintillator temperature at orifice of ~230 C
- Reflective frame with holes produced via FDM, then metal rods placed through the holes to create circular voids (1.1 mm) for WLS fibers (1 mm)
- Voxel filled rapidly in a bottom-to-top motion

No subtractive process is needed!

3D Printing a Monolithic SuperCube with FDM + FIM

3DET, arXiv:2312.04672



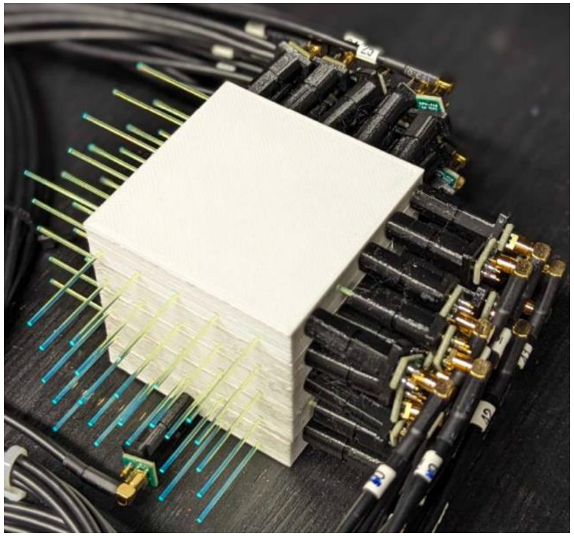


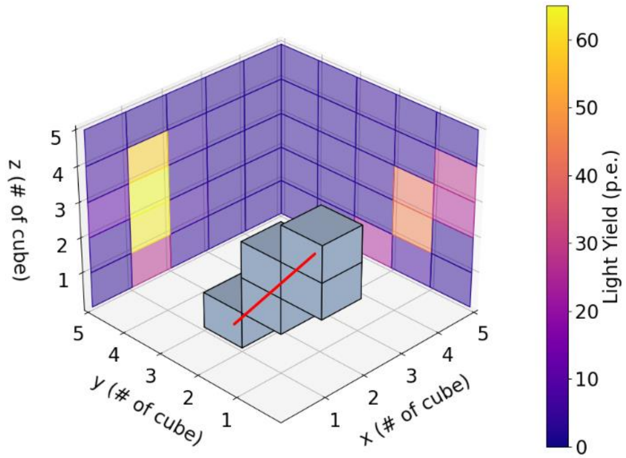
Complete 5th layer, UV-light exposed.

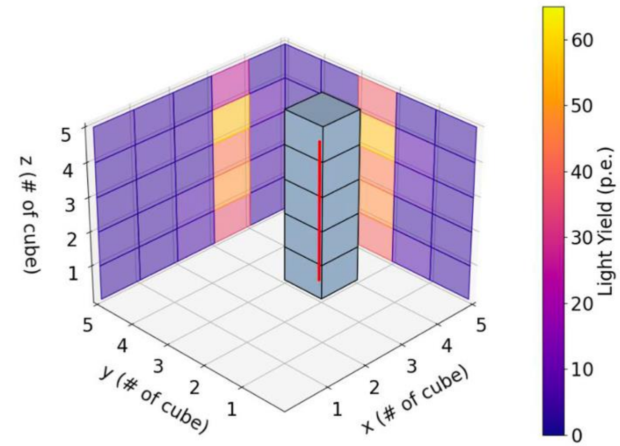
- 5x5x5 matrix of scintillating cubes were manufactured accurately with holes to place WLS fibers, very good transparency and optical isolation
- No postprocessing was required
- As reflector commercial filament of polycarbonate + PTFE used

