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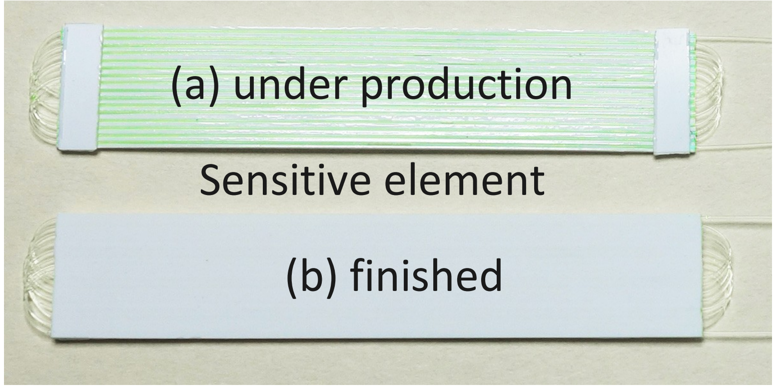
Progress Report PSI: 2D neutron detectors based on ZnS:^{6}LiF read out with WLS fibers and SiPMs

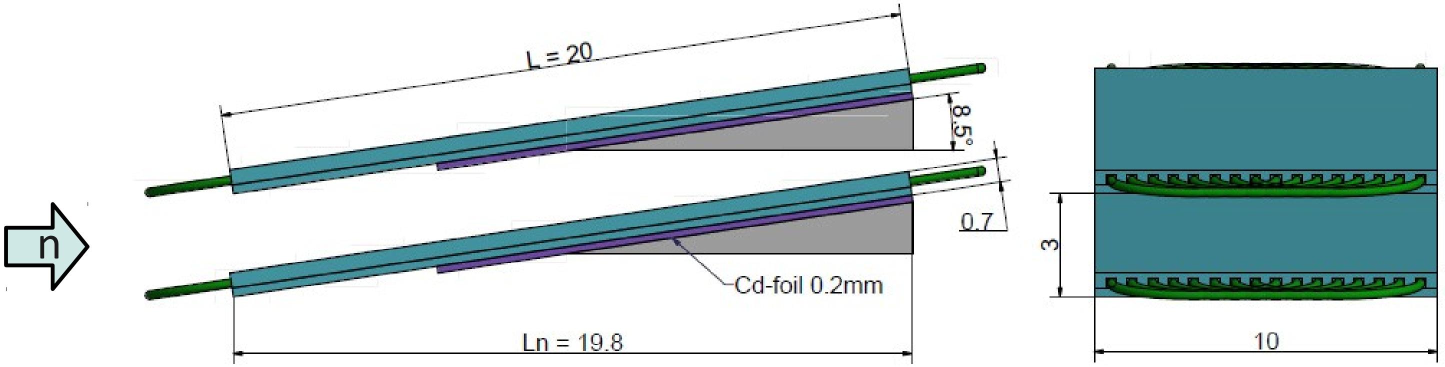
SINE2020 WP9, Coimbra, Portugal, September 2016

2D pixelated detector

- sensitive area of the prototype: (50 × 10) mm^2
- Materials
  - ND2:1 ZnS:^{6}LiF scintillator (Scintacor)
  - WLS fiber : Y11(400)M, Ø=0.25mm (Kuraray)
- Production
  - machining of 16 grooves in a 0.45mm thick strip
  - gluing of a single WLS fiber in the grooves
  - bending of the fiber at T ~ 60°C
  - gluing of a 0.25mm thick scint. strip on the top

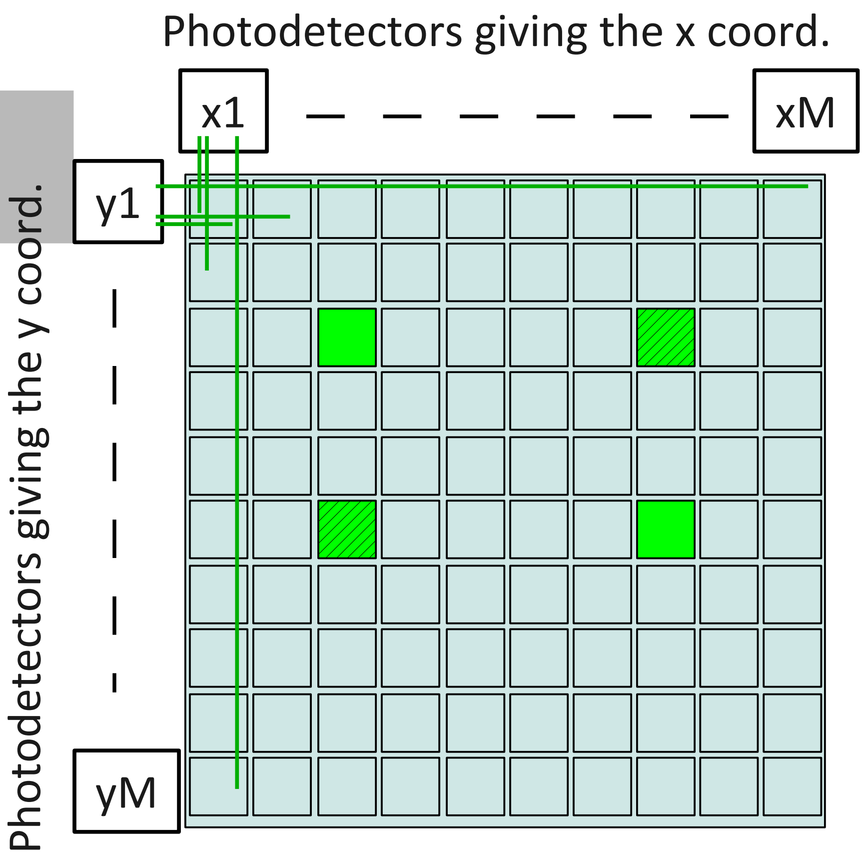


Assembly of sensitive elements of (20 × 10) mm^2 to form pixels of (3 × 10) mm^2



- intrinsic time resolution [μs] = 1.5 λ [Å]

XY-coding

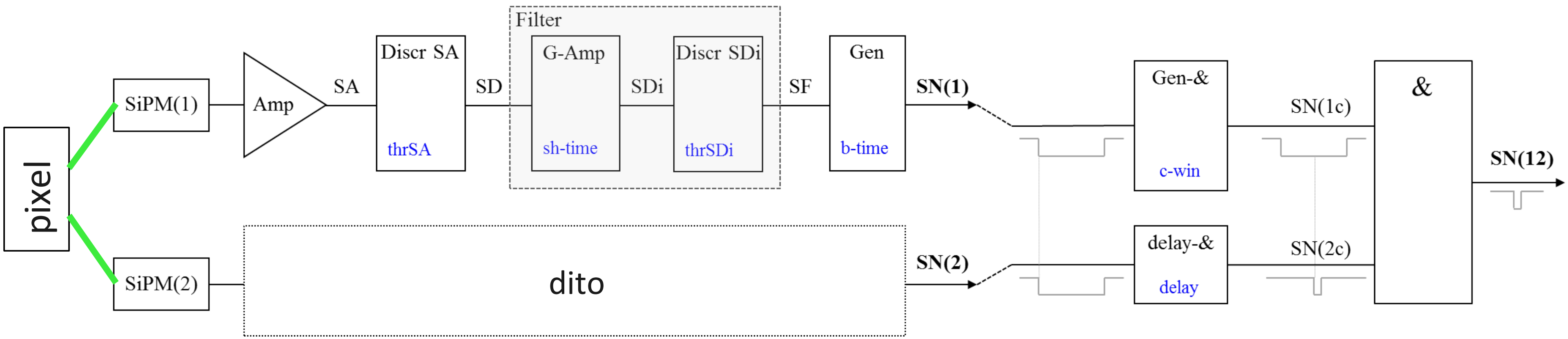


- basic requirement for the pixels: the LY must to be split into two fibers
- 2M photodetectors for M^2 pixels
- for a uniform illumination of the matrix, the rate capability is limited by "diagonal" events
- for a maximum event rejection of 0.1, the maximum rate per pixel is $0.1 / (\Delta c \times (M - 1)^2)$
- To increase the rate capability:
  - Reduce Δc
  - Reduce M

True events arriving within the coincidence resolving time (Δc). The events have to be rejected (ambiguity concerning the position of the events: or ?)

