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

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Introduction

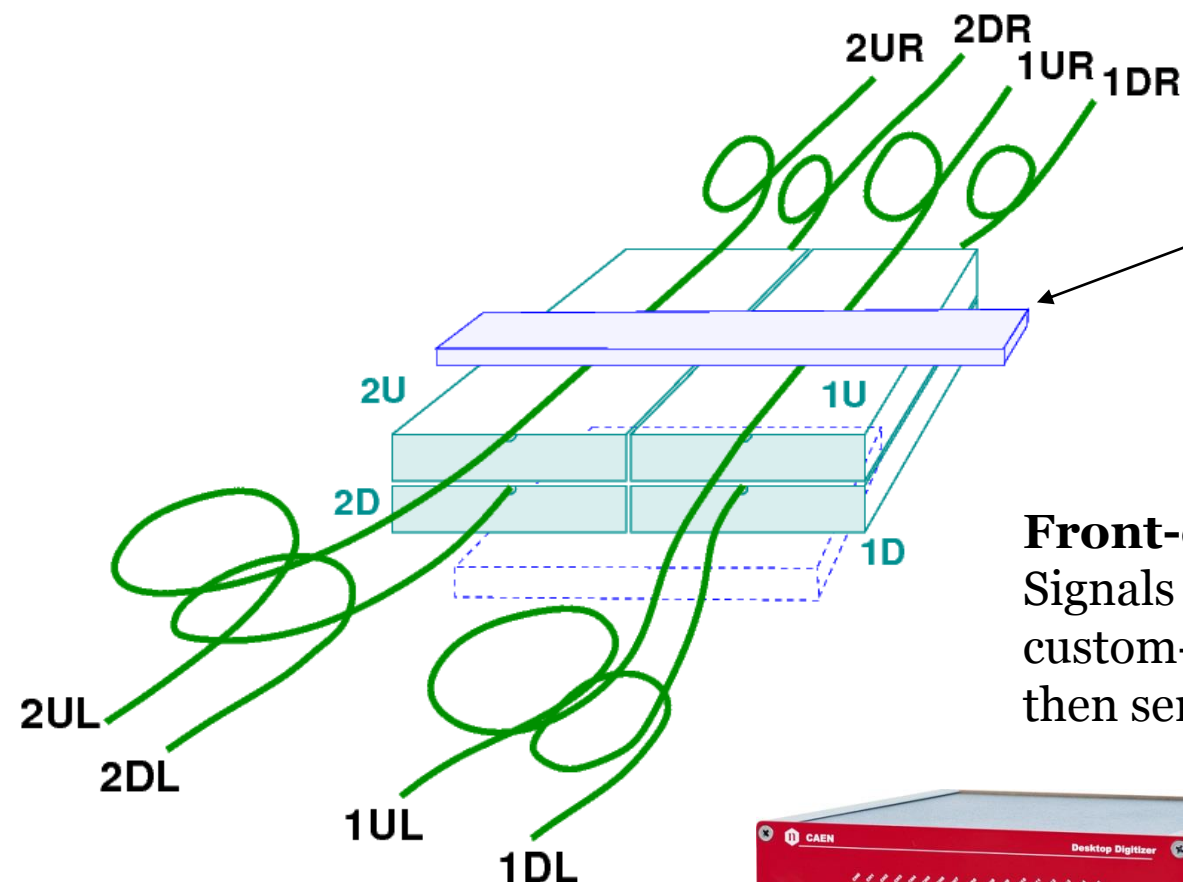
TOF system:

- separation of charged particles and directions by time-of-flight in the inner volume of the electromagnetic calorimeter
- Outer TOF layer (close to ECAL) maximum cover about **82 m² area**
- Provide time resolution **σ_t close to 0.5 ns**

Test features:

- Different scintillator and fibers configurations
- Two types of MPPCs:
 - 3x3 mm²
 - 1x1 mm²
- Various read out configurations

Readout and trigger for cosmic tests



Cosmic trigger is a coincidence of two scintillator counters:

Upper counter: $2 \times 20 \text{ cm}^2$
Bottom counter: $7 \times 7 \text{ cm}^2$

Front-end electronics:

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



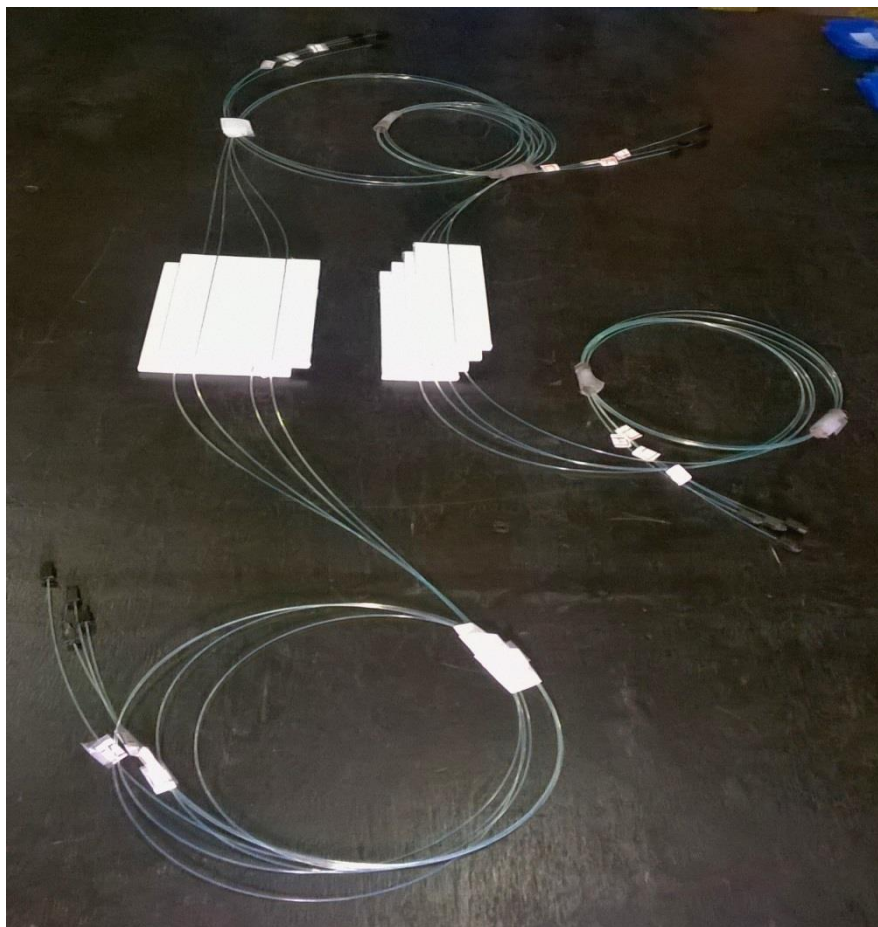
CAEN digitizer DT5742:

**16 channels, 5 GHz sampling rate,
200 ns time window at 5 GHz,
12-bit resolution**

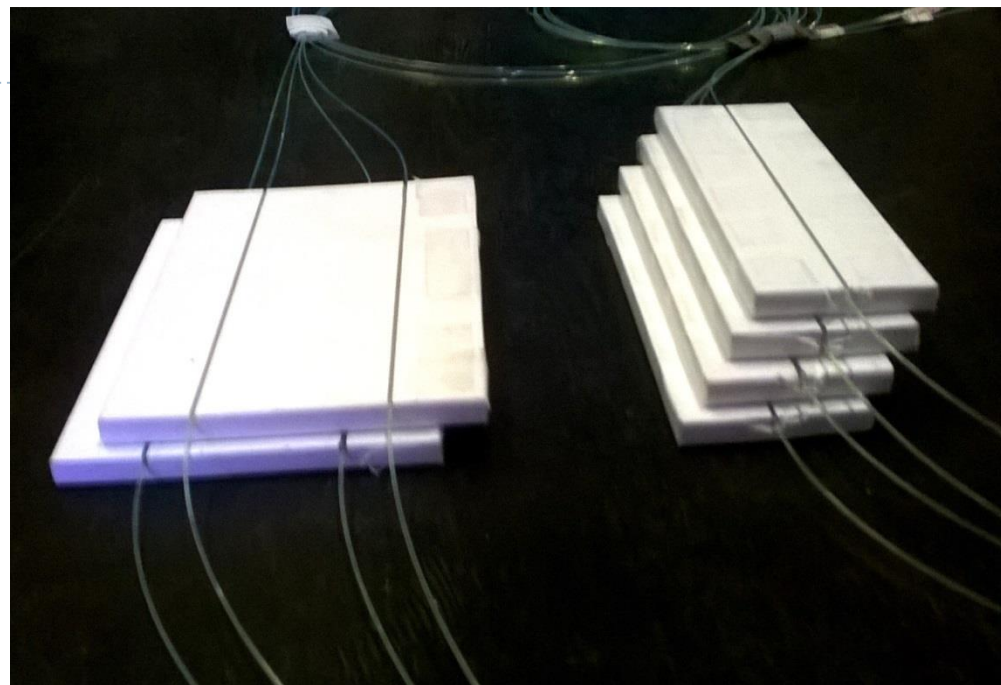
The signal charge: area of signal waveform normalized to photoelectrons

The signal timing: constant fraction (**0.1**) of a signal front

Tested scintillator and fiber configurations

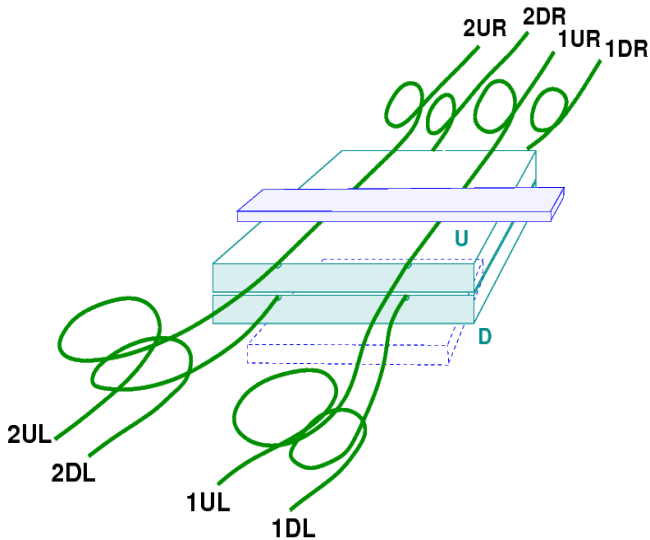
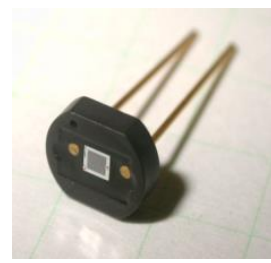
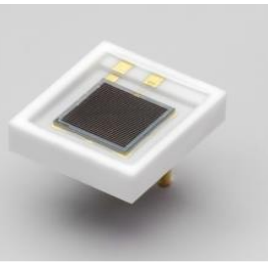


- Reflector: chemical one & Tyvek paper
- Y11 Kuraray multi-clad WLS fibers, 3 m long, 1 mm diameter



- 7-mm thick and 15 cm length extruded slabs
- 5 cm between fibers
- Main samples:
 - 4 samples: 5 cm width, 1 fiber
 - 2 samples: 10 cm width, 2 fibers
- Other configurations:
 - 15 cm width, 120 cm length, 3 fibers
 - 20 cm width, 120 cm length, 4 fibers
 - 10 cm width, 50 cm length, 4 fibers
 - 2.5 cm between fibers

MPPCs comparison



3x3 mm² MPPC:

The counter or two counters combined are viewed by a single 3x3 mm² 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

Configuration:

- 10 cm width counters with 2 fibers
- 3 m long fibers
- Timing is calculated for combination $(T_L - T_R)/2$

1x1 mm² MPPC:

- 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

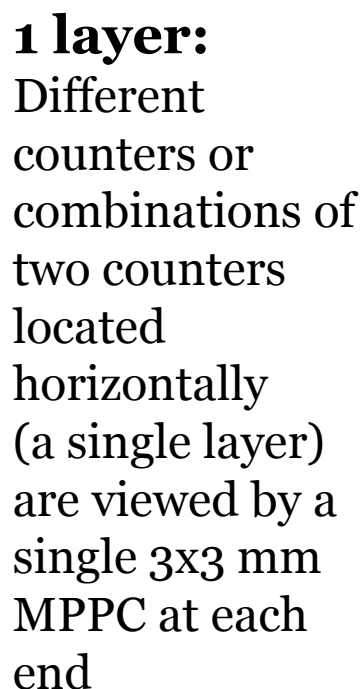
MPPCs comparison

- **3x3 mm² MPPC provide slightly better light yield over 1x1 mm² MPPC because of higher PDE (larger pixel size)**
- **The time resolution is almost the same in both cases, the readout by 3x3 mm² MPPC or 1x1 mm² 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

