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Uniformity study of the light yield and crosstalk in cubic scintillators

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Motivation

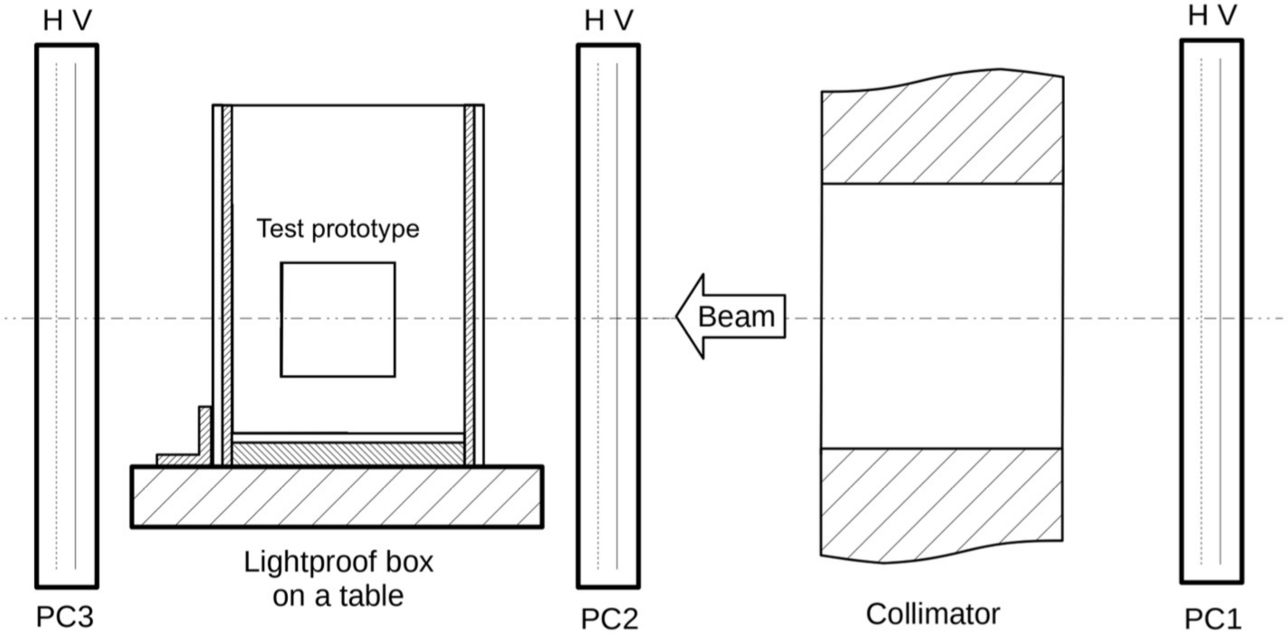
The development of next-generation, highly-segmented neutrino detectors like the SuperFGD demands high light yield, minimal optical crosstalk, and geometric precision from plastic scintillator components.

The primary goals of this study are:

- To measure the light yield per cubic scintillators and its dependence on the particle track position within the cube,
- To study the optical crosstalk between neighboring cubes,

- Use the results from this test for evenrs reconstracrion.

Experimental setup



Test setup at the pion beam line 1 of the proton synchrocyclotron

MPPC's parameters

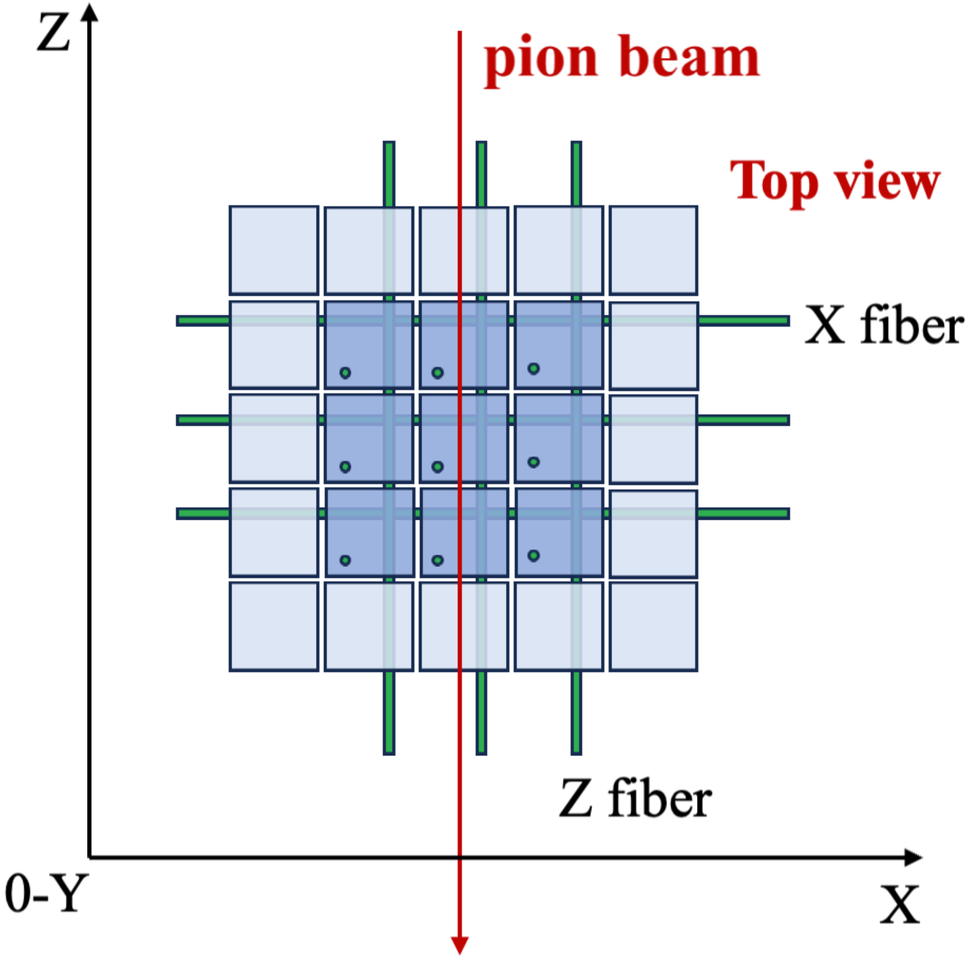
Pixel pitch	25 μm
Number of pixels	1600
Active area	1 x 1 mm^2
Operating voltage	67 – 68 V
Photon detection efficiency (PDE)	35%
Dark count rate	100 kHz
Gain	5.15 x 10^5
Crosstalk probability	10%