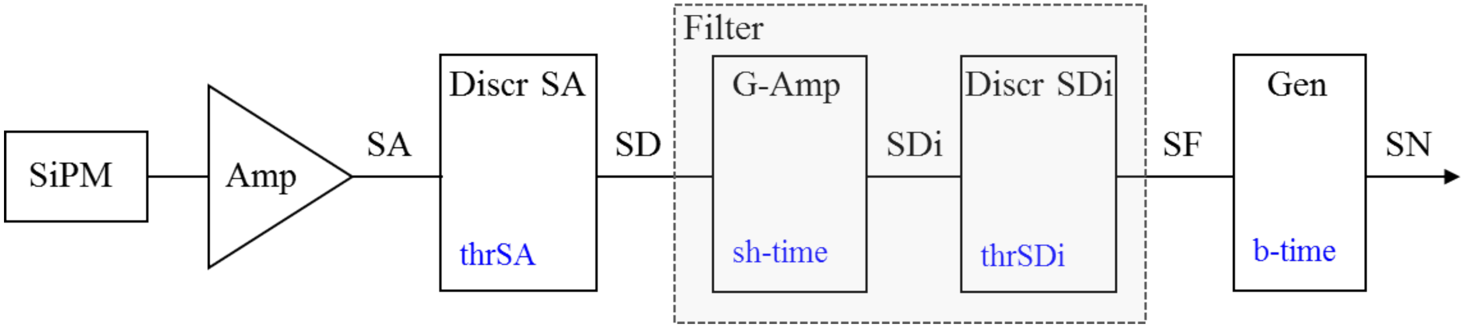
Experimental setup for testing the prototype

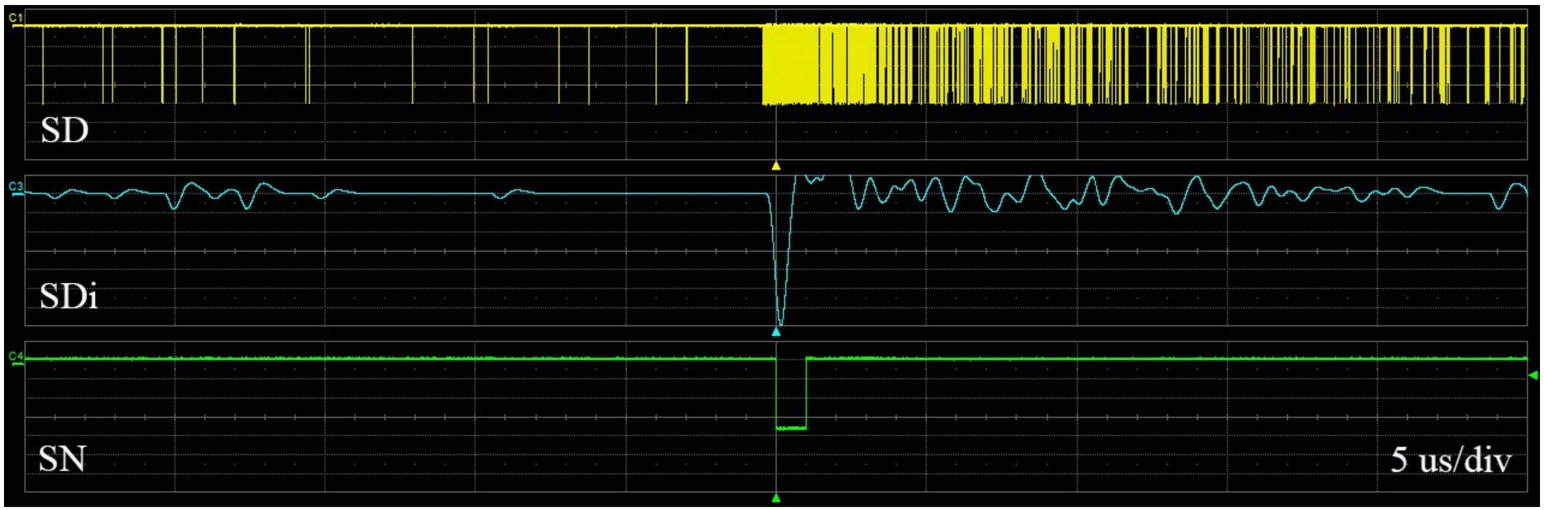
- radioactive source :
  - ^{241}Am/Be neutron source in polyethylene moderator (absorption rate 8.7 Hz)
  - ^{60}Co γ-source (rate of 1.3 MeV γ through pixel = 10^4 1/s)
- Photosensors
  - 2 SiPMs $(1.3 \times 1.3)\text{mm}^2$, MPPC S13360-1350PE (Hamamatsu)
  - overvoltage ΔU = 5.0V (2.0V)
  - PDE~40% (25%) at 480 nm (emission peak of WLS fiber)



- Settings of the signal processing system:
  shaping time = 0.25µs, blocking time = 1µs, coincidence resolving time = 0.5µs

Signals (single channels)



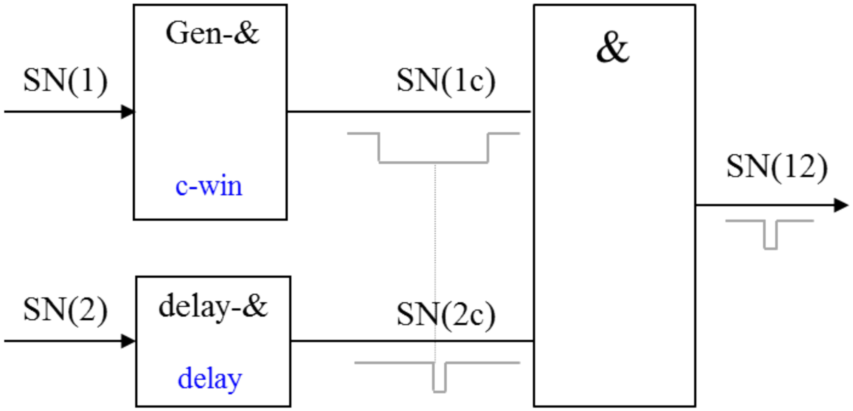


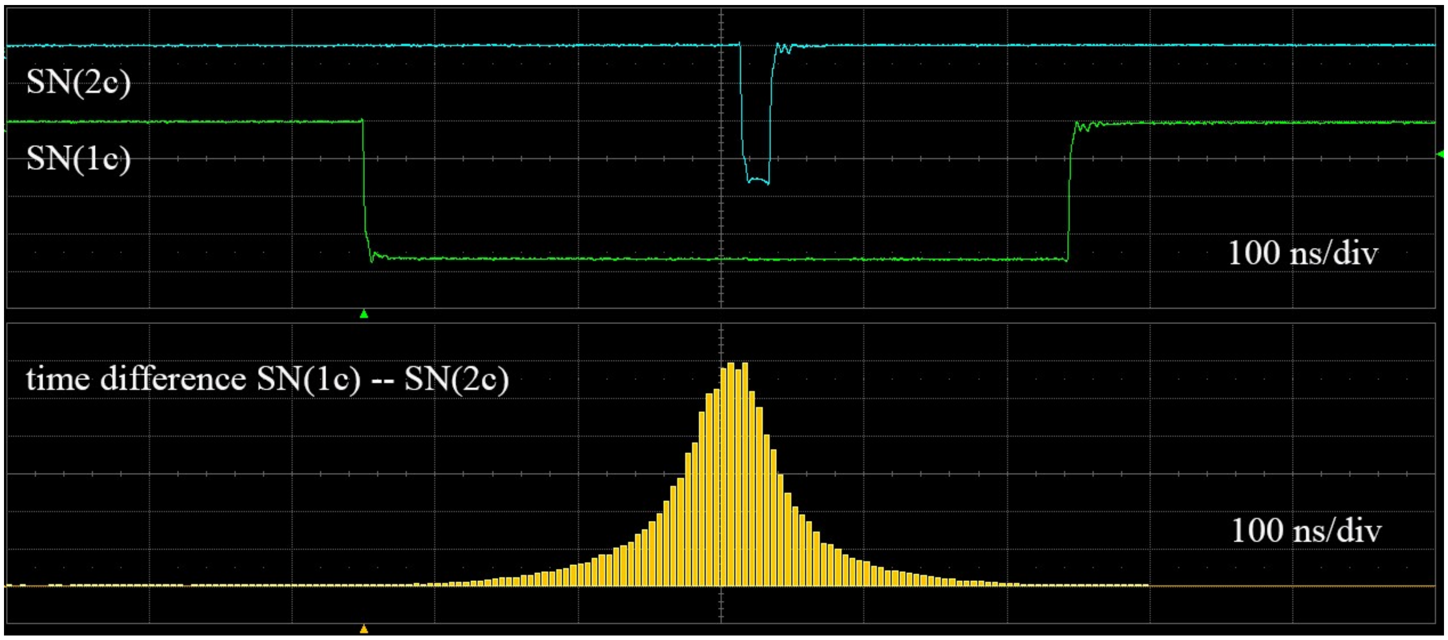
G-Amp : Gaussian amplifier (shaping time sh-time = 0.25µs)

Discr SDi : leading-edge discriminator (threshold thrSDi)

Gen : non-retriggerable monoflop (pulse width b-time = 4 · sh-time)

Signals (coincidences)

