SiPM photosensors and fast timing readout for the Barrel Time-of-Flight detector in PANDA

Ken Suzuki, Stefan-Meyer-Institut, ÖAW
on behalf of the PANDA/Barrel-TOF(SciTil) group

07.08.2017, DIRC2017

Outline

- Introduction: SiPM
- PANDA Barrel-TOF / SciTil
  - R&D History
  - Current design, performance
  - Possibilities for further optimisation

Evolution of Detector Technology

- single channel to multichannel
  - MWPC, hodoscope
- same effect by another mechanism/principle
  - photoelectron multiplication (PMT → SiPM)
  - gas ionisation (PC → GEM, RPC)
  - ionisation (gas → semiconductor, STJ)
- same principle in a different application, readout
- different size (smaller / larger)

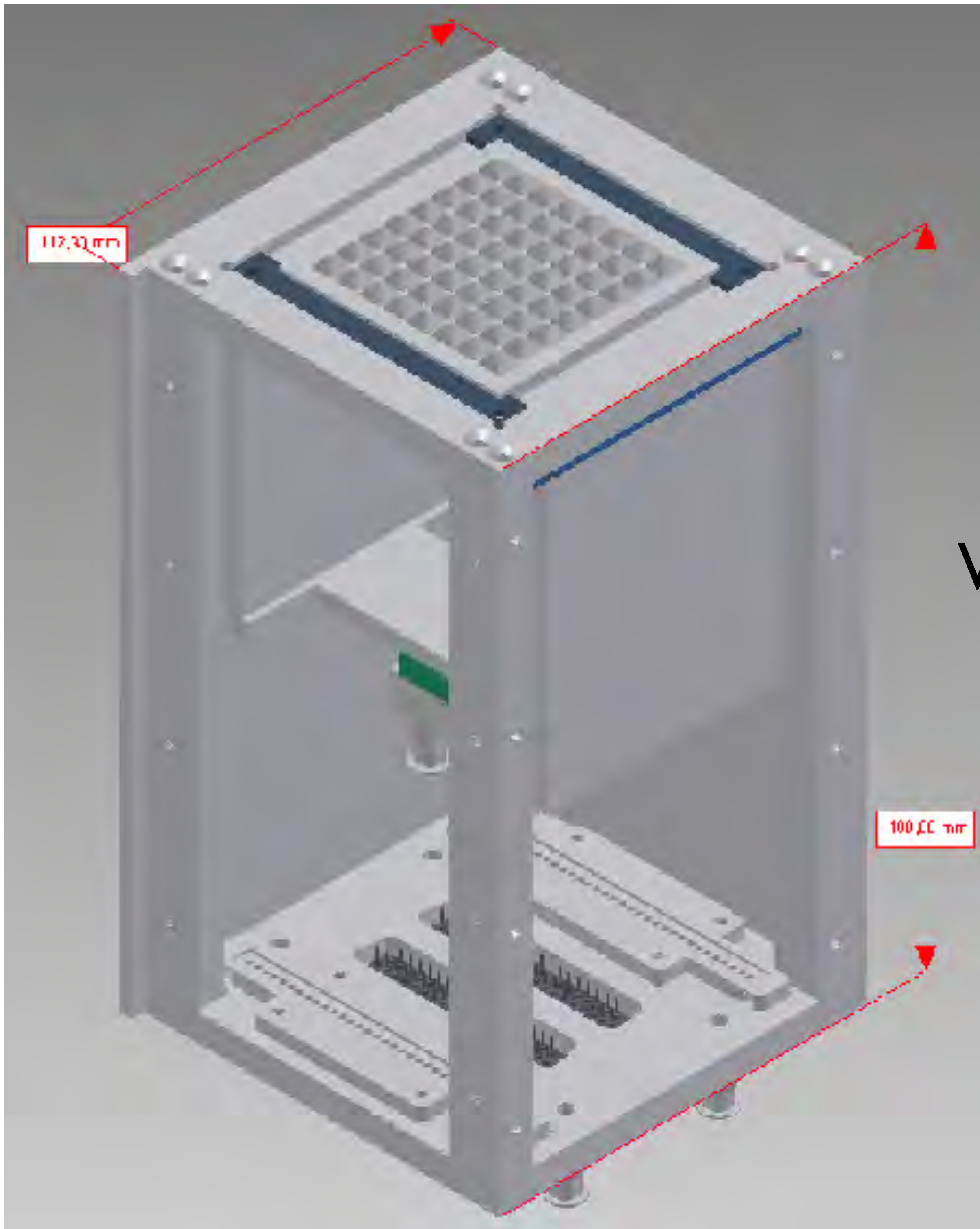
SiPM (PPD)

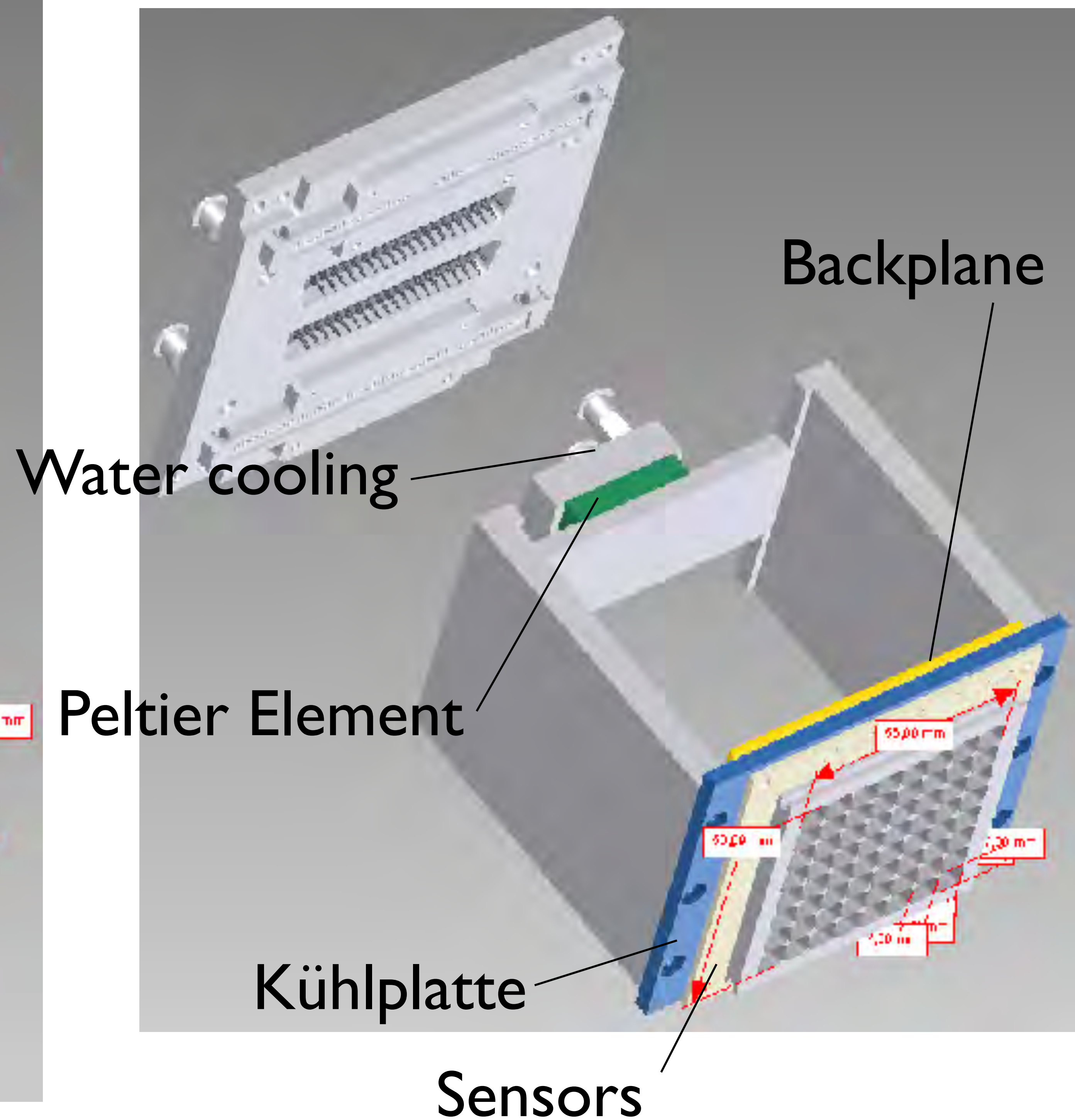
- Evolution from
  - PMT / Geiger-tube / photodiode.
  - Multichannel.
  - Compact.
- Matured technology, yet evolving rapidly.
  - Power relationship among market players also changing.
    - Hamamatsu, KETEK, AdvanSiD, SensL, Philipps, and many smaller manufactures.
- Replace vacuum-PMT?
  - It will come at some point. The question will be when.
    - Price per sensitive area.

Comparison with MCP-PMT/G-APD

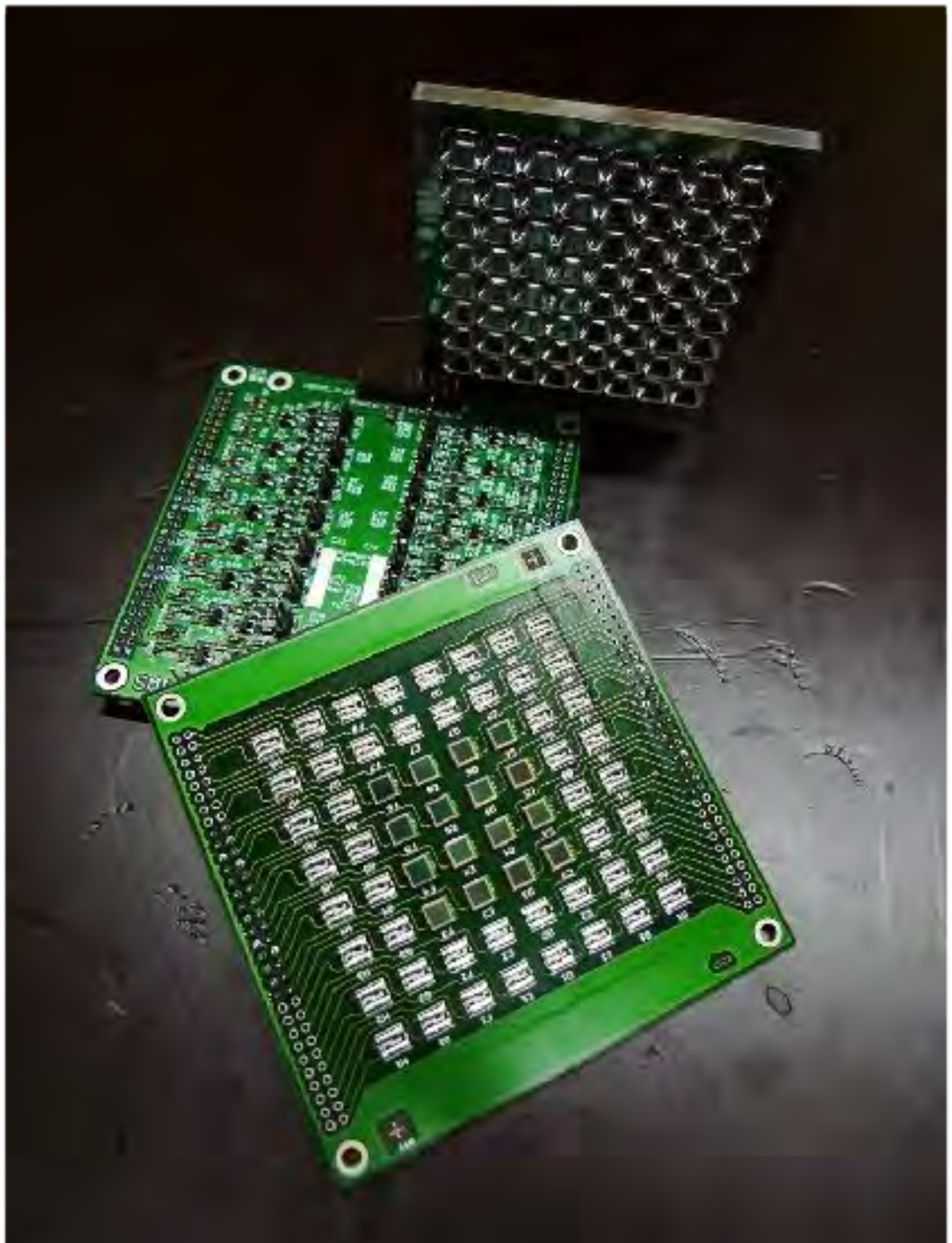
	PMT	*MCP-PMT*	*SiPM*
Gain	*~10^6*	*~ 10^6*	*$10^{5\sim6}$*
Bias Voltage	*1-2k*	*1-2k*	*20~100*
Dark Count	*low*	*low*	*high*
Cost	*~700€/ch?*	*?*	*~30€?*
Sensitive Area	*1" - 2"*	*50x50?*	*1mm^2 ~ 20mm^2*
Cost/Size			
Magnetic Field	*< 0.1T*	*< ~2T*	*< 15T*
Time Resolution	*good*	*very good*	*good*
Linearity	*good*	*good*	*good (<Npix)*
Gain Stability			*temp., voltage sensitive*

Matrix SiPM prototype (56x56mm^2) for the PANDA B-DIRC



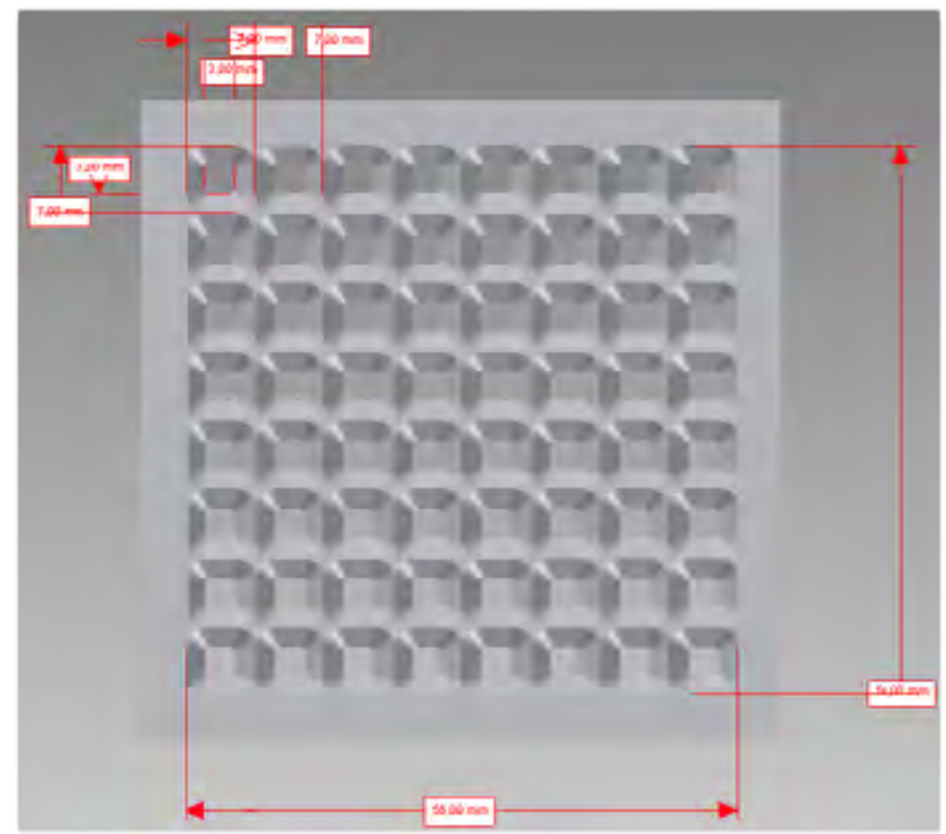


Matrix quardatic mirror light guide



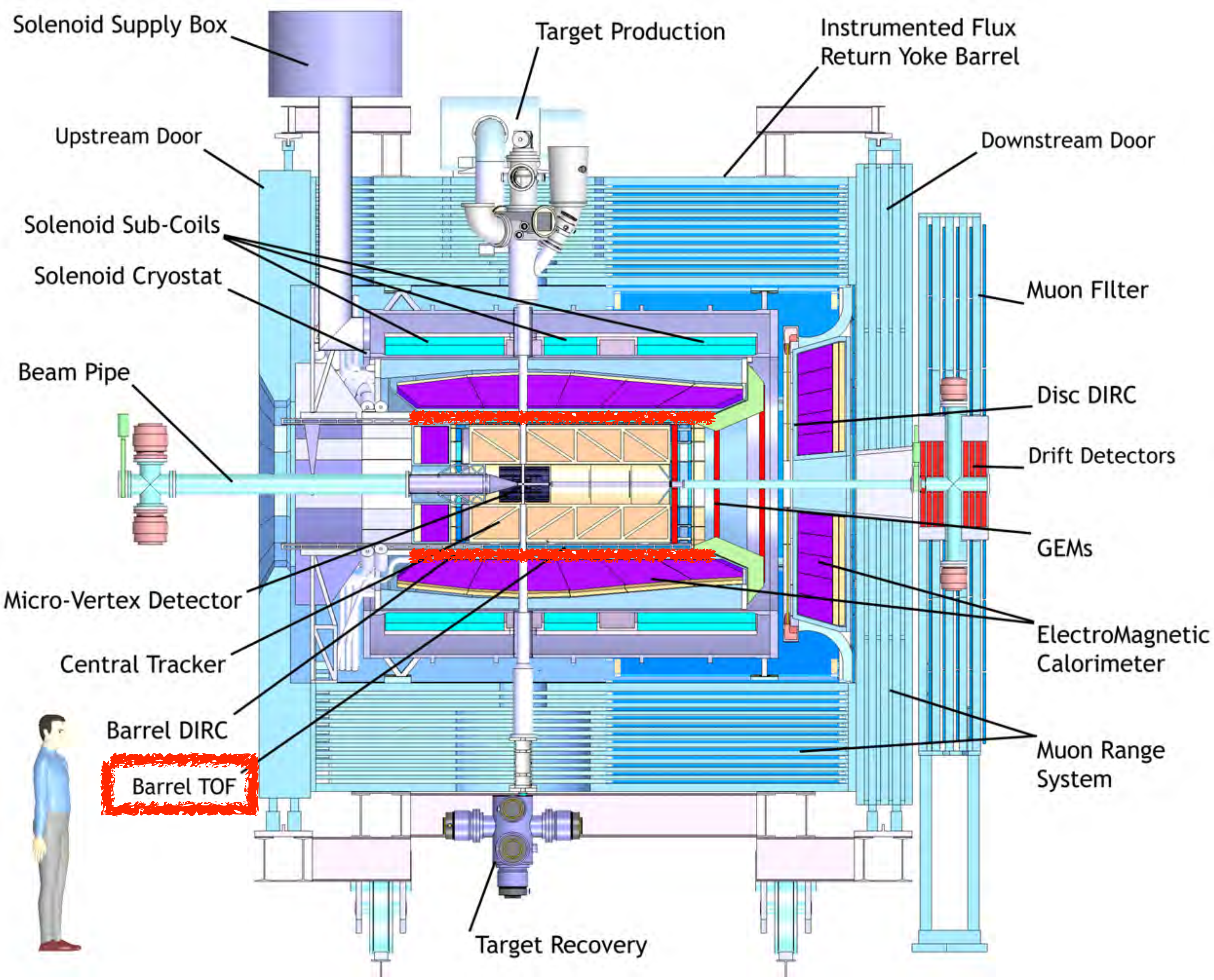
Light Concentrator: Aluminum coated Chromium)
8x8 = 64 cells
1 cell: 7x7mm^2 ⇒ 3x3 mm^2