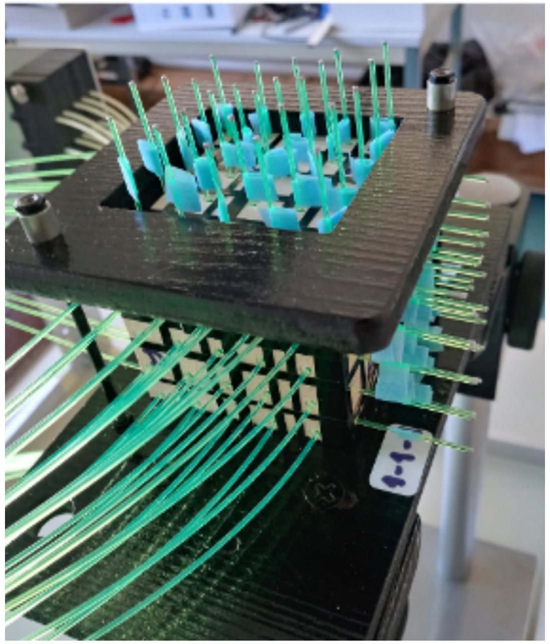
- 5×5×5 array of 1 cm^3 cubic scintillators.
- Cubes are injection molded by Uniplast (Vladimir, Russia).
- Cubes are made of polystyrene, and doped with 1.5% of paraterphenyl (PTP) and 0.01% of POPOP, and coated with a chemical reflector for optical independence.
- WLS fibers pass through each cube, connected to micropixel photosensors MPPCs 12571-025C for signal readout.
- 730 MeV/c pion beam of Synchrocyclotron SC-1000 at PNPI of NRC KI (Gatchina, Russia), cubes are parallel to beam.
- High-resolution tracking system with a spatial resolution of 0.5 mm enabled to reconstruct the particle interaction point.

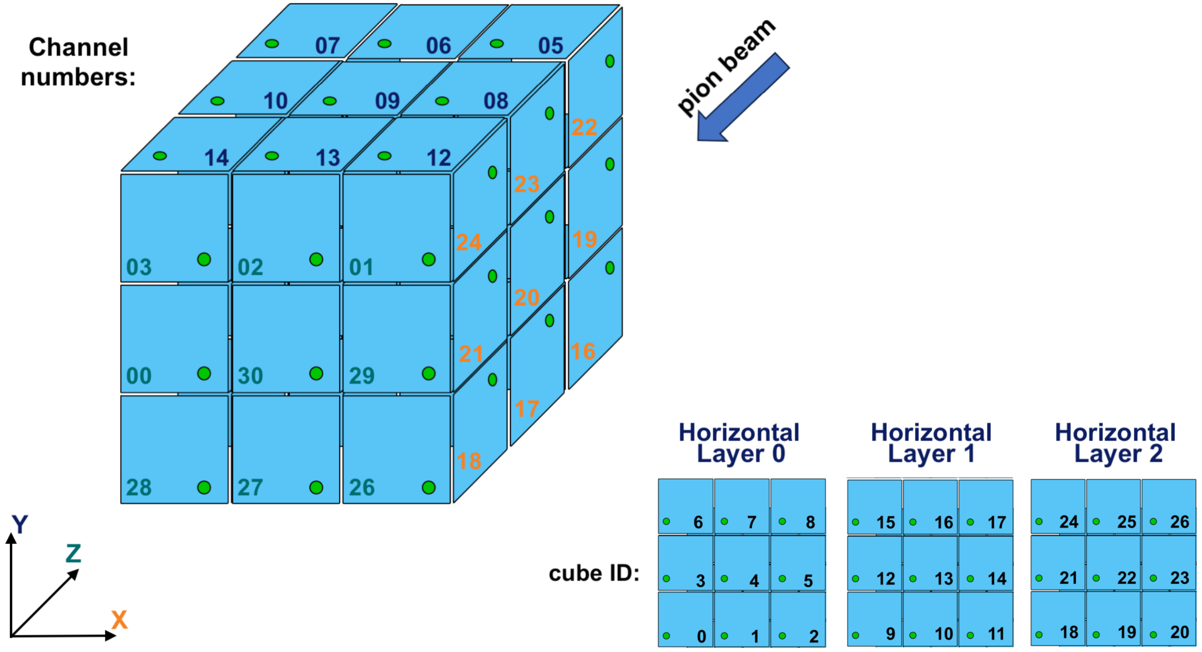
Experimental setup

All channels and cubes were assigned their own numbers (ID).

Analyzed volume: central 3×3×3 cubes.
Readout channels: 27 fibers.