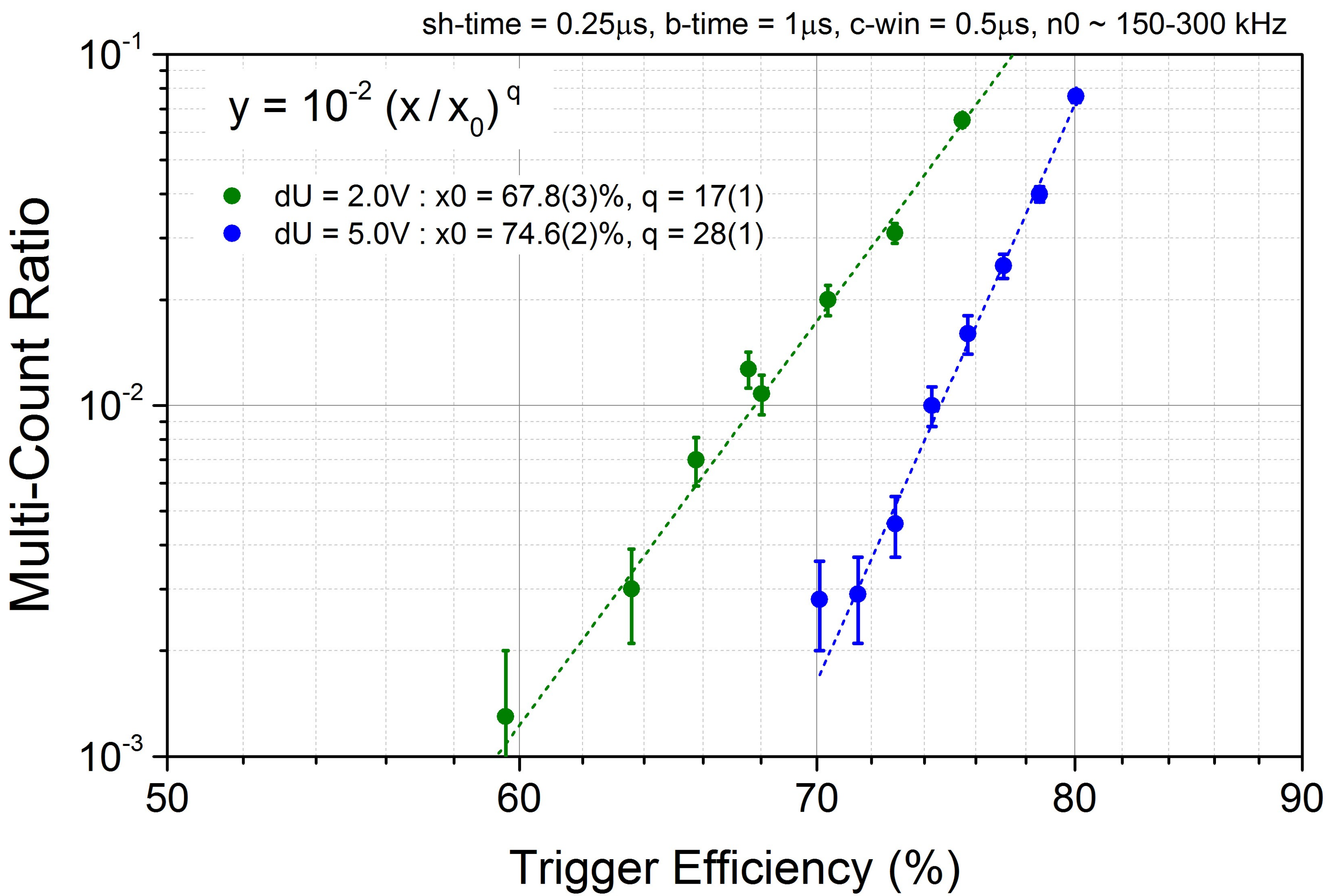




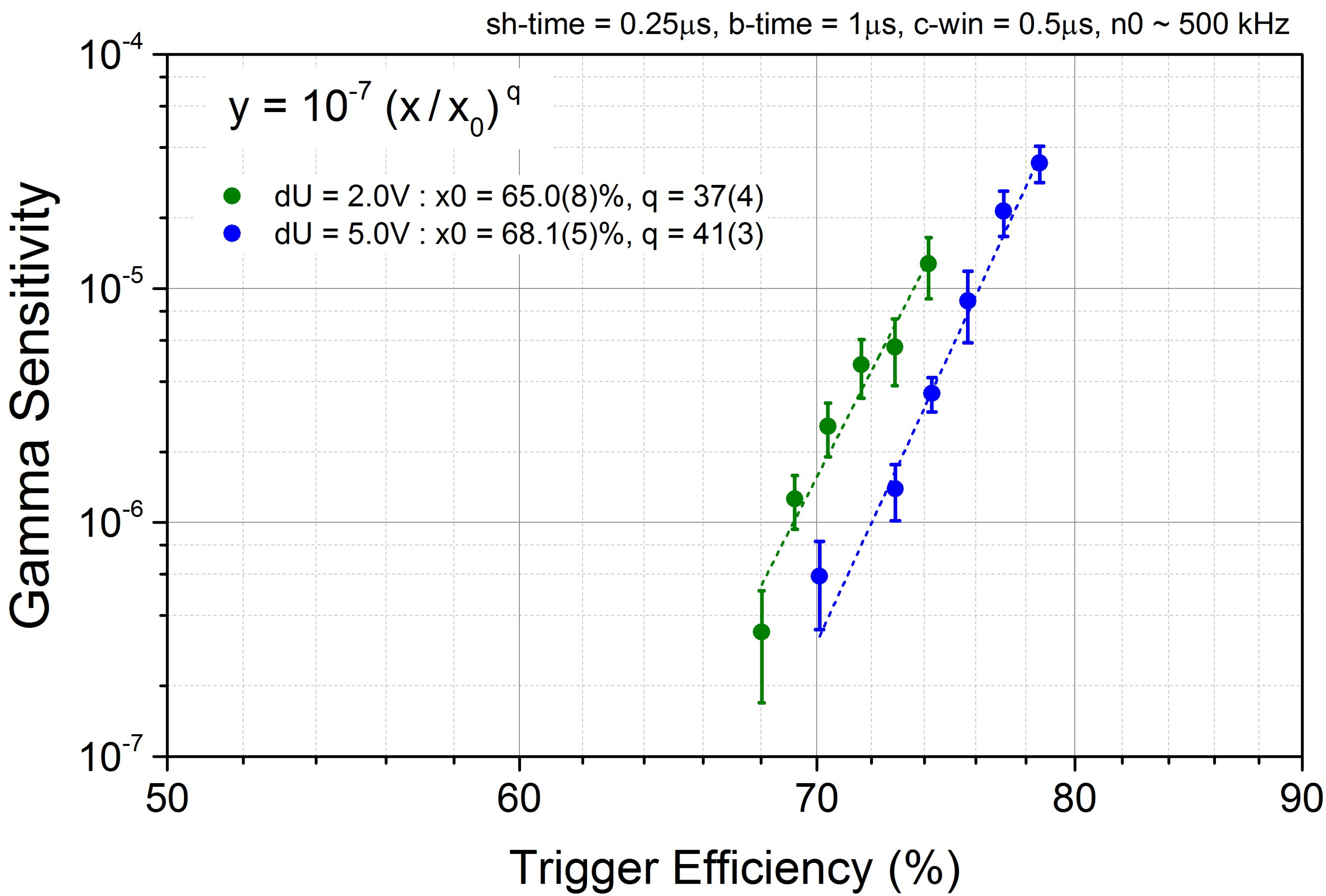
$\Delta c = 0.5\mu s$

> 99% of events within this window

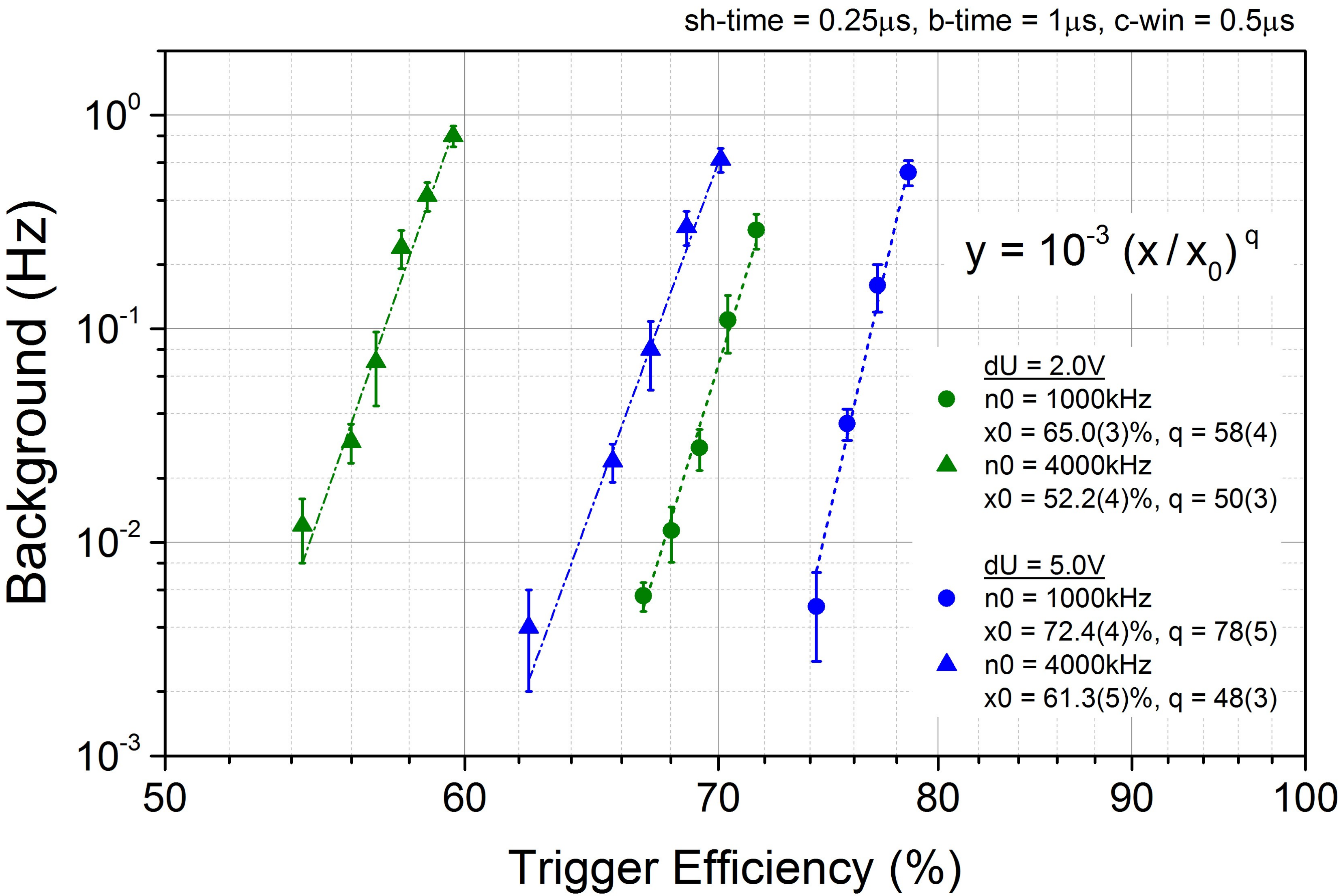
Multi-count ratio



Gamma sensitivity



Background rate



Summary

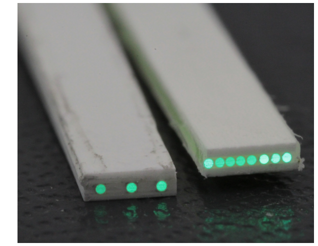
- General features:
  - Gapless large-area detectors
  - XY-coding of pixels arranged in 2D matrix
  - Use of small area SiPMs possible (~1mm^2 up to matrix dimension M = 10)
  - High rate capability due to small M
- Main performance parameters:
  - Detection efficiency at 1 Å (10 Å): 50% (57%) (absorption 80% (95%), trigger efficiency (60%)
  - Multi-count ratio: $< 10^{-3}$
  - γ sensitivity : $< 10^{-7}$
  - Background rate: $< 10^{-3}$ Hz