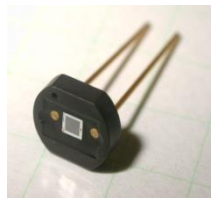
Time resolution vs number of layers

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

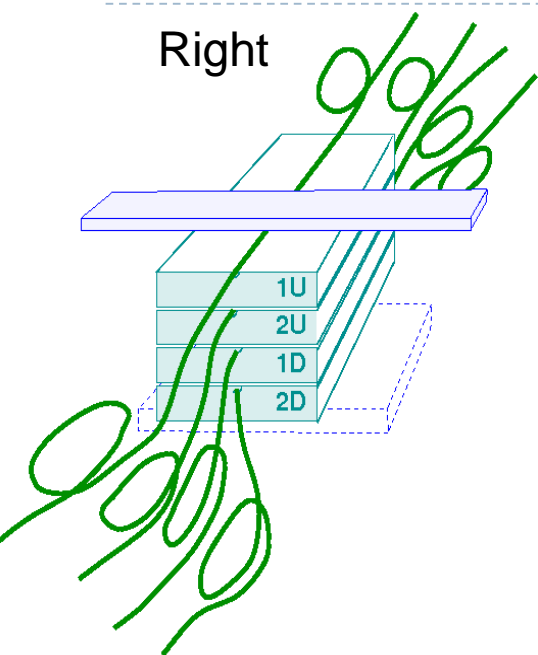


- 2 layers:**
Different combinations of two layers are viewed by a single 3x3 mm MPPC at each end

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



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

Left

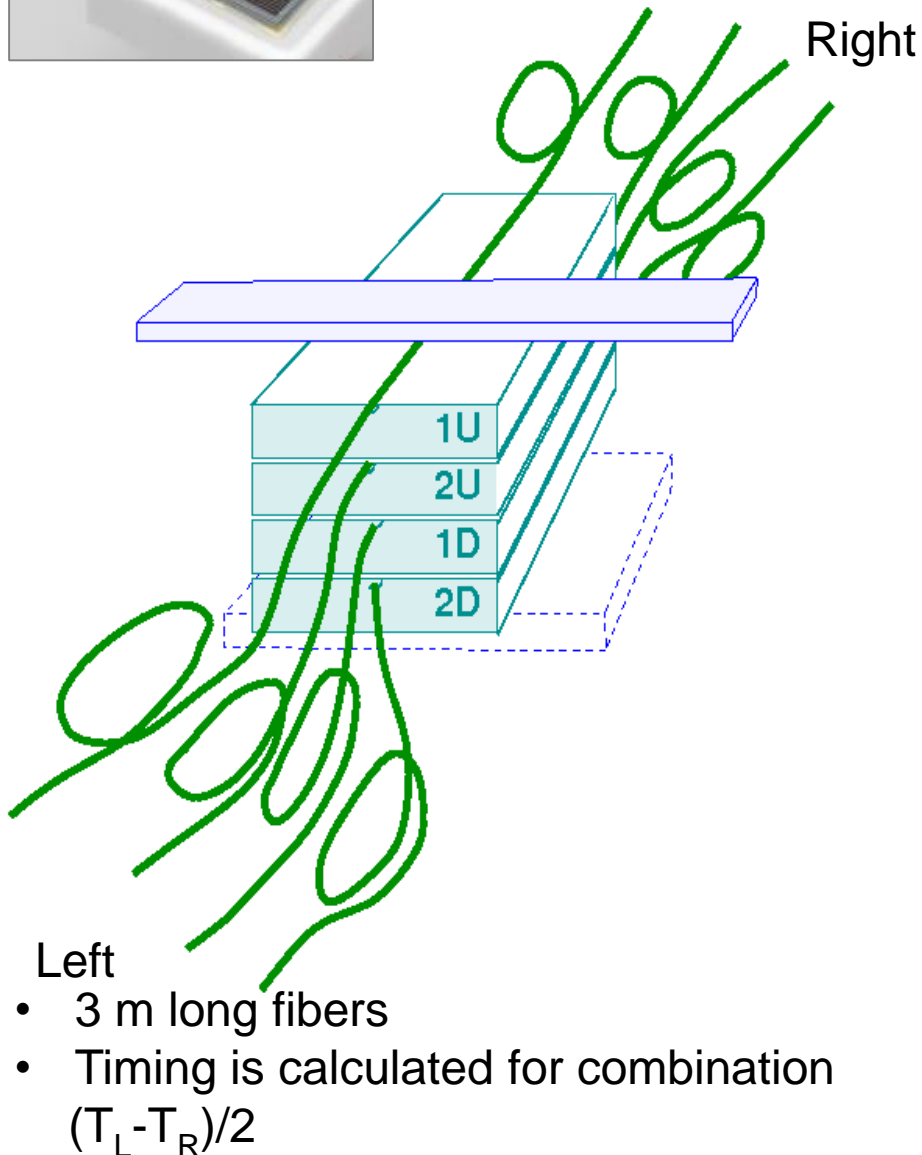
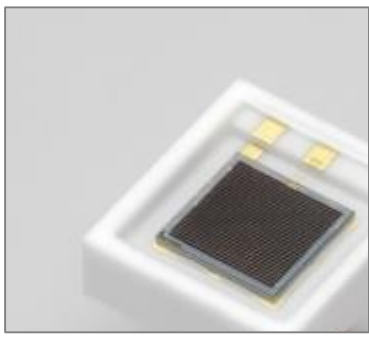
- 3 m long fibers
- Timing is calculated for combination $(T_L - T_R)/2$

Parallel connection 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

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

Time resolution vs number of layers comparison

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

$\sigma = 800\text{-}870$ ps with a single layer

$\sigma = 600\text{-}630$ ps with two layers

$\sigma = 500\text{-}530$ ps with three layers

$\sigma = 450$ ps with four layers

Scintillator width comparison

- **3x3 mm² MPPCs readout**
- **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

Fibers comparison: Kuraray Y11 vs BCF-92

- Slow fibers: 3-m long Kuraray Y11 **multi-clad**, 1 mm diameter
- Fast fibers: 3-m long Bicron BCF-92 **single-clad**, 1 mm diameter
- Light yield is a sum from both ends
- Read out by 3x3 mm² MPPCs
- Single MPPC at one end
- Counters: 0.7x10x50 cm³
- Fiber spacing is 2.5 cm

WLS fiber	Decay time, ns	Light yield, ph.e./MIP	Timing σ , ns
Y11 m.c.	~12	~130	~0.75
BCF92 s.c.	~3	37.8	0.80