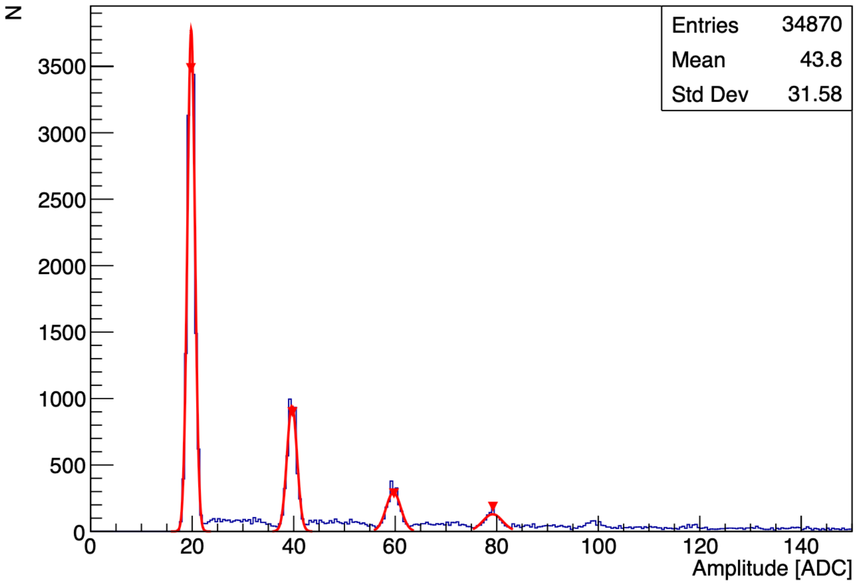




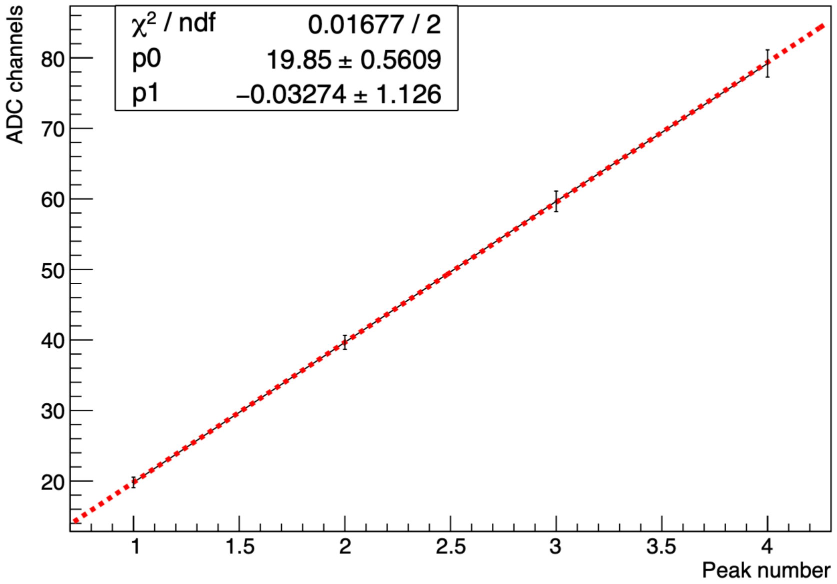
MPPC calibration

- The MPPC calibration data were collected in parallel with beam data.
- Extract the calibration ratio (ADC/p.e.) from MPPC fingerplots. The mean distance between peaks is the **MPPC gain** value.

Number of events on single channel (raw data including background)



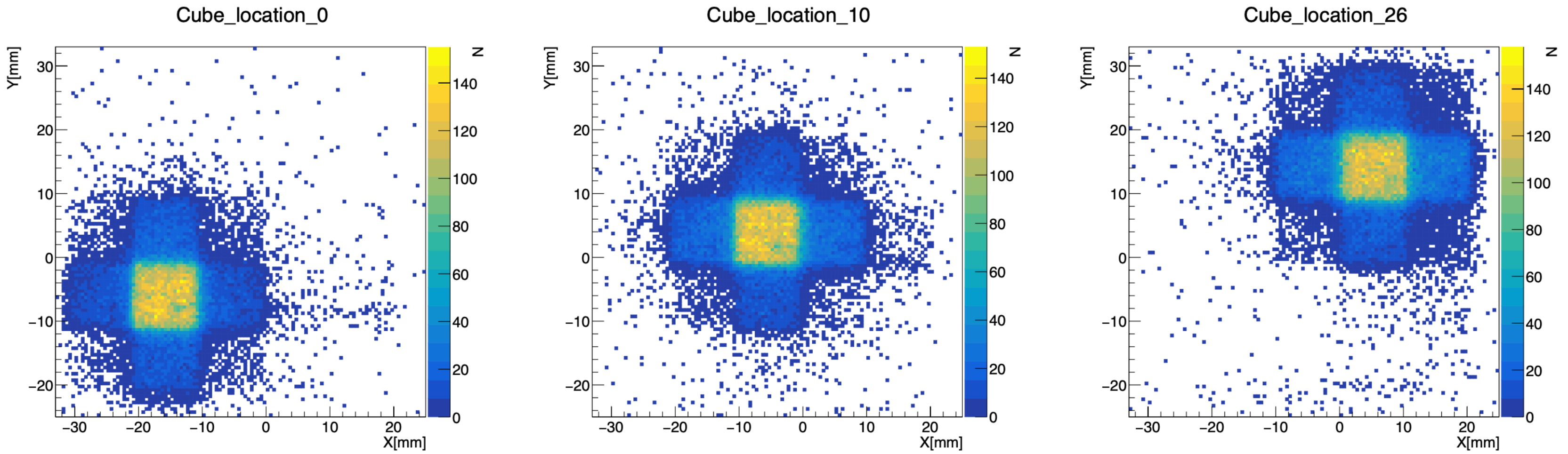
The pedestal calculation for single channel

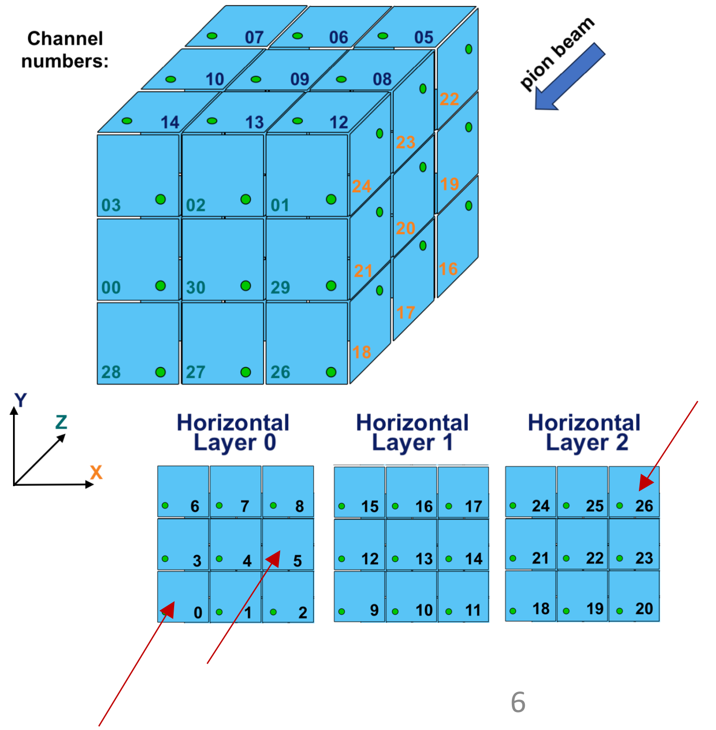


Calculating the position of cubes

- Select events with a clear signal in all three fibers (X, Y, Z) of a cube.
- Select events with single, straight tracks (angle of less than 5°).
- Use high-precision tracking chambers to reconstruct the pion track position.
- Create an event map for each cube with 0.5 mm binning.
- Cube boundaries were defined using an occupancy threshold (80 events), ensuring only events from inside the cube are used for analysis.

