Timing of long scintillator counters with WLS fiber readout for TOF system

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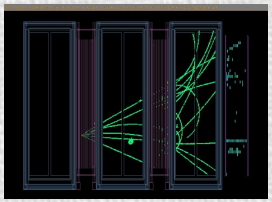


2nd Workshop on Neutrino Near Detectors based on gas TPCs
20-21 March 2017 CERN

Objectives

Primary goal for TOF system: separation of charged particles and directions by time-of-flight in the inner volume of the electromagnetic calorimeter. Outer TOF layer must cover about 82 m^2 area (to the maximum) and provide time resolution σ_t close to 0.5 ns.

Fixed parameters for the conceptual design of counters with WLS fiber readout:

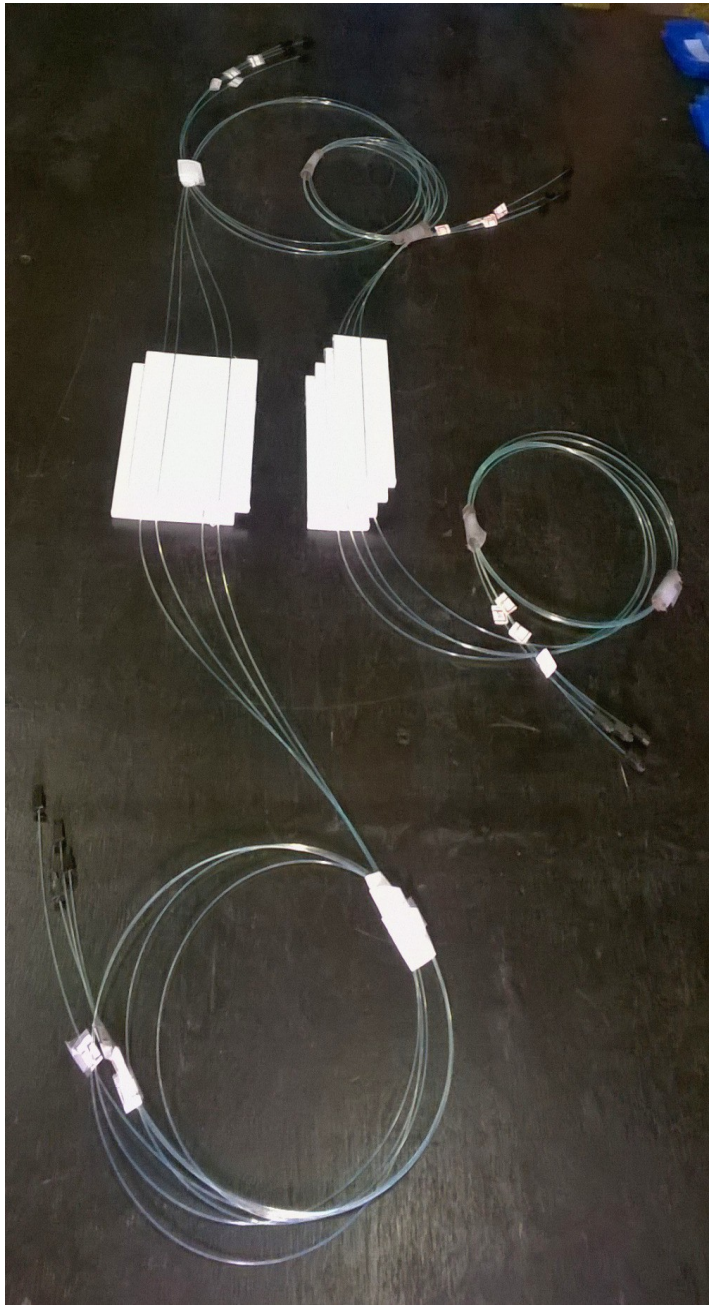
1. **3 m long Y11 Kuraray WLS fibers**
   The best available WLS fibers to obtain the highest light yield which compensates the slow decay time of re-emitting.

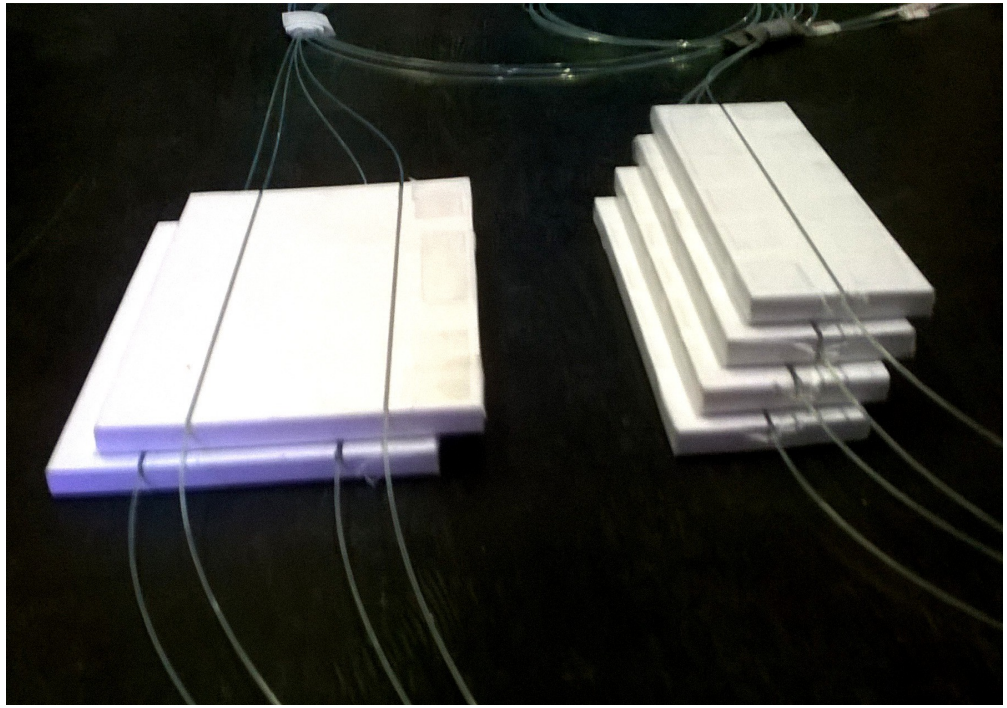
2. **7 mm thick extruded scintillator bars.**
   The established technology in manufacturing of extruded scintillators, proved by time and achieved light yield. Reduced scintillating light fluctuations over scintillator volume.

3. **5 cm spacing between the fibers.**
   This distance looks like the optimum between the performance and cost of the detector (*our feeling based on many tests*).

Then we have to investigate the configuration of detectors which could provide the required performance

