Cosmic ray muon scattering imaging system based on scintillation detector

MIP 2025

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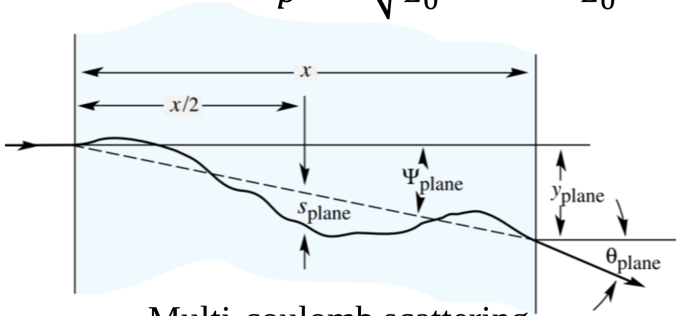
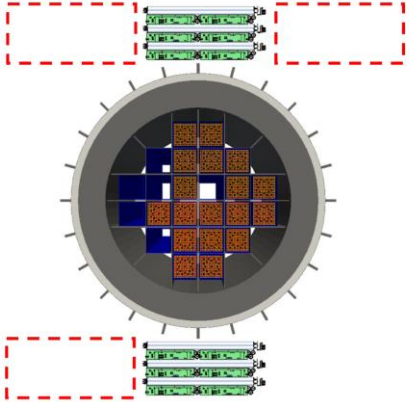
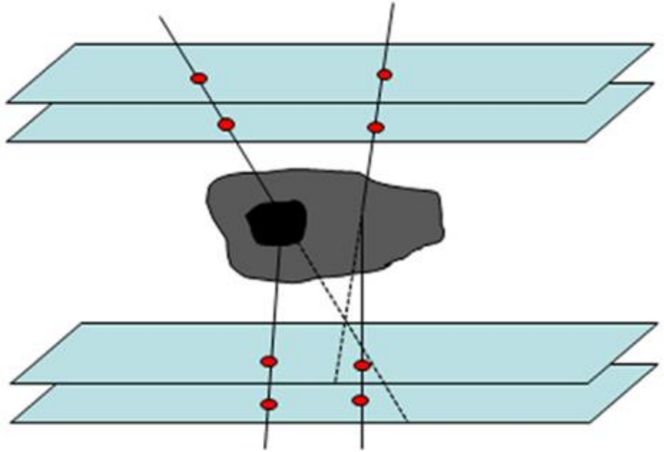
Muon scattering tomography (MST)

- $\sigma_\theta \approx \frac{13.6\text{MeV}}{p}\sqrt{\frac{L}{L_0}}, \sigma_\theta^2 \propto \frac{1}{L_0} \propto \rho \cdot Z \cdot \frac{Z}{A}$



Multi-coulomb scattering




Detection system for MST


Nuclear waste container imaging, LANL
PRA 9, 044013 (2018)

- Cosmic ray muon as probe:
  - High penetration
  - No extra radiation
- Muography: muon absorption
- Muon scattering tomography
  - Measuring scattering angle
  - Faster & more accurate (compared to muography)

- Proposed at 2003 for:
  - SNM controlling (border security)
  - Nuclear reactor & waste container
  - Nuclear weapons
  - …

Track detectors for MST

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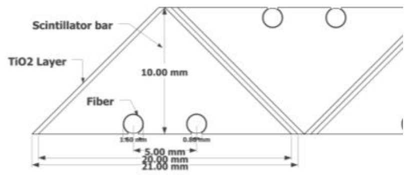
- Muon tracker
  - Gas detector: MRPC, drift chamber, MPGD, etc.
  - Scintillation detector: scint fiber / scint strips
- Challenges:
  - Large detection area (~ 1 m^2)
  - High angular resolution (~3 mrad)
  - Cost-effective, robustness

Project	Date	Type	Area (m^2)	pitch (mm)	σ_x (mm)	σ_x/p
LANL-LMT	2008	Drift Tube	3.65 × 3.65	50	0.4	0.008
AWE	2008	RPC	0.5 × 0.5	1.5	0.5	0.33
FIT	2011	GEM	0.3 × 0.3	0.4	0.13	0.33
INFN Muon Steel	2012	Drift Chamber	3.0 × 2.4	50	0.2	0.004
THU	2012	MRPC	0.7 × 0.7	~ 2.5	~0.5	~ 0.2
USTC	2022	Micromegas	0.15 × 0.15	0.412	0.085	0.21
Glasgow University	2013	Scint Fiber	0.25 × 0.25	2	0.6	0.30
DRDC CRIPT	2011	Triangle scint strips	2 × 2	16.5	3.5	0.21
INFN Muon Portal	2012	Square scint strips	1 × 1 × 18	10	3.2	0.32
LZU	2022	Triangle scint strips	0.48 × 0.48	15	2.5	0.17

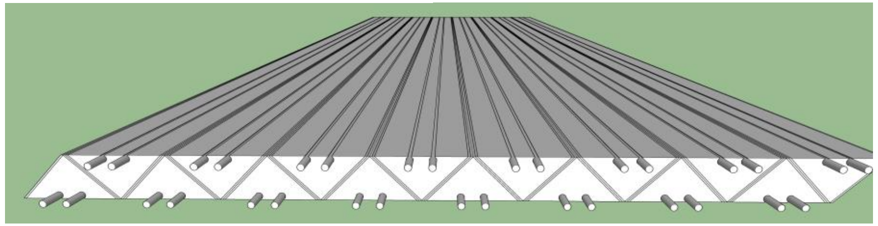
CRIPT MST system (scint.)
IEEE, NSS/MIC 2012, 738-742 (2012)

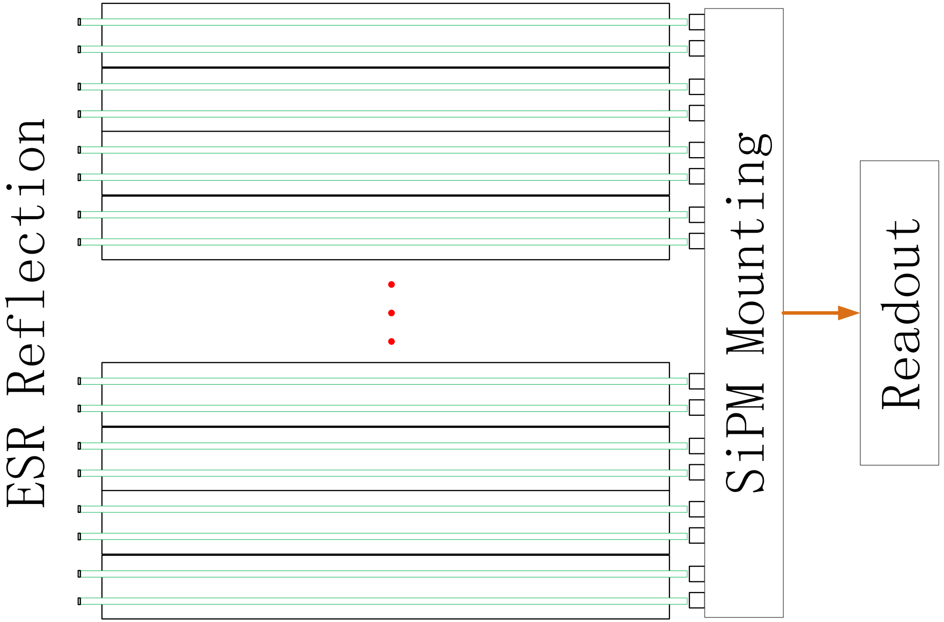
Design of scintillation detector

- Plastic scintillator
  - Effective area: 53 cm × 60 cm, 1.1 cm pitch
  - Triangular strip: centroid-locating, higher resolution
  - Dual-fiber embedded: coincidence to suppress dark count
- WLS fiber
  - Improve uniformity → expand to larger detection area
  - ESR specular reflecting end: $N_{\mathrm{p.e.}}$ ↑ 50%
  - Higher resolution & detection efficiency
- SiPM
  - Placed in the same side
  - Connected to readout electronic board