Conclusion: fast single-clad fibers gives worse timing than slow multi-clad WLS fibers out of low light yield

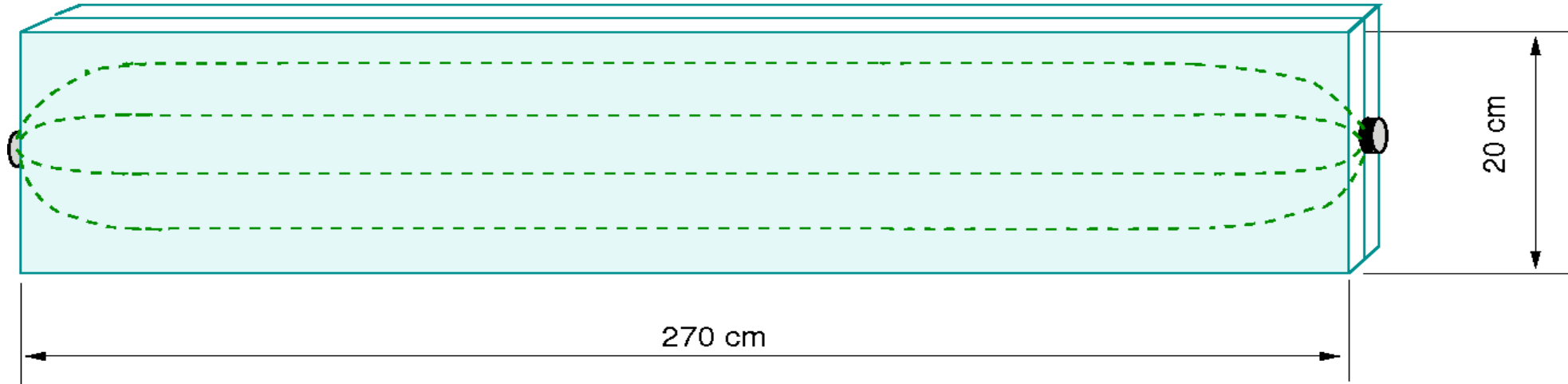
Fiber density comparison

- 3-m long Kuraray Y11 multi-clad, 1 mm diameter
- 10 cm width counters
- 2 grooves, **fiber spacing is 5 cm**
- 4 grooves, **fiber spacing is 2.5 cm**
- Read out by 3x3 mm² MPPCs
- Single MPPC at one end

Fiber spacing	Number of layers	Light yield, ph.e./MIP	Timing σ , ns
5 cm	1	88	0.80
5 cm	2	188	0.60
2.5 cm	1	130	~0.75
2.5 cm	2	~240	~0.55

Conclusion: 2 times more fibers give higher light output but little advantage in timing

Proposed TOF counter conception



- Two scintillator slabs of $0.7 \times 20 \times 270 \text{ cm}^3$ size
- 4 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
- Read out by a single $3 \times 3 \text{ mm}^2$ MPPC at each side
- Expected time resolution σ is 630-650 ps

Conclusion

- No difference if merge WLS fibers light on a single large MPPC or sum pulses from small MPPCs in parallel
- Fast single-clad fibers gives worse timing than slow multi-clad WLS fibers out of low light yield
- 2 times more fibers give higher light output but little advantage in timing
- The best achieved time resolution: **450 ps**
(7-mm thick 3-m long scintillators, Y11 WLS fibers spaced at 5 cm)
- Expected time resolution for proposed configuration:
 $\sigma \leq 600$ ps

► Back up

Introduction

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 m² 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.

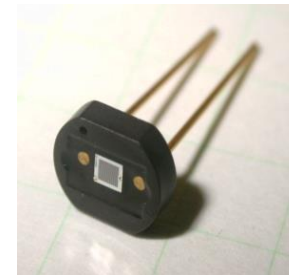
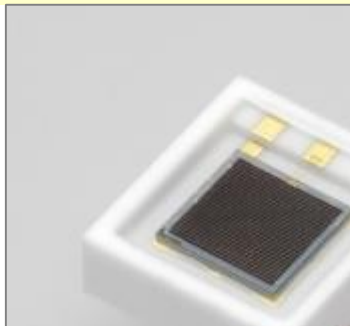
3. **5 cm spacing between the fibers.**

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

Specification of tested Hamamatsu MPPCs

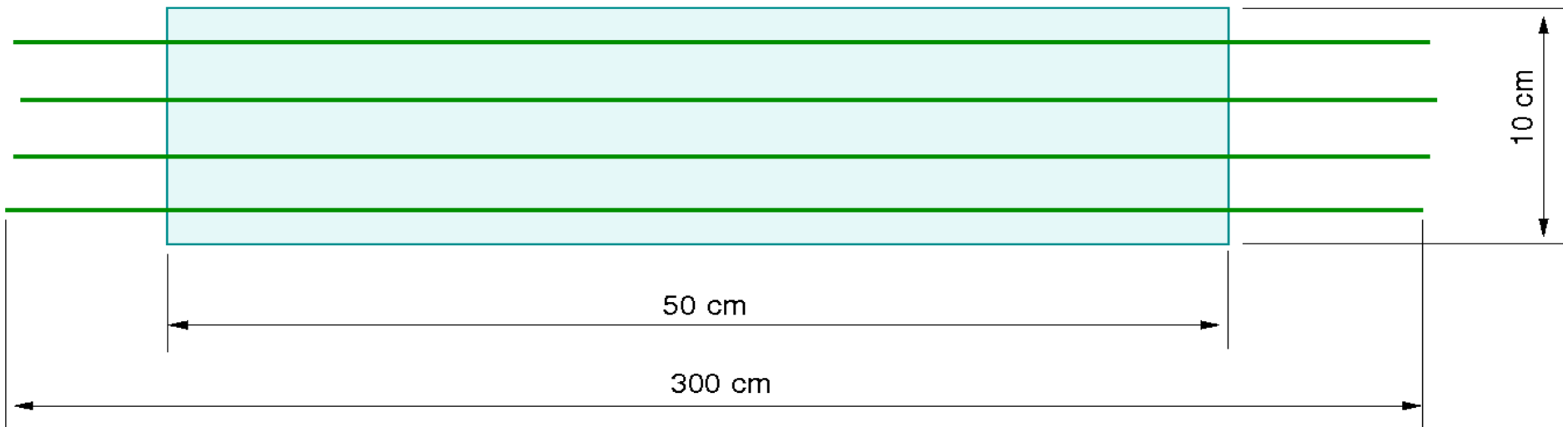
Tested photodiodes are of the same generation and similar parameters, the differences are the total sensitive area size and pixel size