Tested samples of 5- and 10-cm width



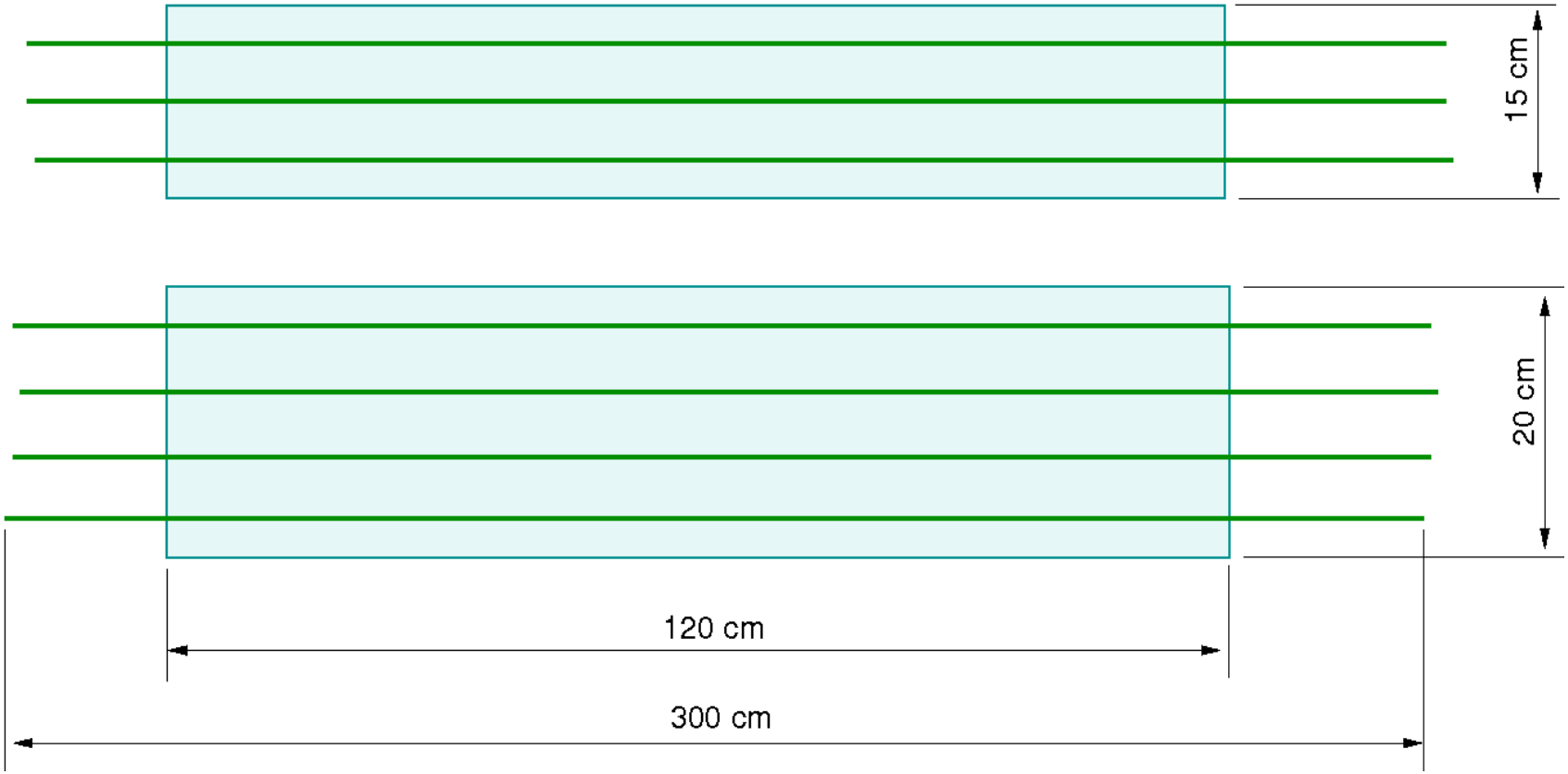


A few scintillator samples were made from 7-mm thick extruded slabs, with a single groove and two grooves spaced at 5 cm.
4 small samples: **0.7 x 5 x 15 cm^3** , 1 fiber glued in.
2 wide samples: **0.7 x 10 x 15 cm^3**, 2 fibers glued in.
Reflector: chemical one plus Tyvek paper.

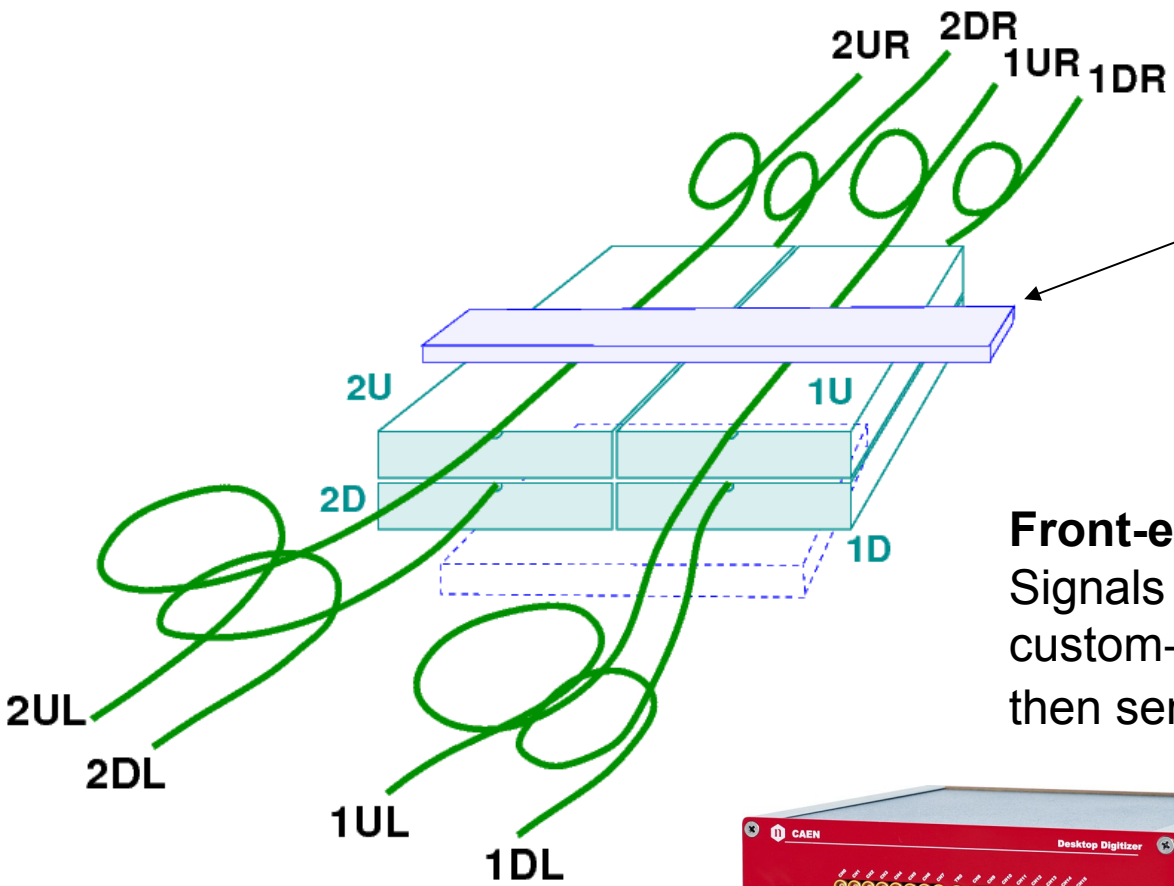
WLS fibers: **3 m long Y11 Kuraray** multi-clad,
1 mm diameter.

Tested samples of 15- and 20-cm width

Two slabs were manufactured: 0.7x15x120 and 0.7x20x120 cm^3 with 3 and 4 grooves. WLS Y11 fibers of 3 m length were glued in. Readout was implemented with 3x3 mm^2 MPPCs, a single MPPC at one scintillator end.



Readout and trigger for cosmic tests



Cosmic trigger is a coincidence of two scintillator counters:

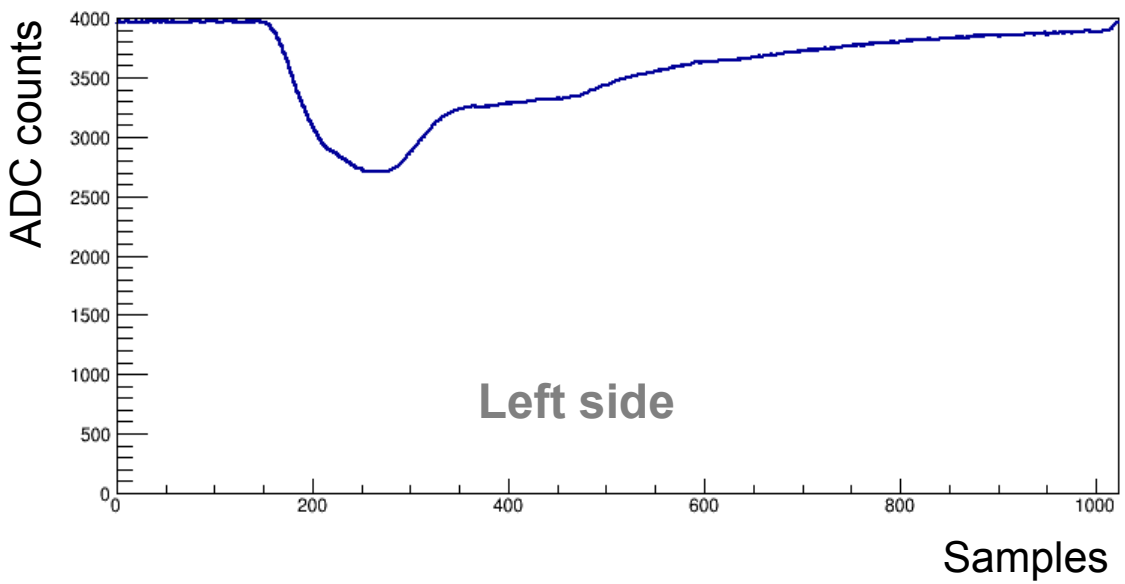
Upper counter: 2 x 20 cm^2
Bottom counter: 7 x 7 cm^2