  - XY-coincidence resolving time : 0.5 µs
  - Count rate capability for a uniform illumination of the matrix: 2.5 kHz / pixel (for M = 10)

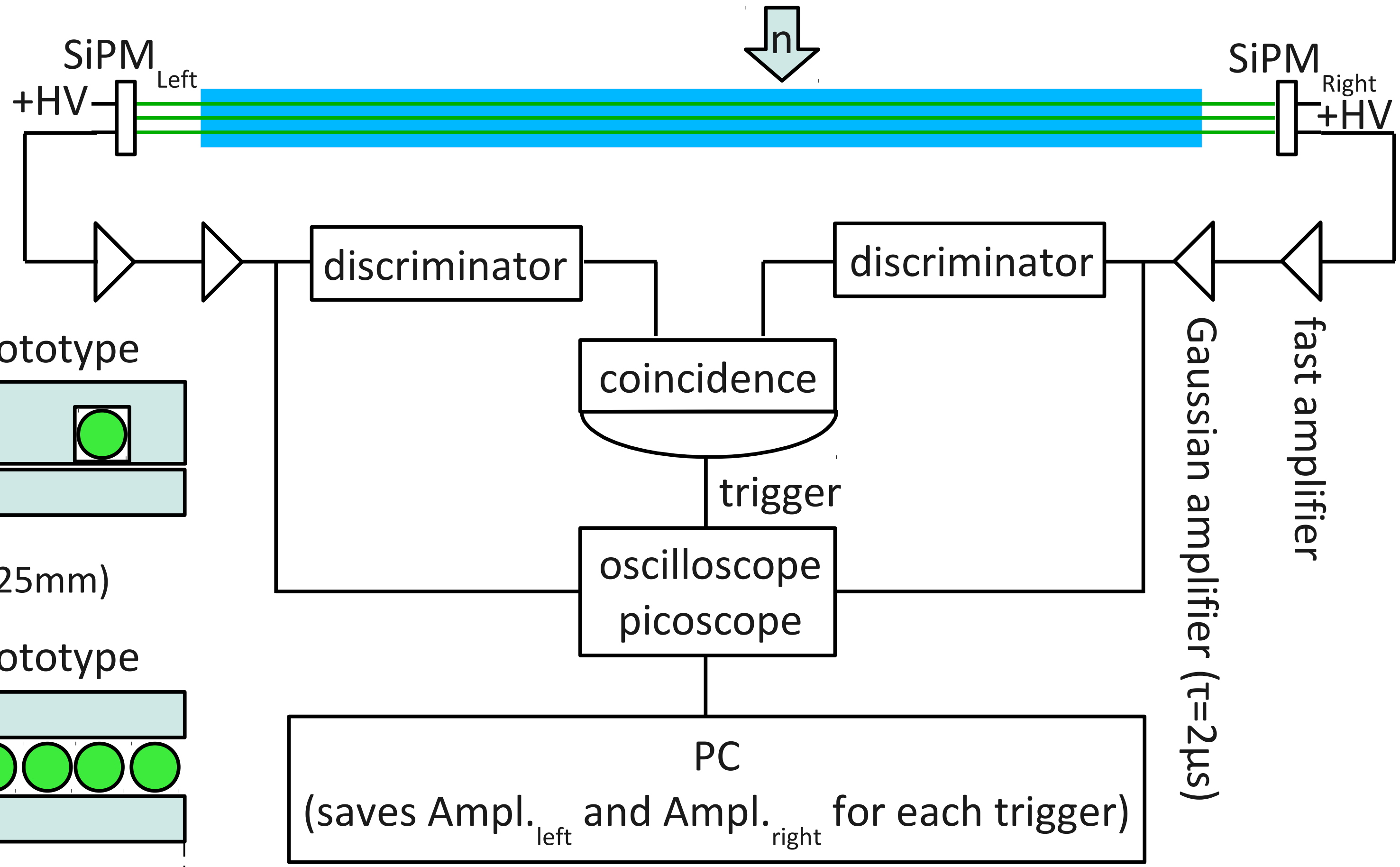
--> Satisfy requirements for NPD detectors at ESS

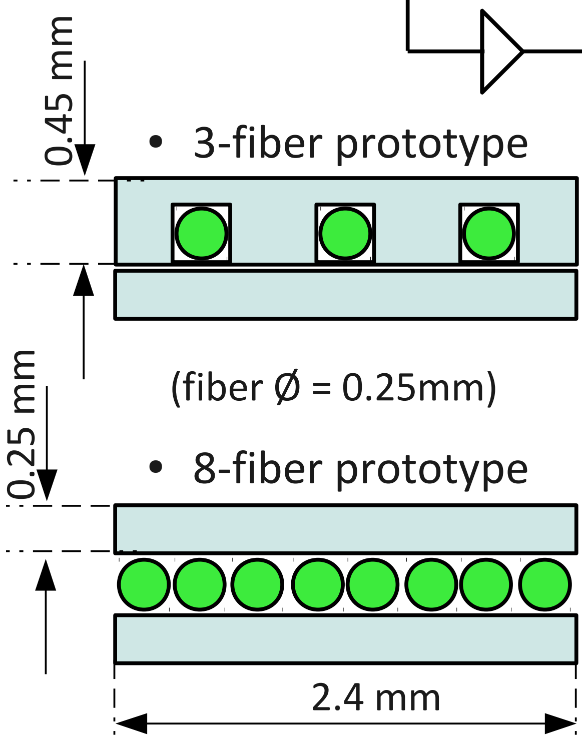
* Details in [A.Stoykov et al., IEEE TNS 63(4) (2016) 2271-2277]

2D detector based on light sharing

- ZnS:^{6}LiF detection unit
  - sensitive area (2.4 × 200) mm^2
  - WLS fibers with short attenuation length (λ≈15cm) from Kuraray
  - fibers are read out on both sides with SiPM







Position reconstruction method

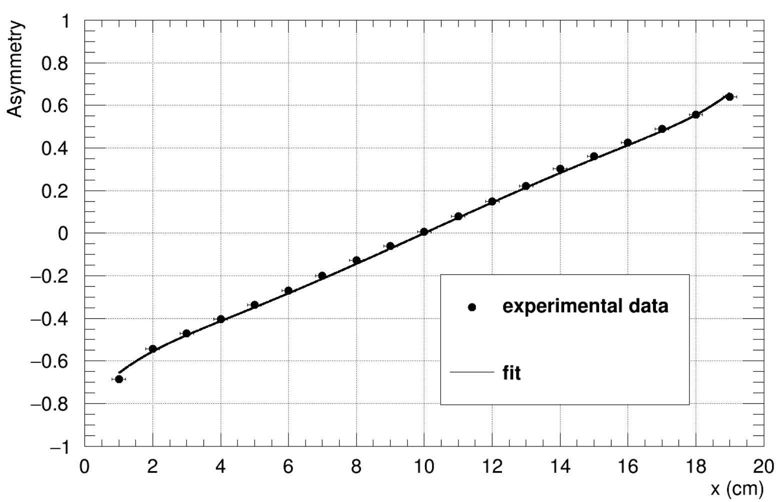
- Calculation of the average asymmetry measured at different positions X_i