	S12572-050C	S12571-025C
Sensitive area size :	3x3 mm²	1x1 mm²
Number of pixels :	3600	1600
Pixel size :	50x50 μm²	25x25 μm²
Gain :	1.25 x10⁶	5.15 x10⁵
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 %



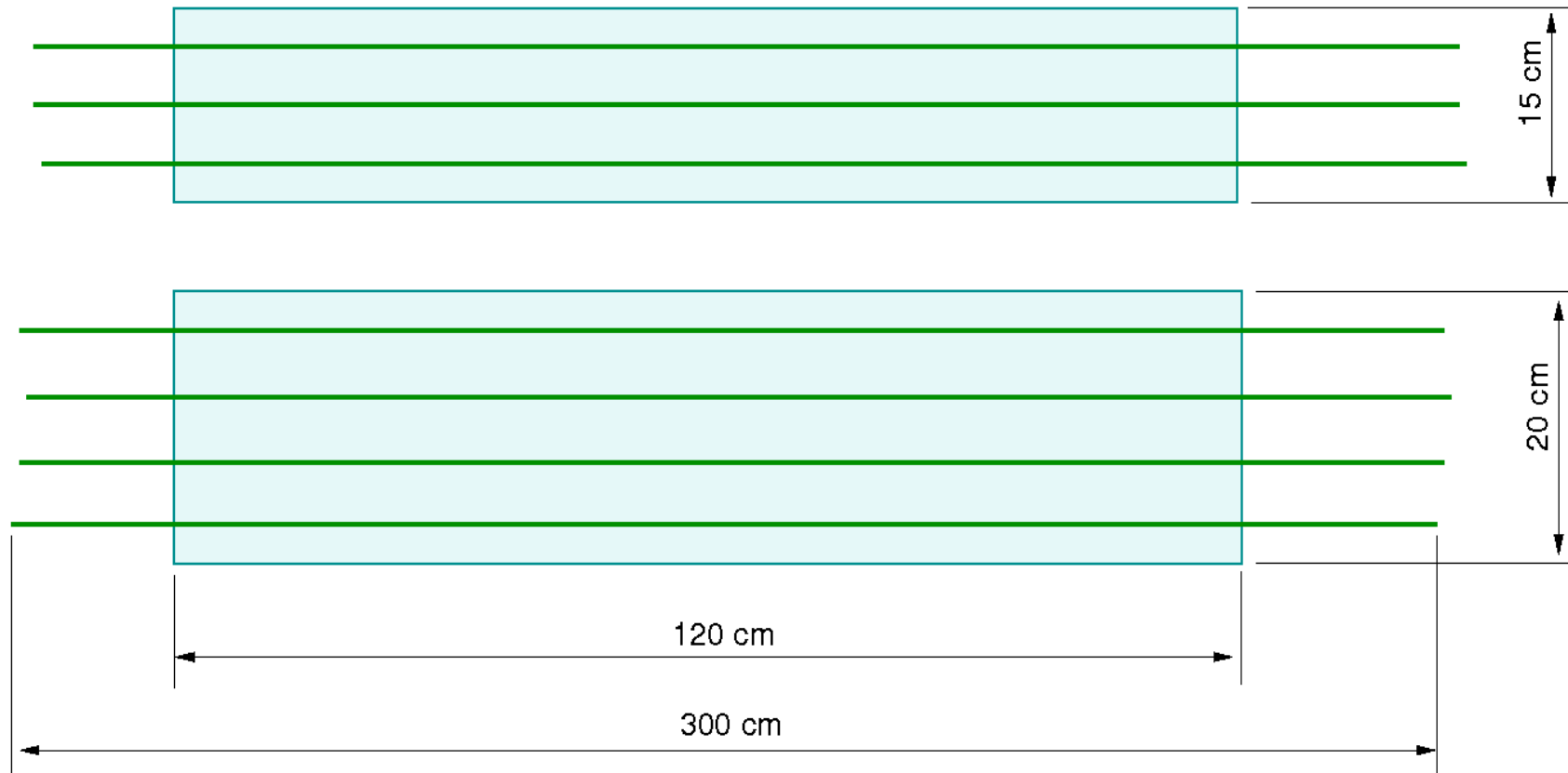
Tested samples of 10-cm width with 2.5 cm spaced grooves

- 10-cm wide counters with **25 mm fiber spacing**
- Twice more fibers
- Scintillator size: **0.7x10x50 cm³**
- Reflector: chemical+Tyvek