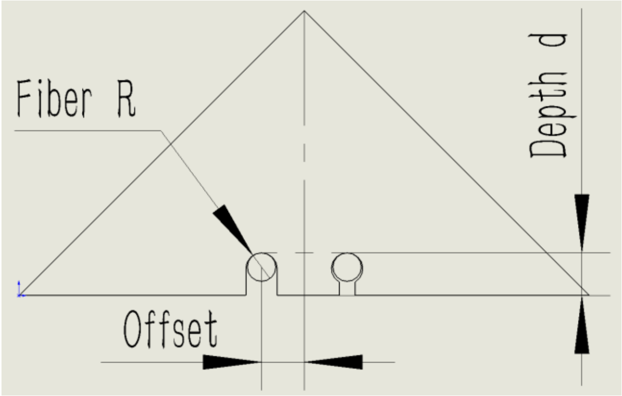


Cross section of a single strip

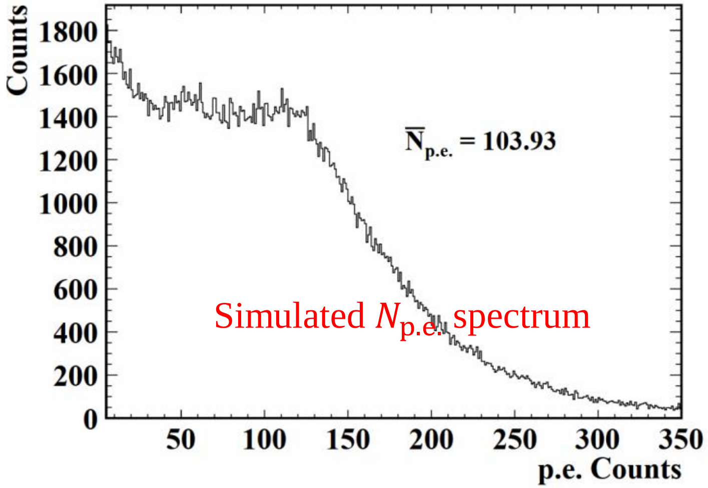


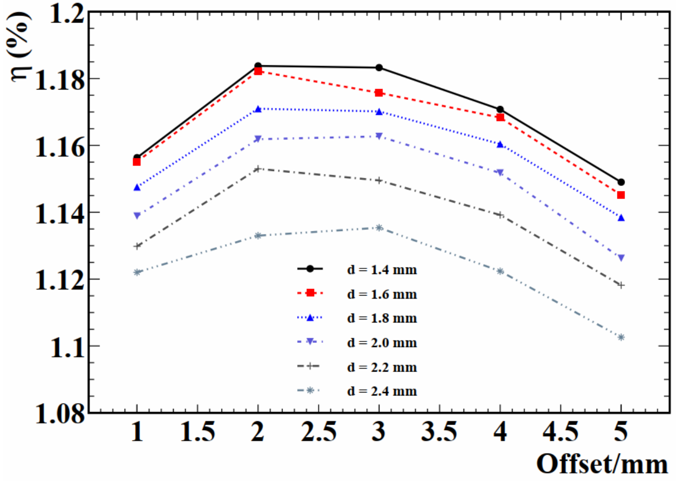


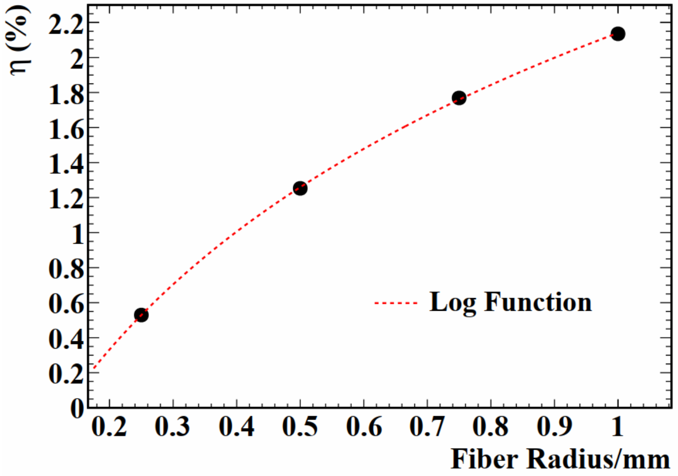
Simulation-based optimization



Cross section of scint. bar





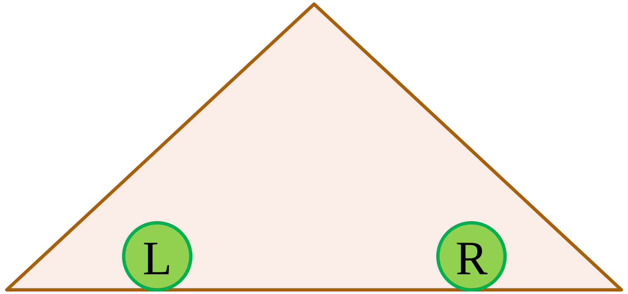


Optimization for fiber offset & depth (left) and fiber radius (right)

- Geometry parameters:
  - Fiber radius R
  - Groove depth d
  - Dual-fiber offset
- Detector performance:
  - Distribution of photon count N_{det}
  - Photon collection efficiency: $\eta = \frac{N_{\text{det}}}{N_{\text{total}}}$
- Optimized detector:
  - $R = 0.75$ mm, $d = d_{\min}$, offset $= 3$ mm
  - $\overline{N_{p.e.}} \approx 104$

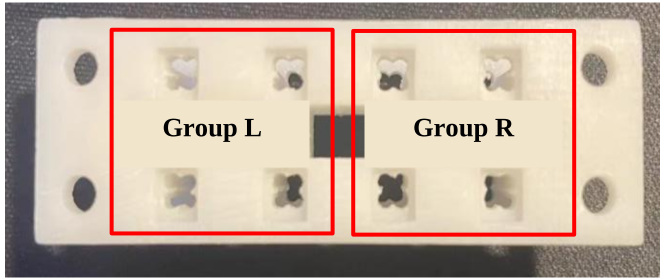
Fiber encoding

- Encode module:
  - 32 fibers from neighboring 16 strips
  - Combine 4 fibers from different strips
  - Reduce readout channel: 32 → 8
- Fiber encoding:
  - Label SiPM & fibers as L,R group
    - 16 fibers & 4 SiPMs in each group
    - 4 fibers → 1 SiPM
  - Coincidence of L & R SiPMs