Front-end electronics:
Signals from MPPCs are amplified by a custom-made preamp with gain of 20, then sent to the digitizer CAEN DT5742

CAEN digitizer DT5742:
16 channels, 5 GHz sampling rate,
200 ns time window at 5 GHz,
12-bit resolution

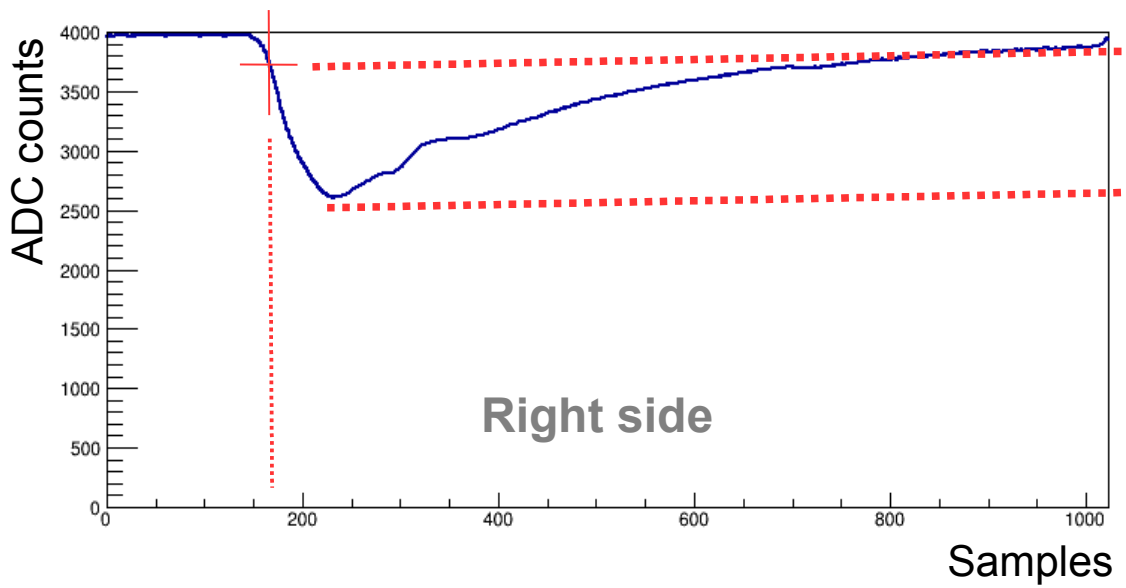
The signal charge: area of signal waveform normalized to photoelectrons
The signal timing: constant fraction (**0.1**) of a signal front

Digitized signal waveforms



Typical digitized waveforms of a cosmic signal from two sides of a tested counter.

Full scale: 1024 samples,
200 ps between samples.



10% from max amplitude

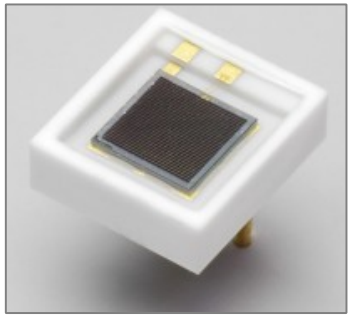
Max amplitude

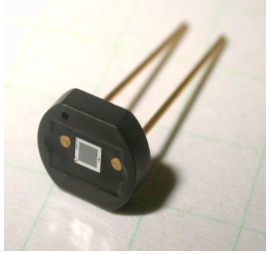
Constant fraction timing

Specification of tested Hamamatsu MPPCs

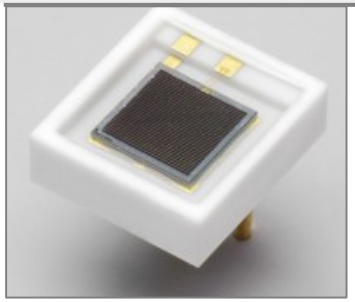
Tested photodiodes are of the same generation and similar parameters, the differences are the total sensitive area size and pixel size

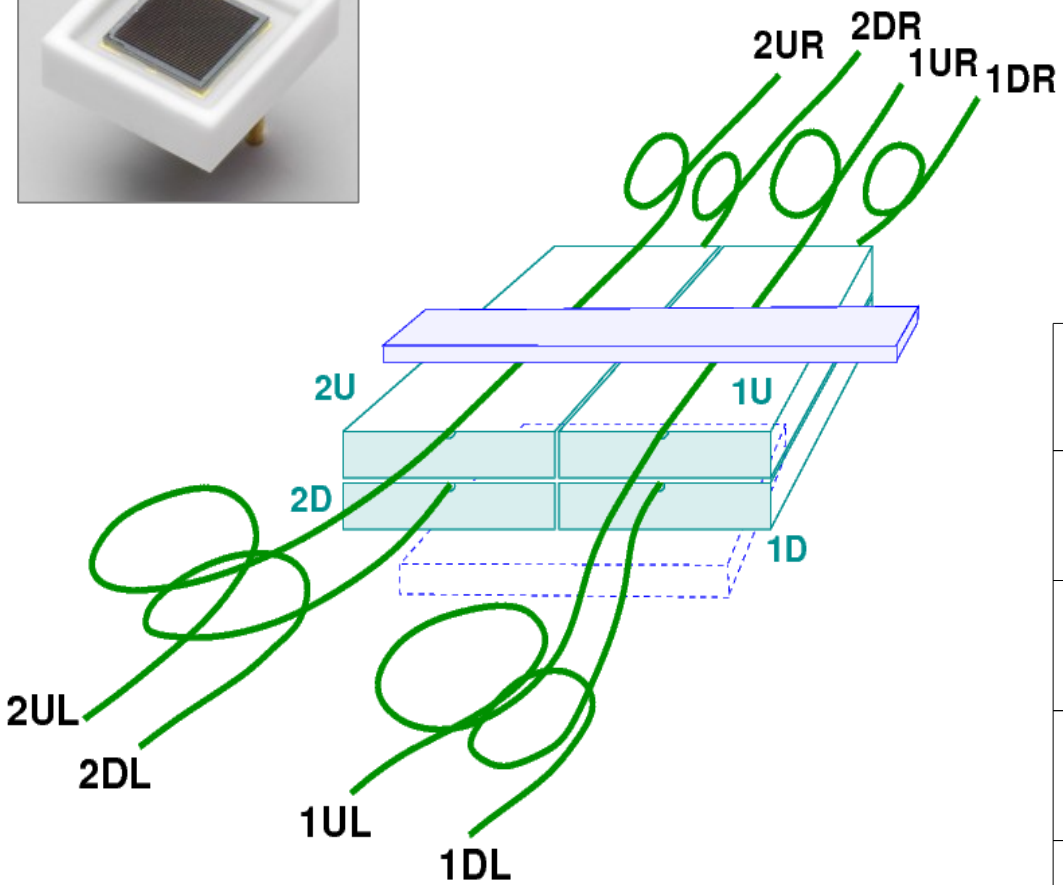
	S12572-050C	S12571-025C
Sensitive area size :	3x3 mm^2	1x1 mm^2
Number of pixels :	3600	1600
Pixel size :	50x50 μm^2	25x25 μm^2
Gain :	1.25 $x10^6$	5.15 $x10^5$
Operating voltage:	~ 67.6 V	~ 68.5 V
Peak spectral sensitivity:	450 nm	450 nm
Dark count (typical) :	1000 kHz	100 kHz
Crosstalk:	~ 25 %	~ 22 %
PDE at 500 nm:	~35 %	~35 %