Characterization of Monolithic SuperCube with Cosmic Rays

3DET, arXiv:2312.04672

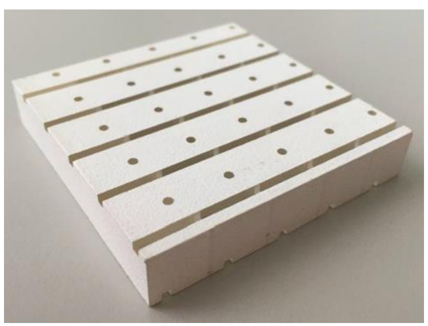




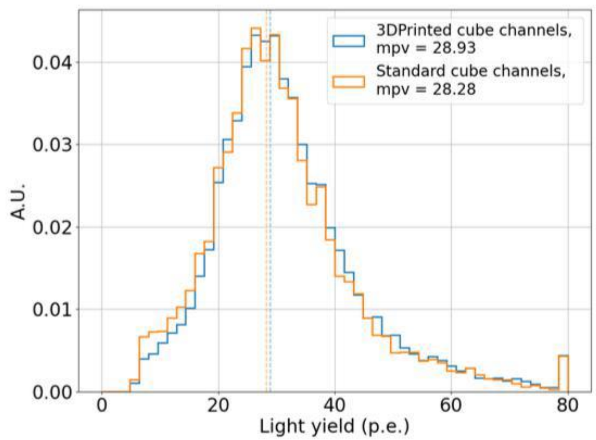


- WLS fibers readout by SiPM on one side
  - Hamamatsu S13360-1325CS with PDE ~ 25%
- CAEN FEB 5702 (FERS, CITIROC ASIC)

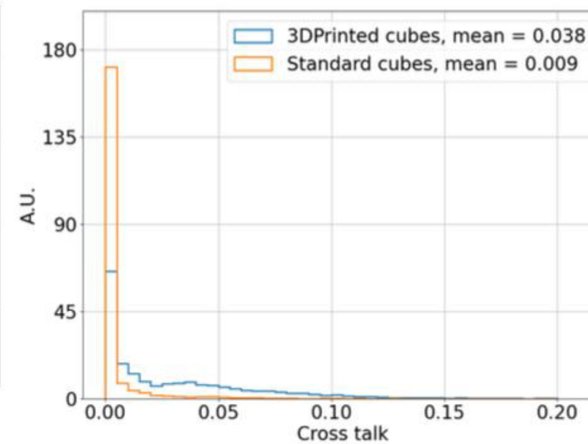
First ever 3D printed scintillator-based particle detector capable of tracking and calorimetry