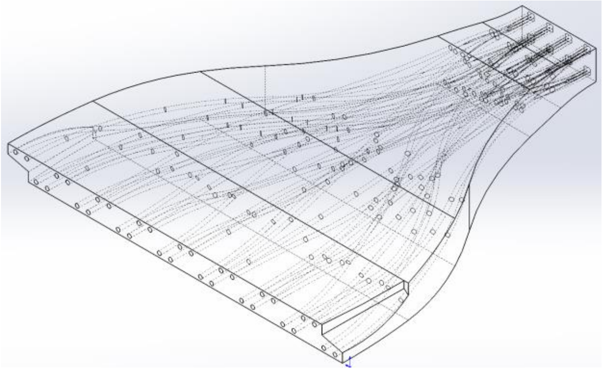


	L0	L1	L2	L3
R0	0	4	8	12
R1	13	1	5	9
R2	10	7	2	15
R3	6	14	11	3

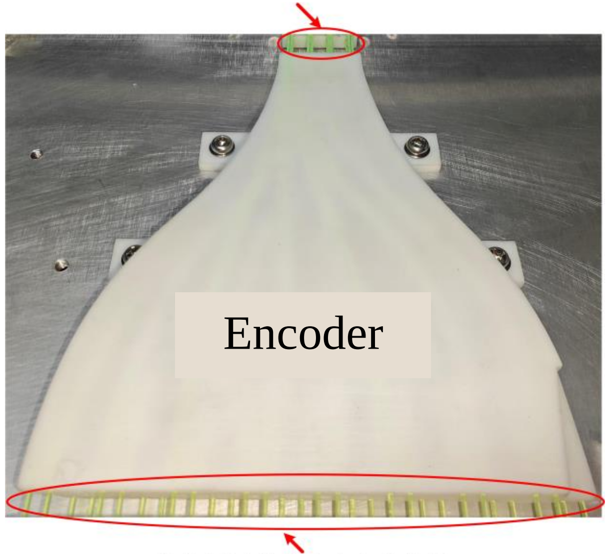
Encoding table



Fiber-SiPM coupler



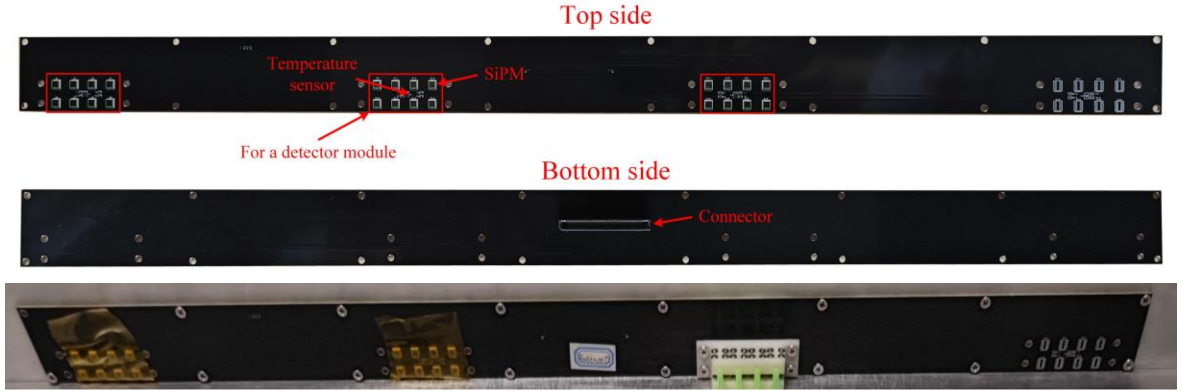
Connected to SiPM

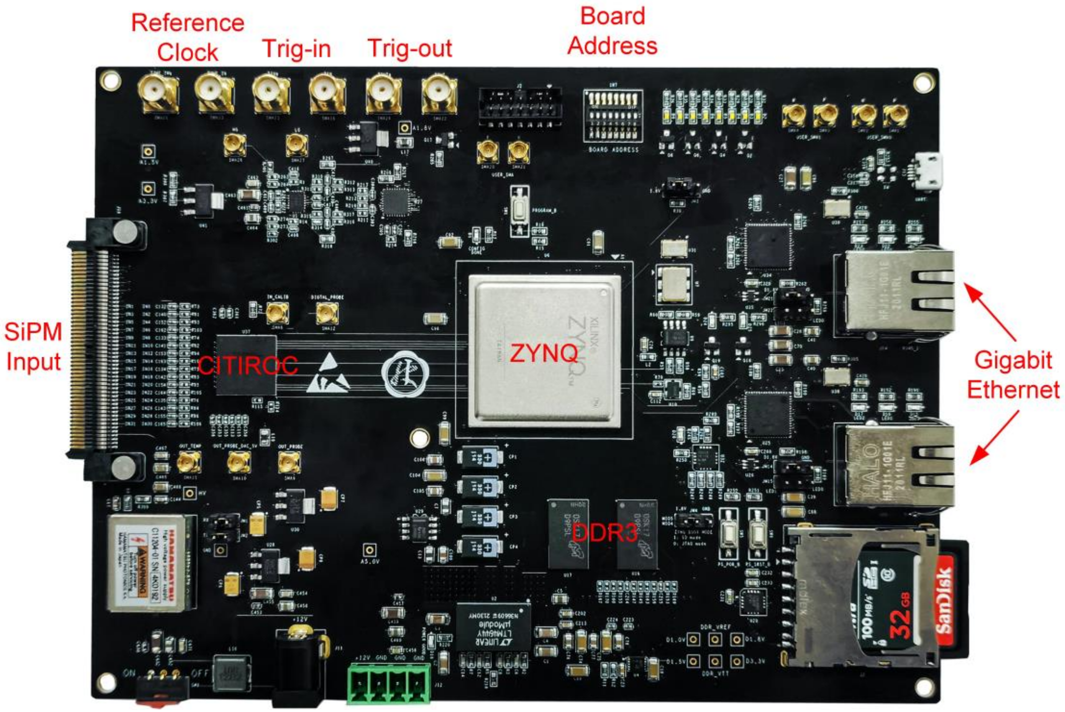


Connected to scintillator

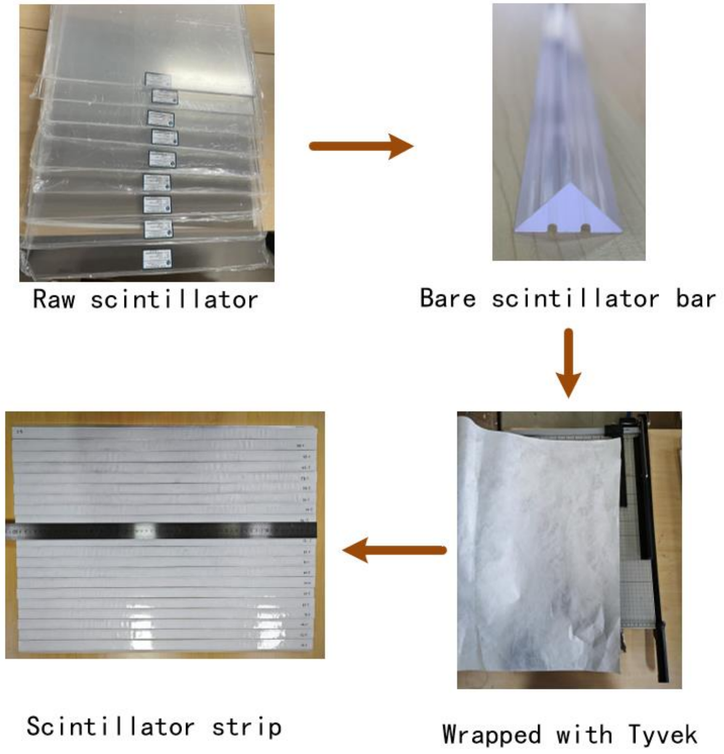
Signal readout

- SiPM mounting board:
  - Support 4 encoding modules, 32 SiPMs
  - 4 temperature sensors
- Readout electronic board:
  - SiPM bias supply & signal readout
  - Charge & time measurement
  - Adjustable coincidence logic
  - Connection to PC