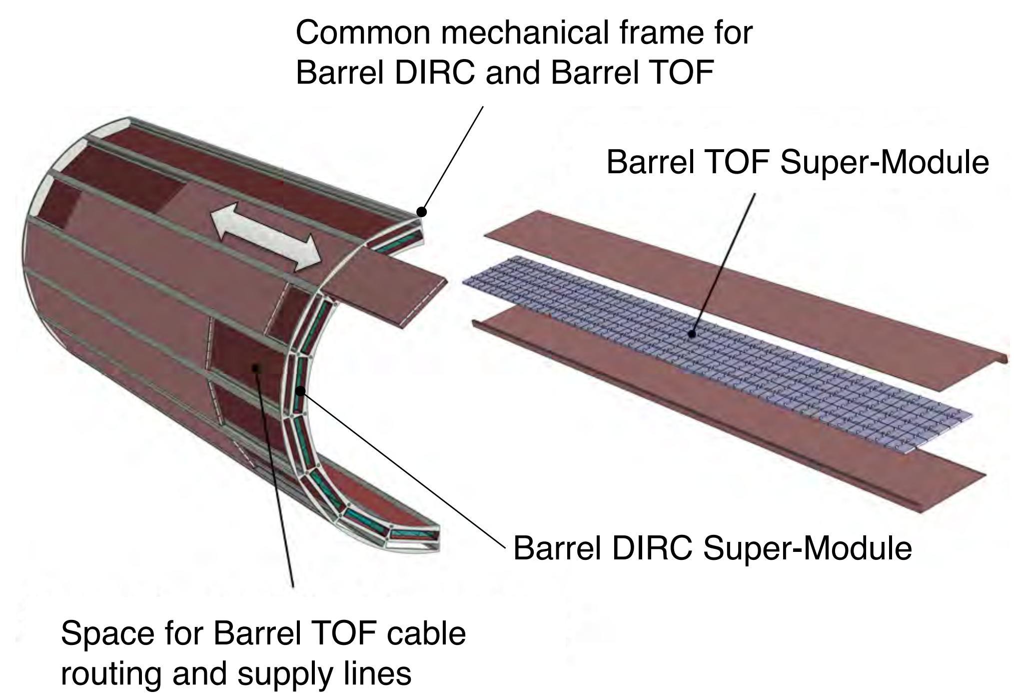
56x56 mm^2 sensitive area
Hamamatsu MPPCs 3x3mm^2



<u>Self-triggering on a single photon was not possible</u>

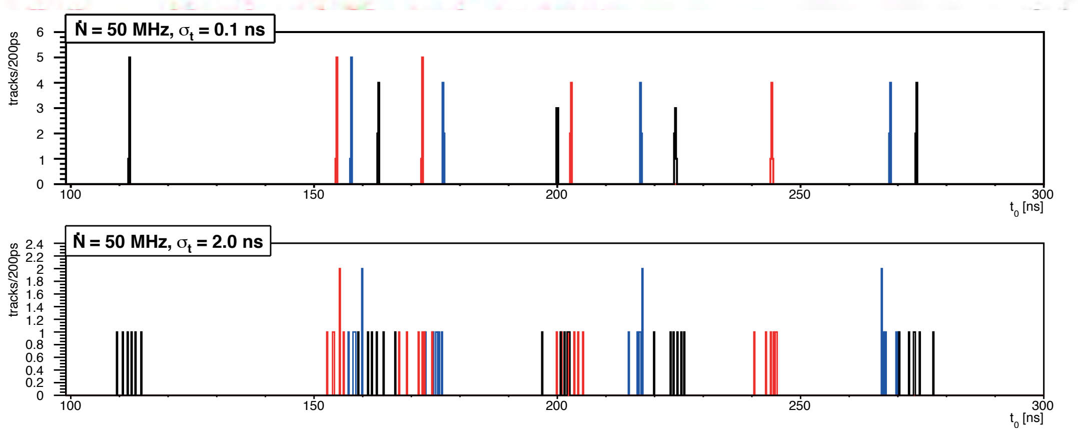
Barrel Time-of-Flight Detector, a.k.a. SciTil

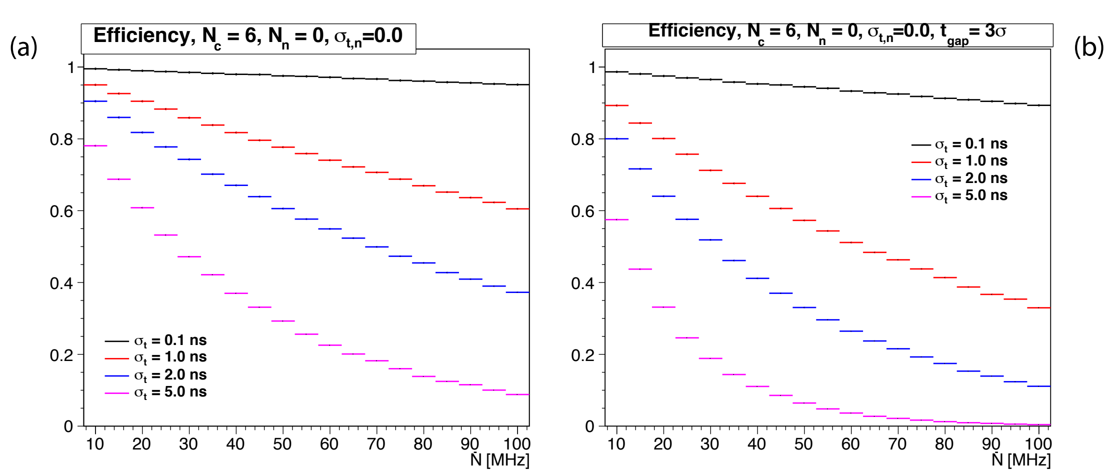




MVD<STT<B-DIRC<B-TOF<EMC

Chapter 3: **Capabilities** and Requirements





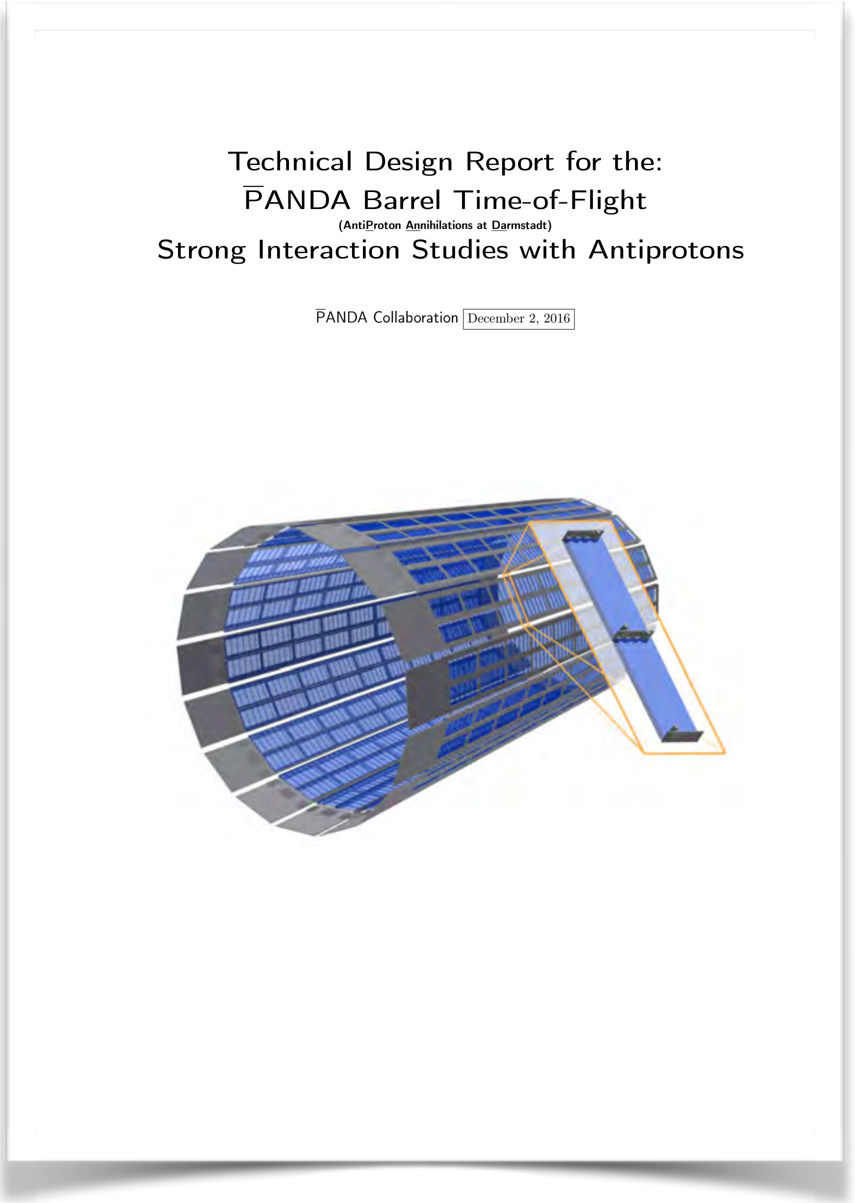
- t_0 determination
- event sorting
  - 20 MHz I.R. in the high luminosity mode
- and actually PID as well are coupled and need to be done iteratively with increasing accuracy

Requirement: σ_t<100 ps
to keep the efficiency loss due to event mixing in a tolerable level

Project Status

- 2017 March
  After an internal review, TDR was approved by the collaboration to submit to FAIR.

- Now
  TDR being reviewed by FAIR/ECE.
  - Received first comments in July.
  - Current main activity = FEE devel.



Conceptual design, Proposal

2012

Proposal for a Scintillator Tile Hodoscope for $\bar{\text{P}}$ANDA

Version 1.1

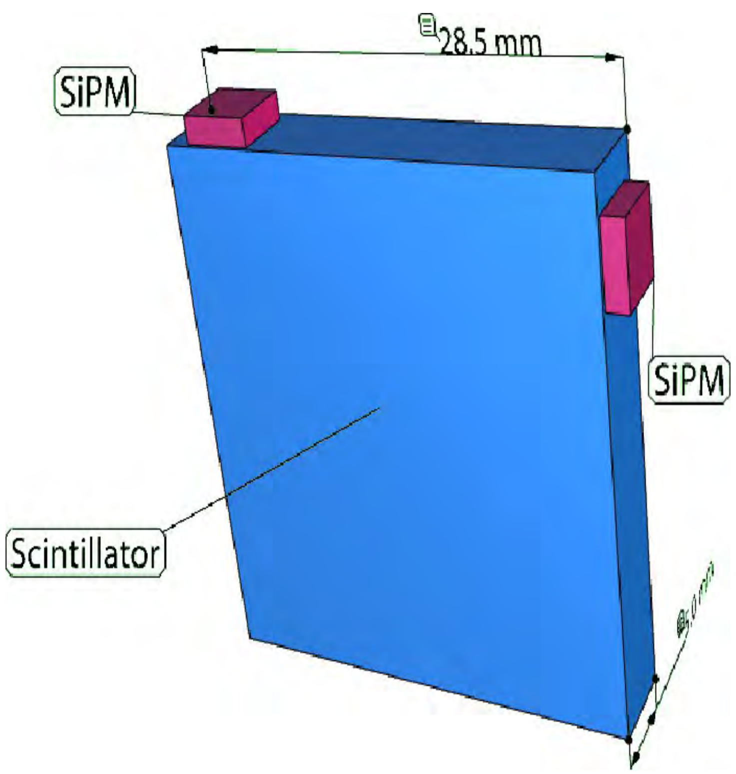
K. Goetzen, H. Orth, G. Schepers, L. Schmitt, C. Schwarz, A. Wilms

Abstract

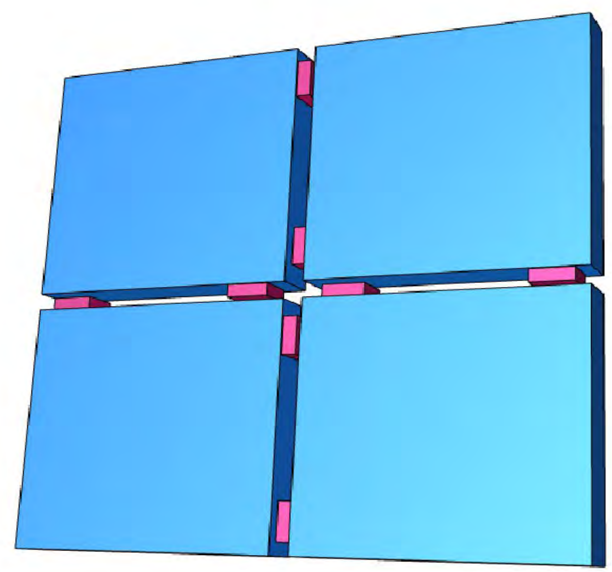
In this document a new detector in place of the barrel time-of-flight detector is proposed. This detector is based on small scintillator tiles read out by silicon photomultipliers. The motivation in terms of physics and technical benefits are summarized. Details of the detector layout are given.