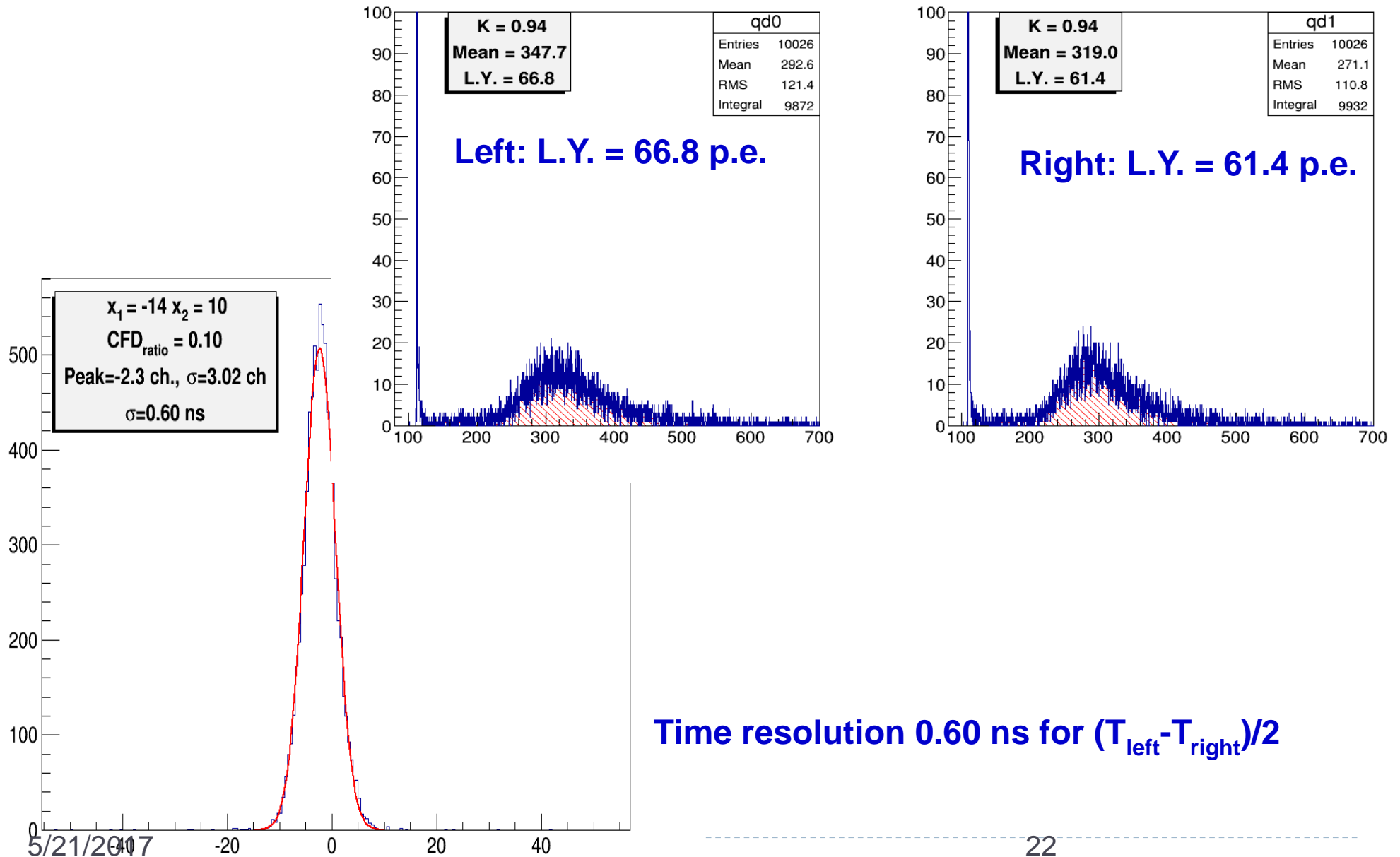


Tested samples of 15- and 20-cm width

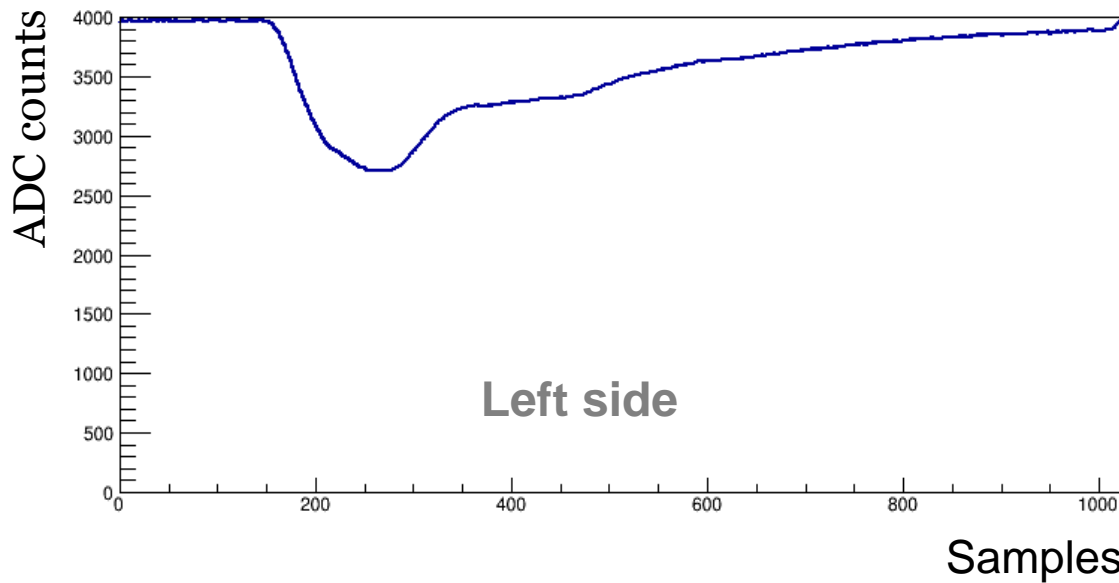
- Two slabs were manufactured:
 - $0.7 \times 15 \times 120$ cm³ with 3 grooves
 - $0.7 \times 20 \times 120$ cm³ with 4 grooves
- WLS Y11 fibers of 3 m length
- Readout with 3×3 mm² MPPCs
- Single MPPC at one scintillator end



Spectra for parallel connection of 4 MPPCs

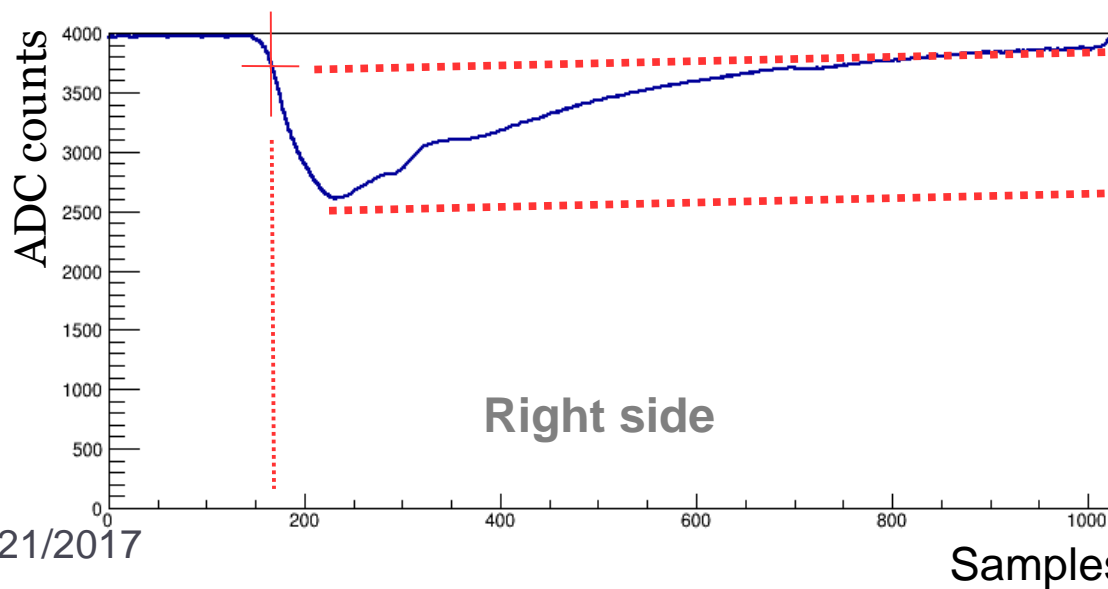


Digitized signal waveforms



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

Full scale: 1024 samples,
200 ps between samples.