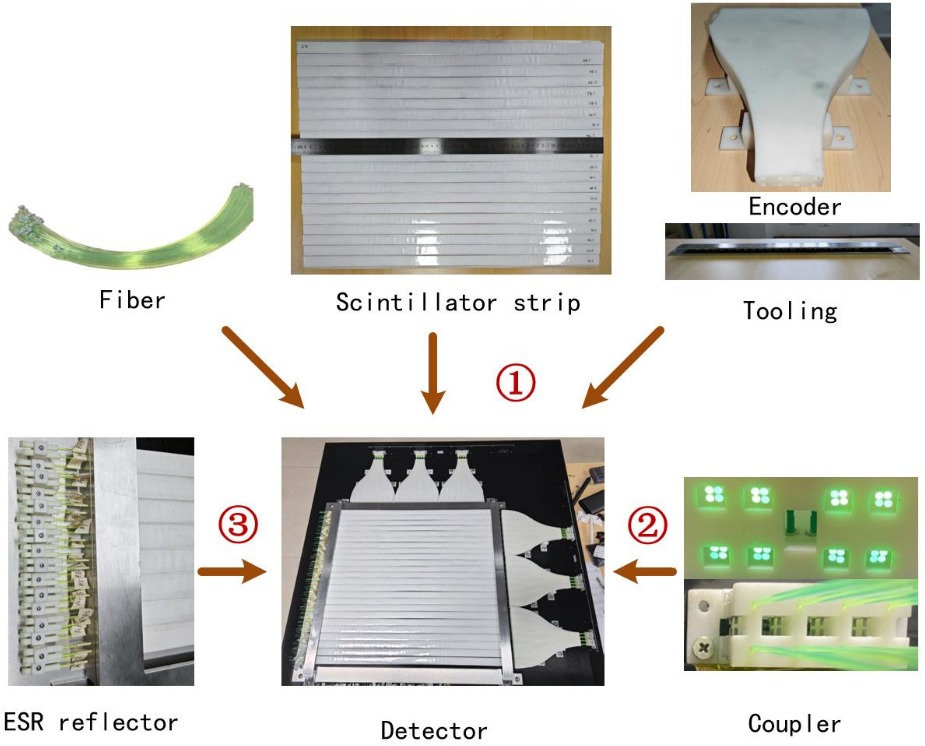


Detector fabrication and assembling



Fabrication of 60 cm scintillator bar

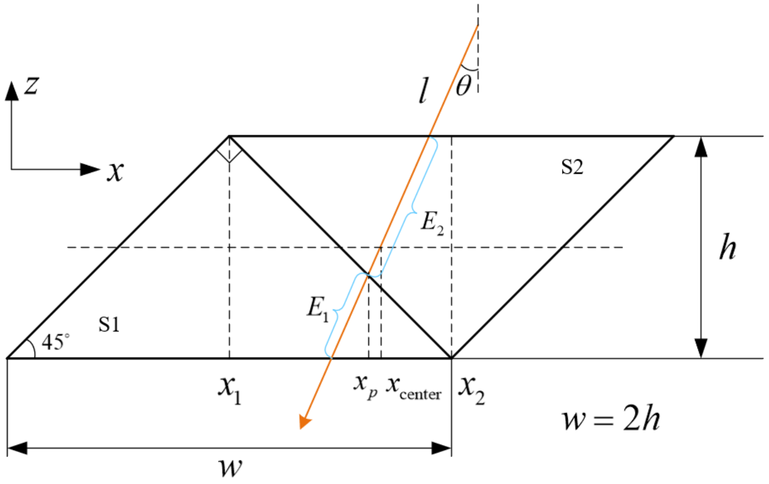
- Quality control: scintillator strip, fiber, SiPM



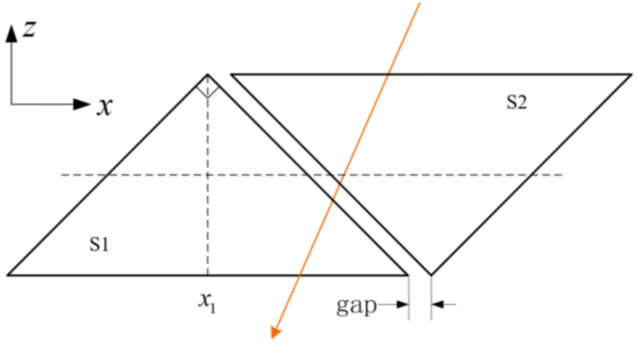
Detector assembling

- 2 orthogonal detection planes (X/Y) in 1 detector
- Detection plane:
  - 3 encode readout module, 48 strips, 96 fibers, 24 SiPMs
  - 1 readout electronic board
  - 53 cm × 53 cm detection area

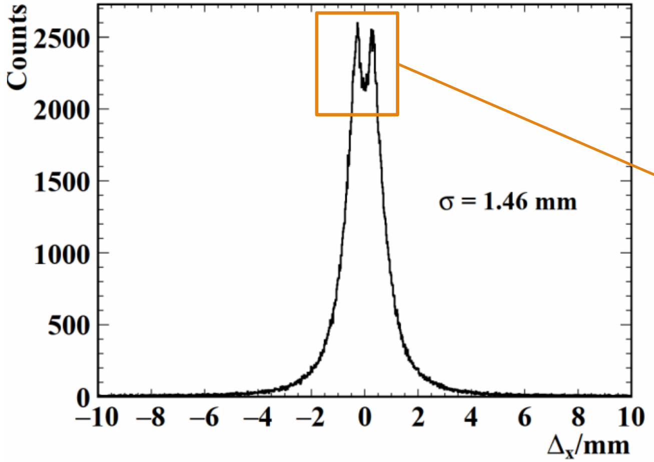
Track reconstruction

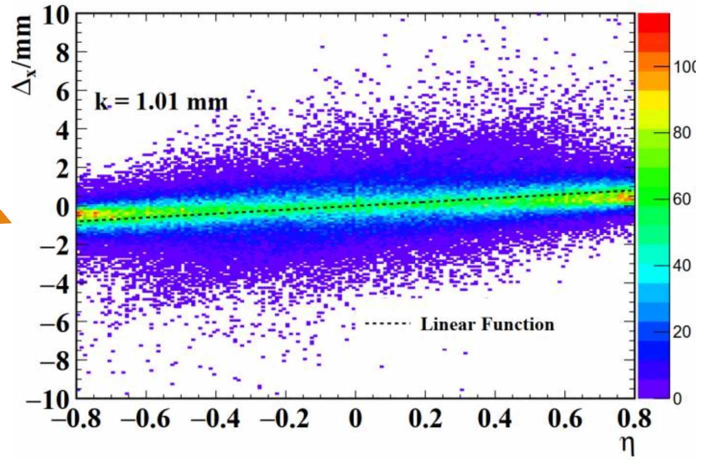


- Centroid-locating: $\eta = \frac{Q_1 - Q_2}{Q_1 + Q_2}, x_p = x_1 + \frac{1-\eta}{2}(x_2 - x_1)$
- Incident angle correction: $x_c = x_p + \frac{h}{2} \cdot \eta \cdot \tan\theta_x$
- Simulation results: $\sigma_x = 0.9$ mm @ pitch = 10 mm



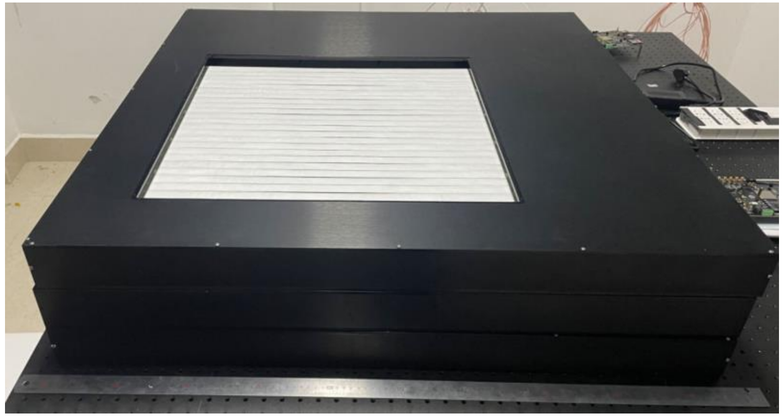
- Air gap correction: $x_c' = x_c - k \cdot \eta$