Compared with standard scintillator cubes layer
JINST 16 (2021) 12, P12010

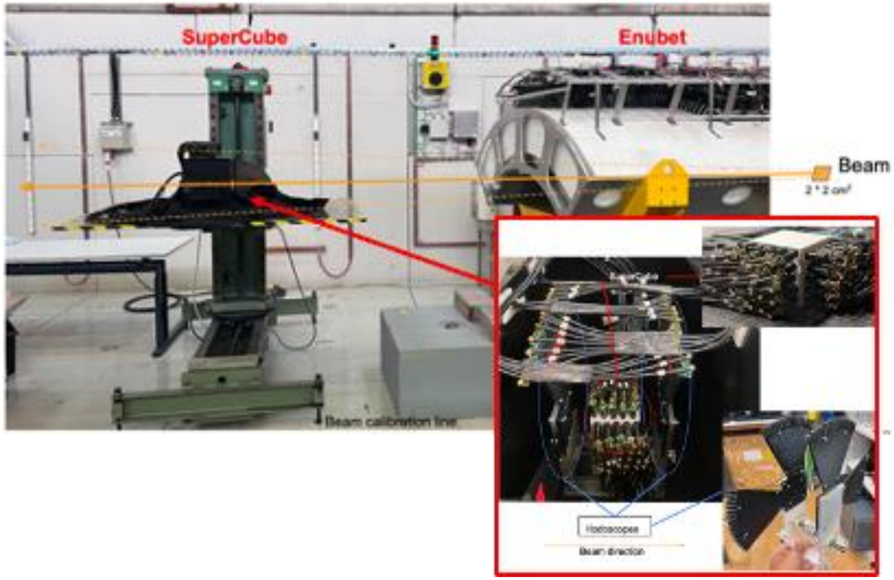


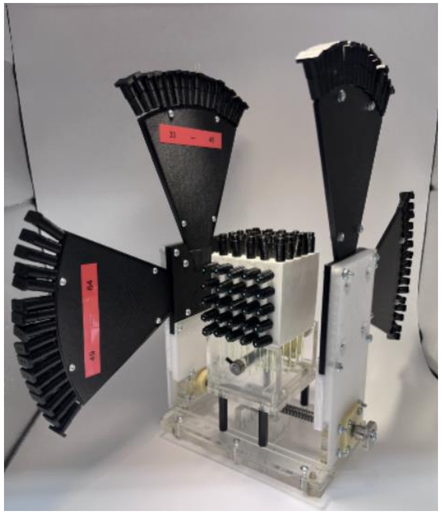
Single channel: ~ 28 pe/cm MIP

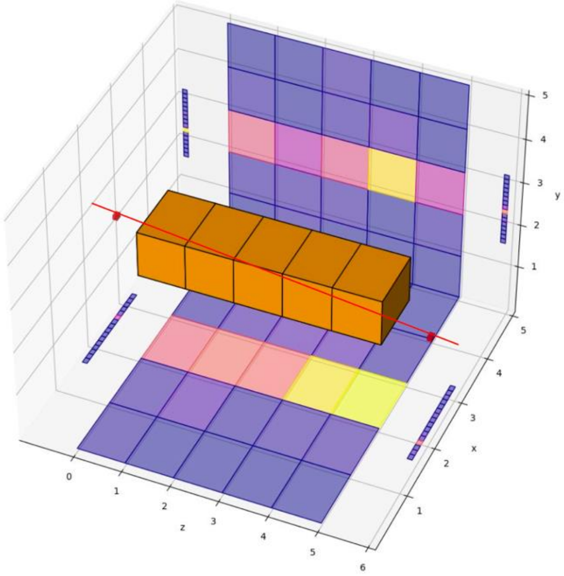


Crosstalk ~ 4%

Charged Particle beam tests with SuperCube

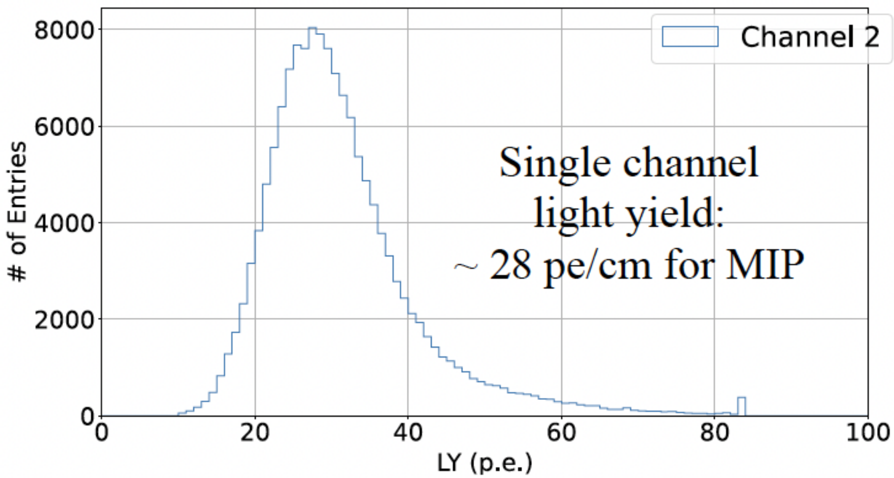


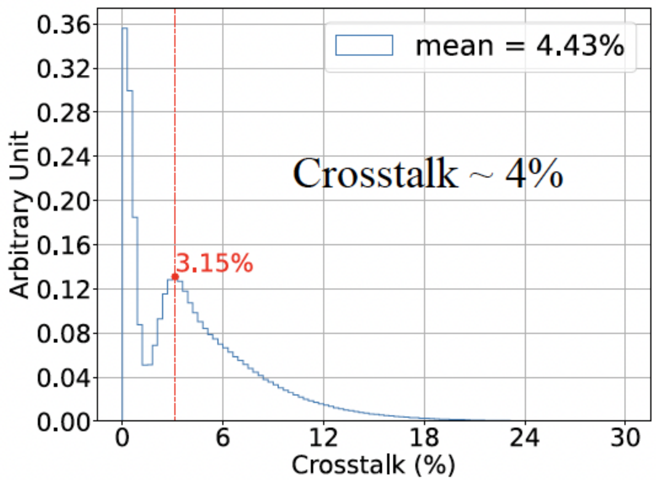