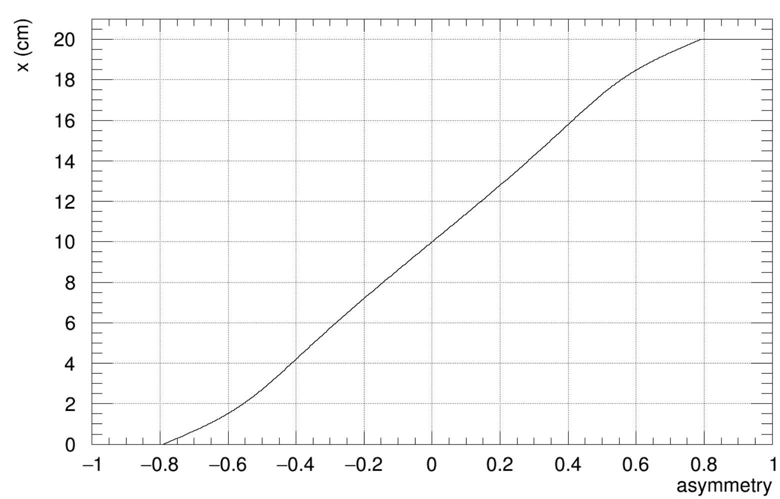
$$\langle asymmetry(x_i)\rangle = \langle \frac{A_L(x_i) - A_R(x_i)\cdot\gamma}{A_L(x_i) + A_R(x_i)\cdot\gamma} \rangle \quad \text{where} \quad \gamma = \langle \frac{A_L(L/2)}{A_R(L/2)} \rangle$$

- γ factor --> corrects for possible left / right difference of the readout gain and the optical coupling
- fit of the average asymmetry curve with $f_{asym}(x) = \frac{att_L(x) - att_R(x)}{att_L(x) + att_R(x)}$

where $att_L(x) = \frac{I_{long}\cdot e^{-x/\lambda_{long}} + I_{short}\cdot e^{-x/\lambda_{short}}}{I_{long} + I_{short}}$ (λ_{long} , λ_{short} , I_{long} and I_{short} are free parameters)

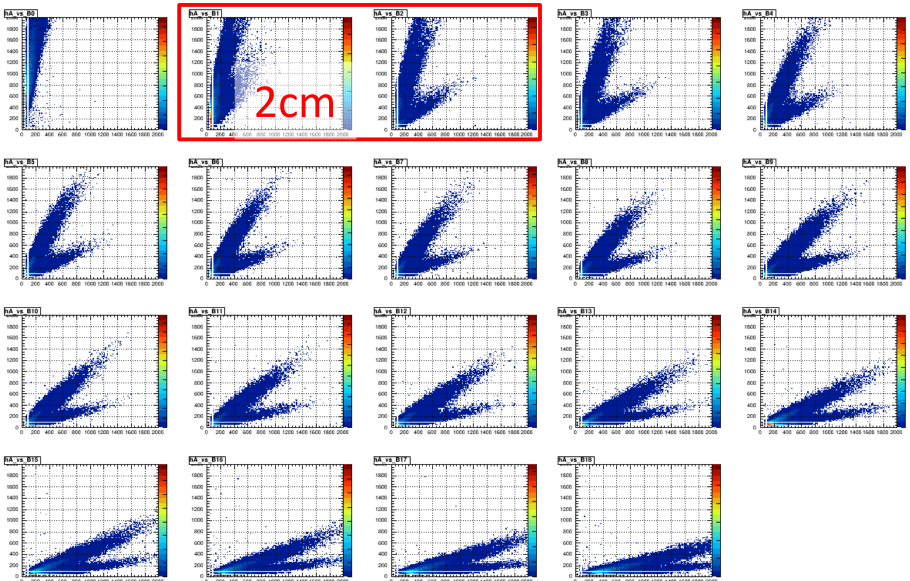
- position reconstruction of individual events with $f_{position}(asym) = f_{asym}^{-1}(x)$



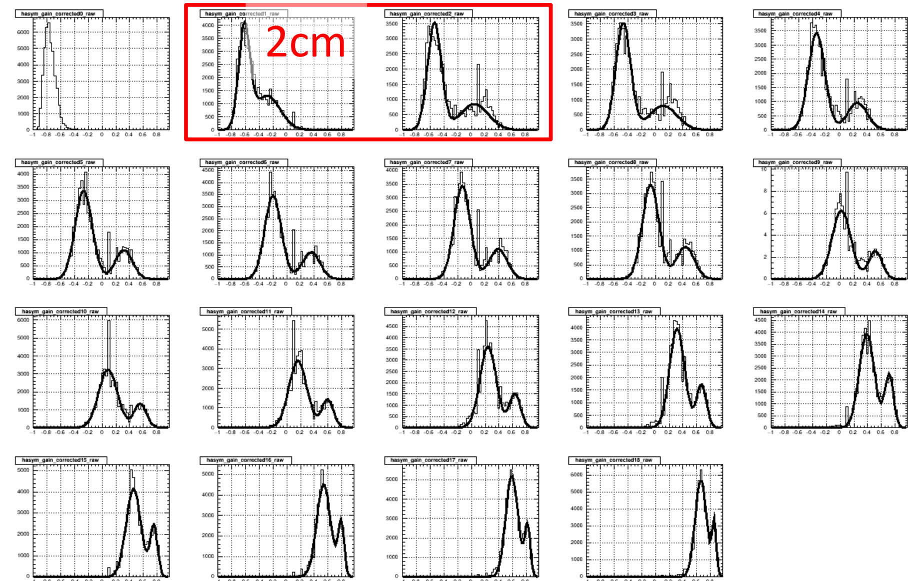


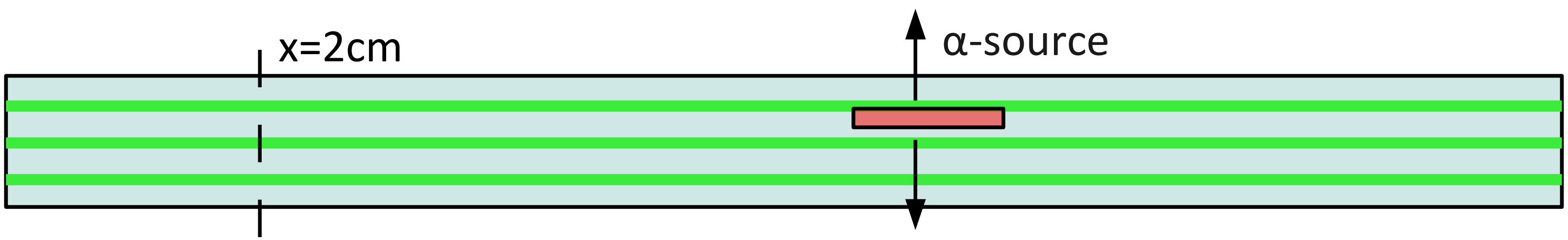
Anomaly observed with the 3-fiber prototype

A_{left} vs A_{right} at diff. positions (1, 2, .., 19cm)



Asymmetry at diff. positions (1, 2, .., 19cm)

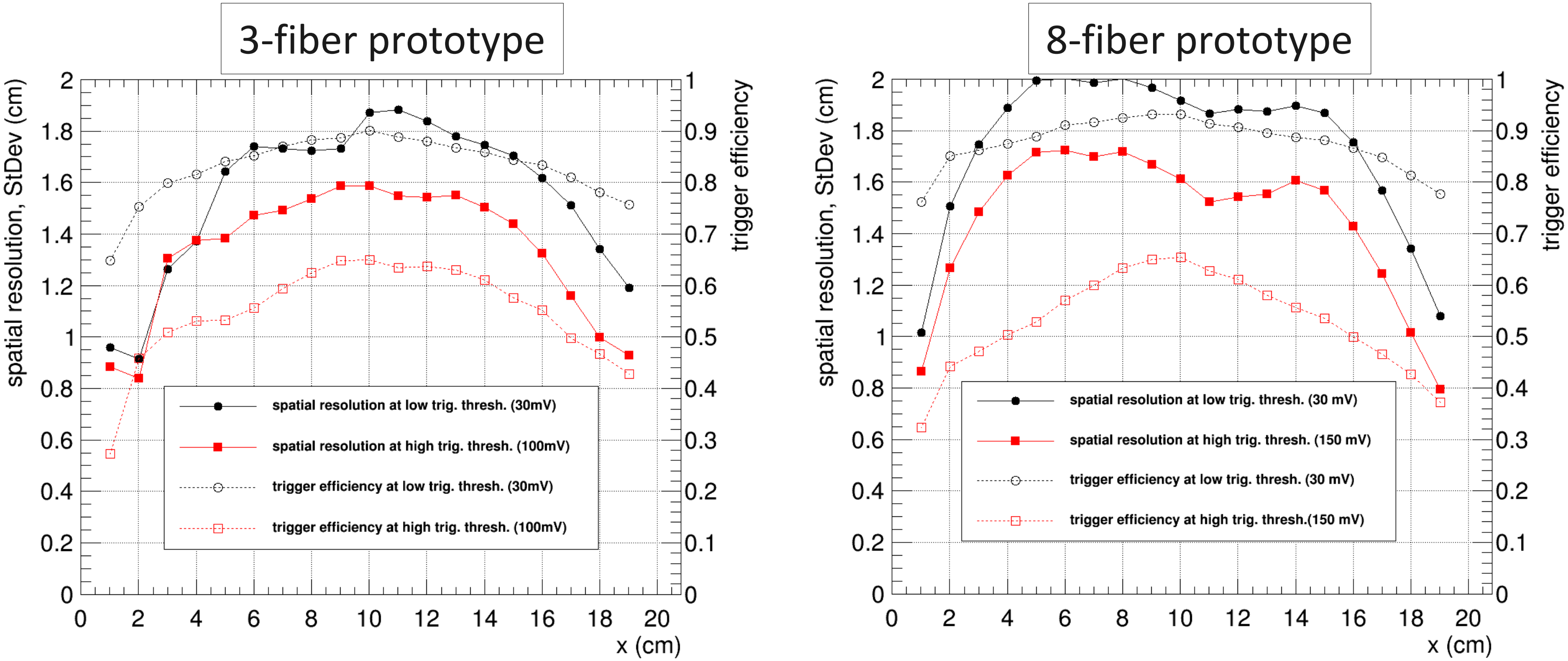




- we suspect that one of the fiber has an "optical defect" at x ≈ 2 cm:
  - non-uniform PMMA concentration in the core
  - crack