3x3 mm^2 MPPC, 5-cm wide counters, 1 layer



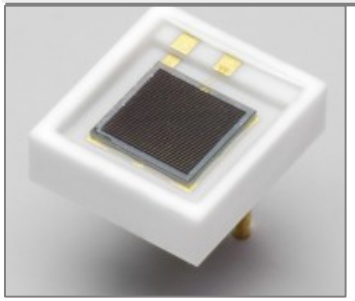


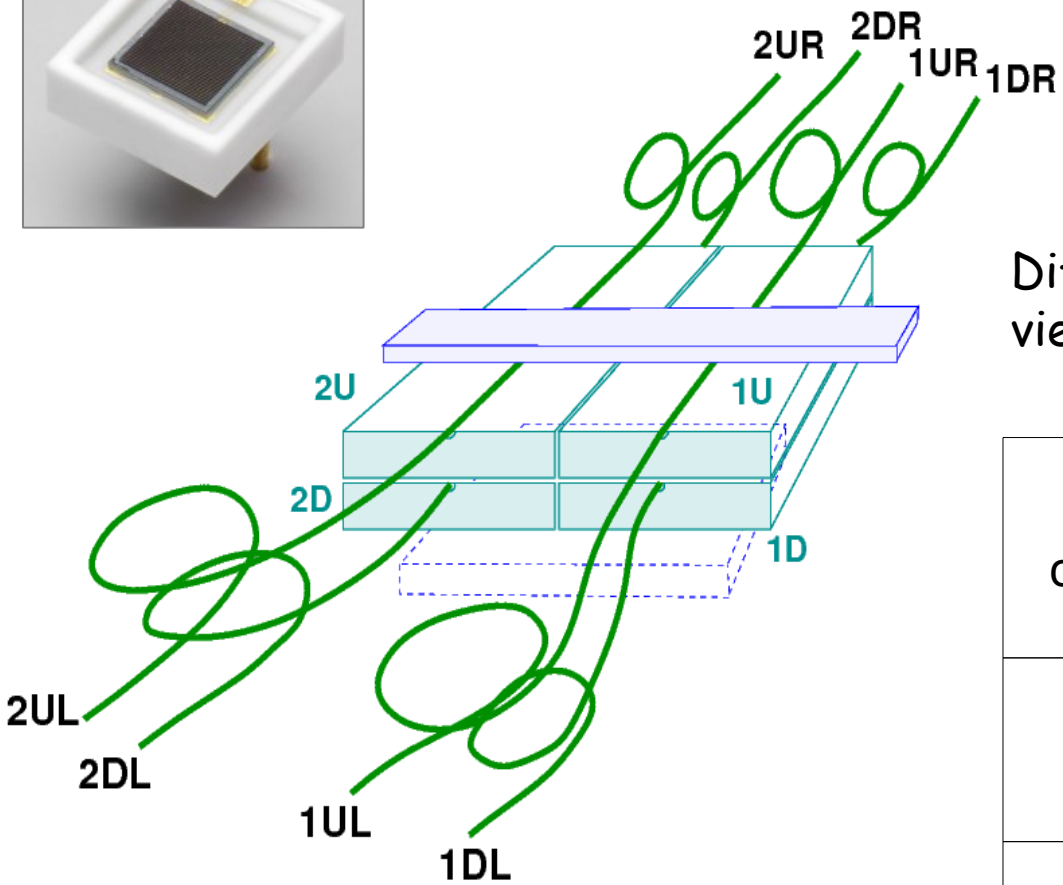
Different counters or combinations of two counters located horizontally (a single layer) are viewed by a single 3x3 mm MPPC at each end

Viewed counters	Light yield, ph.e./MIP	Timing σ, ns	Number of layers
1U	80	0.85	1
2U	81	0.84	1
1D	76	0.85	1
2D	83	0.85	1
1U+2U	84	0.87	1
1D+2D	83	0.86	1

3 m long fibers. Timing is calculated for combination $(T_L-T_R)/2$.

3x3 mm² MPPC, 5-cm wide counters, 2 layers

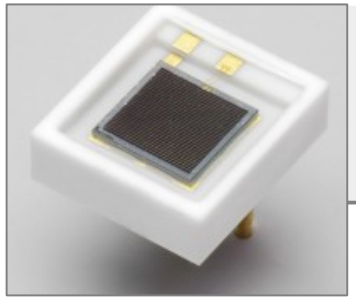




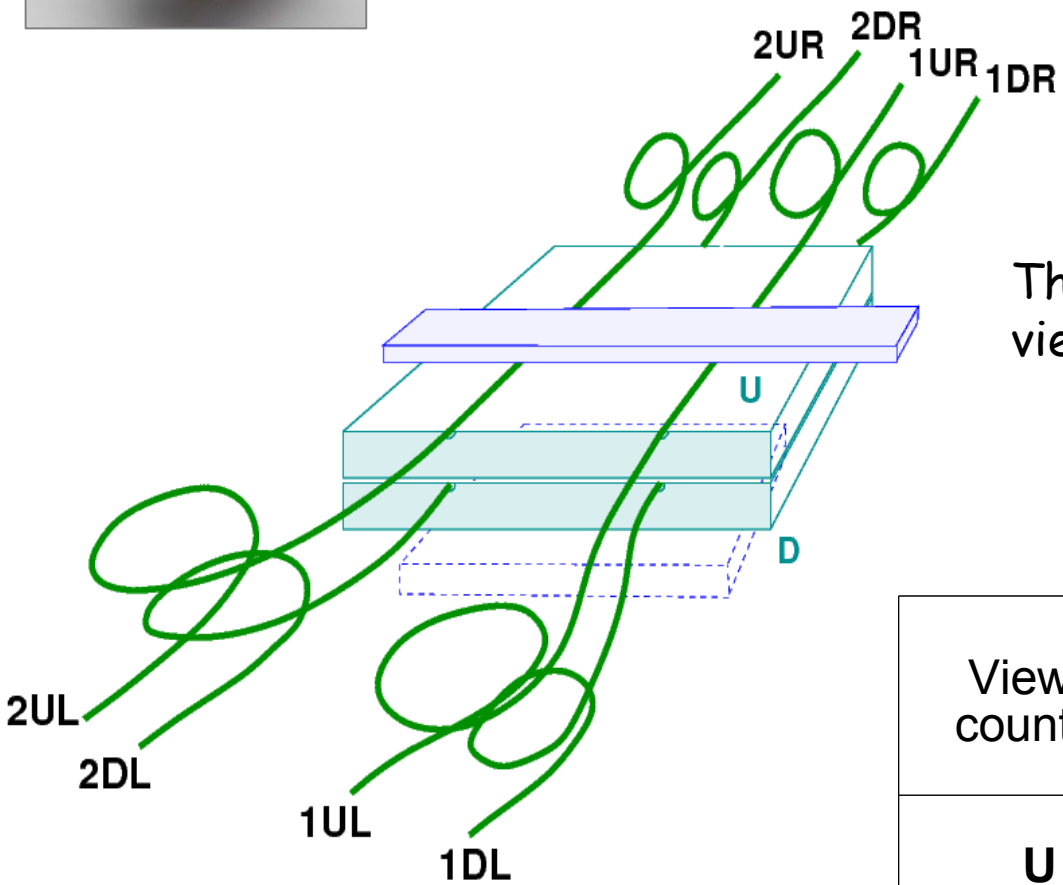
Different combinations of two layers are viewed by a single 3x3 mm MPPC at each end

Viewed counters	Light yield, ph.e./MIP	Timing σ, ns	Number of layers
1U+1D	164	0.63	2
2U+2D	171	0.63	2
1U+1D+ 2U+2D	175	0.64	2

3 m long fibers. Timing is calculated for combination $(T_L-T_R)/2$.



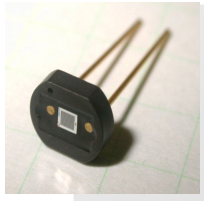
3x3 mm^2 MPPC, 10-cm wide counters



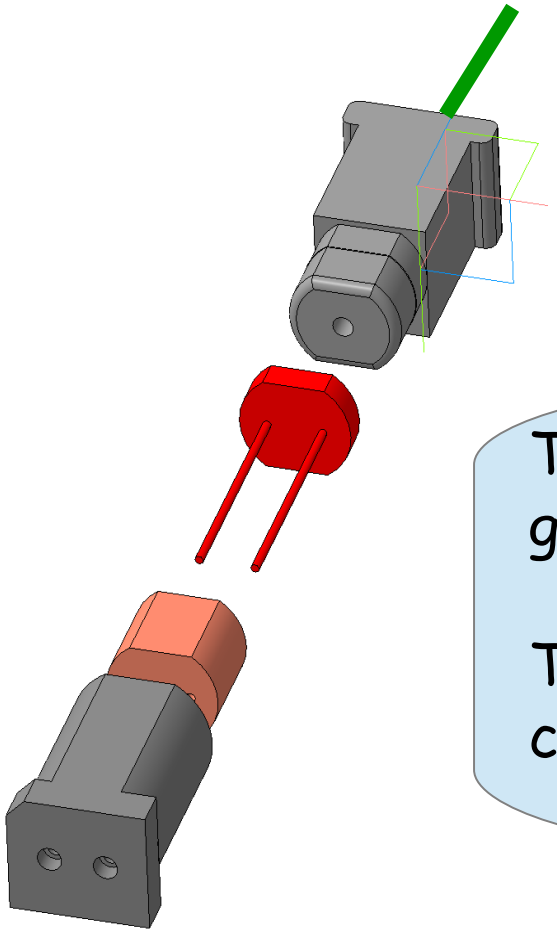
The counters or two counters combined are viewed by a single 3x3 mm MPPC at each end

Viewed counters	Light yield, ph.e./MIP	Timing σ, ns	Number of layers
U	88.6	0.84	1
D	88.0	0.76	1
U+D	188	0.60	2

3 m long fibers. Timing is calculated for combination $(T_L-T_R)/2$.