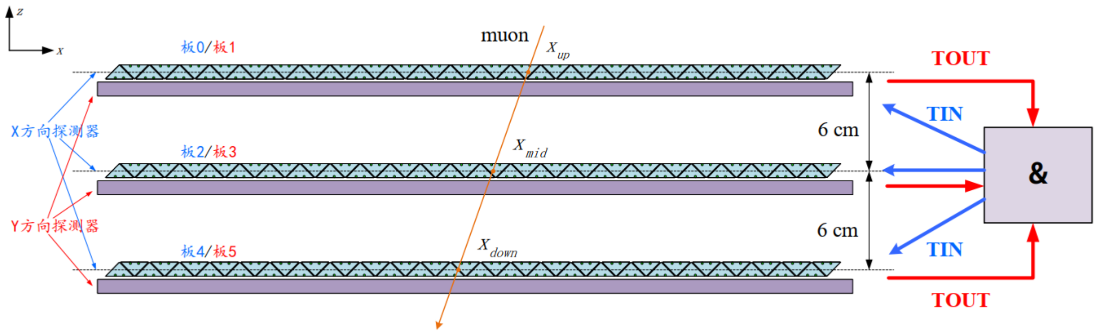


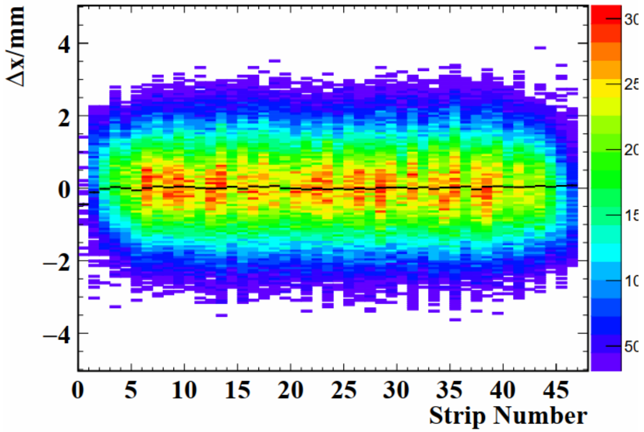
Reconstruct track in Geant4 simulation, where $\Delta x = x_{\mathrm{c}} - x_{\mathrm{real}}$

Spatial resolution



- High uniformity across strips
- Residual distribution: $\sigma_{\Delta x} = 1.22\ \sigma_x = 1.2$ mm
- Spatial resolution: $\sigma_x = 1.0$ mm @ pitch = 11 mm
- Higher light yield, precise correction





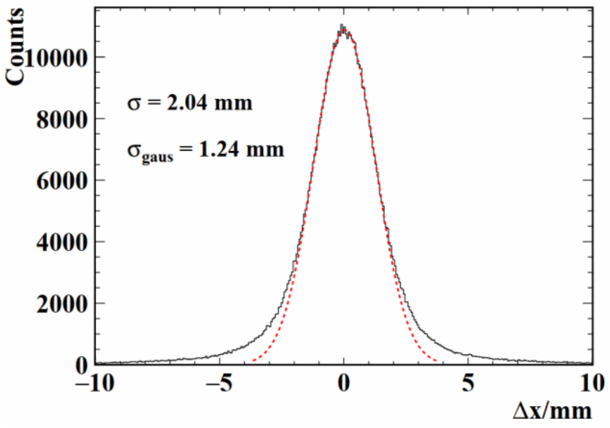
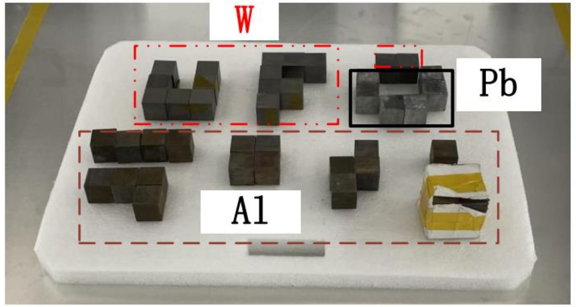
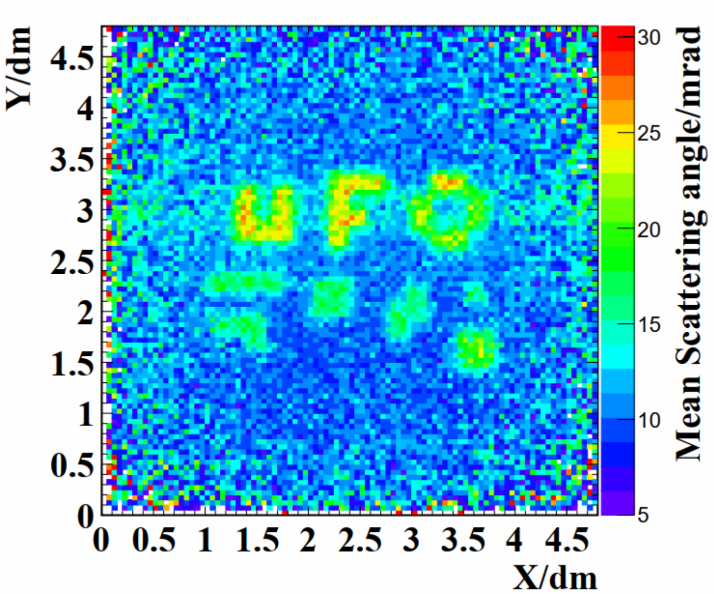