  (to be confirmed with a lateral scan of the bar with a linear and collimated α-source)
- **only events with an asymmetry in the left peak are selected**

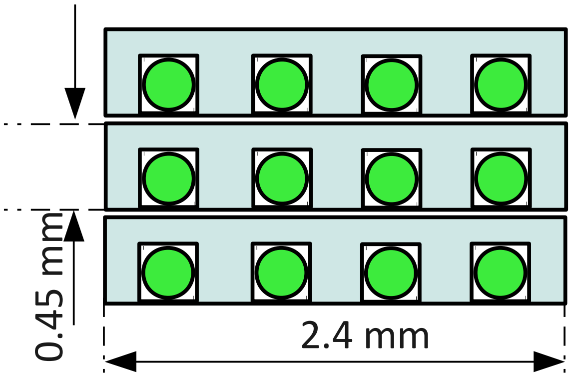
Results



- High light yield is crucial for
  - spatial resolution
  - trigger efficiency
- LY ratio between 8-fiber and 3-fiber proto = 1.4
- At the same trigger efficiency, the 3-fiber proto has a better spatial resolution than the 8-fiber proto
  --> the 8-fiber proto might have one or more fibers with an “optical defect”.

Next step

- test of a new structure
- expected LY: more than twice higher as for the 3-fiber prototype (fiber density is twice --> average distance to a groove is half)
- quality control of the fibers before manufacturing regarding *cracks* and *uniformity of the attenuation length* (with LED)



	3-fiber proto	8-fiber proto	New geometry
Fiber density (fiber / mm^2)	1.79	4.17	3.70
Max. distance from a point in the scintillator to a groove (mm)	0.35	0.25	0.21
Fiber distribution in the sensitive volume			
Production			

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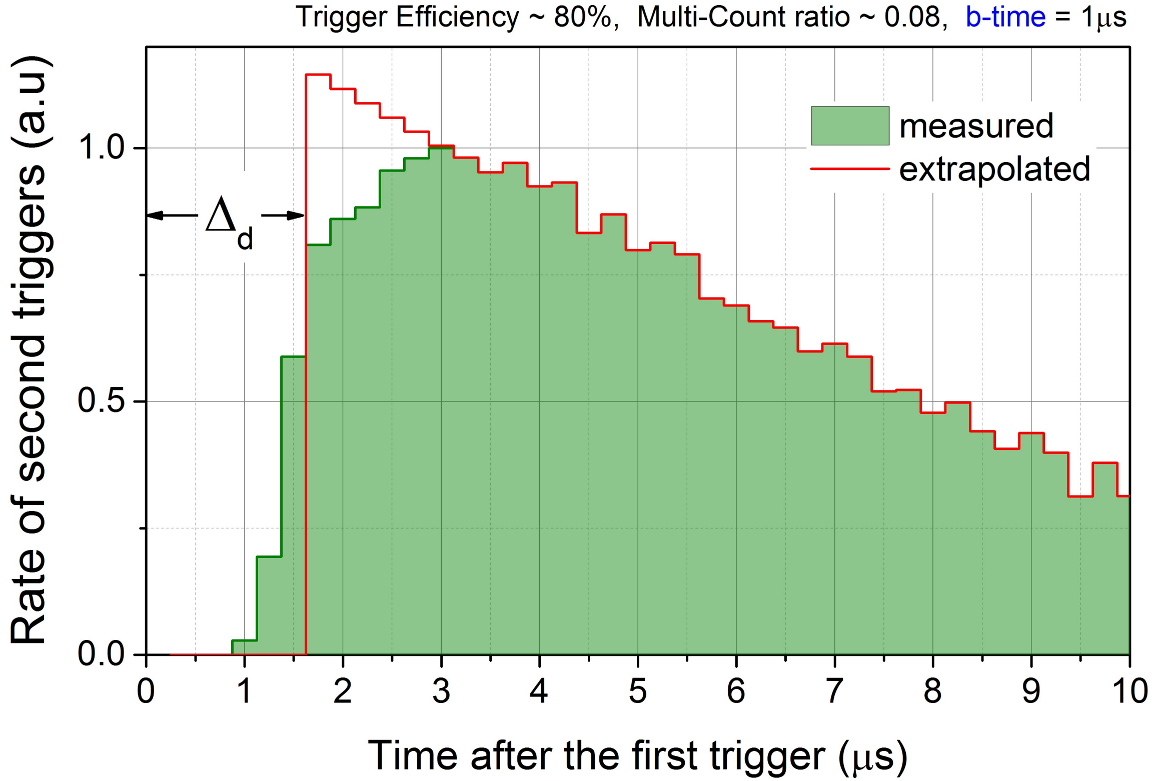
Thank you for your attention !

Annex: dead time (estimate with multi-counts)



- Time distribution of second triggers (multiple counts) in respect to the first trigger (main event). Allows to obtain an upper limit (~ 1.7μs) on the dead time.
- More close* estimate is Δd ~ 6 · sh-time ~ 1.5μs
- Count rate capability for a uniform illumination of a row or column: 6.5 kHz / pixel ($N_{max} = 0.1 / (\Delta d \times M)$)

* Details in [A.Stoykov et al., IEEE TNS 63(4) (2016) 2271-2277]

Annex: neutron absorption probability (MC simulation)

Input conditions

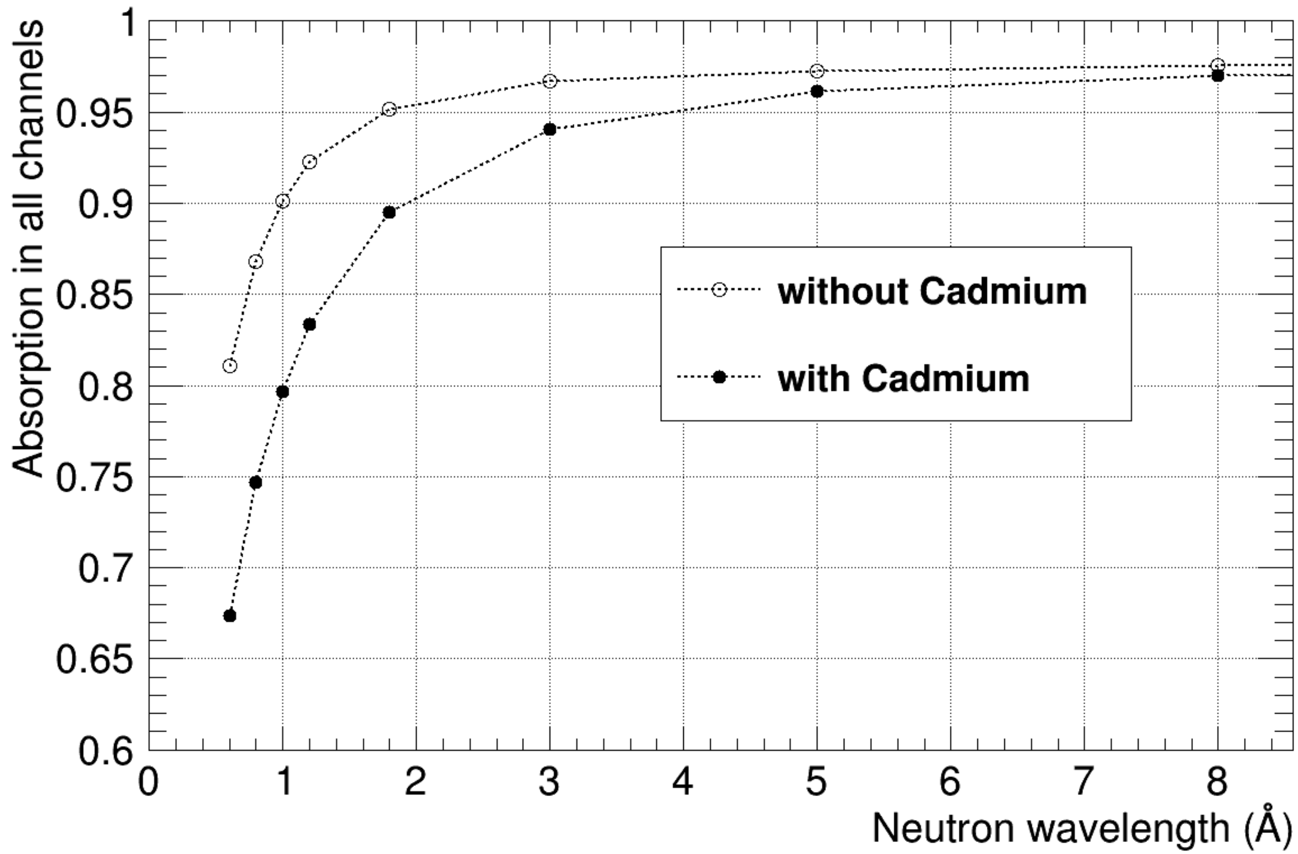
- scintillator matrix of dimension M (M – large enough to follow scattered neutrons)
- incoming neutrons (λ = 0.5 – 10Å) uniformly distributed within central pixel