K. Goetzen et al., Proposal for a scintillator barrel hodoscope for $\bar{\text{P}}$ANDA

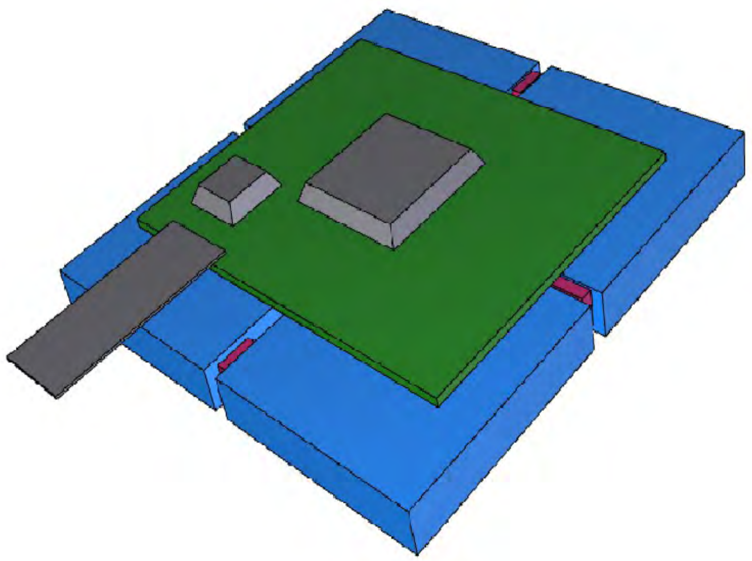
Scintillator Tile Hodoscope



Readout at 2 positions



Quad module

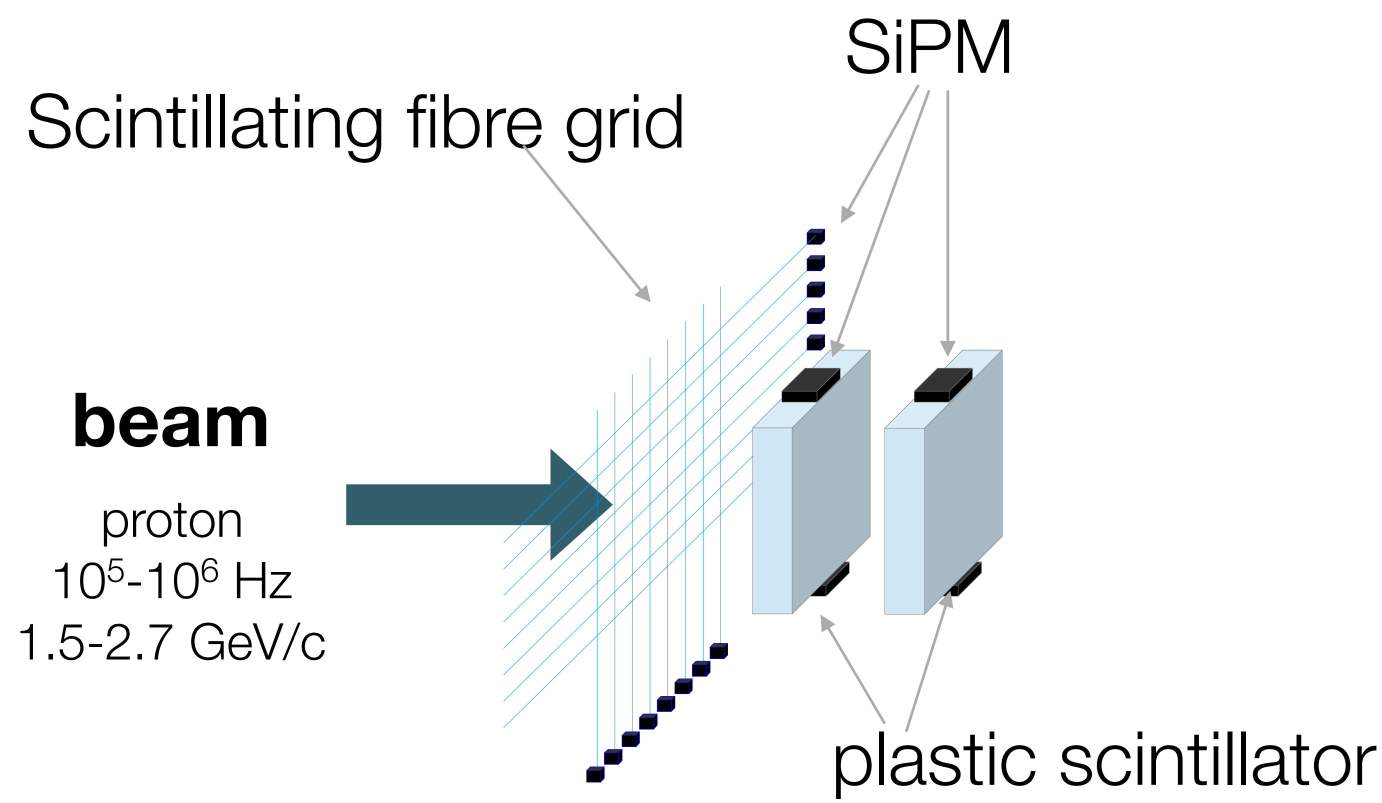


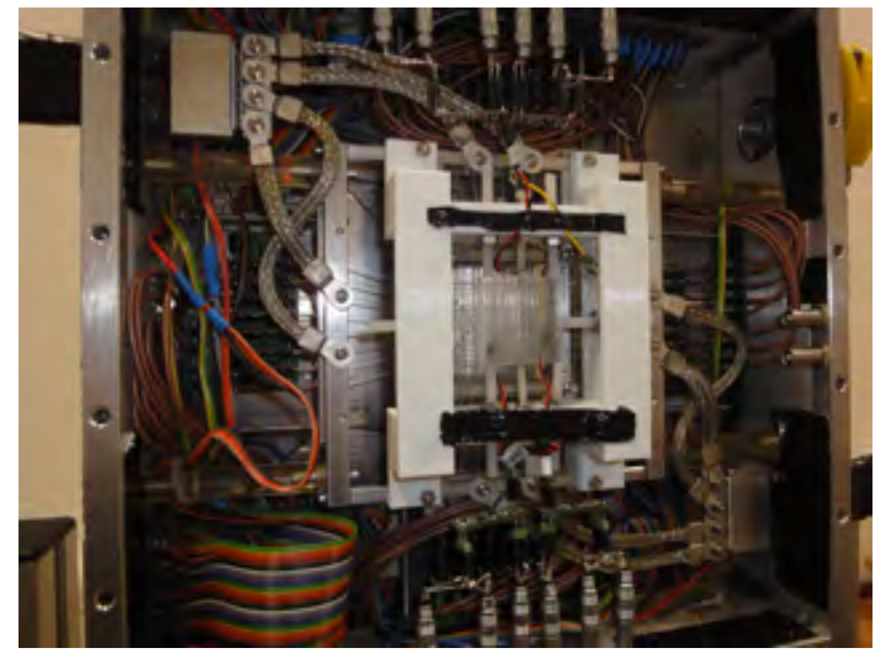
with electronics
8ch ASIC
data transfer IC

K. Goetzen et al., Proposal for a scintillator barrel hodoscope for P̄ANDA

Single tile performance (original geometry) fulfilled the target time resolution

JESSICA@COSY@FZ-Jülich, Jan2014

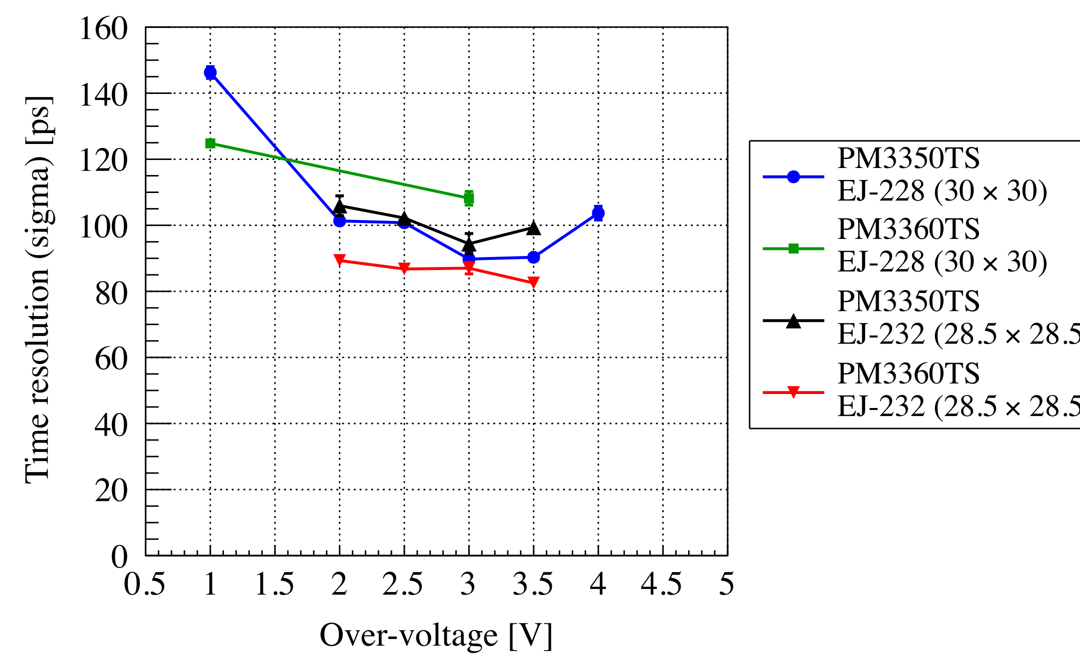




SiPMs:
HPK MPPC S12572-025C
HPK MPPC S12572-050P
KETEK PM3350
KETEK PM3360

×

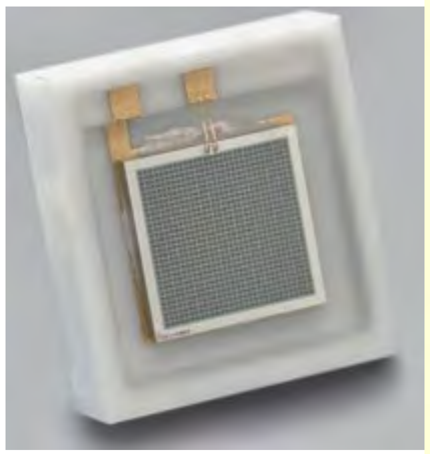
Scintillators:
EJ-228 (Pilot-U/BC-418)
EJ-232 (BC-422)

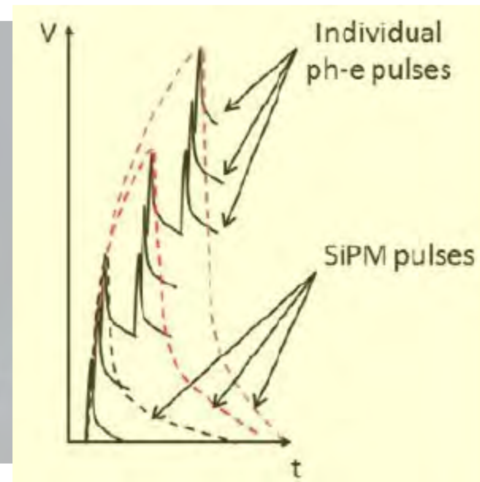


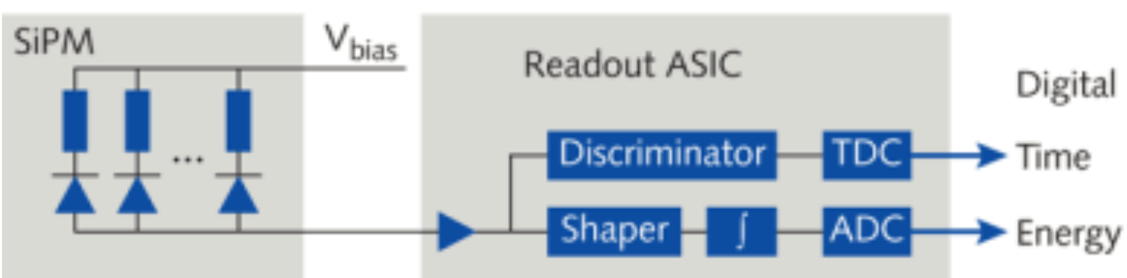
L. Gruber Ph.D Thesis

Analog and Digital SiPM

analog

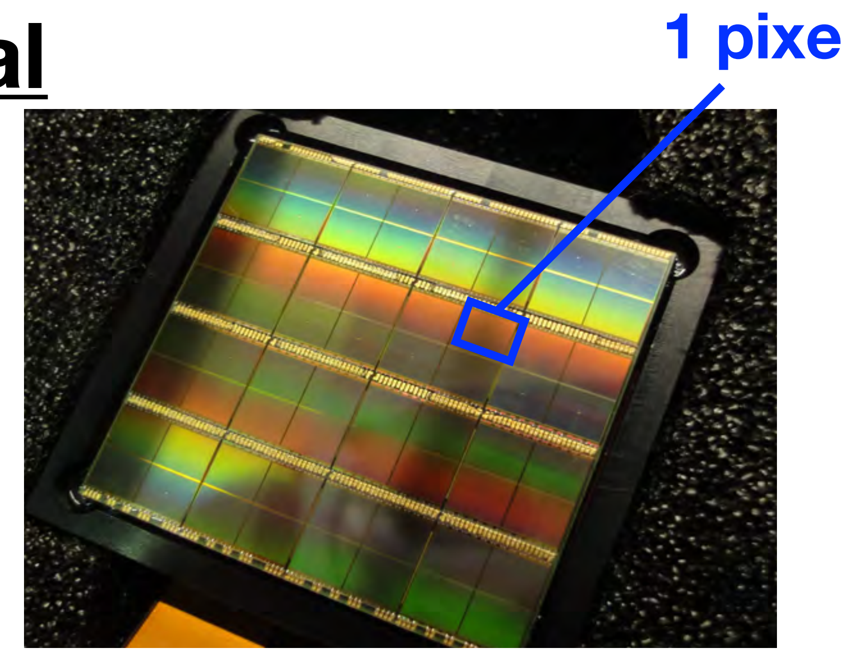


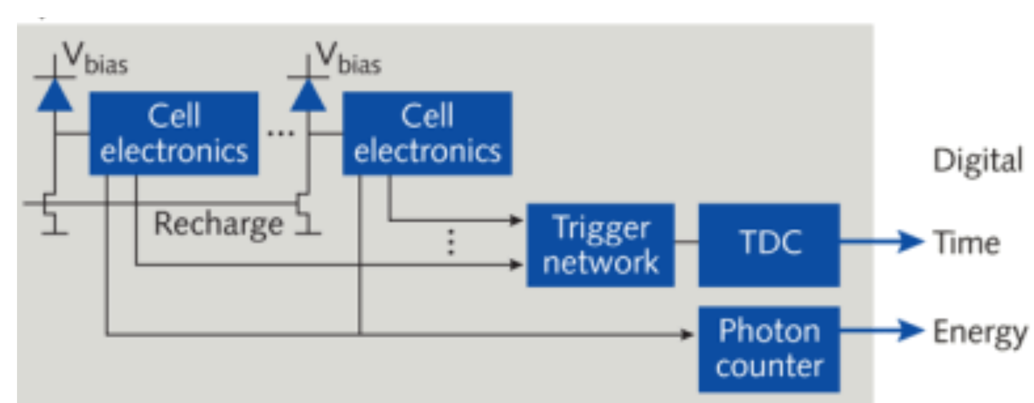




Array of SPADs (Single Photon Avalanche Diode)
A few 100-1000 SPADs
Signal: analog sum of individual pulses
Pulse amplitude depends on gain/temperature
Hamamatsu, KETEK, AdvanSiD, SensL, ..

digital

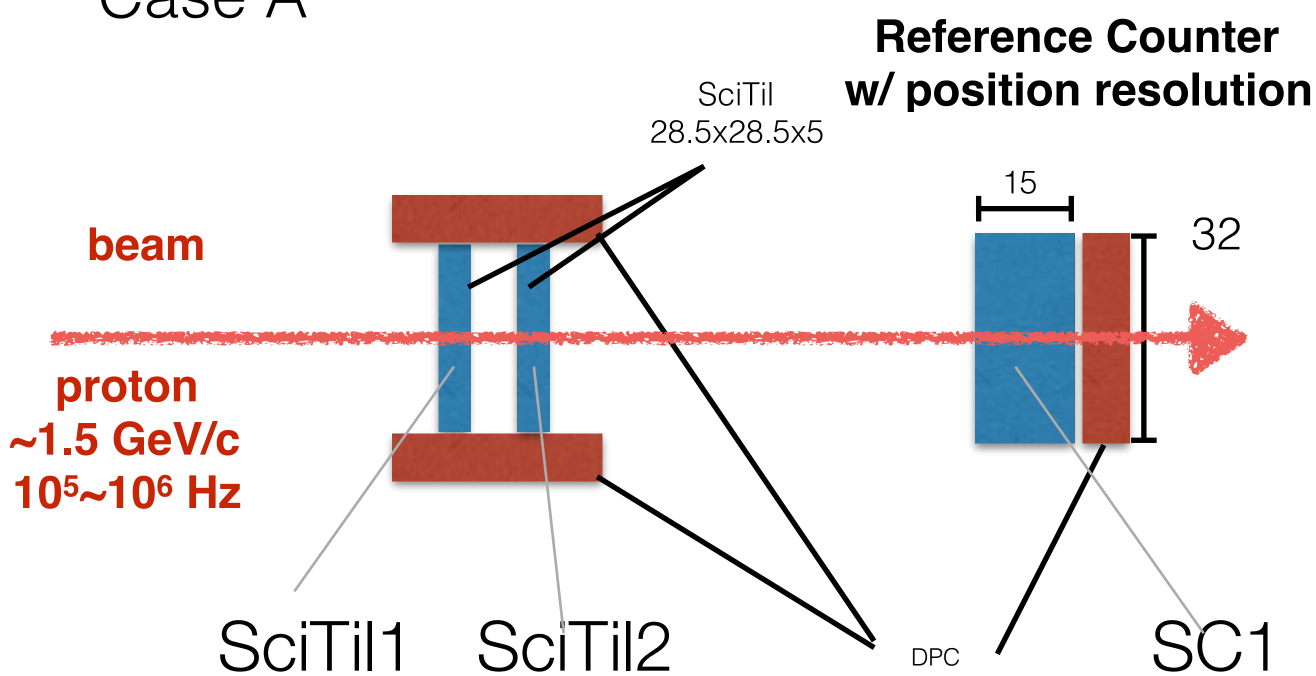




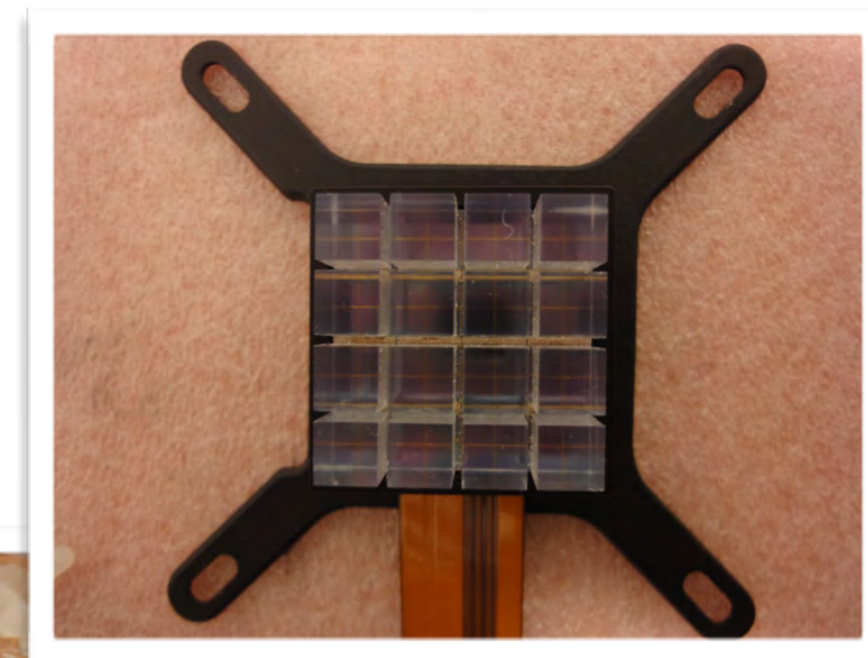
Array of SPADs (Single Photon Avalanche Diode)
3200 / 6400 SPADs per pixel
Signal: digital sum of trigger bins (breakdowns)
& digital time stamp from TDC
Pulse amplitude is not relevant
Philips