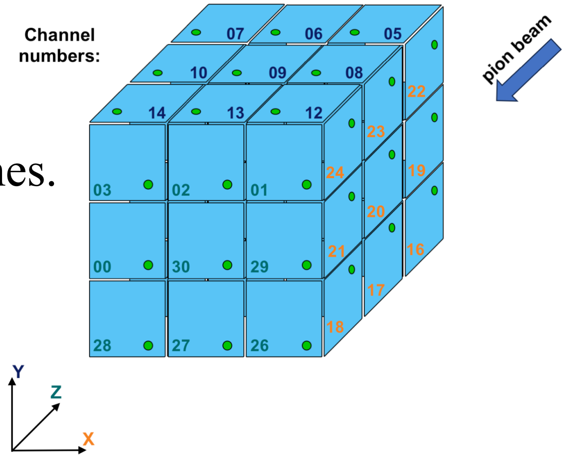
Reconstructed hit position maps for cubes 0, 5, and 26 in the (X, Y) plane





- Successfully mapped all 27 cubes within the array volume.

Light yield (LY) from each fiber

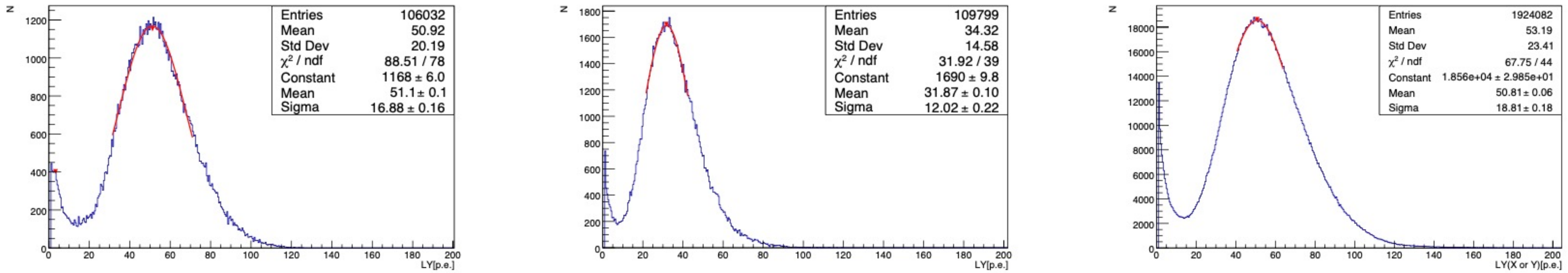


- Used calibrated beam data, selecting only tracks passing through defined cube volumes.
- Converted signal to p.e. using MPPC gain and crosstalk corrections:

$$LY_{\text{p.e.}} = \frac{LY_{\text{ADC}} - \text{pedestal}}{\text{gain} \times (1 + \text{crosstalk})}$$

- Significant light yield variations were observed between different readout channels, primarily due to differences in fiber-to-MPPC coupling.
- A normalization procedure was applied to all data, scaling each channel's response to a global average.

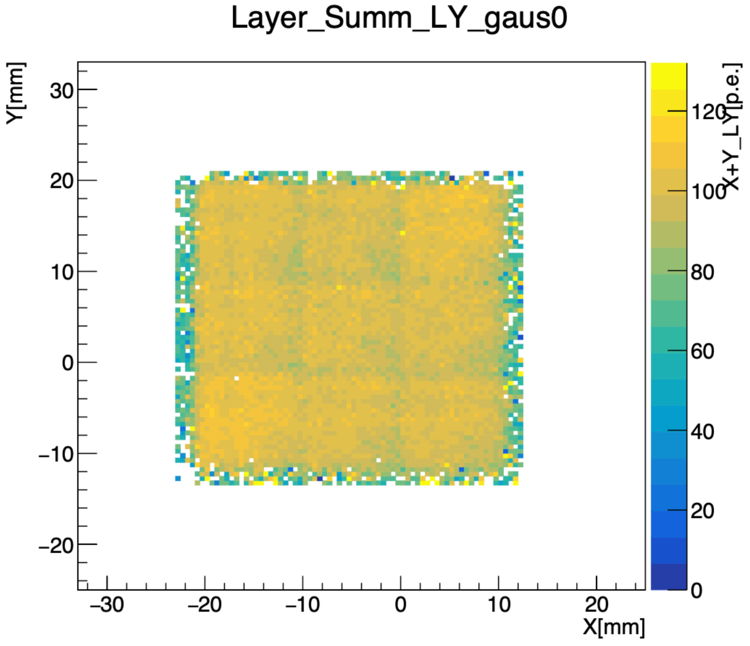
LY distributions for cubes connected to channel 6 (left), channel 21 (center), and all channels combined (right)



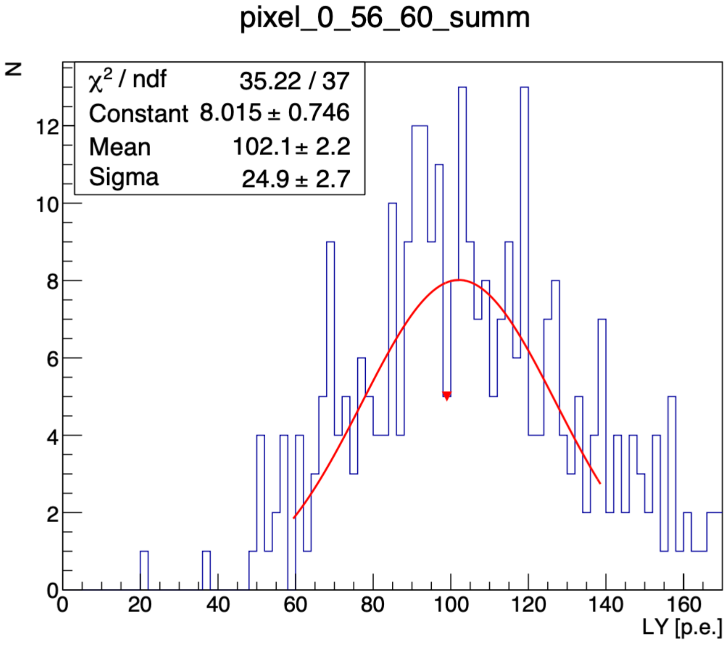
Light yield (LY) distribution inside cube layers