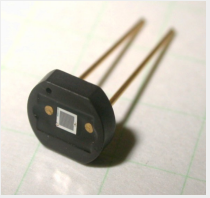


Switch to using 1 mm MPPCs

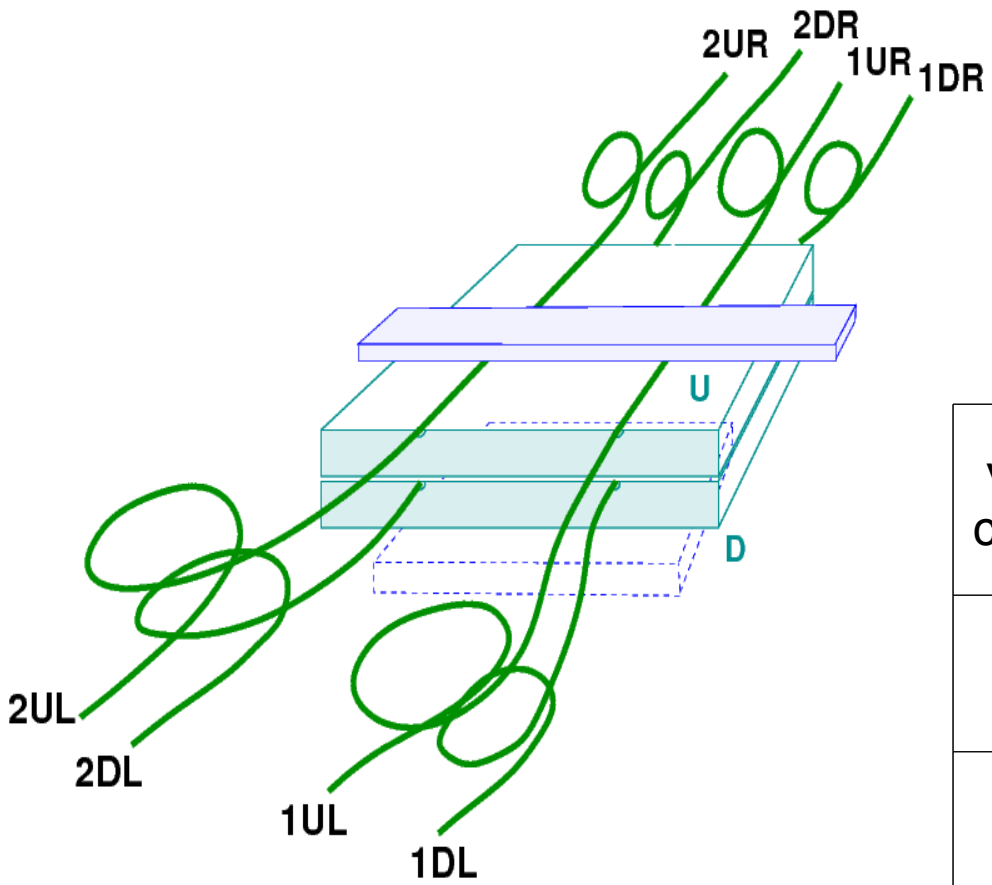


The optical connectors for 1 mm MPPCs were glued on fibers in the same tested counters.

The measurements were repeated with MPPCs connected in parallel.



1x1 mm² MPPC, 10-cm wide counters, parallel connection of MPPCs

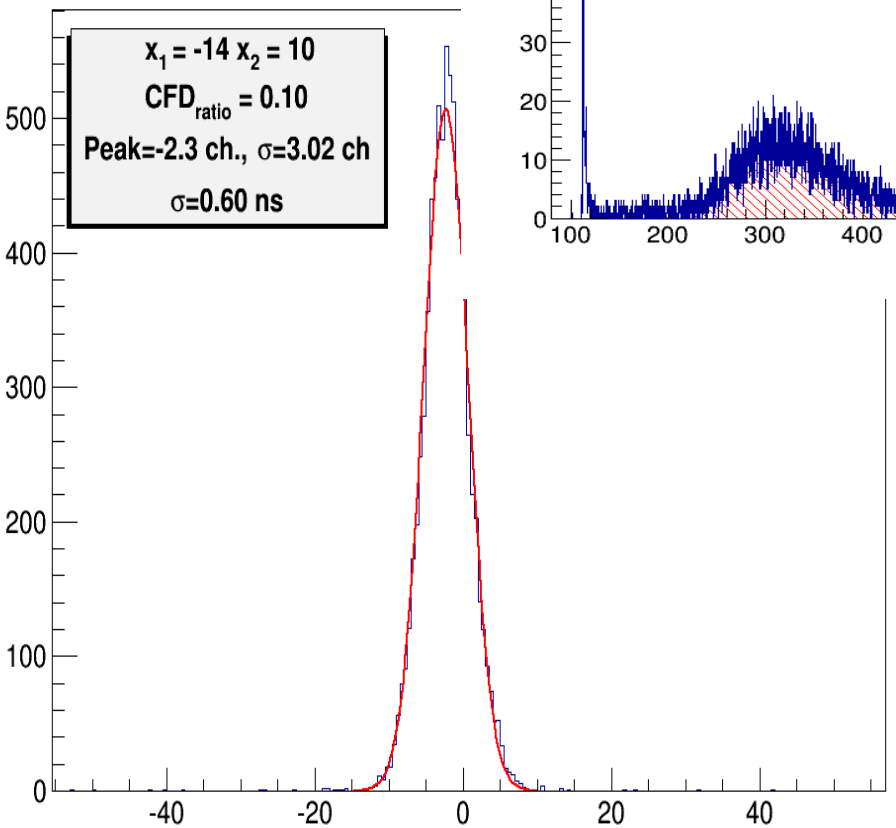


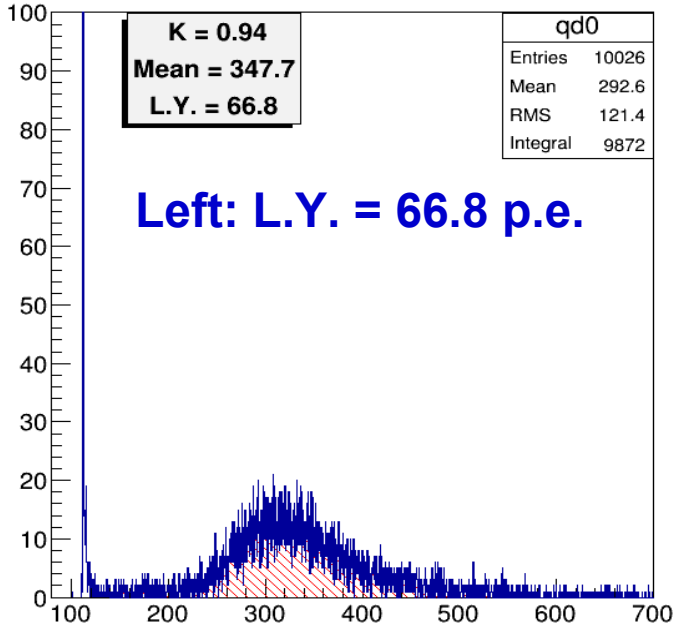
Configuration:
All fibers at each end are coupled to individual 1x1 mm² MPPCs. All MPPCs at one side are connected in parallel.