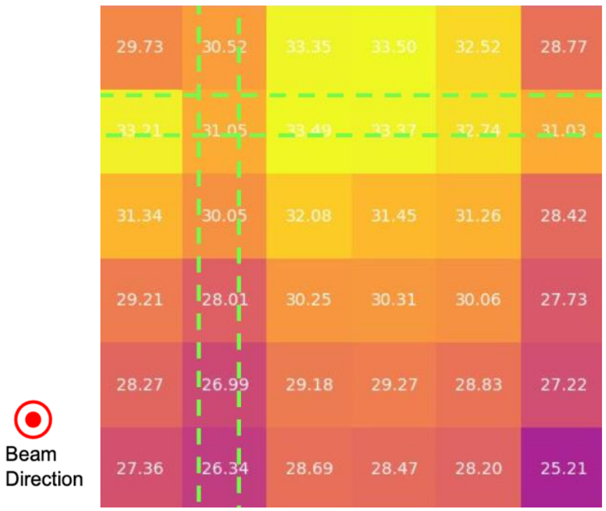
- Beam test at CERN T9 to confirm the performance with cosmic and evaluate scintillation light yield uniformity
  - Thanks to ENUBET colleagues for sharing their beam time
- Hodoscope of (16 X + 16 Y) 1 mm square scintillating fibers (Kuraray SCSF-78)

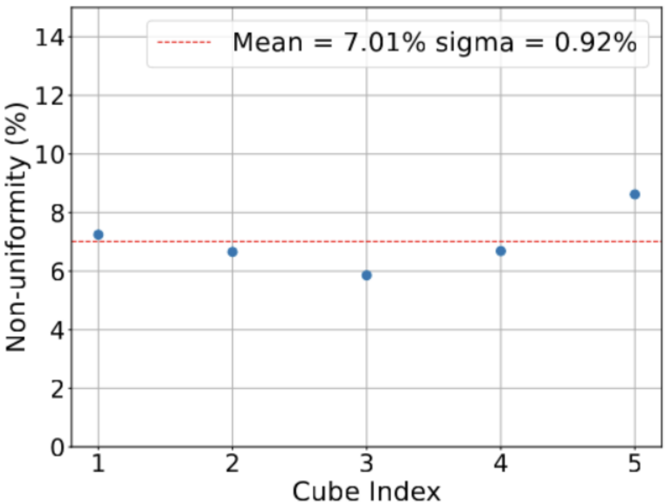
Performance of SuperCube at the Beam Tests