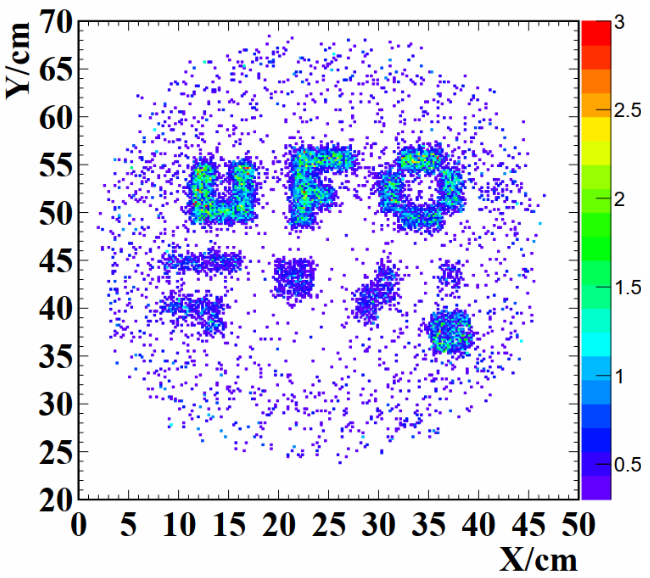
Image reconstruction by PoCA



- Distance between each detector: 0.9 m
- 10 days, 250 k events



Distribution of scattering angle



Imaging reconstruction

Organic liquid scintillator

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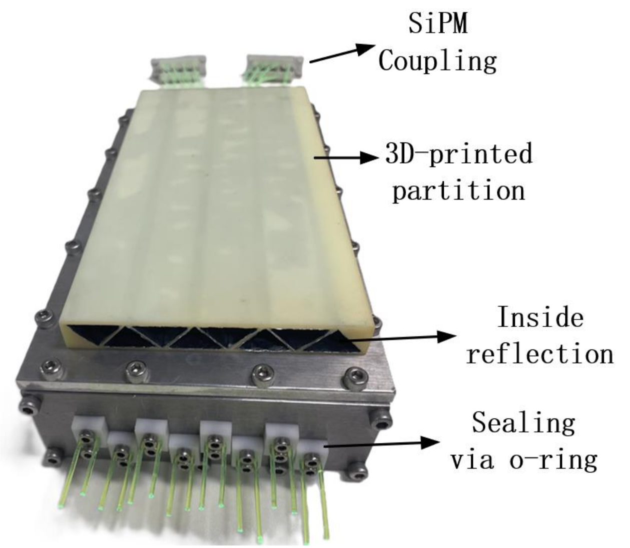
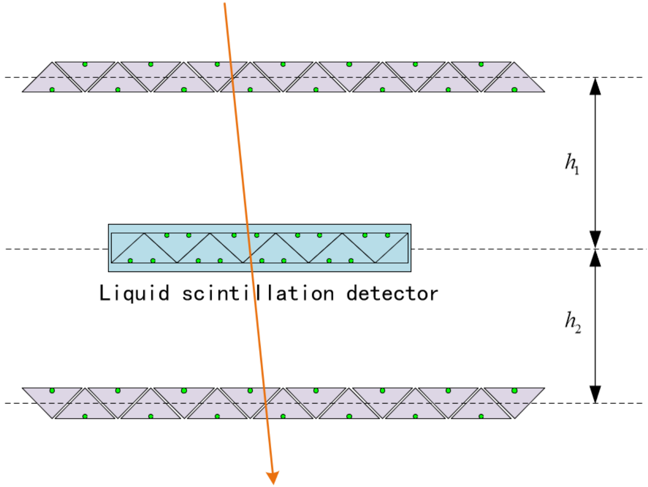
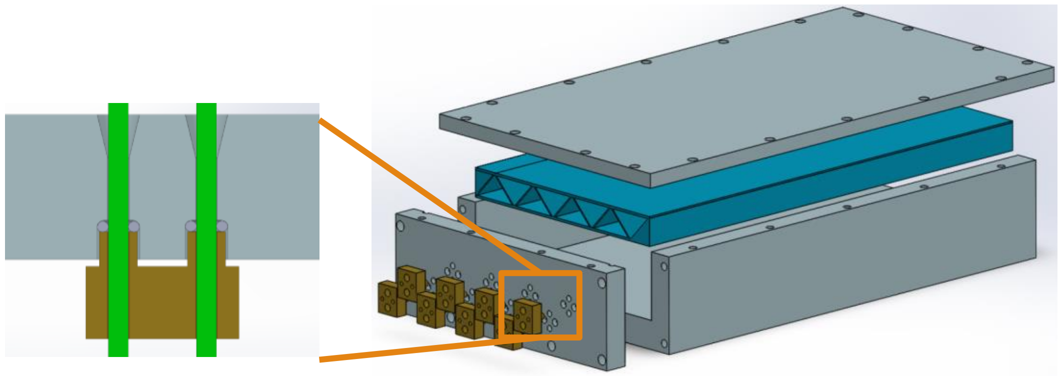
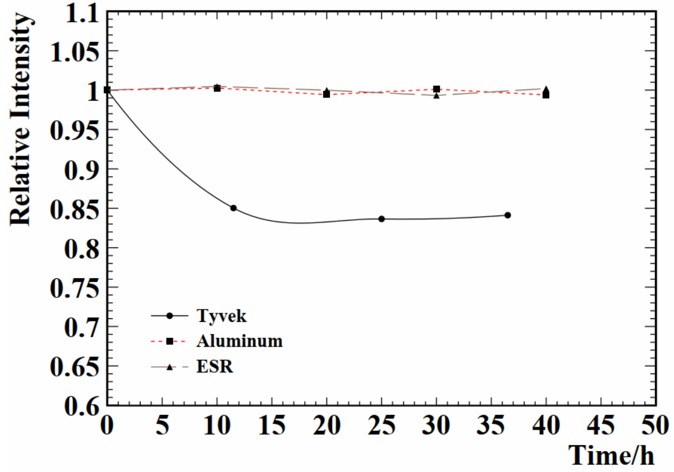
- Reduce fabrication costs
- Liquid scintillation detector
  - Easy to shape
  - Higher light yield
  - Sealing & chemical compatibility





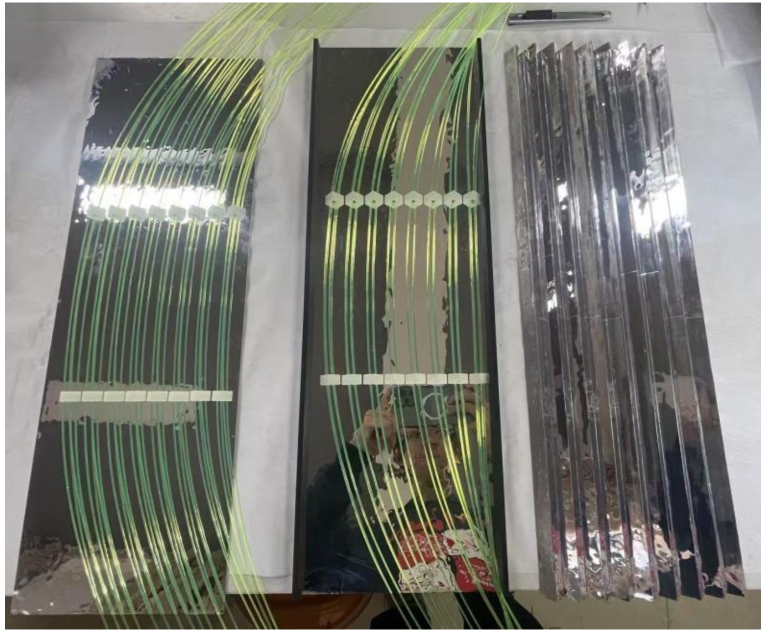
- Prototype detector:
  - Detection area: 8 cm × 16 cm
  - Light yield: 70 % to plastic scintillator
  - Spatial resolution: 1.5 mm (preliminary)





Large area prototype

- Sensitive area: 17.6 cm×60 cm
- One-piece molding partition
- ESR specular reflection inside


Partition Design



Assembling process

Summary

- Muon scattering tomography system based on plastic scintillation detector
  - Large area: 53 cm × 53 cm, high spatial resolution: $\sigma_x = 1$ mm @ 11mm pitch, low cost
  - High light yield: $\bar{N} \approx 92$ p.e., uniformity across channels: $\frac{\sigma_{\bar{N}}}{\bar{N}} \approx 7.3\%$
  - WLS fiber: extend detection area, improve light yield
  - Fiber encoding readout: reduce electronic channel consumption
  - Precise track reconstruction: triangular cross-section & multiple corrections

- Verification of liquid scintillator implementation feasibility in MST system
  - Extend detection area & reduce fabrication budget

Backup

Muon scattering tomography (MST)

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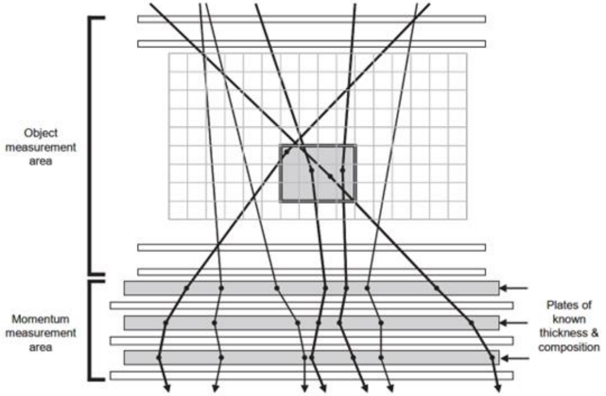
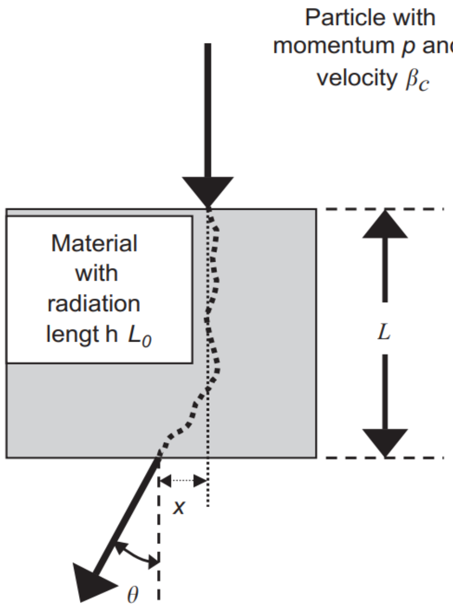
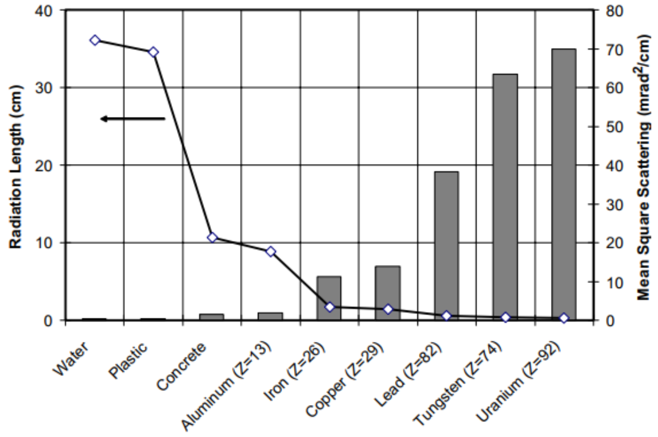