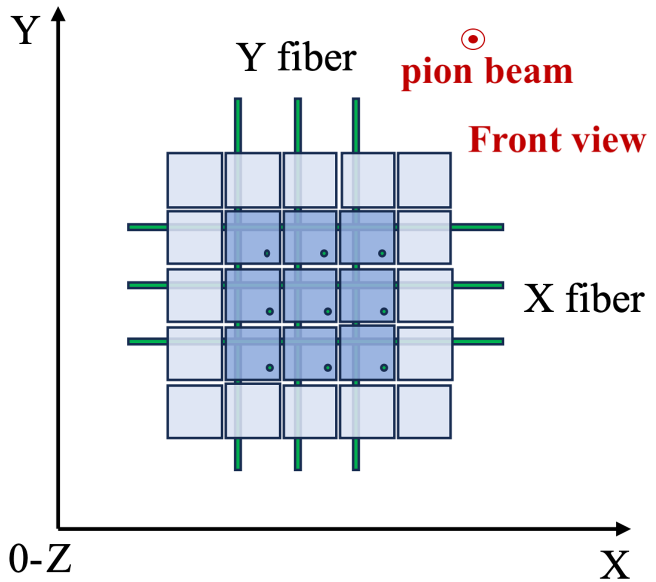
- Analyze LY in 0.5 mm bins within each cube.
- Compare signals from: X fiber only, Y fiber only, X+Y fibers.
- X+Y fiber sum shows a reasonably uniform response across the cube. Signal is highest in the center and attenuates towards the edges.

LY map from combined X+Y fibers



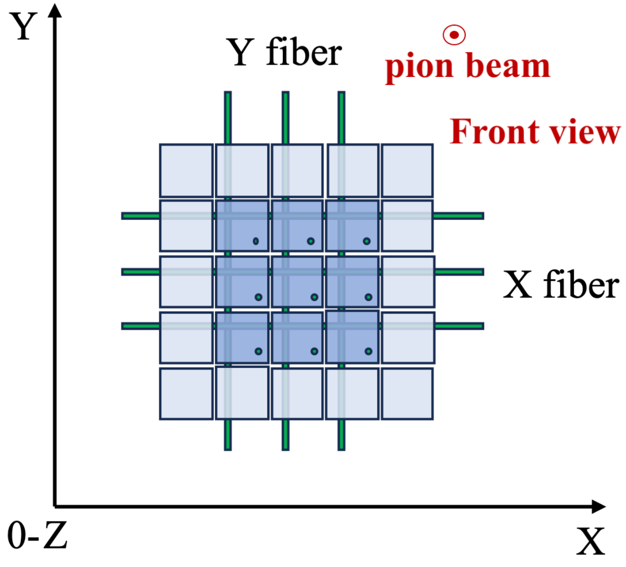
LY distribution in a single bin



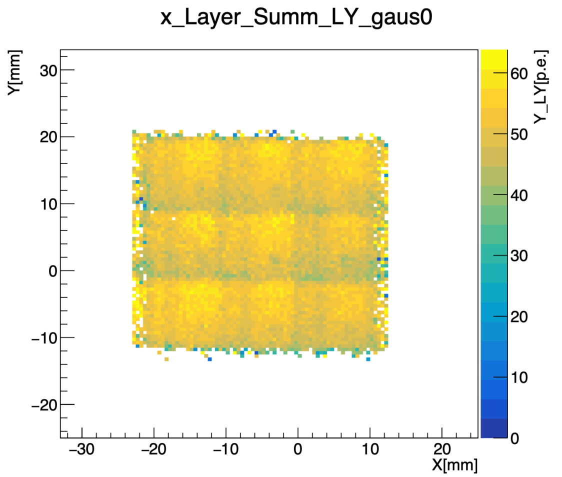


Light yield (LY) distribution inside cubes

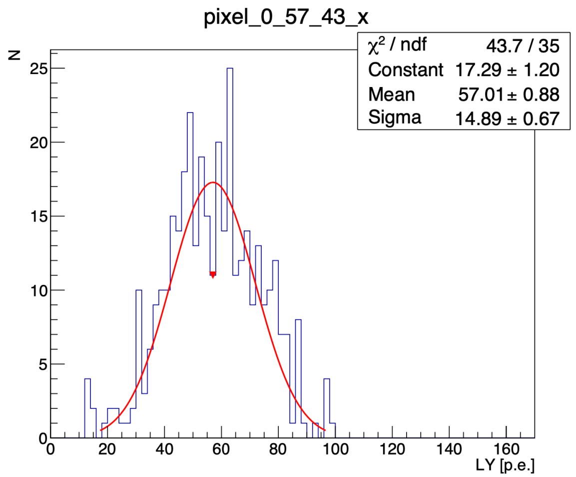
- Individual fibers (X or Y) show a clear and expected asymmetry.
- The LY is higher when the particle track passes close to the fiber.