Confirmed the results obtained with cosmic ray data



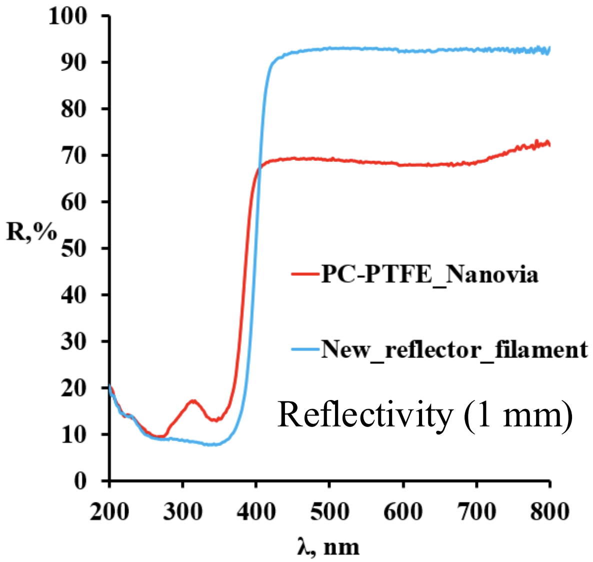


Light yield variance within a single cube within 7%

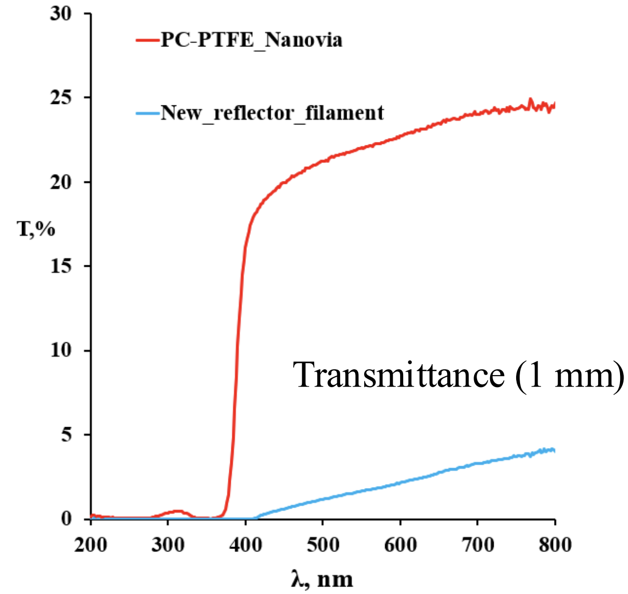
Advancement on Reflector Filament: Heat Resistant Reflector

Goal: reduce the light crosstalk (lower transmittance) and increase the light yield (higher reflectivity)

We developed a novel polycarbonate-based filament similar to the commercial one but with improved optical properties



Preliminary



Performance @420 nm :

1mm thickness: Refl. ~89%, Transm. ~0.2%

0.2mm thickness: Refl. ~81%, Transm. ~9.4%

Conclusions:

- Successfully demonstrated the use of 3D printing to fabricate plastic scintillator particle detectors with high granularity, and integrated holes for WLS fibers in a single monolithic block, without the need for any subtractive processes.
- Performance comparable to detectors with similar geometries produced using traditional manufacturing processes: cast, extrusion.
- Development is underway on 3D printing a new, heat resistant, high performance white reflector to minimize light crosstalk.
- Developed also 3D printing inorganic scintillator detector, see T. Sibilieva et al. JINST 18 (2023) P03007
- Future plans:
  - Development of SuperCube: Achieving a few mm granularity.
  - Process Engineering: Advancing towards a fully automated 3D printing process.
  - Introduction of Metal Filament: Creating the first 3D printing sampling calorimeter.
  - Optimized 3D printing: Producing plastic scintillators specifically designed for neutron capture.
- For those interested, 3DET is open to collaboration for applications and projects.

The 3d printed DETector (3DET) R&D collaboration
CERN, ETH Zurich, HEIG-VD, ISMA

- The collaboration profiting from expertise in particle detector development, scintillator materials and additive manufacturing
- Ongoing collaboration with IP2I Lyon on muon tomography
- Possibility to extend the collaboration to new institutes focused on specific developments

CERN ETH zürich heig-vd ISMA institute for scintillation materials

https://threedet.web.cern.ch

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

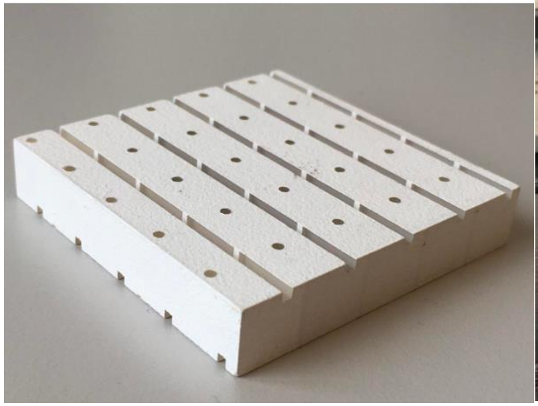
[5] Demonstrating a single-block 3D-segmented plastic-scintillator detector,
A. Boyarintsev et al., *JINST* 16 (2021) 12, P12010