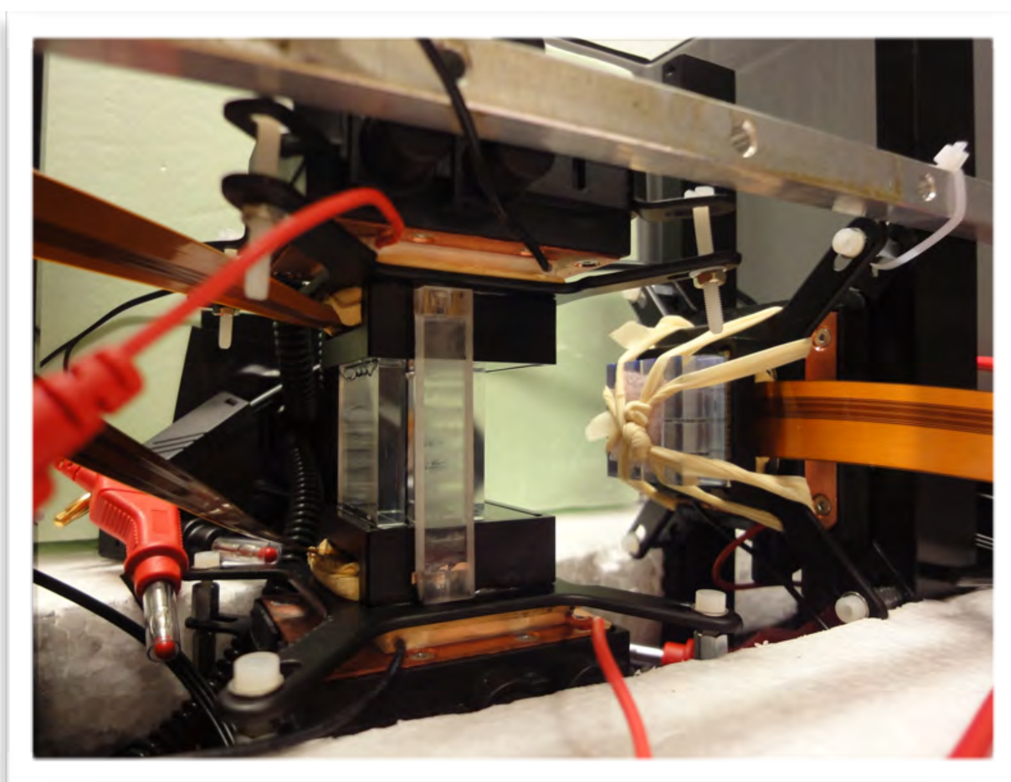
Results using DPC: time resolution

Case A



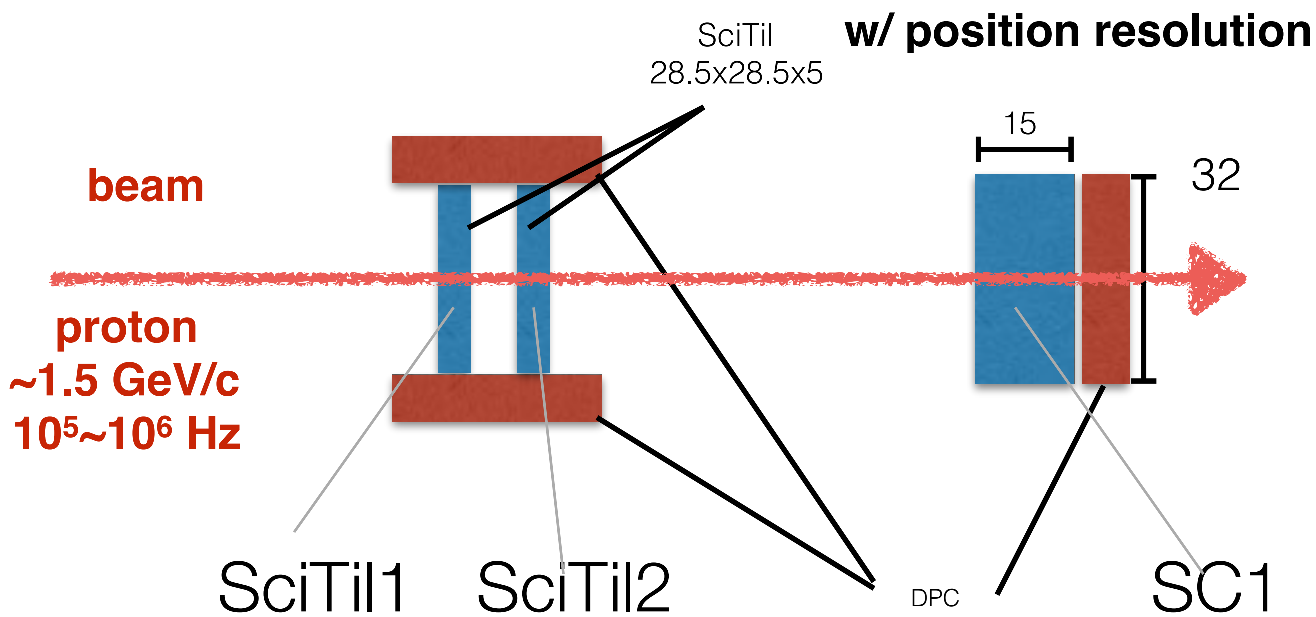
SciTil1: EJ-228 with Philips DPC
SciTil2: EJ-228 with Philips DPC
SCI1: BC-408 with Philips DPC





Results using DPC: time resolution

Case A



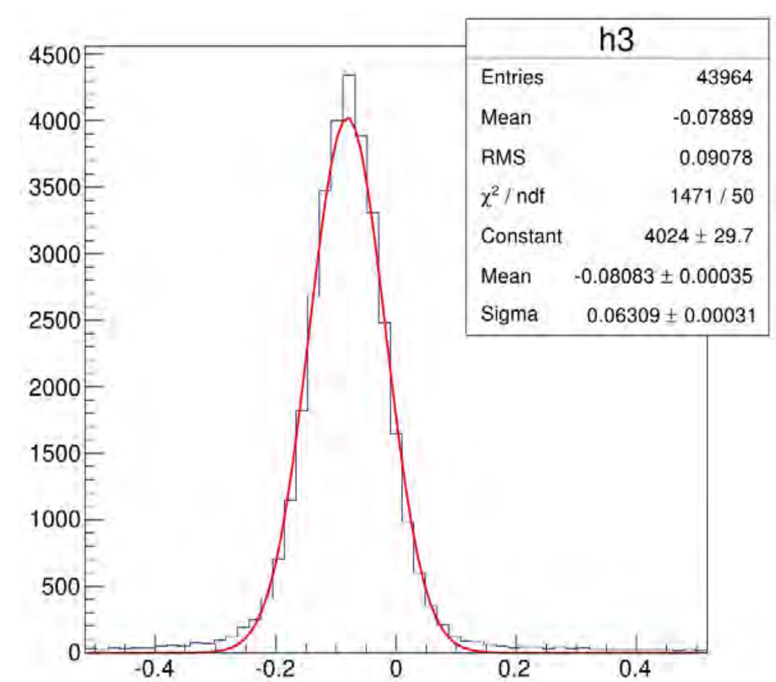
SciTil1: EJ-228 with Philips DPC
SciTil2: EJ-228 with Philips DPC
SCI1: BC-408 with Philips DPC

Calculate σ_i from TOF resolutions:

$\sigma_{SciTil1} = 46.9 \pm 0.6$ ps

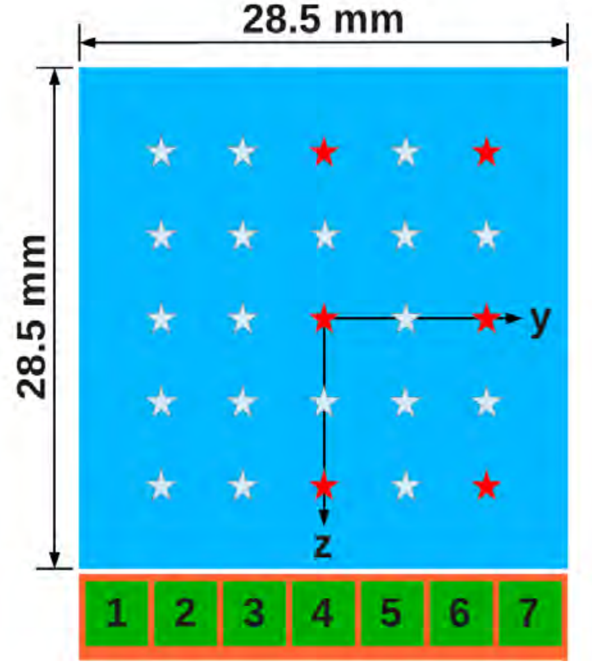
$\sigma_{SciTil2} = 42.2 \pm 0.7$ ps

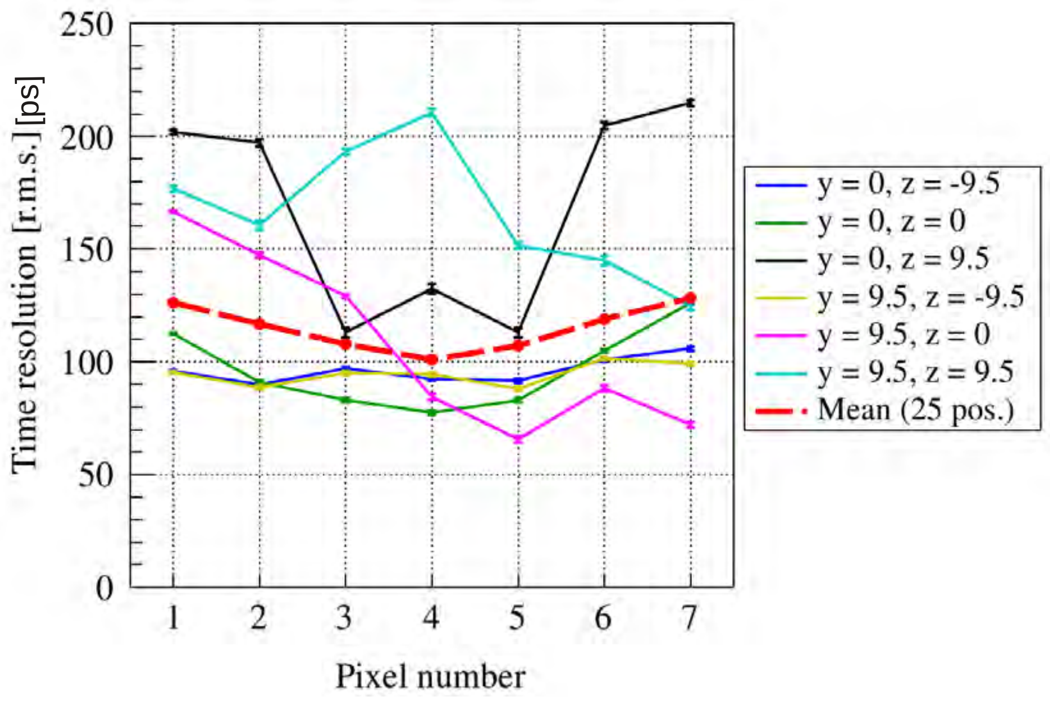
$\sigma_{SCI1} = 57.0 \pm 0.5$ ps



Photodetector position

Time resolution:





Strong position dependency !
Central position of the sensor is favored !

"Time resolution below 100 ps for the SciTil detector of PANDA employing SiPM"
S.E. Brunner, L. Gruber, J. Marton, H. Orth, K. Suzuki.

SciRod (Erlangen)

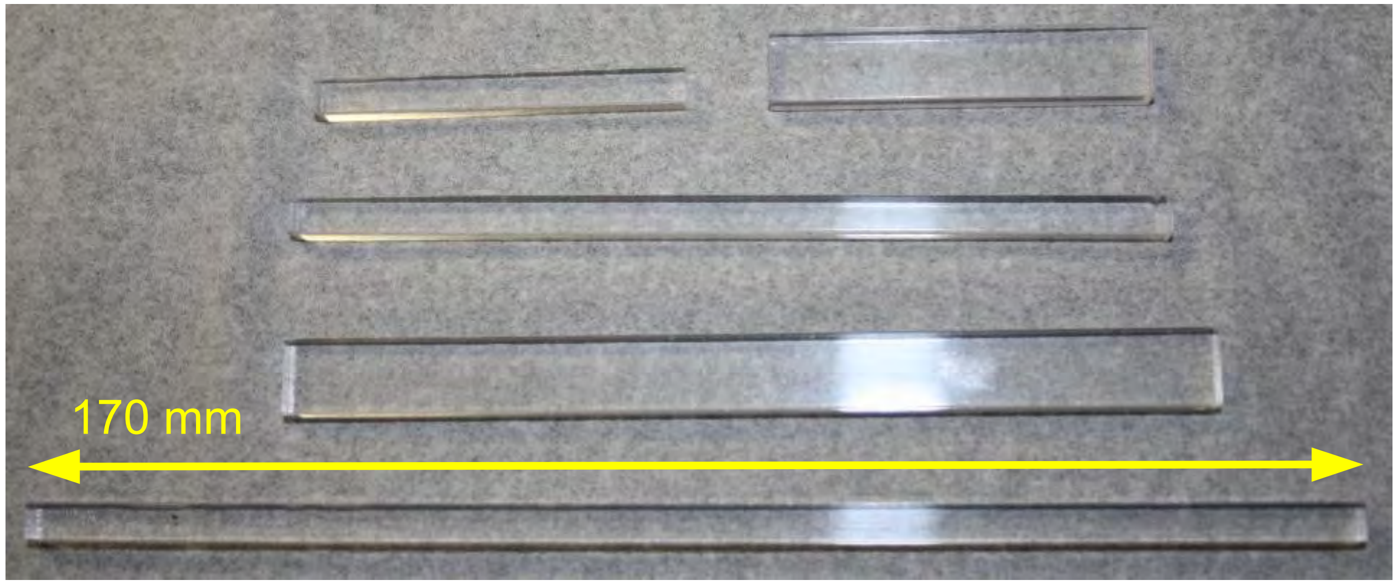
more lightguide-like tile geometry

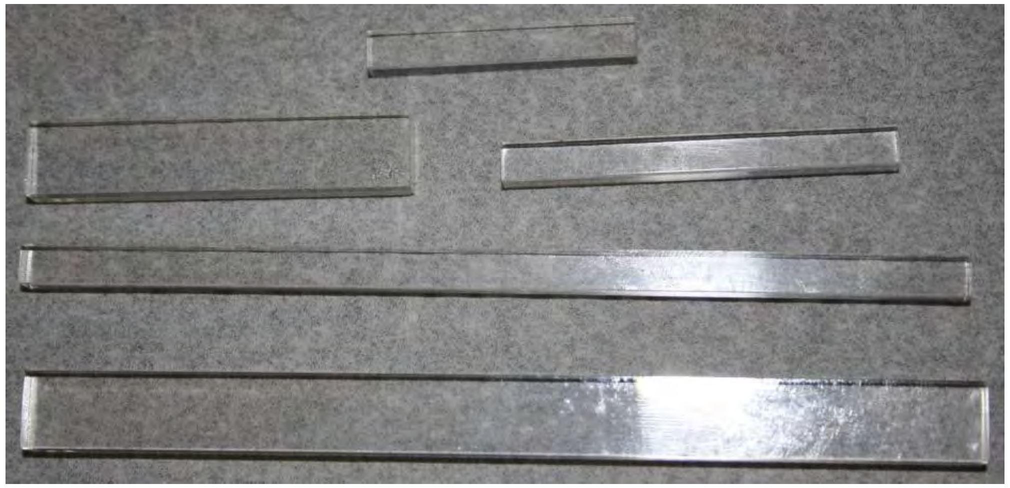
Scintillator Samples

BC408 (τ = 2.1 ns)

- 5 x 5 x 170 mm^3
- 5 x 5 x 120 mm^3
- 5 x 5 x 50 mm^3
- 5 x 10 x 120 mm^3
- 5 x 10 x 50 mm^3