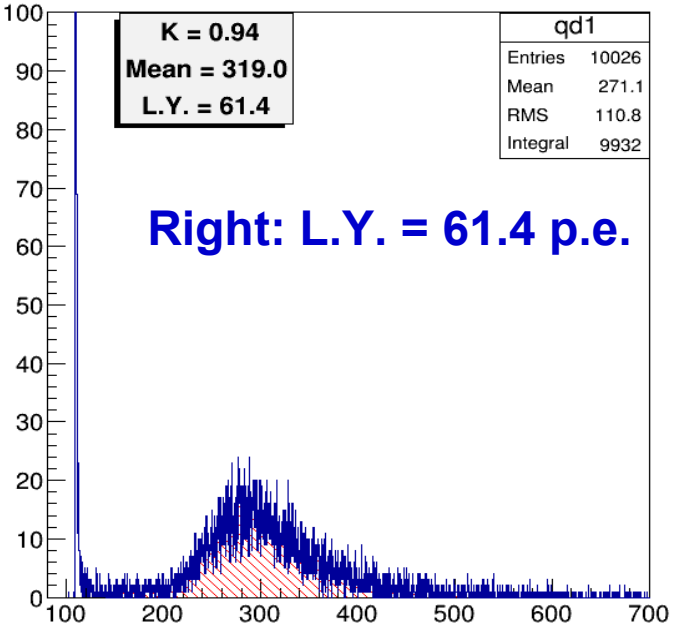
Viewed counters	Light yield, ph.e./MIP	Timing σ, ns	Number of layers
U	72.0	0.81	1
D	67.4	0.86	1
U+D	128.3	0.60	2

3 m long fibers. Timing is calculated for combination $(T_L-T_R)/2$.

Spectra for parallel connection of 4 MPPCs







Time resolution 0.60 ns for $(T_{left}-T_{right})/2$

3x3 mm^2 MPPC vs 1x1 mm^2 MPPC

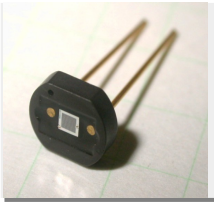
3x3 mm^2 MPPC provide slightly better light yield over 1x1 mm^2 MPPC because of higher PDE (larger pixel size).

The time resolution is almost the same in both cases, the readout by 3x3 mm^2 MPPC or 1x1 mm^2 MPPCs connected in parallel.

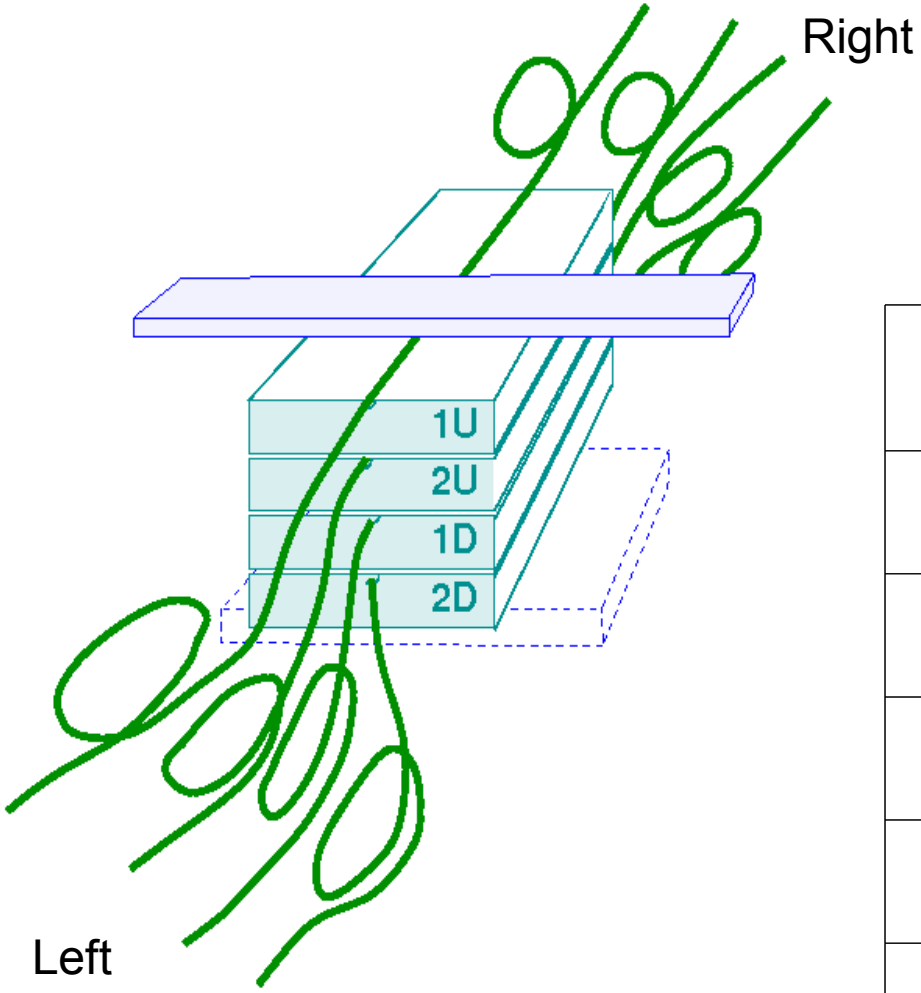
Conclusion: no difference if merge WLS fibers light on a single large MPPC or sum pulses from small MPPCs in parallel.

Time resolution vs number of layers

Measurements were done to study how the timing depends on the number of scintillator layers.



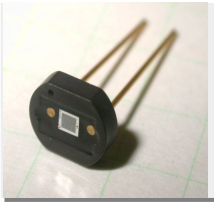
1x1 mm² MPPC, 4 counters, individual readout



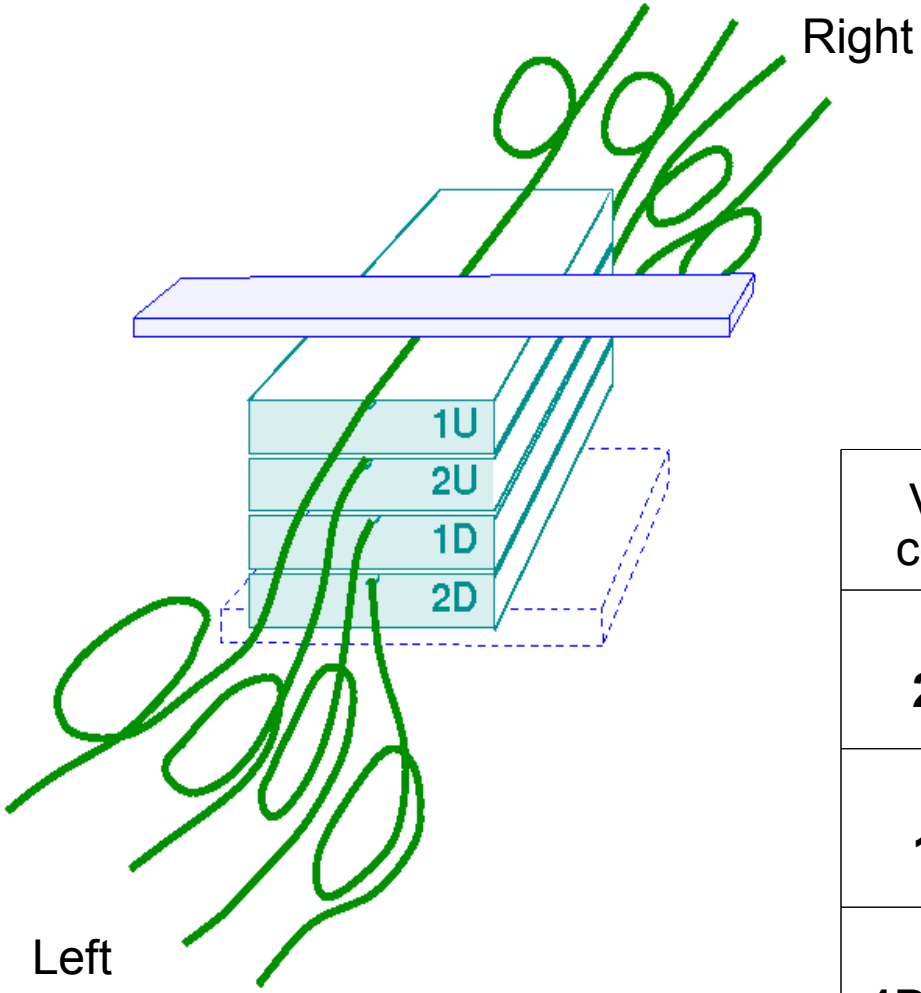
Configuration:
All fibers at each end are coupled to an individual 1x1 mm MPPC. Each MPPC is amplified and digitized.