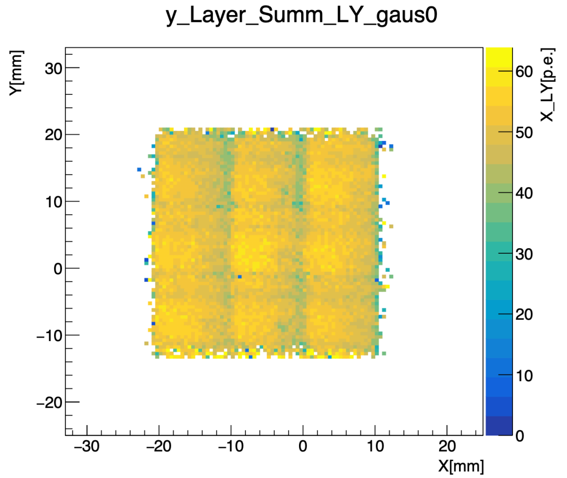
LY map from X fibers only



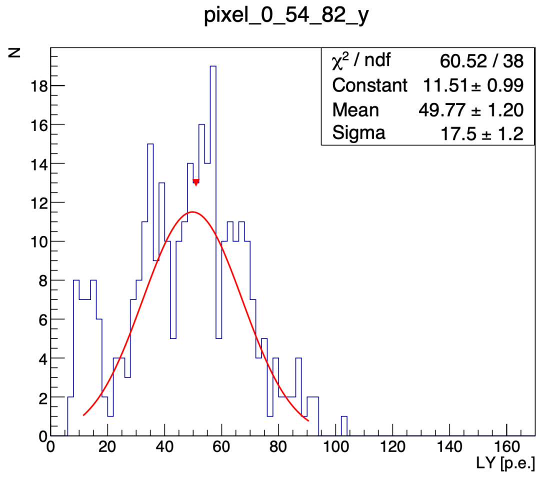
LY distribution in a single bin



LY map from Y fibers only



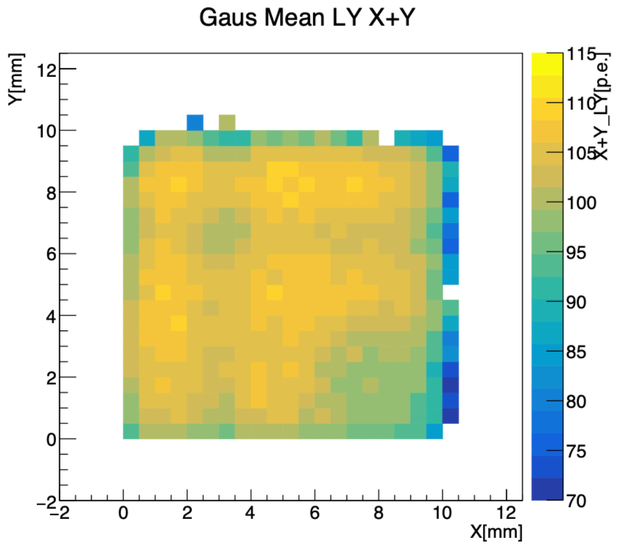
LY distribution in a single bin

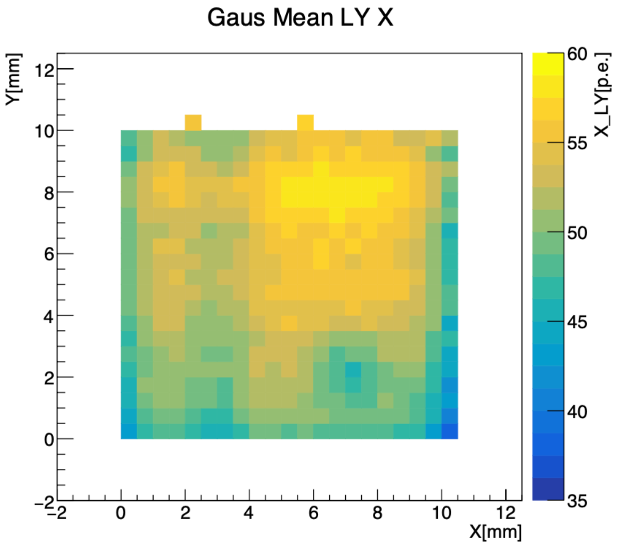


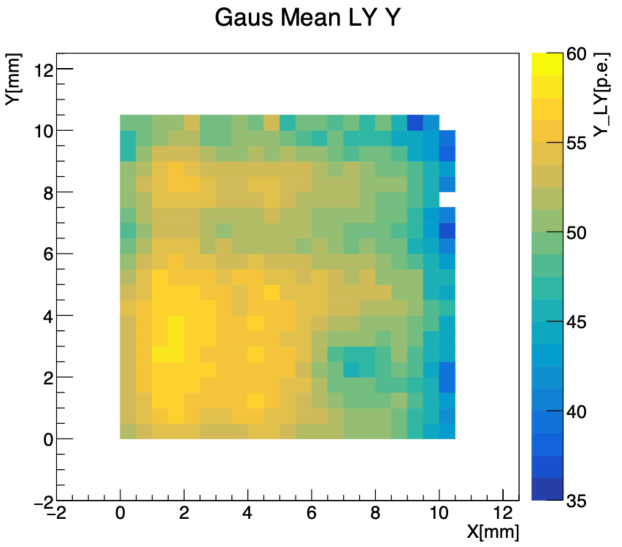
Average light yield (LY) distribution across multiple cubes

- Combine high-resolution (0.5 mm) LY maps from all 27 cubes.
- Perform a bin-by-bin average to create a representative "average cube" map.
- Combined X+Y fibers:
  Local decrease near Z fiber,
  Enhanced collection along X and Y fiber paths.
- Individual fiber response:
  X (Y) fiber: Max signal when track is close to X (Y) axis.

LY maps averaged over 27 cubes. ***Left****: combined X + Y fiber signals;* ***center****: X fiber only;* ***right****: Y fiber only*

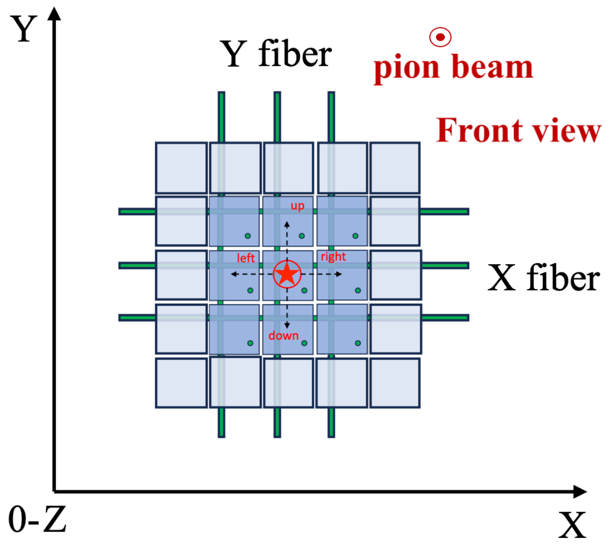






Optical crosstalk between cubes

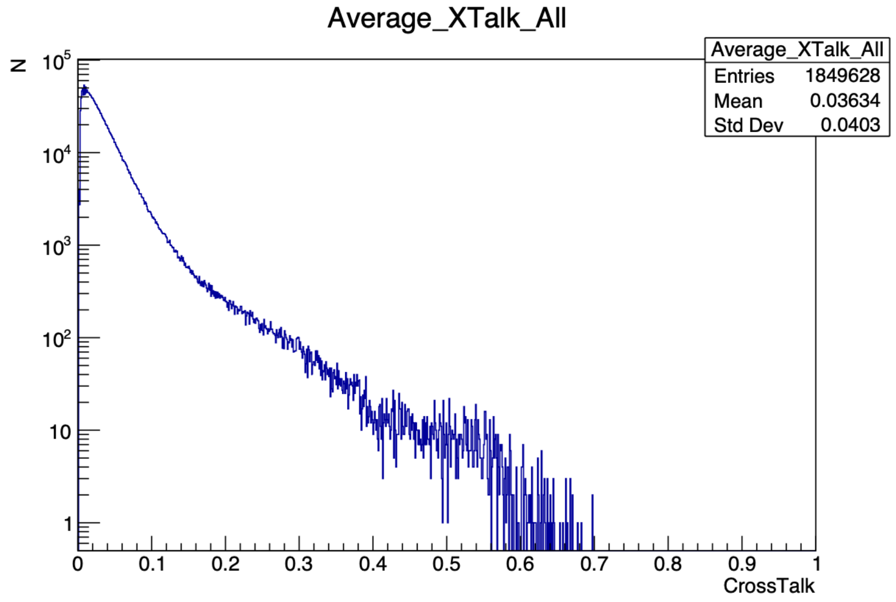
- Select pions crossing a well-defined central cube.
- Measure signal in the four adjacent neighbors: left, right, up, down.
- Isolate crosstalk by using only the Z fiber signal in the neighbor cubes.
- Restrict analysis to regions near the cube boundary to ensure clean sample.
- Crosstalk is calculated event-by-event:



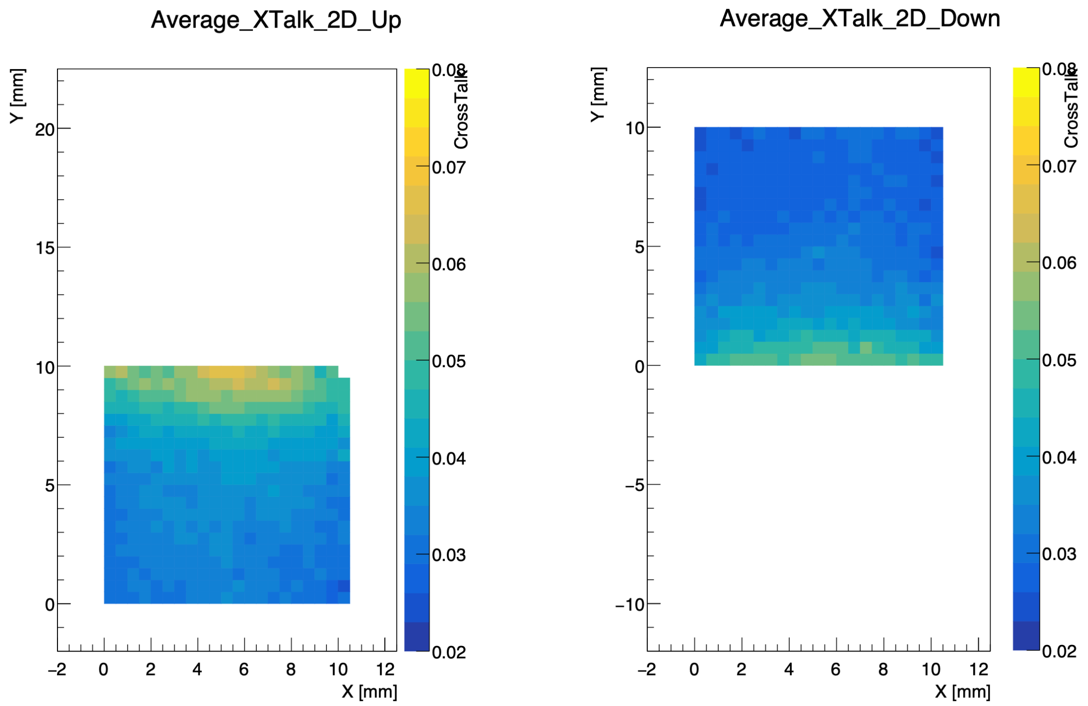
$$\text{crosstalk} = \frac{LY_{\text{Z fiber neighbor cube}}}{5 \times LY_{\text{avr}}},$$

where $LY_{Z\,fiber\,neighbor\,cube}$ is the LY from Z fiber in a neighboring cube, LY_{avr} is the average LY per fiber.

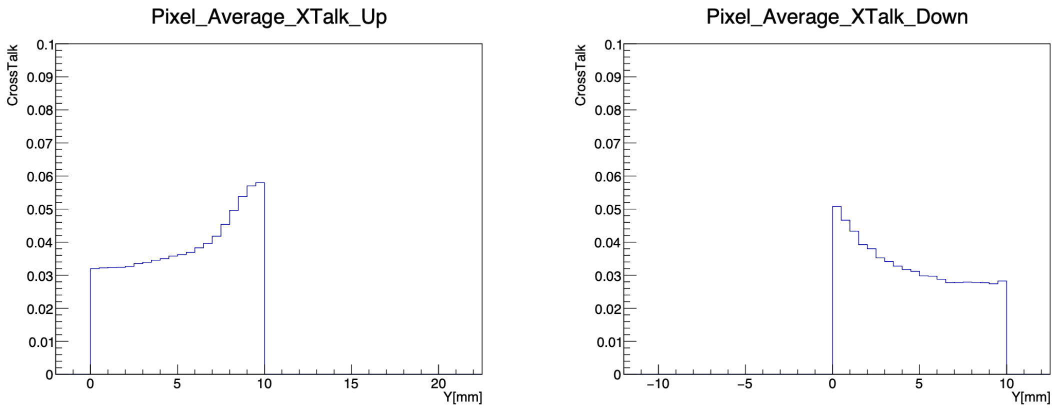
Average crosstalk distribution (X and Y directions)



Crosstalk maps (up and down)



2D maps of average crosstalk for up (left panel) and down (right panel) neighbor cubes