- 5 x 30 x 30 mm^3





BC420 (τ = 1.5 ns)

- 5 x 5 x 120 mm^3
- 5 x 5 x 50 mm^3
- 5 x 5 x 30 mm^3
- 5 x 10 x 120 mm^3
- 5 x 10 x 50 mm^3
- 5 x 10 x 30 mm^3

SciRod (Erlangen) cont'd

More Time Resolutions (1)

Scintillator 5 x 5 x 120 mm^3

Scintillator	MPPC	left		center		right
		σ_t	σ_t	σ_t	σ_t	σ_t
BC408	S10362-100P	88		94		101
	S10362-100P(x10)	71		77		74
	S12572-050P	72		77		74
BC420	S12572-015P	60		108		63
	S12572-050P	50	79	74	57	52

Scintillator 5 x 10 x 120 mm^3

Scintillator	MPPC	left		center		right
		σ_t	σ_t	σ_t	σ_t	σ_t
BC408	S10362-100P	88	116	132	98	93
BC420	S10362-100P	75		121		82

BC420 scintillator provides better results than BC408

SciRod (Erlangen) cont'd

More Time Resolutions (2)

Scintillator 5 x 5 x 50 mm^3

Scintillator	MPPC	left		center		right
		σ_t	σ_t	σ_t	σ_t	σ_t
BC408	S10362-100P	68		103		74
	S12572-050P	74		67		68
BC420	S12572-050P	78		64		51

Scintillator 5 x 10 x 50 mm^3

Scintillator	MPPC	left		center		right
		σ_t	σ_t	σ_t	σ_t	σ_t
BC408	S10362-100P	113		123		92

Scintillator 5 x 5 x 170 mm^3

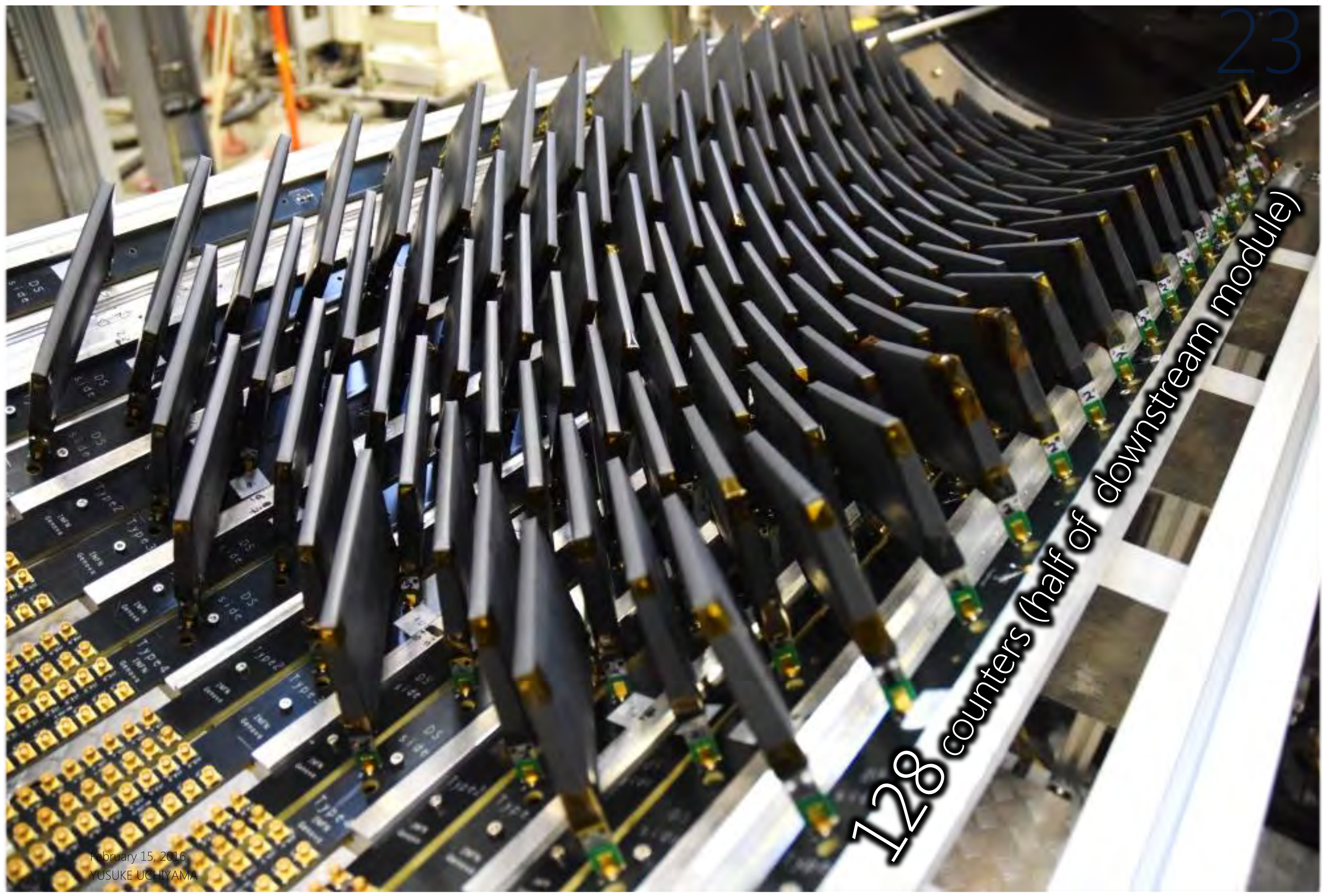
Scintillator	MPPC	left		center		right
		σ_t	σ_t	σ_t	σ_t	σ_t
BC408	S10362-100P	88	85	129	85	99

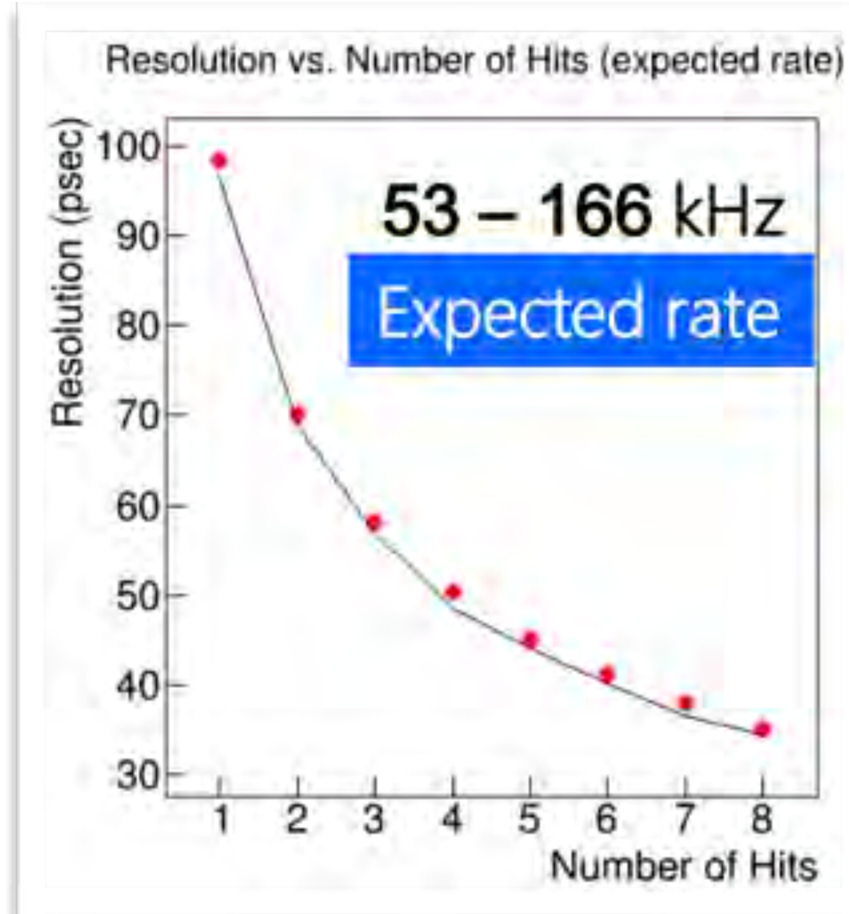
Longer and wider rods tend to give worse time resolution

SciRod Summary

- Various geometry tested. Convincingly better.
- Gives better results primarily due to better light collection.
- Time resolution 50-100 ps.
- shorter, narrower geometry preferred.
- Different $\Delta\theta$, $\Delta\phi$ granularity
    - position resolution 13mm. Actually better.

MEG2 TOF counter





Y. Uchiyama, VCI2016

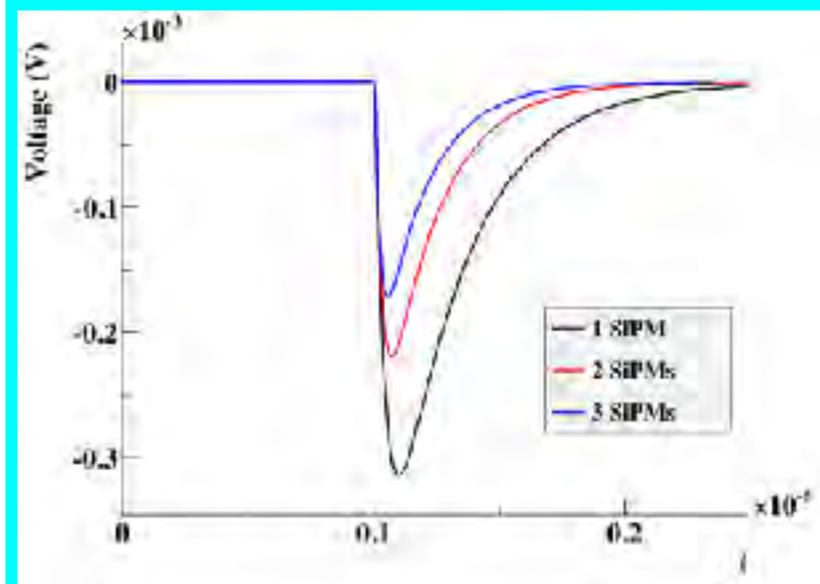
AdvanSiD: ASD-NUV3S-P-50 (3 × 3 mm2, 50 μm)
This prototype model was found to have worse performance
Scintillator: EJ232, 120 × (40 or 50) × 5 mm^3

1.: Series connection of multiple SiPMs
2.: Signal transmission over a long PCB board

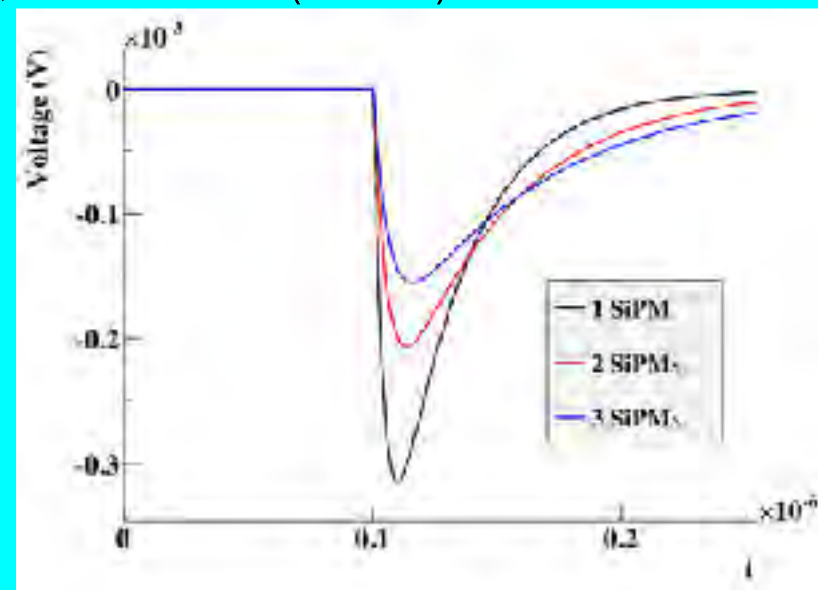
Series connection of multiple SiPMs

relatively new technique to increase effectively the sensitive area of SiPM (typically 3x3mm^2)

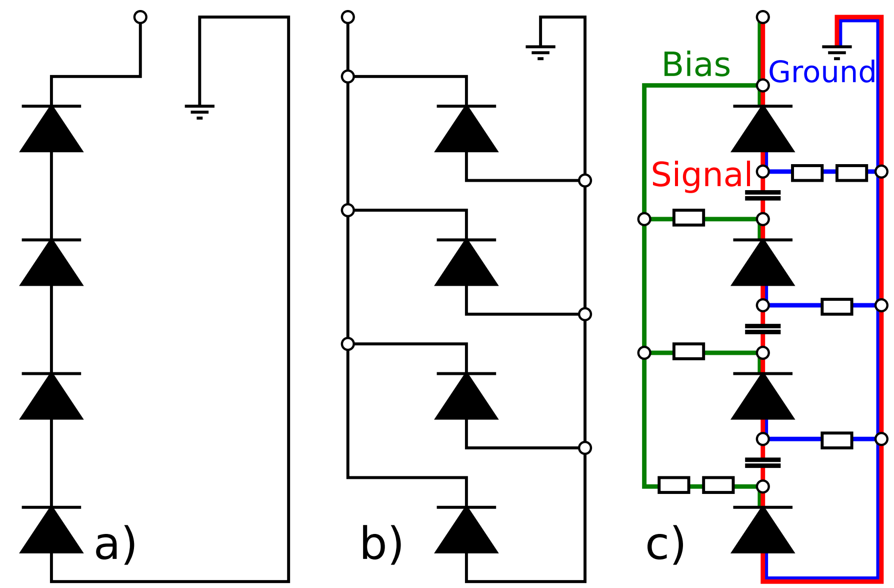
M. Nishimura, M. thesis (2014)