Viewed counters	Light yield, ph.e./MIP	Timing σ, ns	Number of layers
1U	48	0.99	1
2U	64	0.86	1
1D	57	0.87	1
2D	64	0.85	1
1D+2D	122	0.62	2
All 4 layers	233	0.48	4

3 m long fibers. Timing is calculated for combination $(T_L-T_R)/2$.



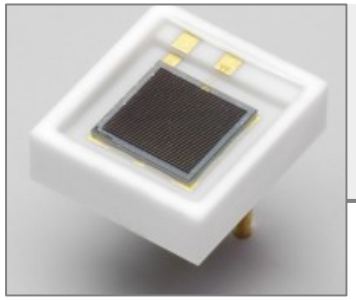
1x1 mm² MPPC in parallel, 4 counters



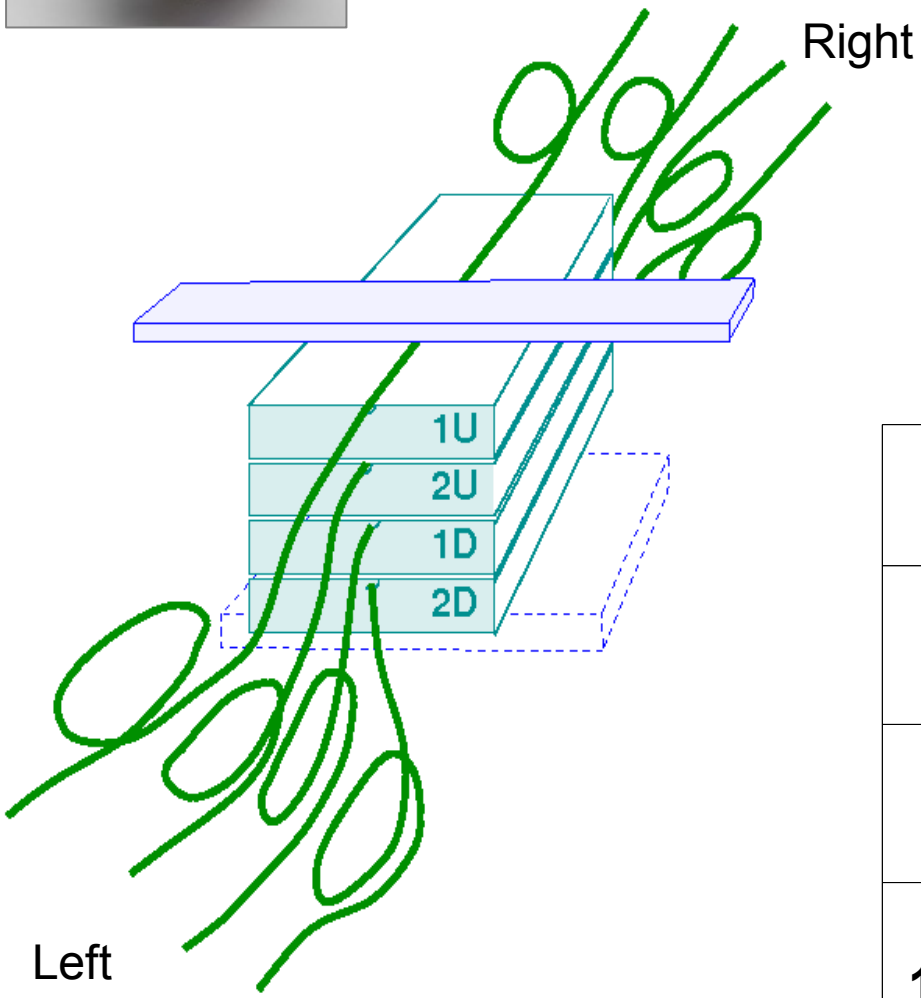
Configuration:
All fibers at each end are coupled to an individual 1x1 mm MPPC. All MPPCs at each side are connected in parallel.

Viewed counters	Light yield, ph.e./MIP	Timing σ, ns	Number of layers
2D+2U	126	0.60	2
1D+2D	130	0.57	2
1D+2D+2U	180	0.50	3
All 4 layers	220	0.45	4

3 m long fibers. Timing is calculated for combination $(T_L-T_R)/2$.



3x3 mm² MPPC, 4 counters



Configuration:
All fiber ends at each side are coupled to a single 3x3 mm MPPC.

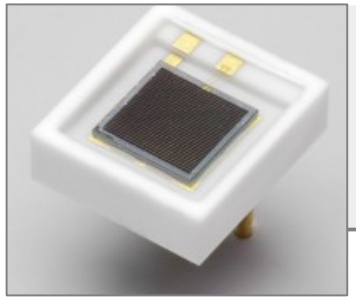
Viewed counters	Light yield, ph.e./MIP	Timing σ, ns	Number of layers
1U+2U	164	0.63	2
1D+2D	171	0.63	2
1D+2D+2U	239	0.53	3
All 4 layers	334	0.46	4

3 m long fibers. Timing is calculated for combination $(T_L-T_R)/2$.

Time resolution vs number of layers

Conclusion: 7-mm thick 3-m long scintillators and Y11 WLS fibers spaced at 5 cm provide the time resolution:

σ = 800-870 ps with a single layer
σ = 600-630 ps with two layers
σ = 500-530 ps with three layers
σ = 450 ps with four layers



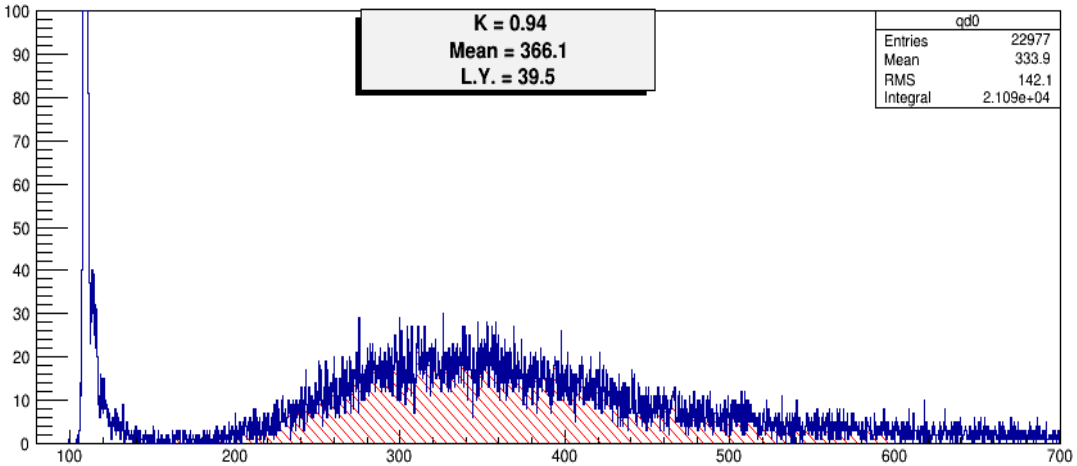
Parameters vs scintillator width

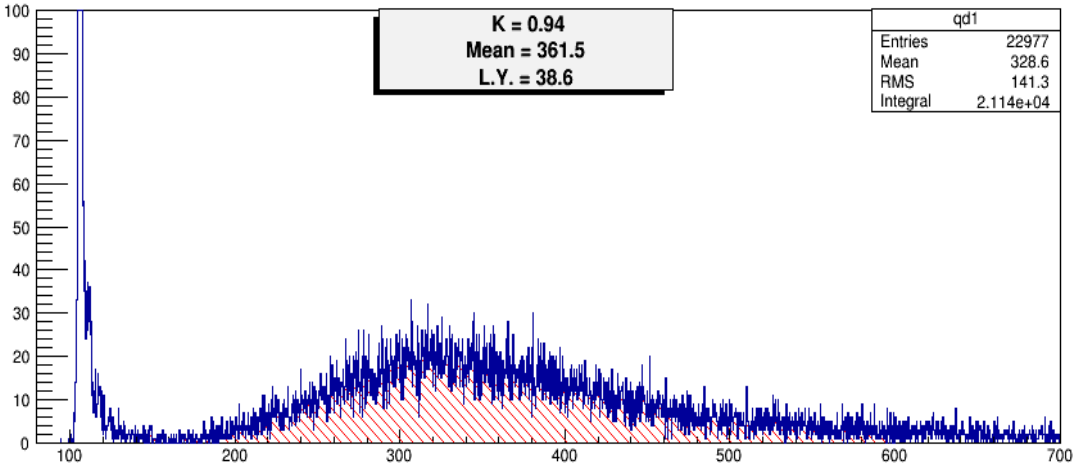
All fibers were read out by 3x3 mm^2 MPPCs, a single MPPC at one end.
WLS fibers: 3-m long Kuraray Y11 of 1 mm diameter.
Fiber spacing: 5 cm.
Scintillator thickness: 0.7 mm.
Number of layers: 1.