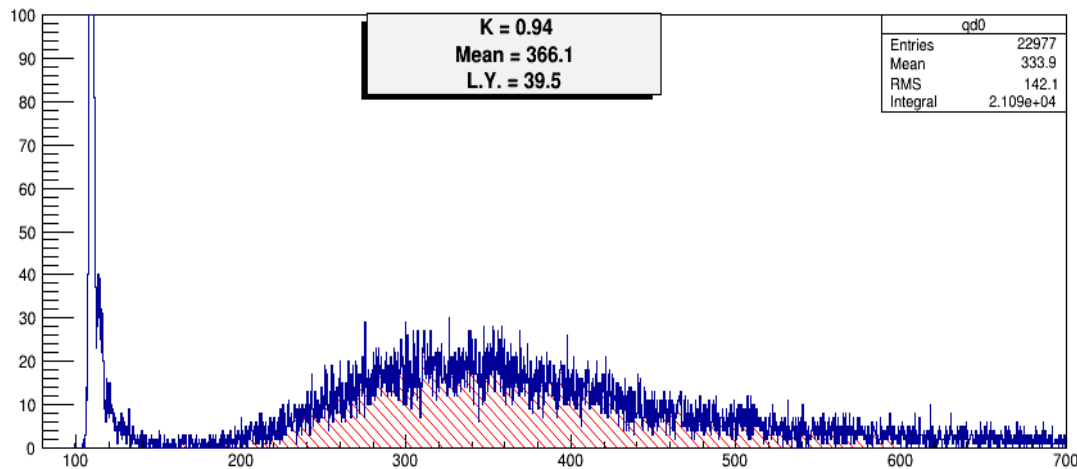
10% from max amplitude

Max amplitude

Constant fraction timing

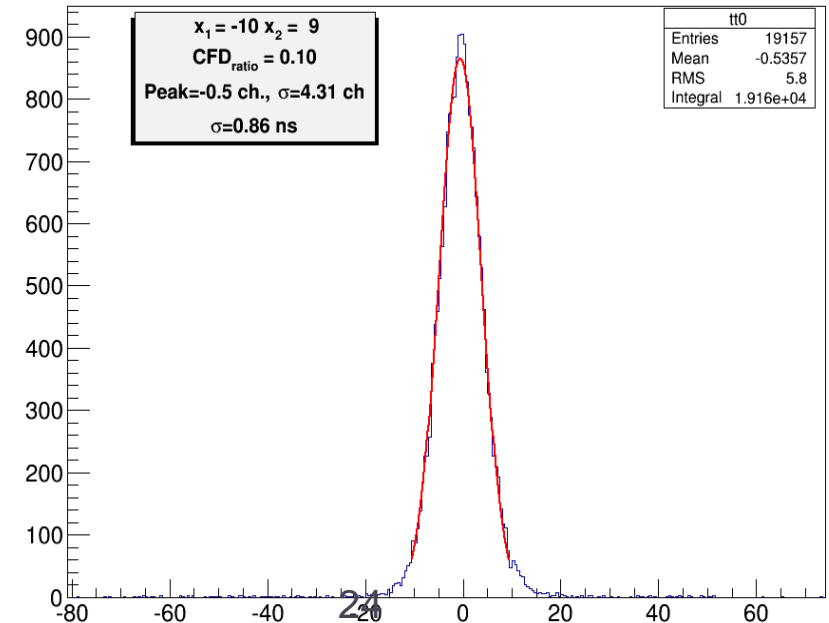
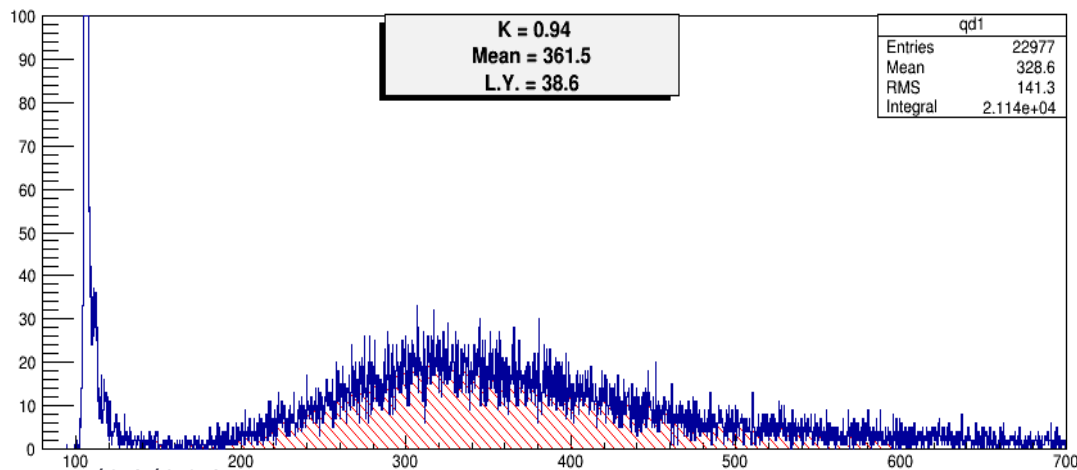
Spectra for the 20-cm wide slab

A single scintillator slab of **0.7x20x120 cm³** size with 4 WLS 3-m long fibers. Cosmic muons spectra were obtained over the center line across the slab.