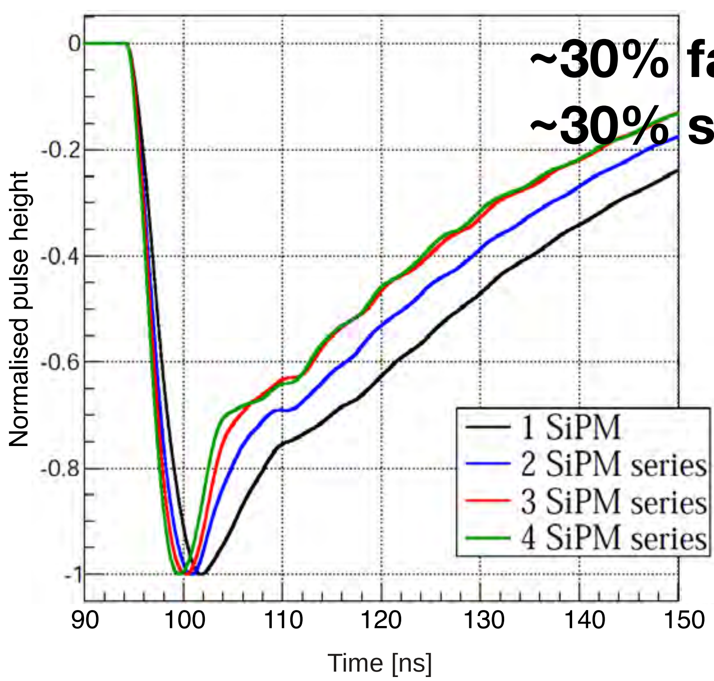


series connection



parallel connection





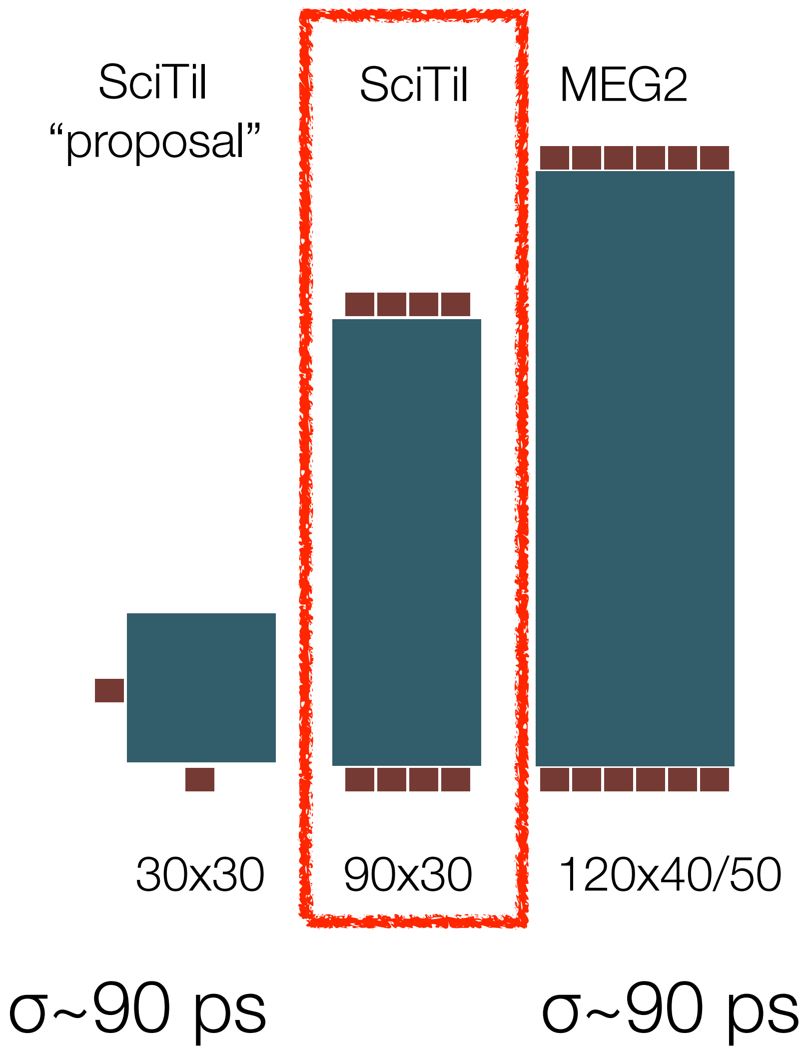
~30% faster rise time

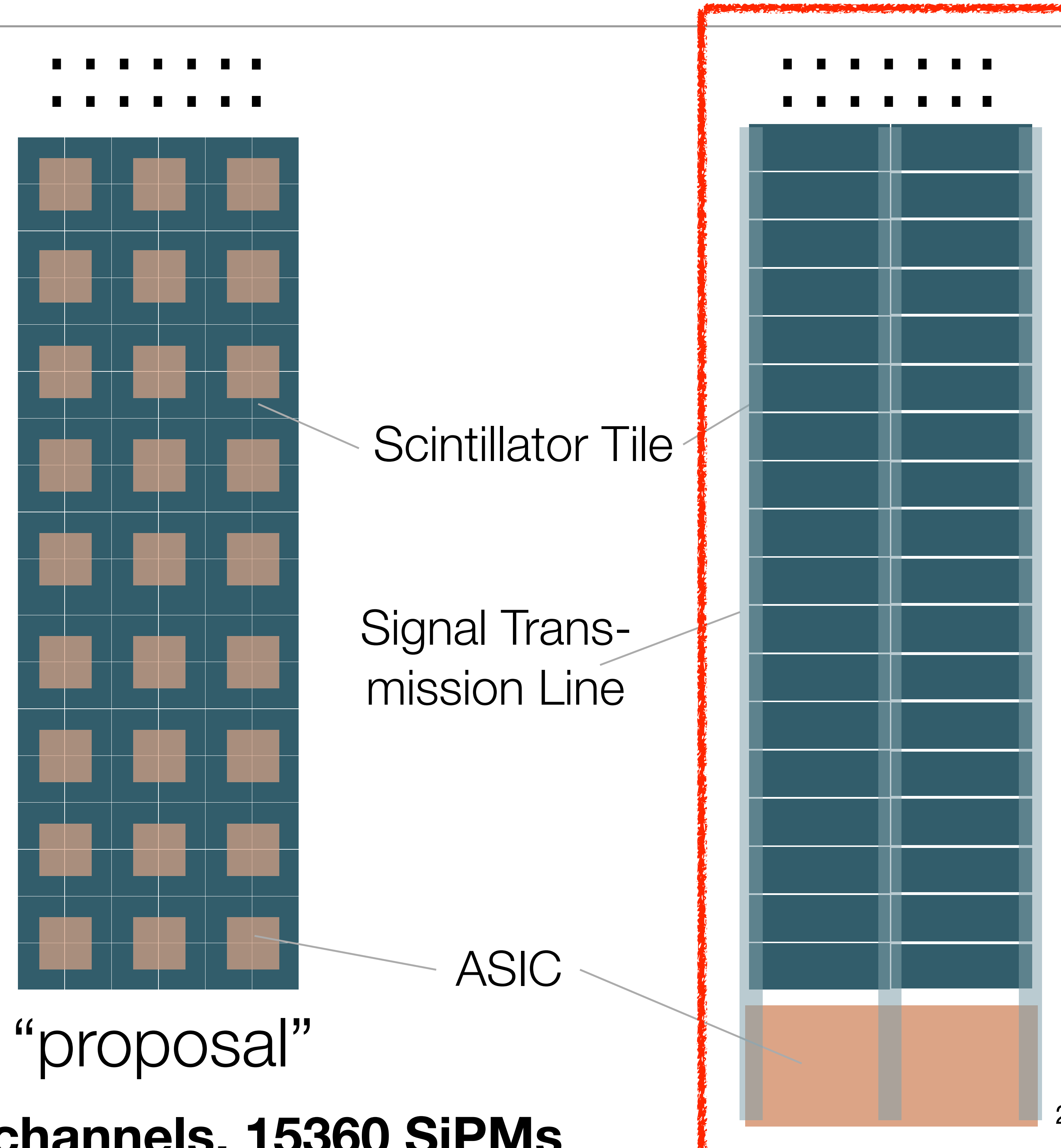
~30% smaller signal width

	Sensitive area	Bias Voltage	Signal shape	Gain	V_{BD} adjustment
Single	1	V_{br}+OV	-	1	-
Series	N	N×(V_{br}+OV)	faster	1/C	Yes
Parallel	N	V_{br}+OV	slower	C	No
Hybrid	N	V_{br}+OV	faster	1/C	No

Table 4.1: Comparison of series, parallel and hybrid connections of N SiPMs with reference of a single senso

SciTil, new design

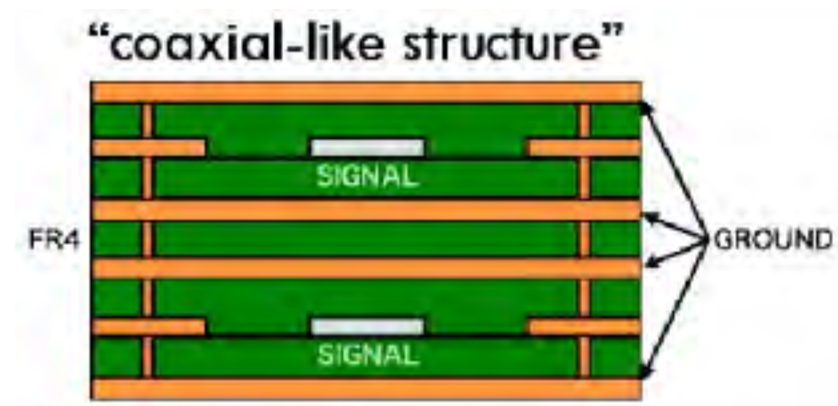




<u>Total 1920 tiles, 3840 channels, 15360 SiPMs</u>

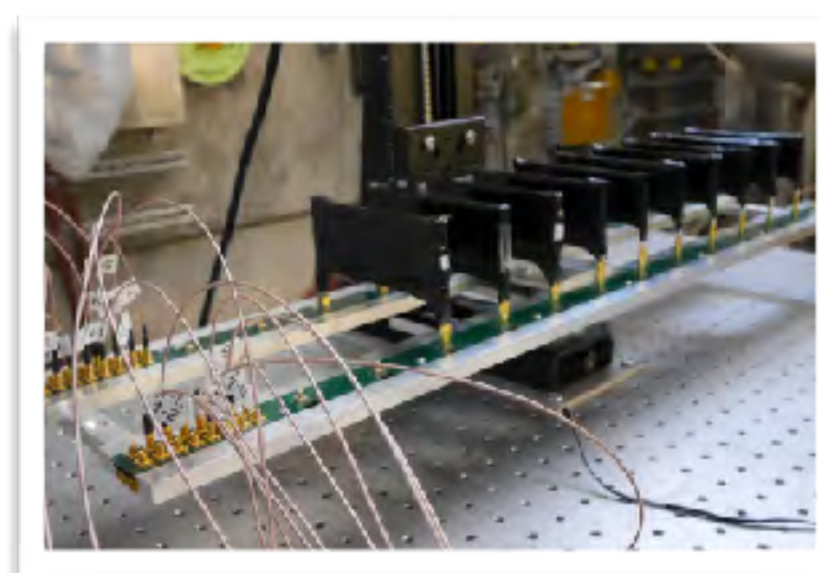
Micro Stripline Technique

- Coaxial-like structure to transmit signals over a PCB board, realised on a multilayer PCB board, that features
  - High density
  - Good shielding from external noise
  - High bandwidth
  - Low crosstalk
  - Mechanical strength
- 3 (cupper) layers per signal



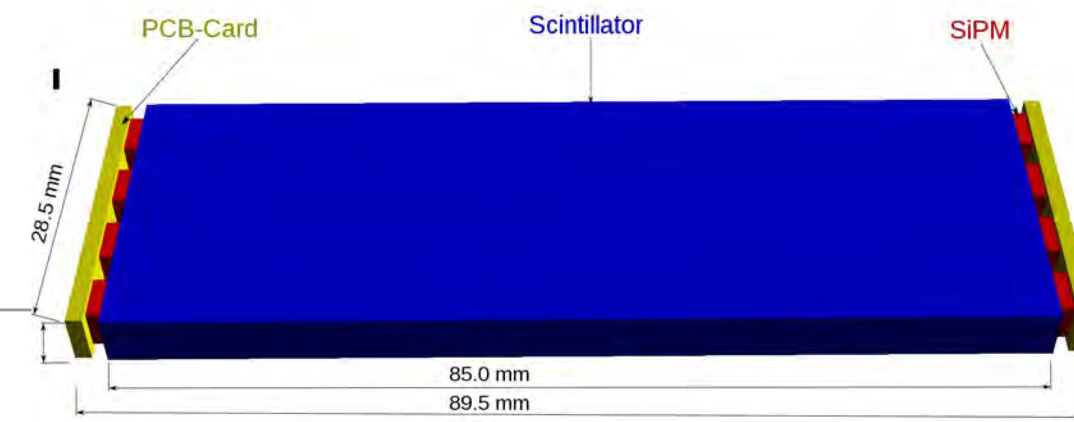
Designed by INFN-Genova

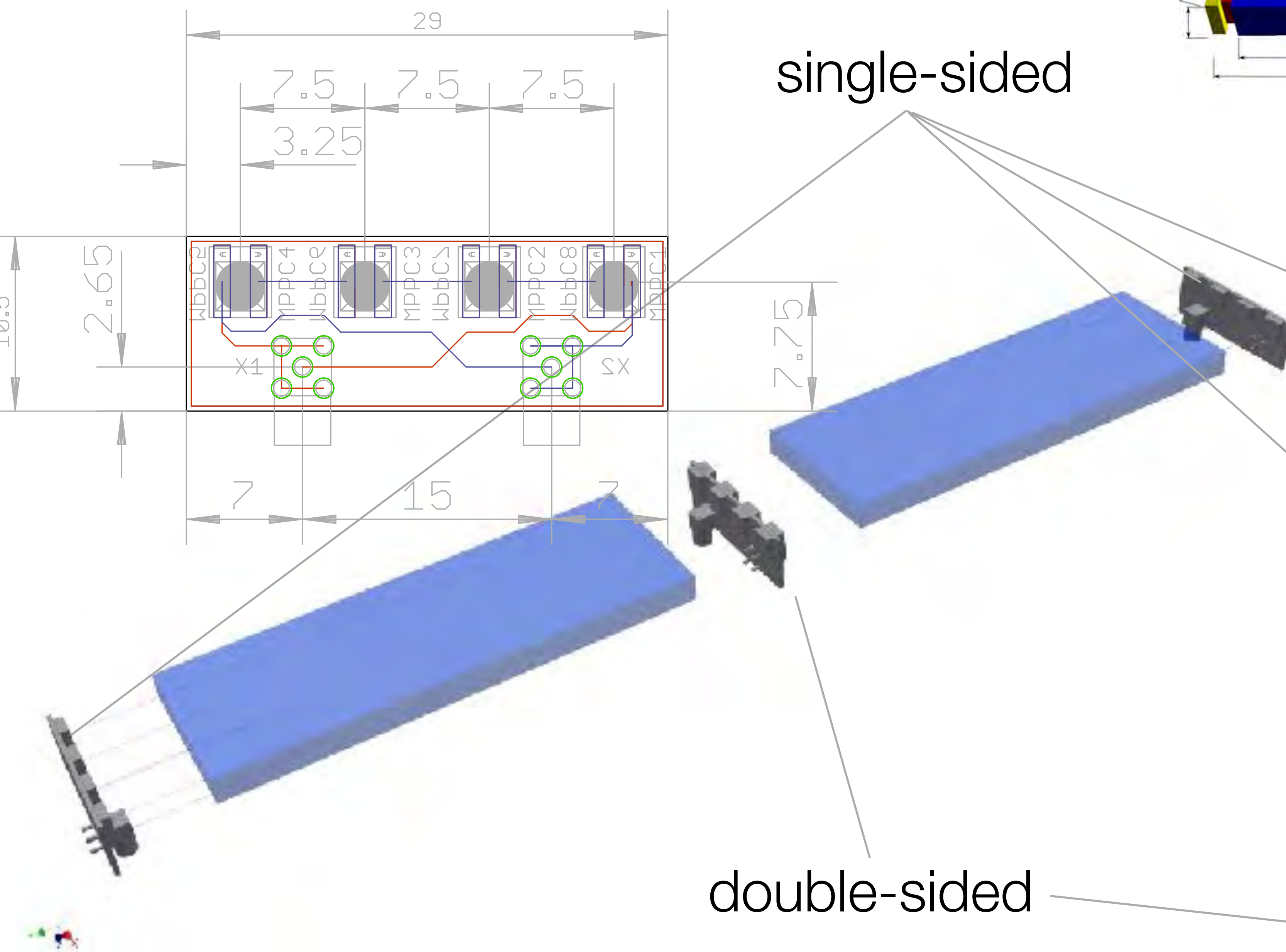
Matteo De Gerone <matteo.degerone@ge.infn.it>