To be calculated

- absorption probability
- spatial resolution

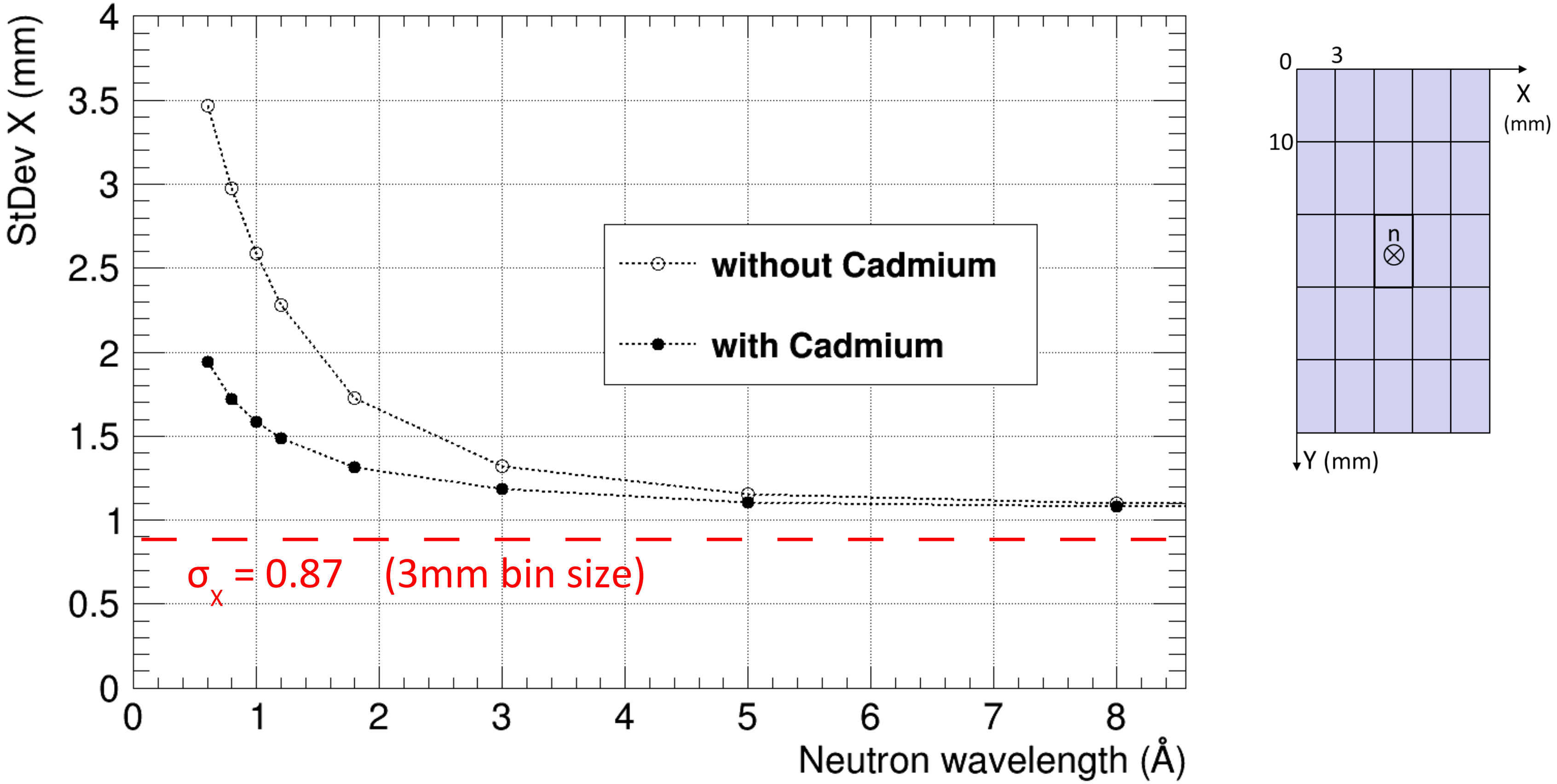
- **^{6}Li and hydrogen concentration in the materials of the sensitive elements**
  - **ZnS:^{6}LiF scintillator** – ND2:1 (Scintacor)
    - → ^{6}Li atoms $1.4 \cdot 10^{22}$ cm^{-3}
    - → hydrogen in organic binder $2.4 \cdot 10^{22}$ cm^{-3}
  - **WLS-fibers** Y11(400)M (Kuraray)
    - → hydrogen $4.8 \cdot 10^{22}$ cm^{-3}
  - **Optical glue** EJ500 (ELJEN)
    - → hydrogen $5.4 \cdot 10^{22}$ cm^{-3}

Annex: absorption

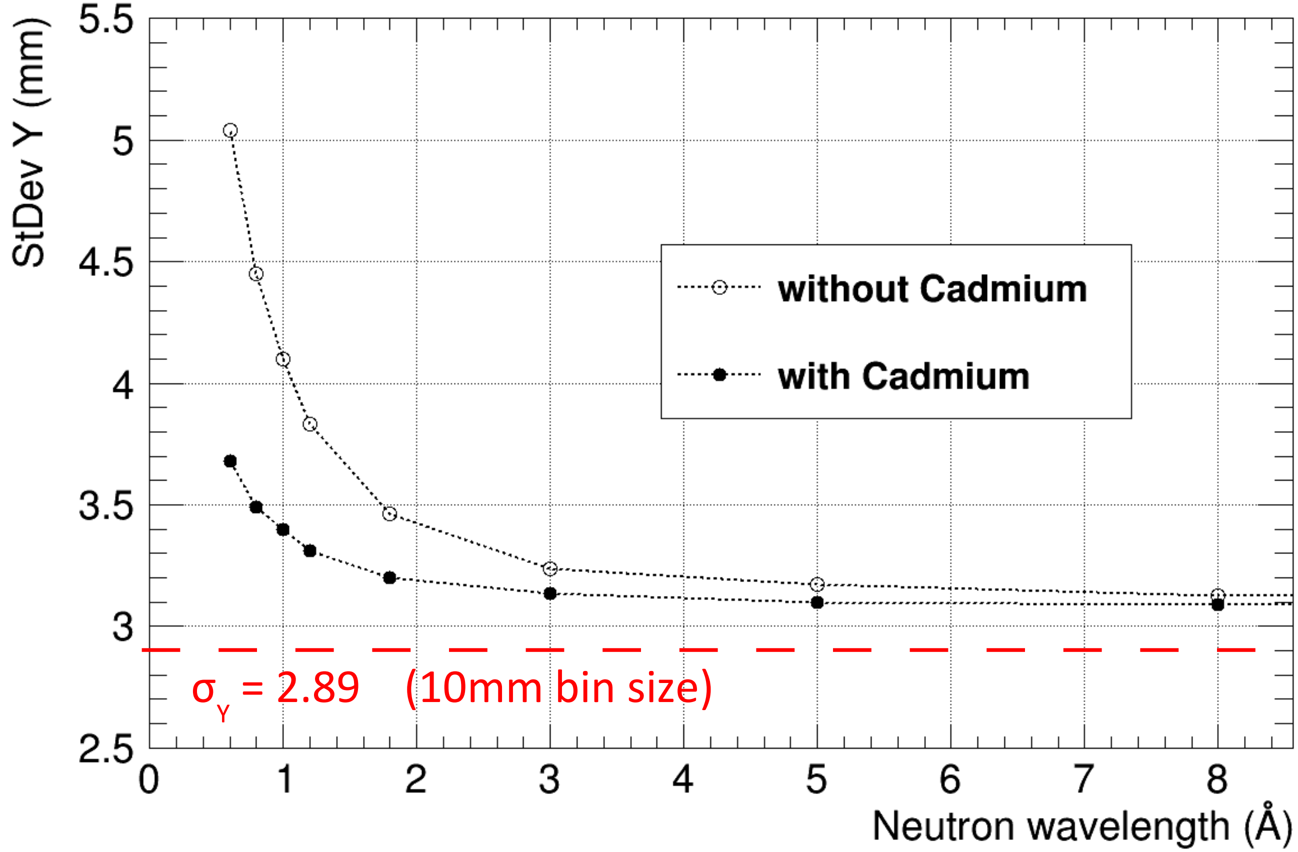


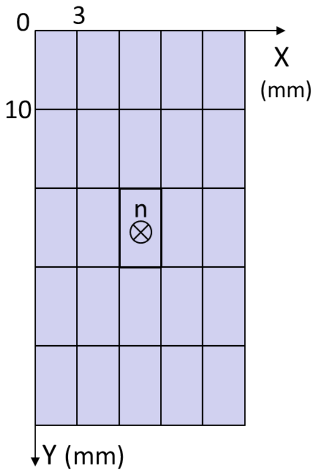
- high absorption probability in the matrix as a whole (≥ 80% at 1Å)
- due to scattering, some neutrons are absorbed in “wrong” channels
  --> degradation of the spatial resolution