Width	Number of fibers	Timing σ, ns	Light yield, ph.e./MIP
5 cm	**1**	**0.85**	**80.0**
10 cm	**2**	**0.80**	**88.3**
15 cm	**3**	**0.87**	**78.6**
20 cm	**4**	**0.86**	**78.1**

Spectra for the 20-cm wide slab

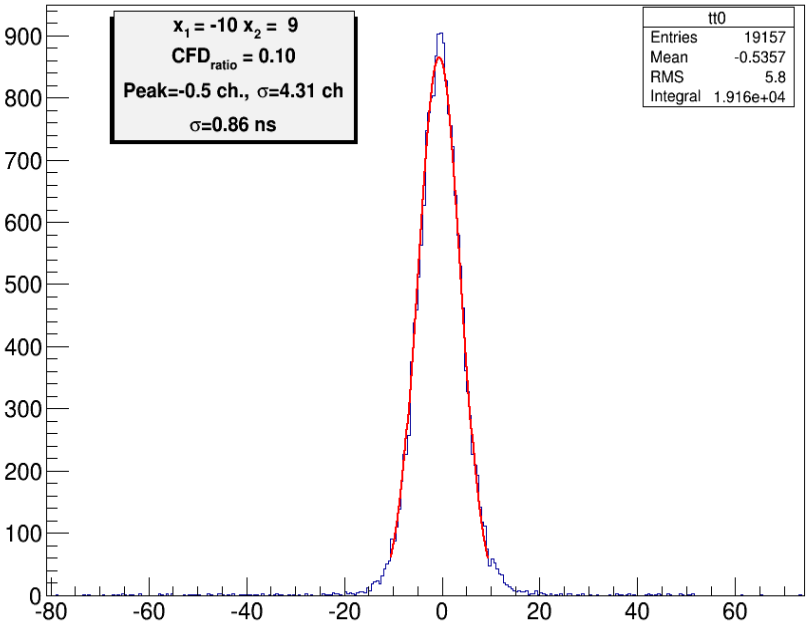
A single scintillator slab of 0.7x20x120 cm^3 size with 4 WLS 3-m long fibers. Cosmic muons spectra were obtained over the center line across the slab.



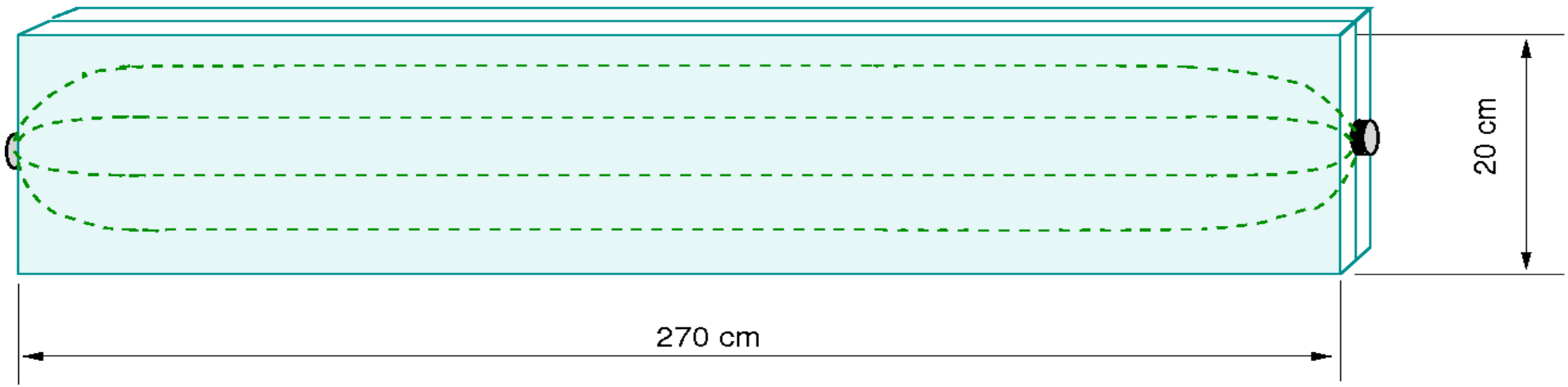


Light yield at both ends:
39.5 and 38.6 p.e./MIP

Timing spectrum $(T_{LEFT}-T_{RIGHT})/2$
Resolution: σ_T=0.86 ns



Proposed TOF counter conception



The TOF counter consists of two scintillator slabs of 0.7x20x270 cm^3 size.

Four WLS Kuraray Y11 fibers of 1 mm diameter are glued in the slab.

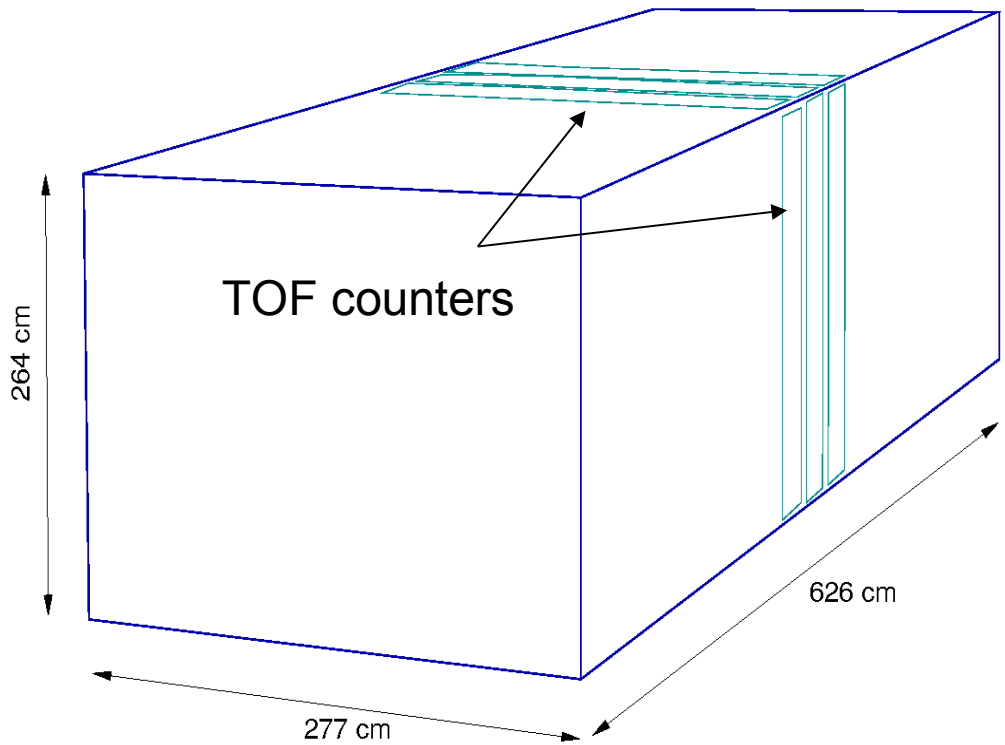
8 WLS fibers are bundled within a scintillator slab at each side of the counter into a connector. Connector is mounted directly at the scintillator.

The fibers are read out by a single 3x3 mm^2 MPPC at each side.

Expected time resolution σ is 630-650 ps.

Number of TOF channels for the outer level

TOF outer layers are mounted at the inner surface of e-m. calorimeter. Simplified picture combines both inner barrel and POD parts of e.-m. calorimeter, total size is about 2.6 x 2.8 x 6.3 m^3.



Estimation to the max coverage:

Length of sci. slabs: 260-270 cm
Width of sci. slabs: 20 cm
Two slabs per a TOF counter, both side readout.

Number of TOF counters: 152
Number of readout ch. : 304

Number of sci. slabs : 304
Total sci. weight: ~1300 kg
Number of 3x3 mm^2 MPPCs : 304
WLS fiber length: 3.6 km

Number of channels in TOF inner layer around the active target is more difficult to estimate and depends on the configuration of the active target and TOF counters.