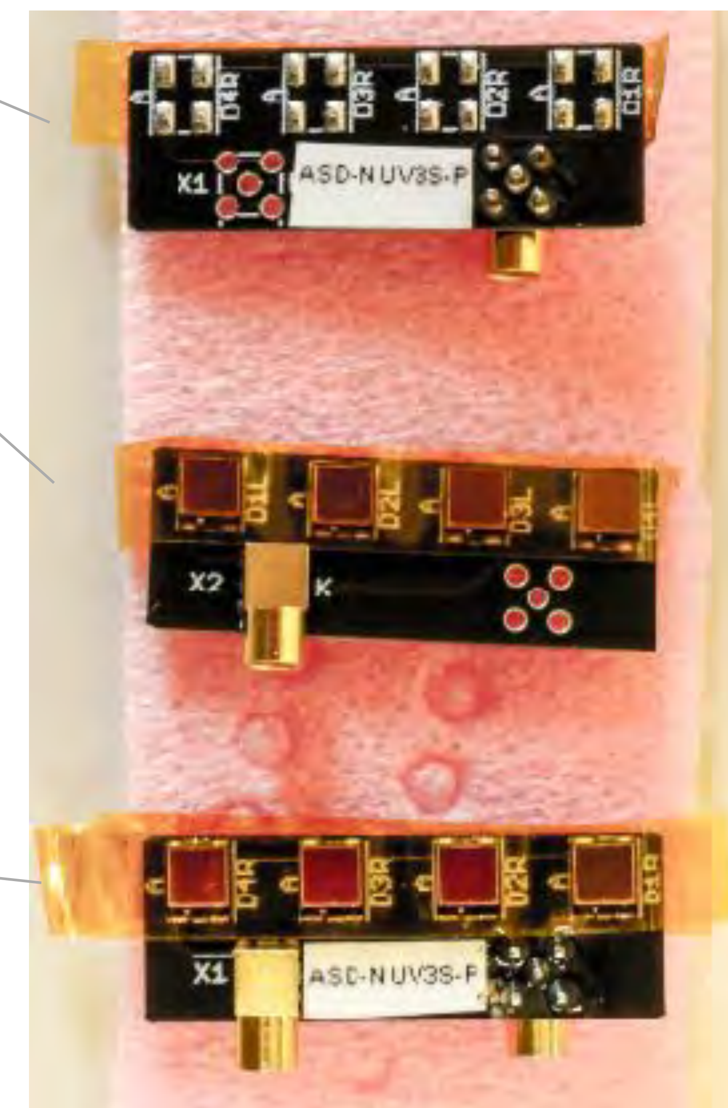
Example of MEG2 TOF

Dual Module





single-sided

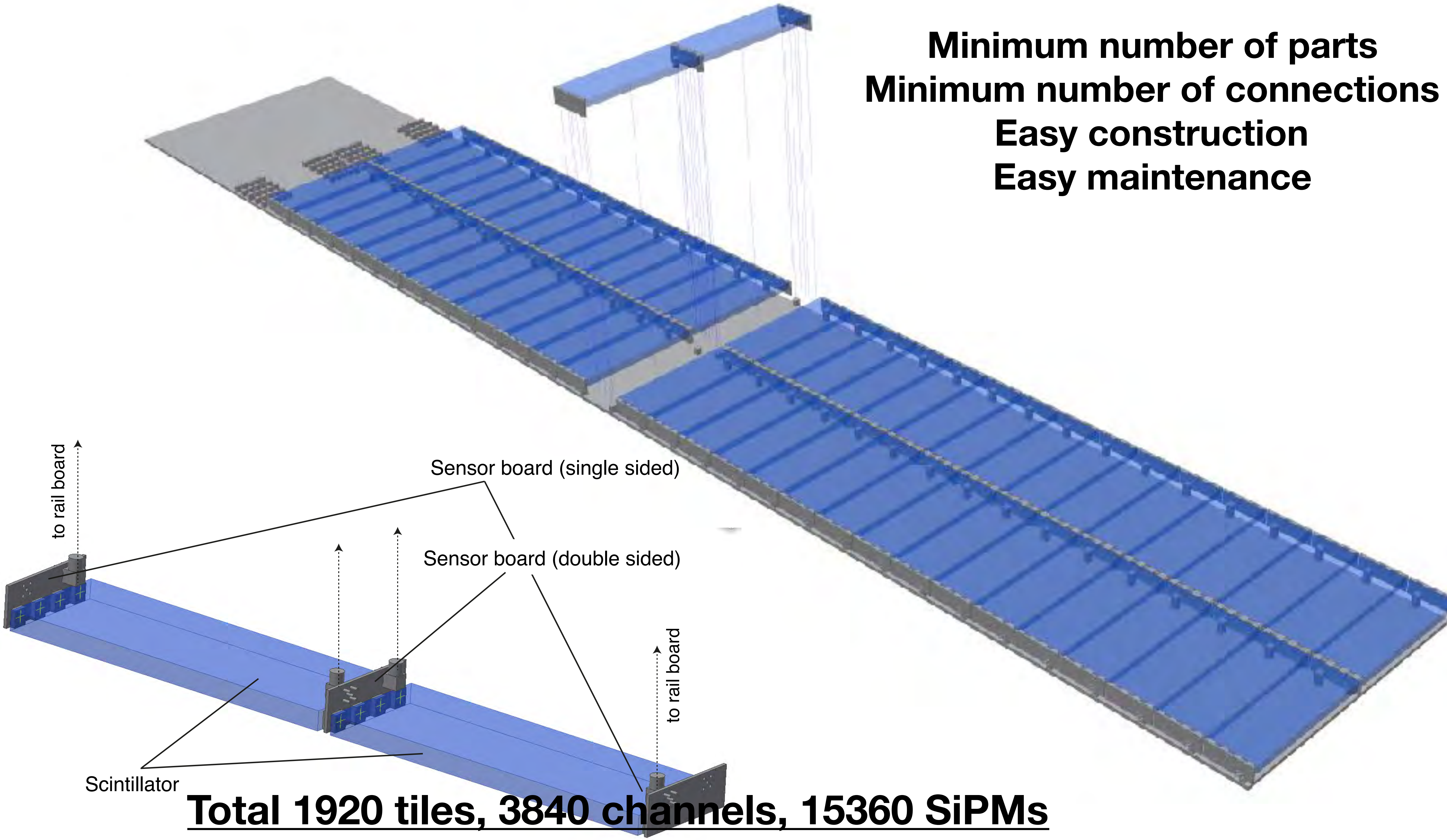


double-sided

MMCX connector

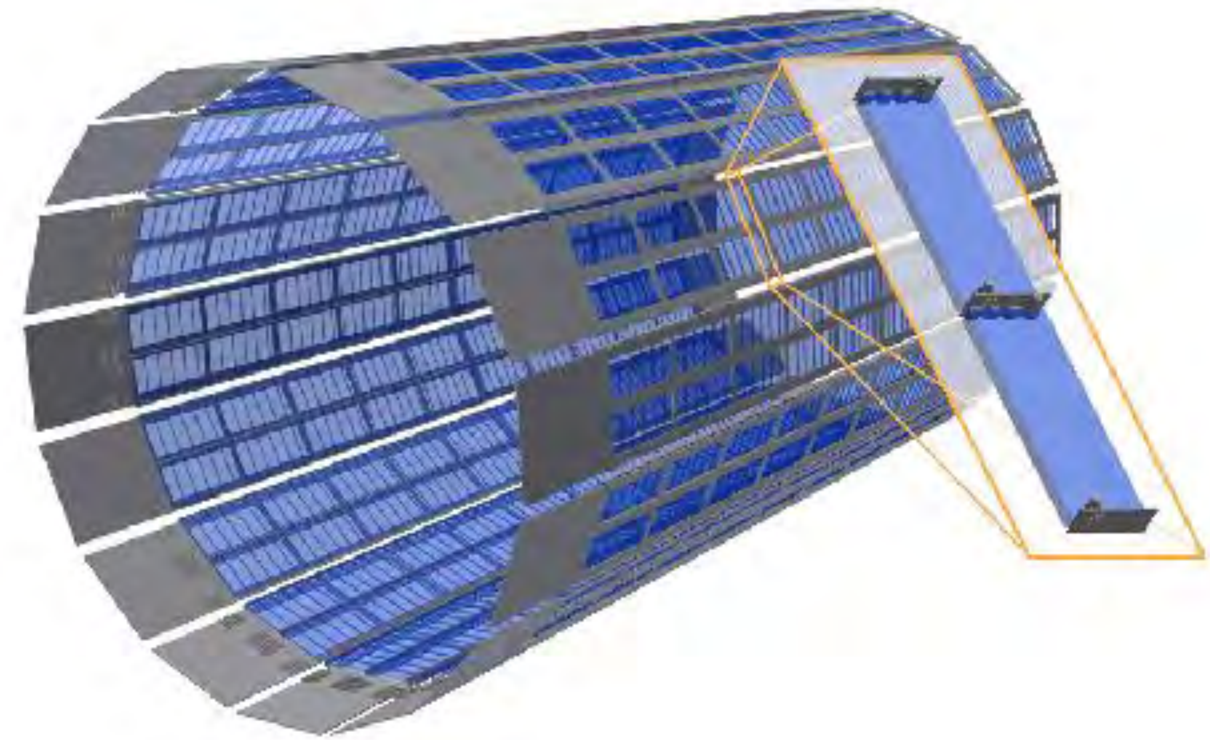
Super Module

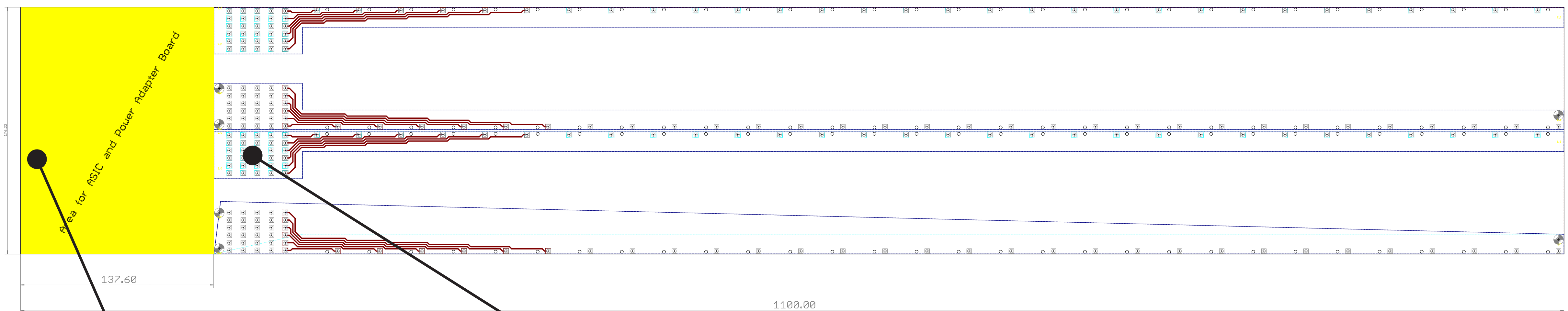
Minimum number of parts
Minimum number of connections
Easy construction
Easy maintenance



<u>Total 1920 tiles, 3840 channels, 15360 SiPMs</u>

Super Module
- a half length prototype

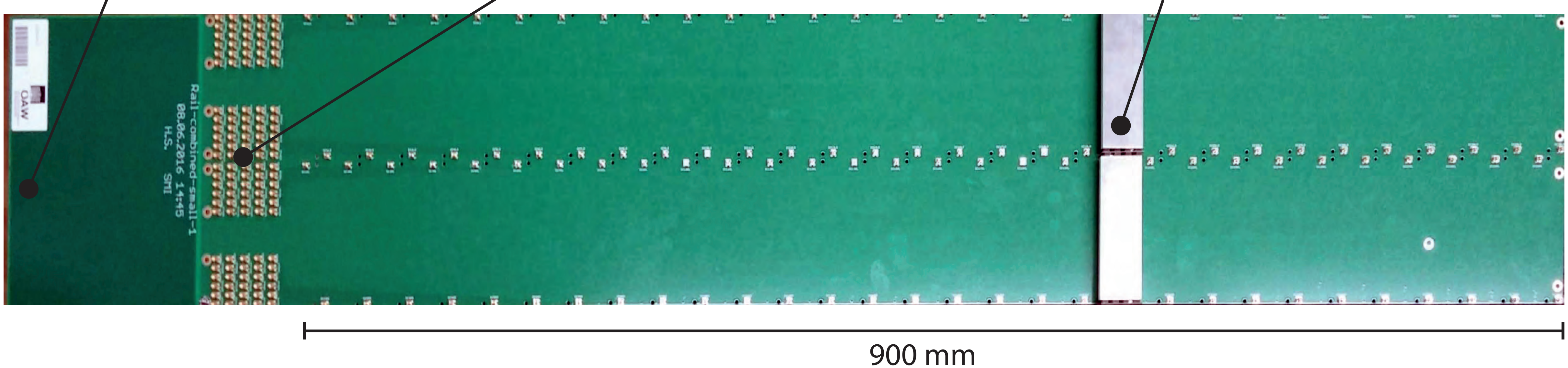




Space for FEE implementation

MMCX connectors (Signal Out)

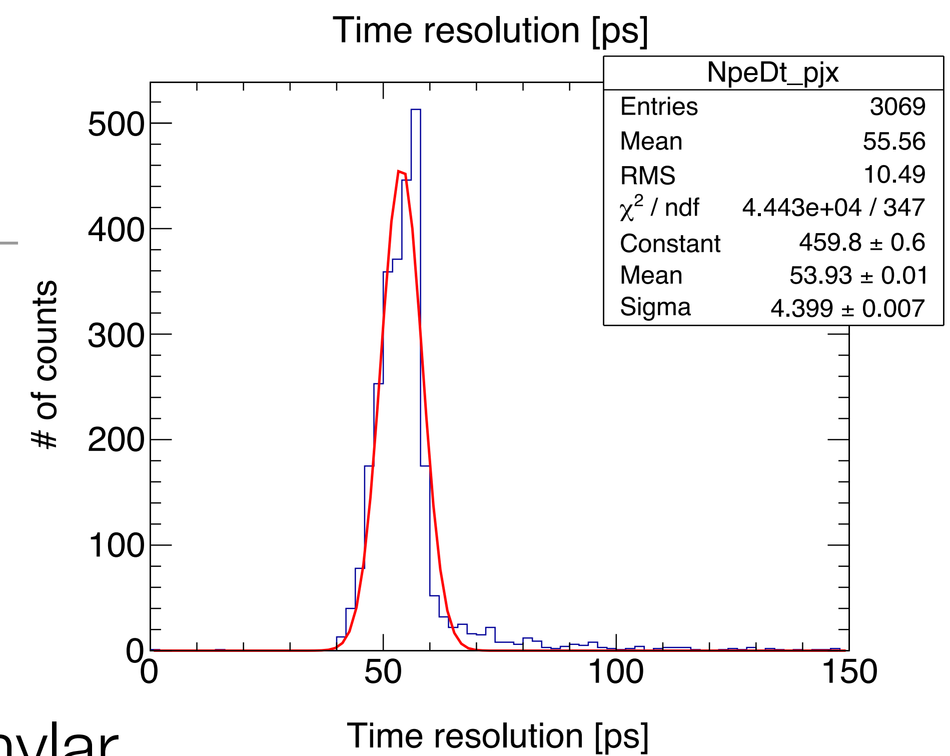
Dual-module



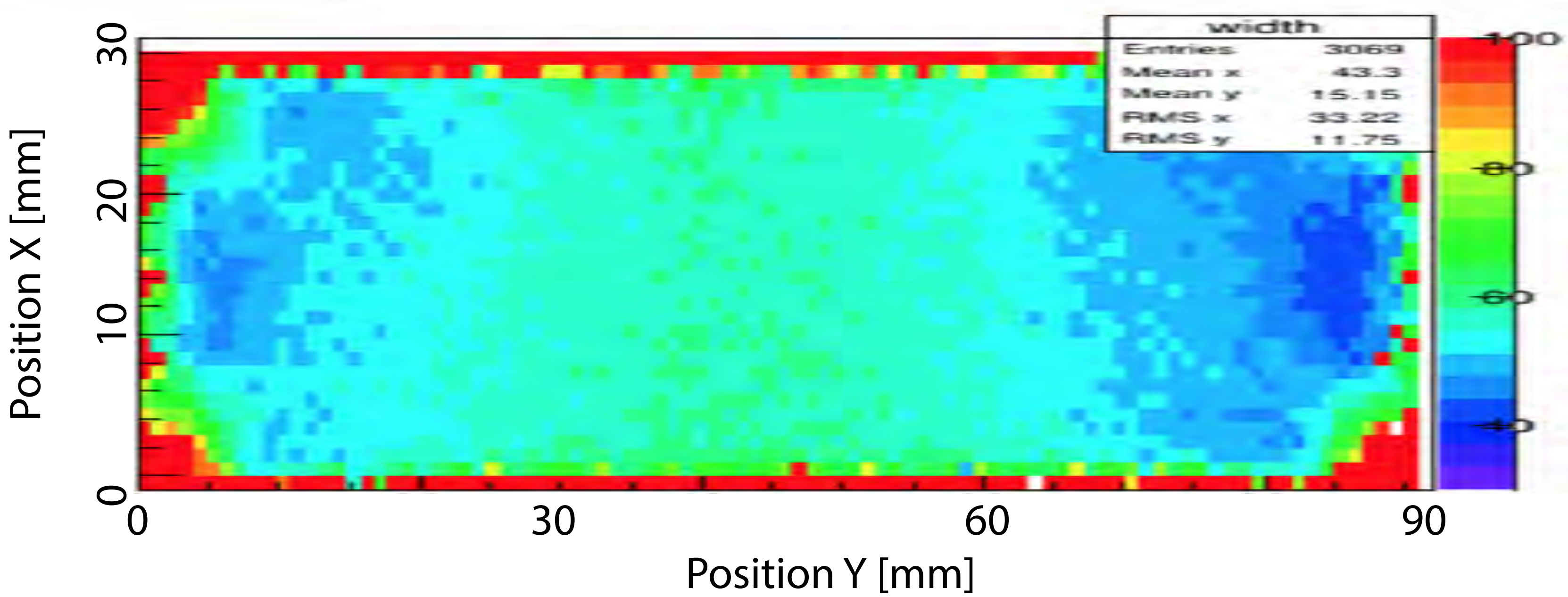
Performance - single tile

joint work with Erlangen

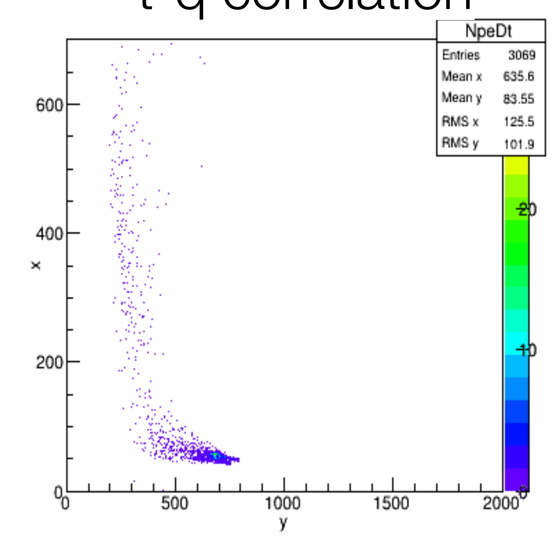
Very fine position dependence measurement of the performance with the optimised condition with well collimated ^{90}Sr source



EJ-232/HPK S13360-3050PE/wrapped with aluminised mylar



t-q correlation



HV 240V, threshold -30 mV, 2000 events/position, 3069 positions

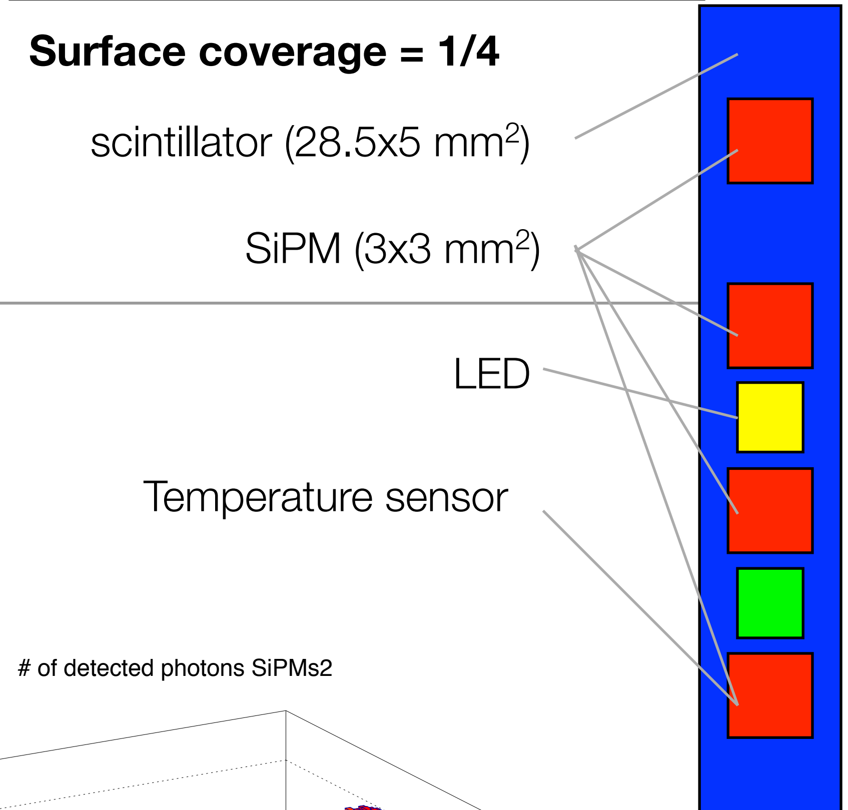
Mean time resolution σ = 53.9 ps

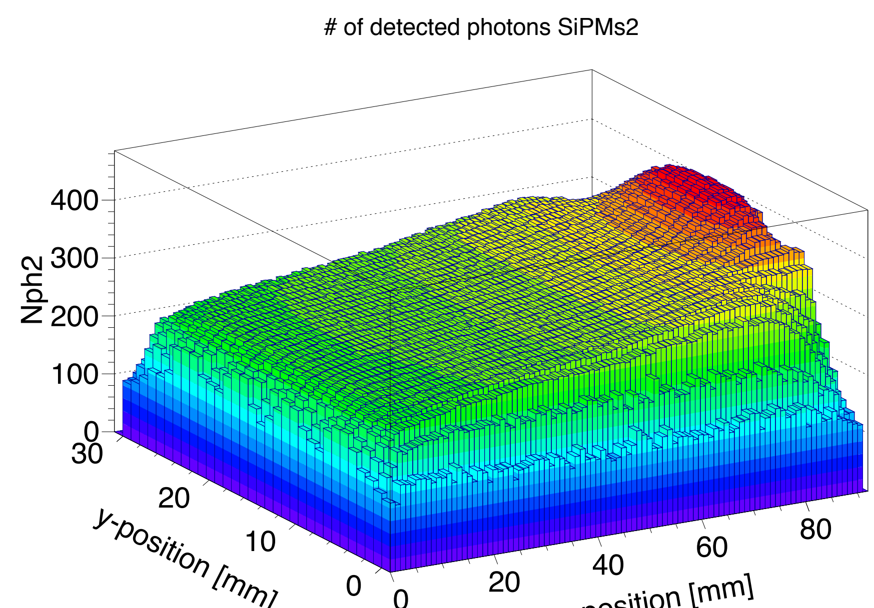
Position resolution σ_x = 5.5 mm

Further optimisation?