Detector for scattering imaging

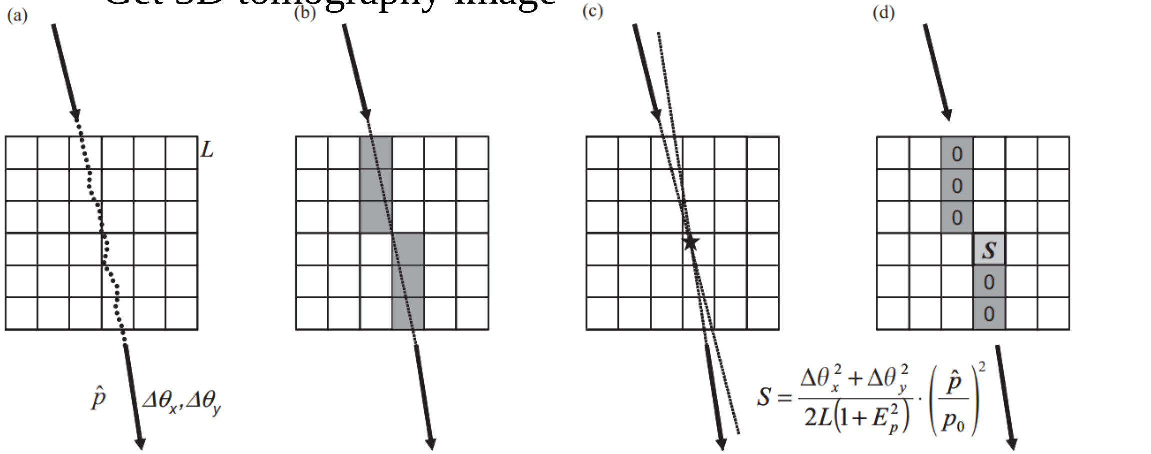


MCS of muon passing



Radiation Length and mean square scattering per unit depth of 3 GeV muon

- Multiple Coulomb Scattering (MCS):
  - $\sigma_\theta \approx \frac{13.6\text{MeV}}{p}\sqrt{\frac{L}{L_0}}, \sigma_\theta^2 \propto \frac{1}{L_0} \propto Z$
- $p = 3\ \text{GeV}, L = 1\ \text{cm}$:
  - $\sigma_\theta \approx 0.7$ mrad for water, 8 mrad for Uranium
  - Distinguish high Z material
- Reconstruction algorithm:
  - Measure $\Delta\theta_x, \Delta\theta_y$, estimate $\hat{p}$, get point of closet approach (PoCA)
  - Assign signal S to PoCA voxel, 0 to other candidate voxels
  - Get 3D tomography image



Scattered point can be deducted by measuring ingoing and outgoing tracks

https://doi.org/10.1016/j.nima.2003.11.035

Detector module test

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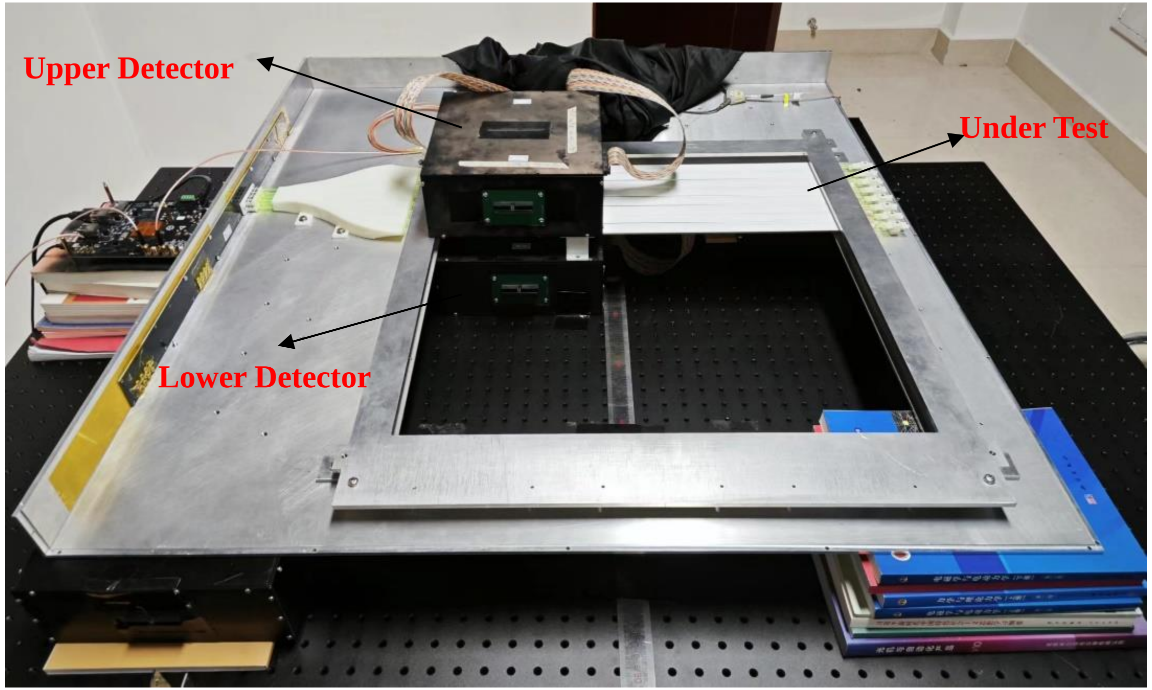

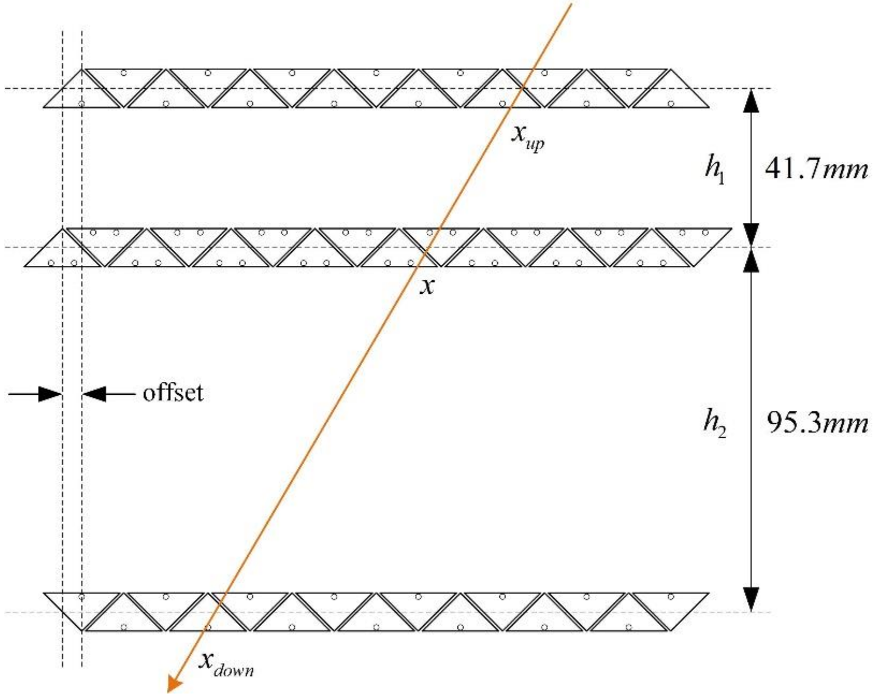

Layout of test system & trigger logic of the system

- A module has been tested under cosmic ray
  - 16 strips, with 16 cm × 55 cm sensitive area
  - Pitch 11 mm
- 2 prototype detectors:
  - Trigger & track measurement

- Purposes:
  - Verify encoding design
  - Verify ESR reflection film
  - Measure rough spatial resolution