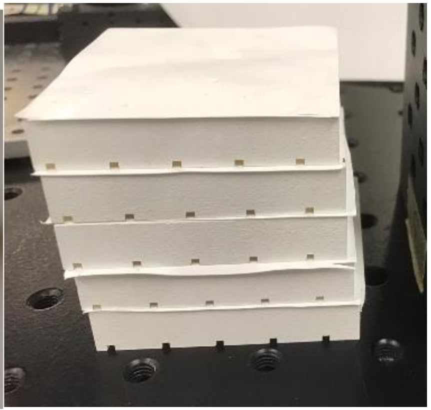
[6] 3D printing of inorganic scintillator-based particle detectors
T. Sibilieva et al., JINST 18 (2023) 03, P03007

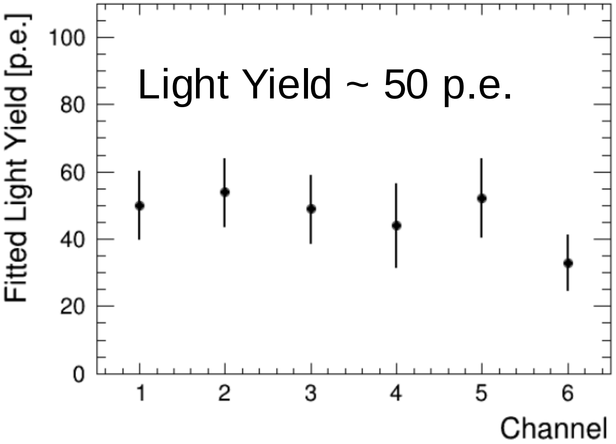
Back-up

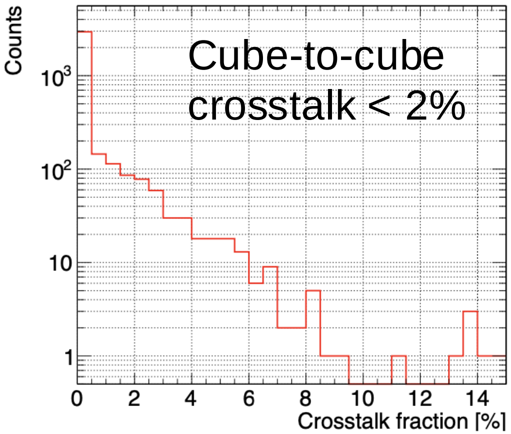
A single-block 3D-segmented plastic-scintillator detector

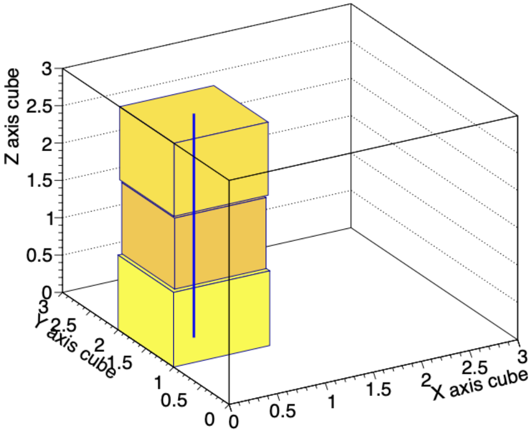
- A plastic scintillator is produced
- 1 mm gaps are created in the layer using CNC machining to form a matrix of cubes.
- Gaps are then filled with a white reflective epoxy resin
- Groves along X-Y and hole along Z
- Performance test: three 2D readout view and tyvek sheets to isolate layers; single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