- #sensor 4 → 5 or 6
- sensor size 3x3 mm^2 → 4x4 mm^2 or 5x5 mm^2
- scintillator thickness 5 mm → 4 mm or 3 mm?

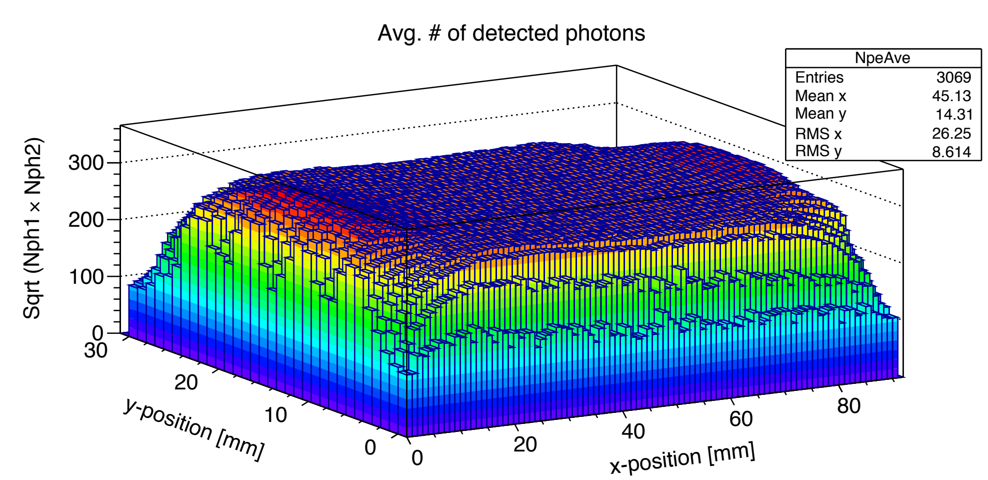
Side view of the SciTil





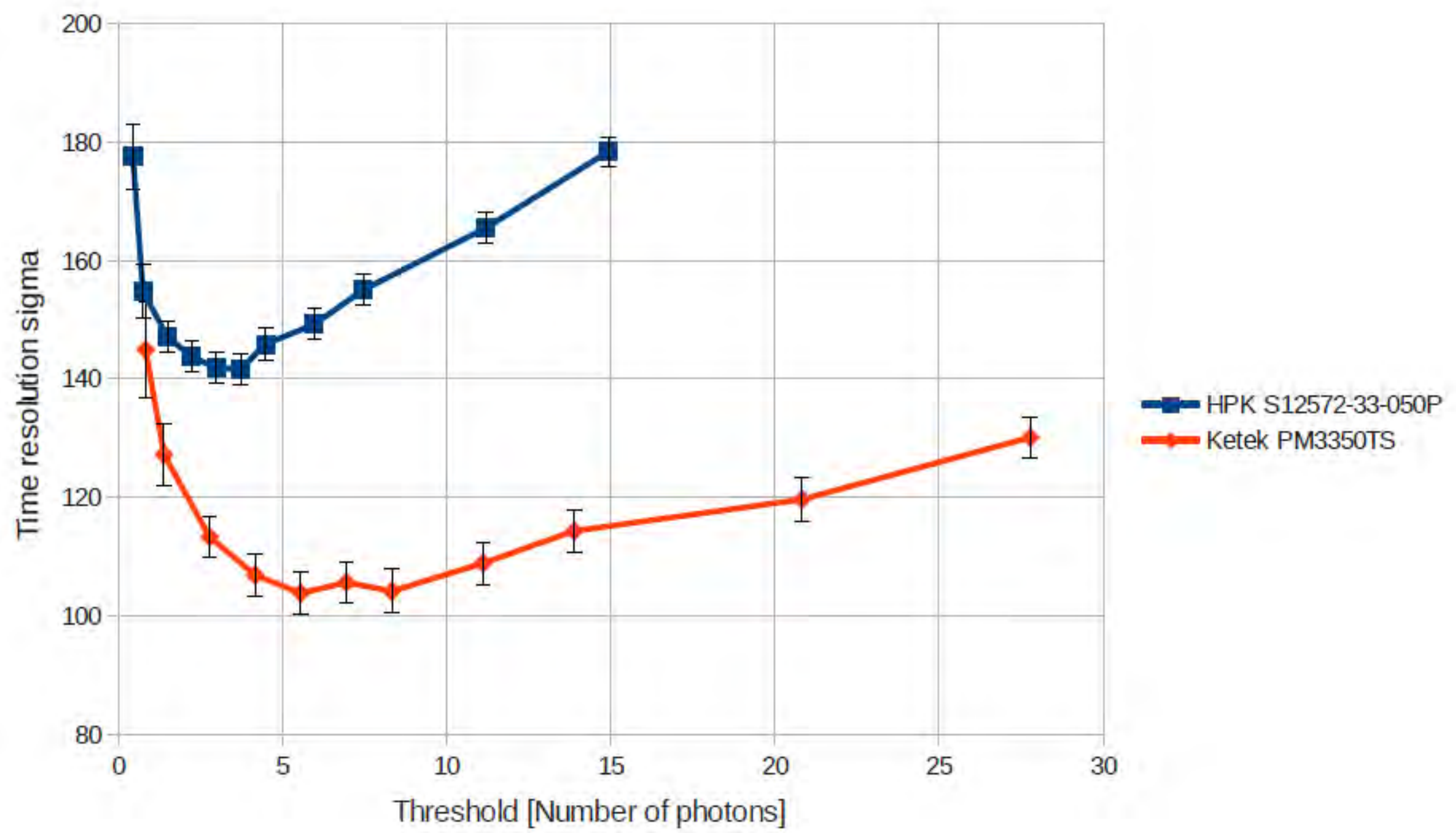
Wrapping material	Time resolution [ps]	Number of detected photons
No wrapping	55.0 ± 0.3	288 ± 2
Aluminised Mylar foil	52.7 ± 0.3	355 ± 2
Tyvek hardstructure 1057D	55.0 ± 0.3	394 ± 3
Enhanced specular reflector (ESR)	55.2 ± 0.3	355 ± 3
Teflon tape	59.4 ± 0.3	408 ± 4
aluminium foil	54.2 ± 0.3	344 ± 3

Wrapping material	Time resolution [ps]	Number of detected photons
No wrapping	61.3 ± 0.3	371 ± 2
Aluminised Mylar foil	59.7 ± 0.3	445 ± 3



The best time precision when triggering on the first photon? Analog SiPM

Time resolution of a scintillator tile read-out with the Hamamatsu SiPMs



No, the trigger threshold should not be set to the first detected photon, due to electronics noise and the SPTR of the SiPM.

Electronics threshold: SiPM

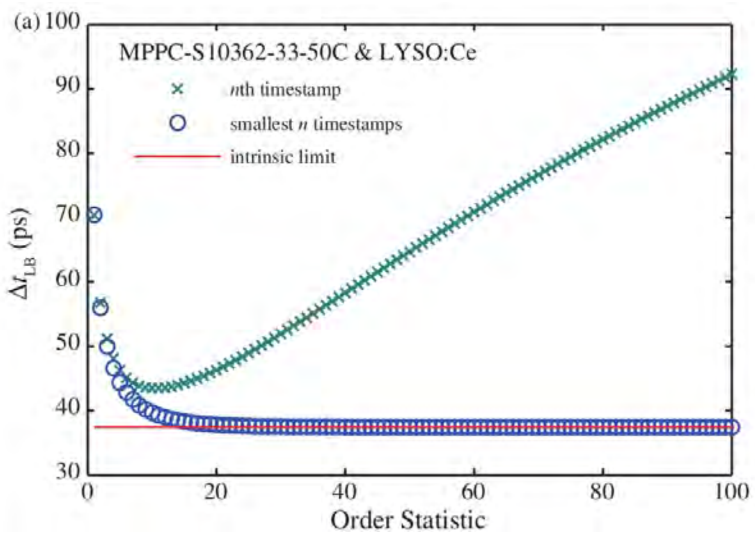
- **A similar behavior has been also reported by others**

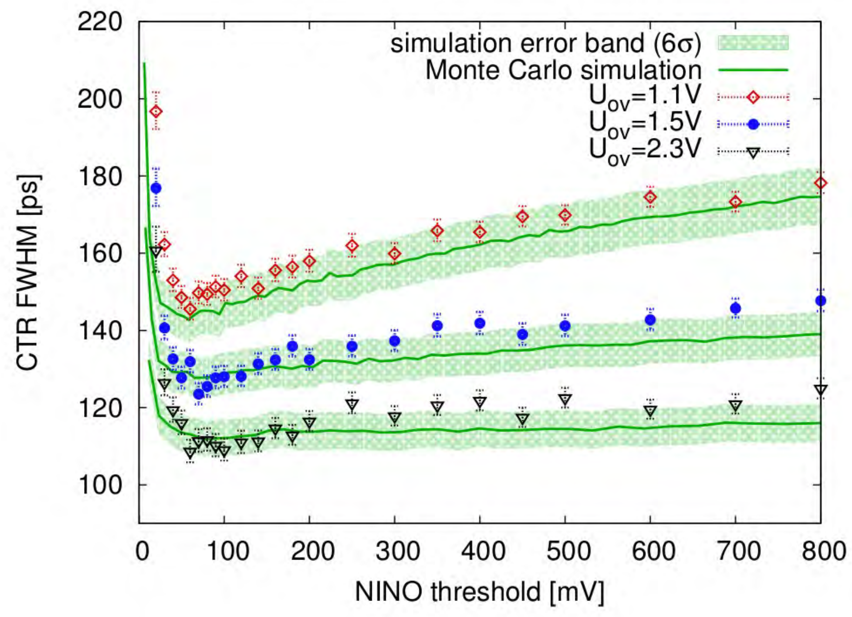
S. Gundacker et al., Time of ight positron emission tomography towards 100ps res-olution with L(Y)SO: an experimental and theoretical analysis, J. Instrum. 8 (2013) P07014.

S. Seifert, H. van Dam, D. Schaart, The lower bound on the timing resolution of scintillation detectors, Phys. Med. Biol. 57 (2012) 1797-1814.

S. Seifert et al., A Comprehensive Model to Predict the Timing Resolution of SiPM-Based Scintillation Detectors : Theory and Experimental Validation, IEEE Trans. on Nucl. Sci., Vol. 59, pp. 190-204, 2012.

Effects of scintillation light collection on the time resolution of a time-of-flight detector for annihilation quanta
S. Ziegler at al. (1990)





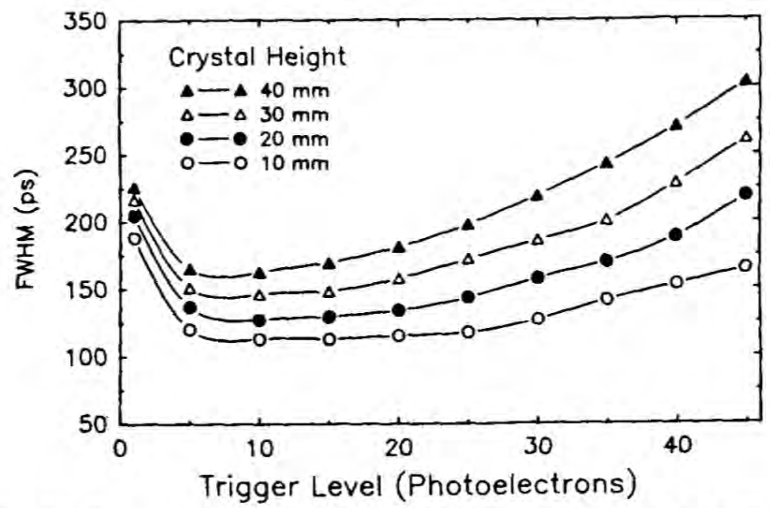
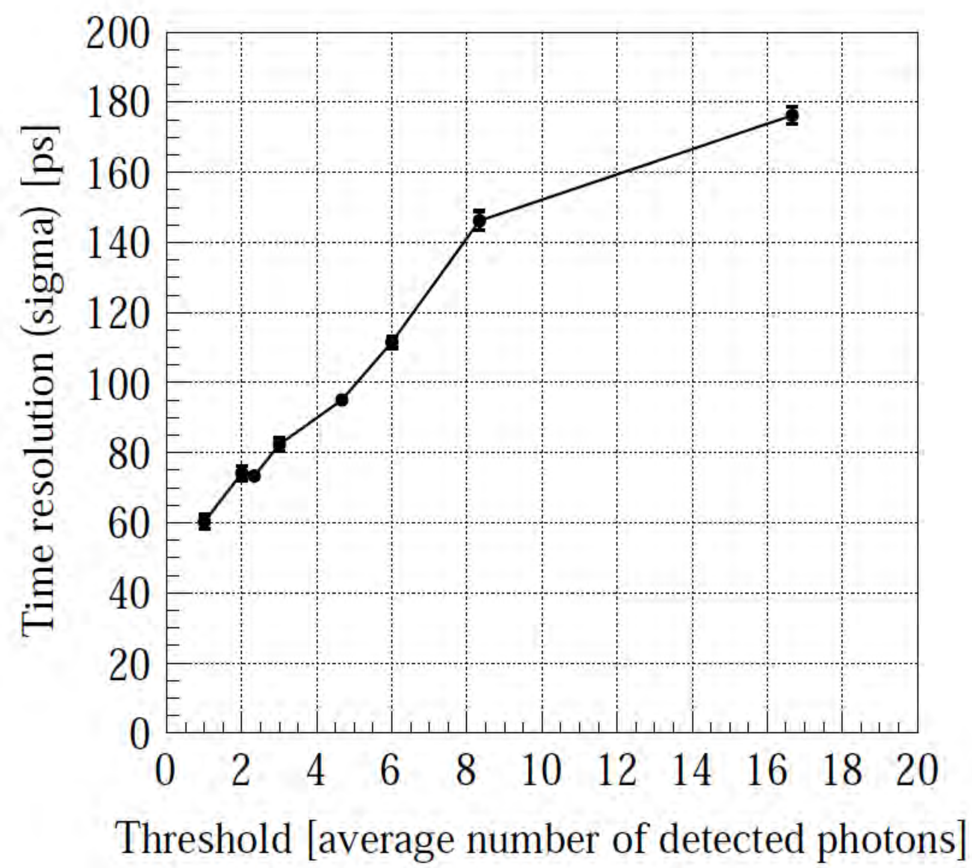


Fig. 2. Calculated width of trigger time distribution for cylindrical BaF_2 crystals with radius 15 mm, energy threshold 480 keV.

The best time precision when triggering on the first photon? Digital SiPM

Time resolution of a scintillator tile read-out with the Philips DPC



Yes, the trigger threshold should be set to the first detected photon

Summary

- SiPM (analog / digital)
- Barrel Time-of-Flight Detector for PANDA
    - series connection of 4 SiPMs
    - signal transmission lines with PCB board
    - σ_t~60 ps, lab / beam test
- Still some rooms for improvements