Test results

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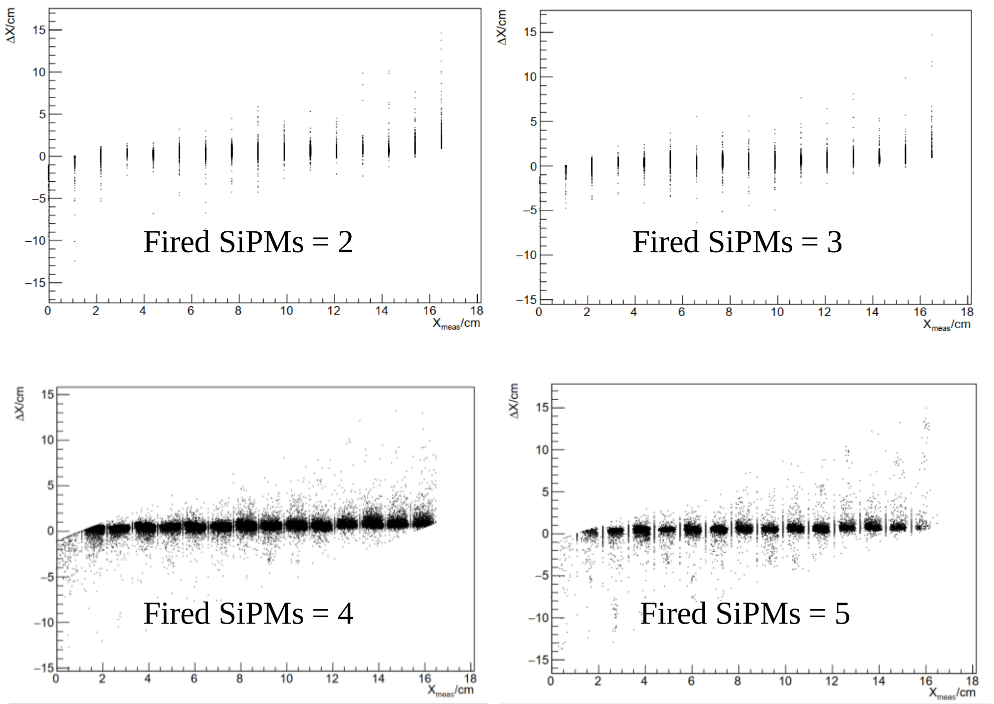
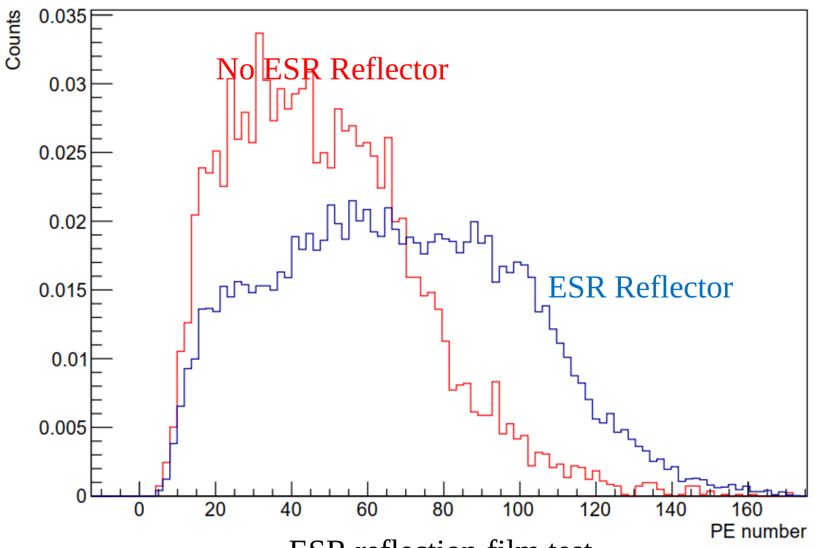
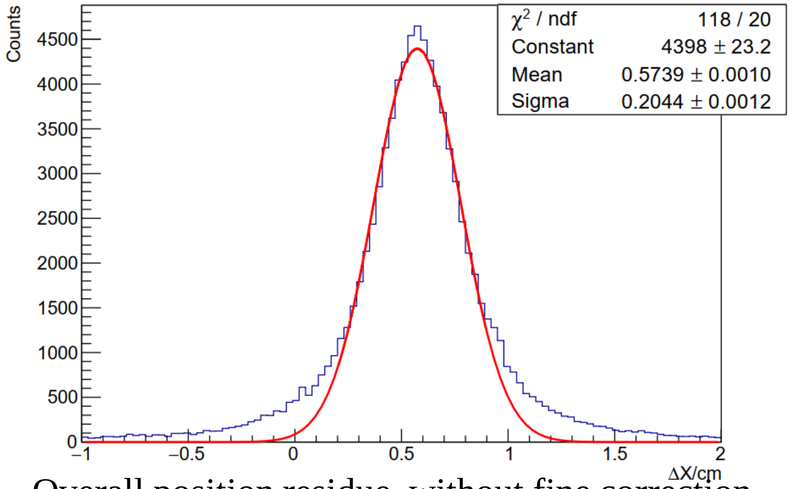


Position residue with different fired SiPM counts



ESR reflection film test



Overall position residue, without fine correction

- Decode & calculate position separately successfully
- Photon collection efficiency increase 40% with ESR film
- Measure overall spatial resolution:
  - pitch $p = 11\text{mm}$
  - $\sigma_x = 2.0$ mm (0.18 pitch)

Decoding test

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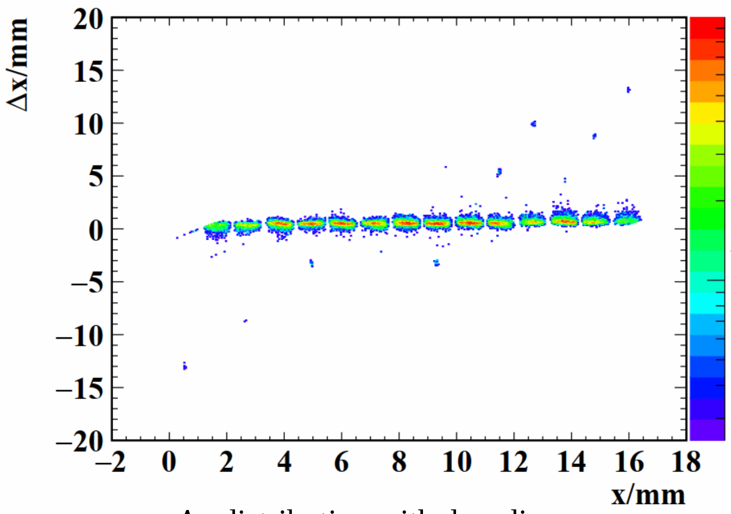
- Decoding:
  - Unreliable via direct decoding
  - Pick 1 strip with maximum signal and decode
  - Judge whether neighbor strips show signal

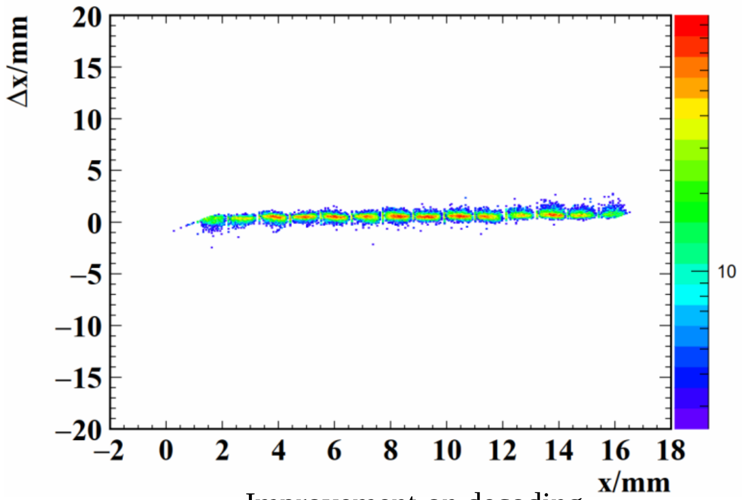
	B0	B1	B2	B3
A0	0	4	8	12
A1	13	1	5	9
A2	10	7	2	15
A3	6	14	11	3

	B0	B1	B2	B3
A0	0	4	8	12
A1	13	1	5	9
A2	10	7	2	15
A3	6	14	11	3

Decoding errors



Δx distribution with decoding errors



Improvement on decoding