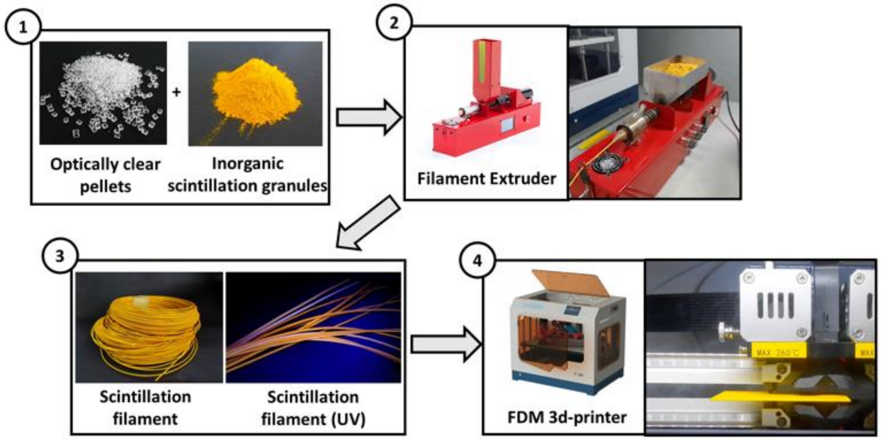


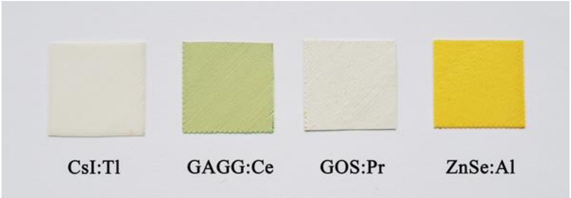
Such technique can be scaled up to at least 50x100cm^2, a single block layer of 5000 optically isolated 1cm^3 cubes.

3D printing inorganic scintillator-based particle detector

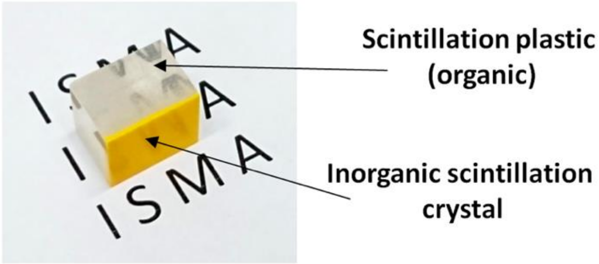
- For alpha, beta, gamma and X-ray radiation
- 3D printed and tested samples from ZnSe:Al, GOS:Pr, GAGG:Ce, CsI:Tl

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

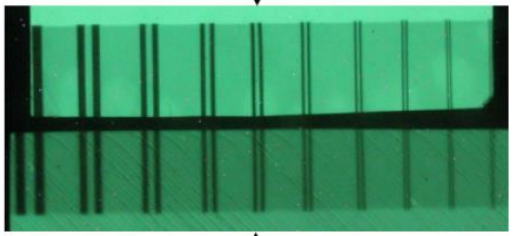




3D printing multi-material scintillators

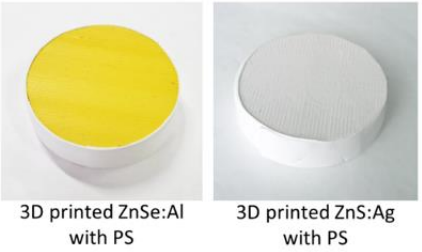


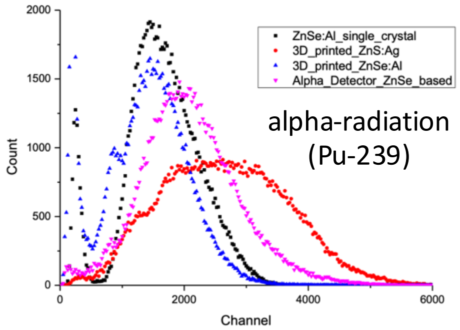
X-ray imaging screen
Reference GOS:Pr



3D printed GOS:Pr

Alpha-particle registration





ETH Eidgenössische Technische Hochschule Zürich Swiss Federal Institute of Technology Zurich