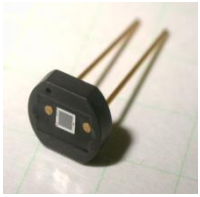


Light yield at both ends:
39.5 and 38.6 p.e./MIP

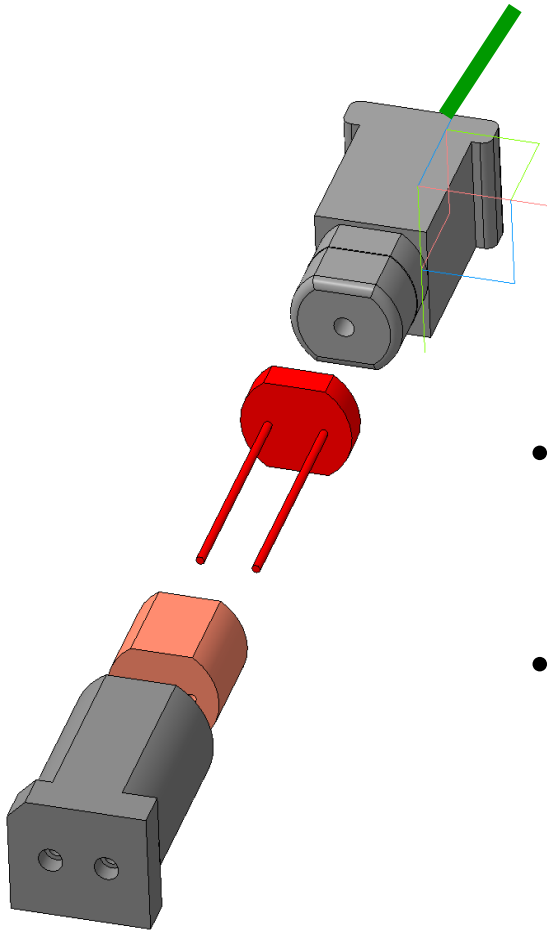
Timing spectrum ($T_{\text{LEFT}} - T_{\text{RIGHT}}$)/2
Resolution: **$\sigma_T = 0.86$ ns**



5/21/2017



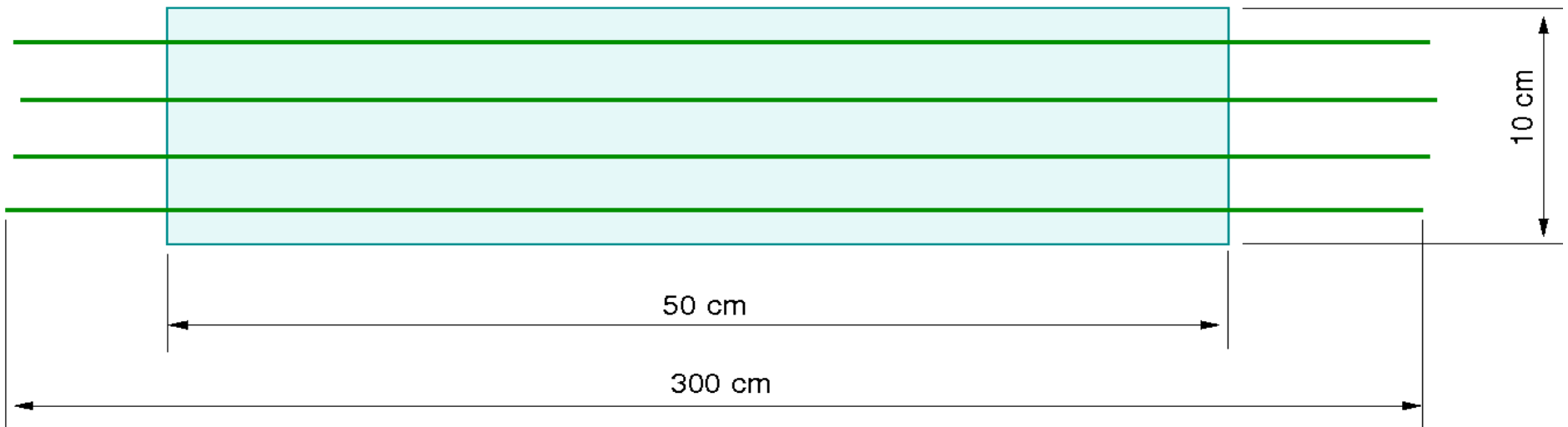
Tests with 1 mm MPPCs



- Optical connectors for 1 mm MPPCs were glued on fibers in the same tested counters
- Measurements were repeated with MPPCs connected in parallel

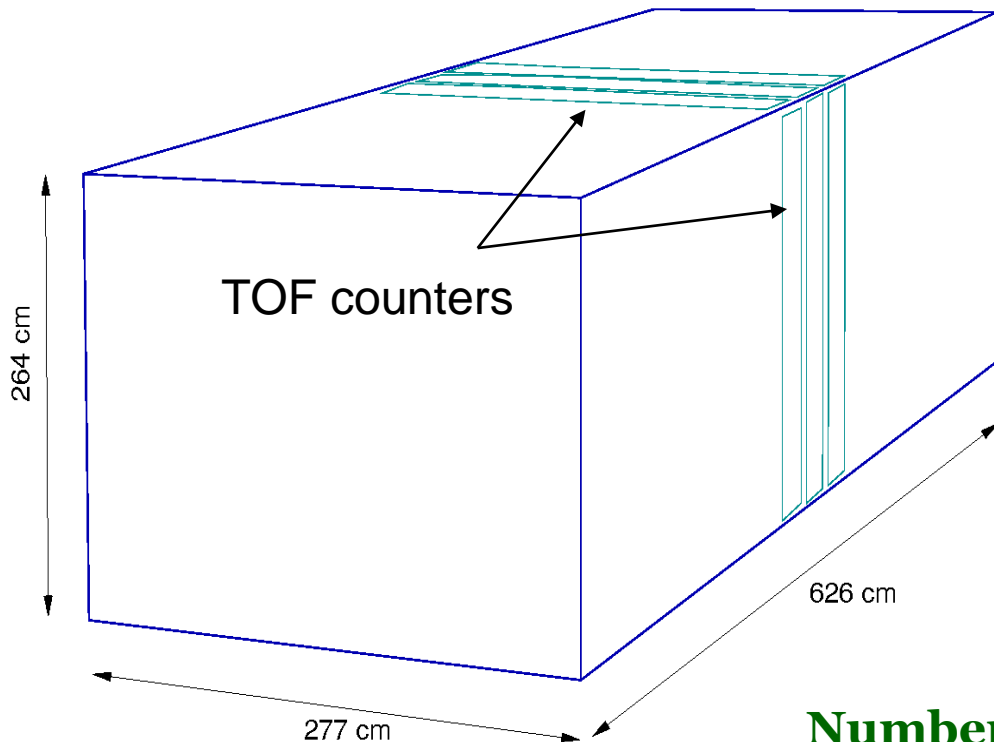
Fibers comparison: Kuraray Y11 vs BCF-92

- A few 10-cm wide counters were manufactured with **25 mm fiber spacing**
- Twice more fibers
- WLS fibers:
 - 3-m long **Kuraray Y11** of 1 mm diameter
 - 3-m long fast **BCF-92** WLS fibers of 1 mm diameter
- Scintillator size: $0.7 \times 10 \times 50 \text{ cm}^3$.
- Reflector: chemical+Tyvek
- $3 \times 3 \text{ mm}^2$ MPPC



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 m³**



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 mm² 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