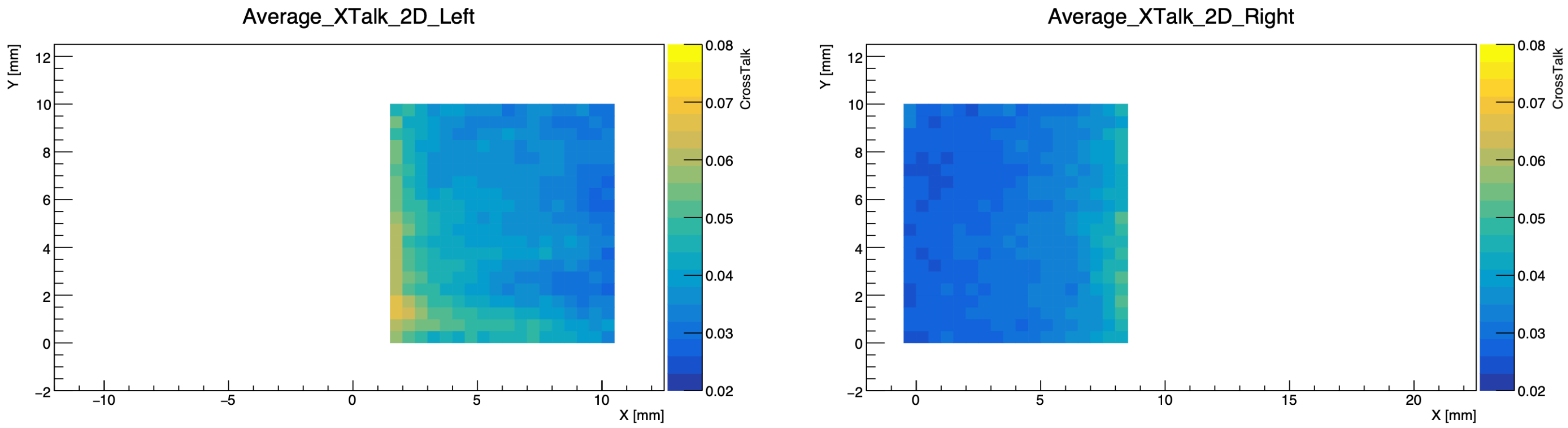


One-dimensional crosstalk profiles for up (left panel) and down (right panel) neighbor cubes

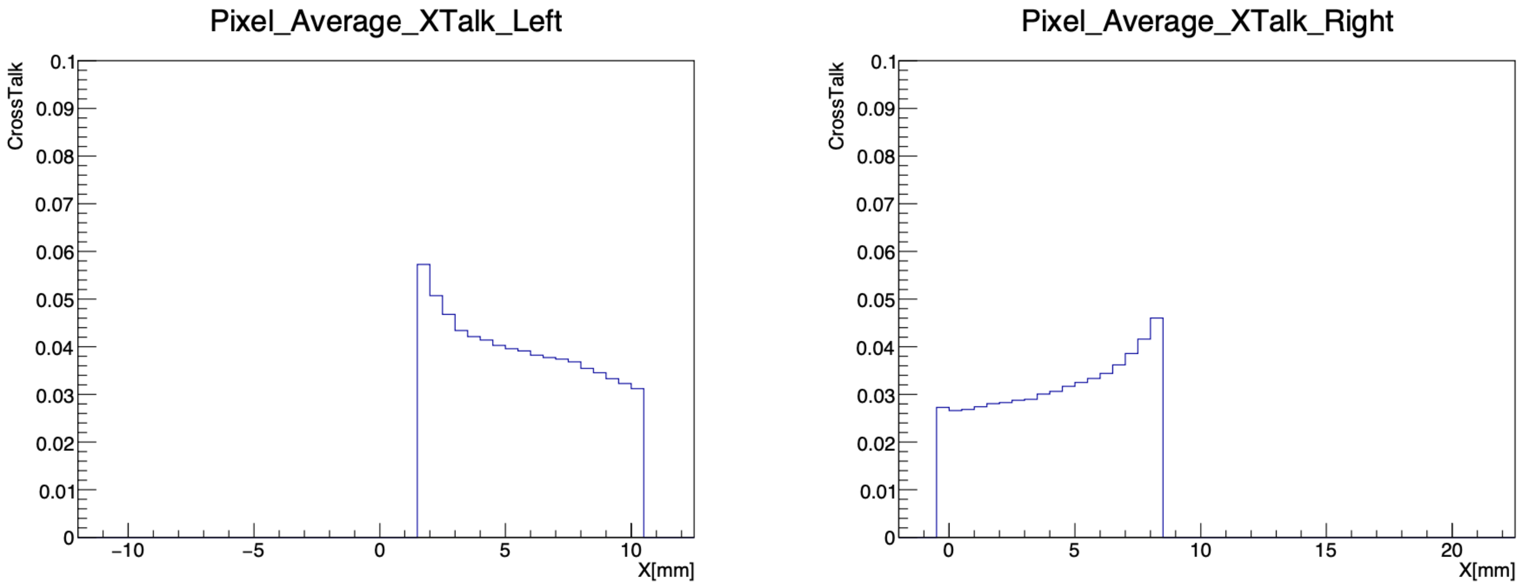
Detailed 2D maps reveal how crosstalk depends on the track's position:

- Higher crosstalk (up to 6%) occurs when the track is close to the shared face with the neighbor.
- Crosstalk decreases to below 2% deeper inside the cube.

Crosstalk maps (left and right)



2D maps of average crosstalk for right (right panel) and left (left panel) neighbor cubes



One-dimensional crosstalk profiles for left (left panel) and right (right panel) neighbor cubes

1D profiles confirm the strong dependence on distance from the cube boundary:

- Crosstalk falls from ~6% at the boundary to ~3% just 1.5 mm away.
- A small asymmetry is observed between directions due to the position of the readout fiber in the neighboring cube.

Conclusion

The key parameters for 1 cm^3 cubic scintillators were estimated.

Light yield:

- Measured ~51 p.e. per fiber for MIPs.
- Up to ~100 p.e. collected per cube from two orthogonal fibers.

Spatial response & Uniformity:

- Mapped light yield collection with 0.5 mm resolution.
- Light yield depends on the distance from the particle interaction point to the readout fiber.

Optical crosstalk:

- Measured between 2% to 7% to adjacent cubes.
- Its value depends on the distance from the particle interaction point to the cube edge.

These detailed measurements provide a foundation for significantly improving the simulation accuracy and event reconstruction of highly-segmented scintillator detectors.

*This work is supported by the Russian Science Foundation grant number **24-12-00271***

Back up

More information about test

- A 730 MeV/c pion beam from the SC-1000 synchrocyclotron at the PNPI of NRC "Kurchatov Institute" (Gatchina, Russia) was used.

- The test was performed by a collaboration of researchers from INR RAS, LPNI RAS, and PNPI.

MPPC calibration (Crosstalk)

The optical crosstalk, defined as the probability of simultaneous firing of multiple microcells in response to a single photoelectron, was estimated for each channel as:

$$\text{crosstalk} = \frac{\overline{A} - A_{\text{pedestal}}}{A_{\text{1pe}}} - 1,$$

where $\overline{A}$ is the average signal amplitude, $A_{pedestal}$ is the pedestal level, and A_{1pe} is the mean position of the first p.e. peak.