Annex: spatial resolution along X

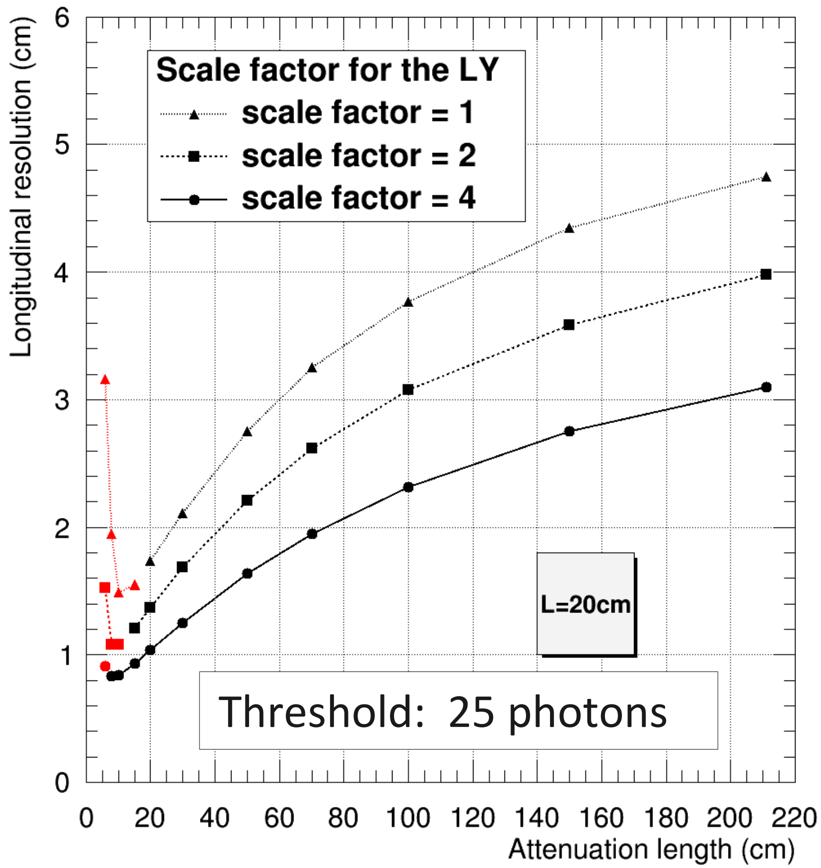


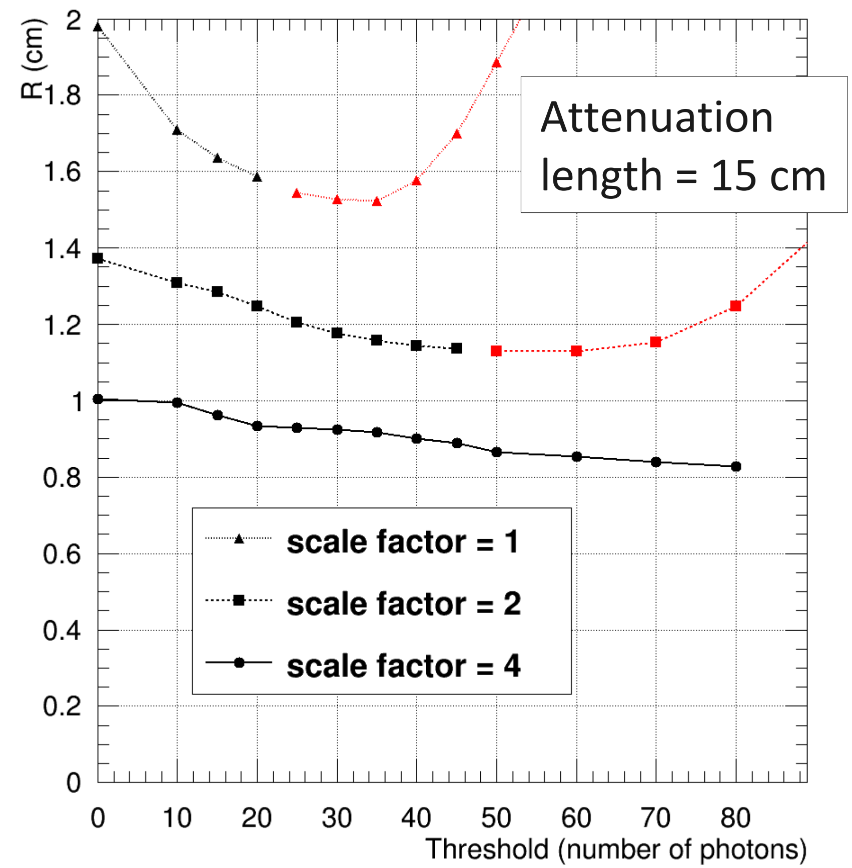
Annex: spatial resolution along Y





Annex: Model for a 20 cm long detection bar

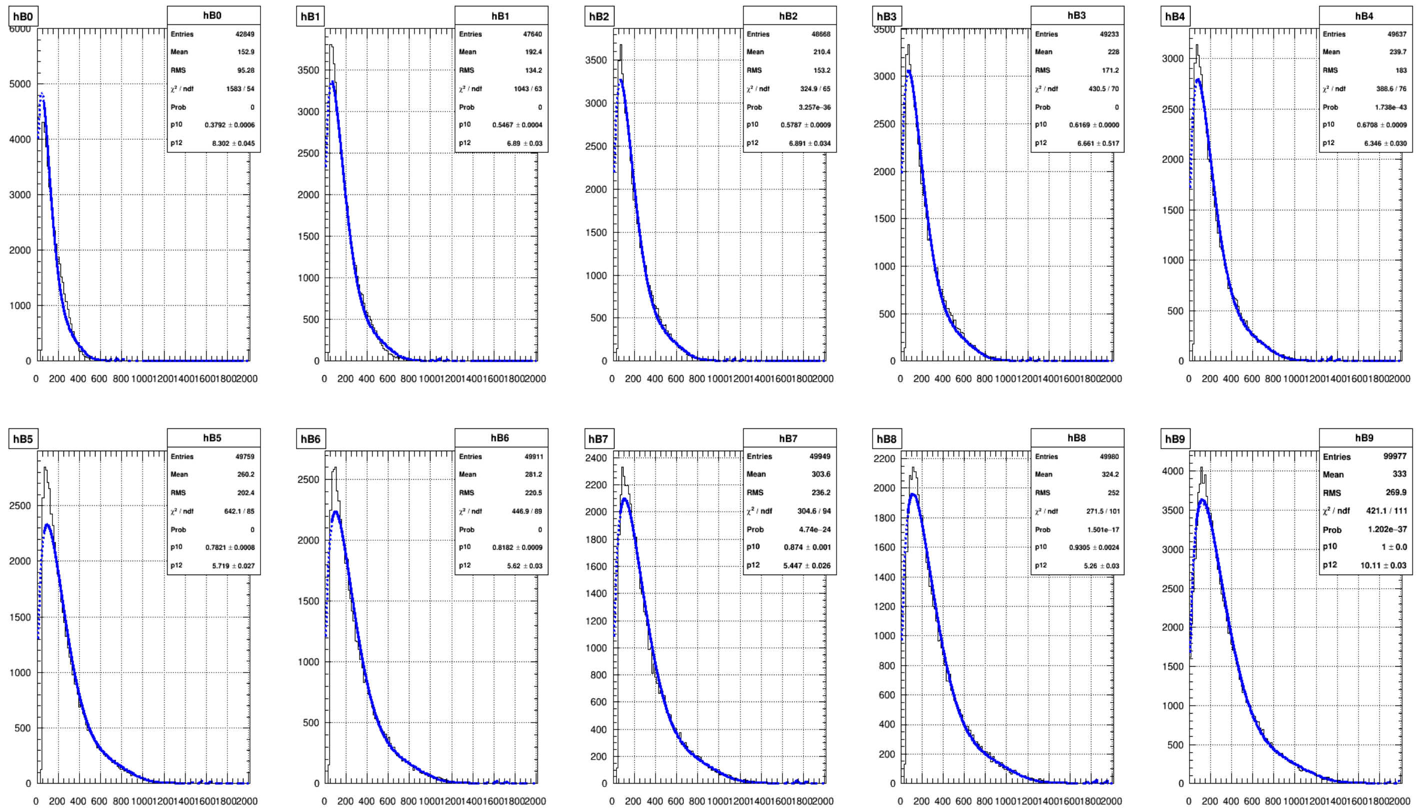




Remark: In this model, the trigger condition is (A_{left} > thr.) || (A_{right} > thr.)

Annex: Absolute trigger efficiency estimation

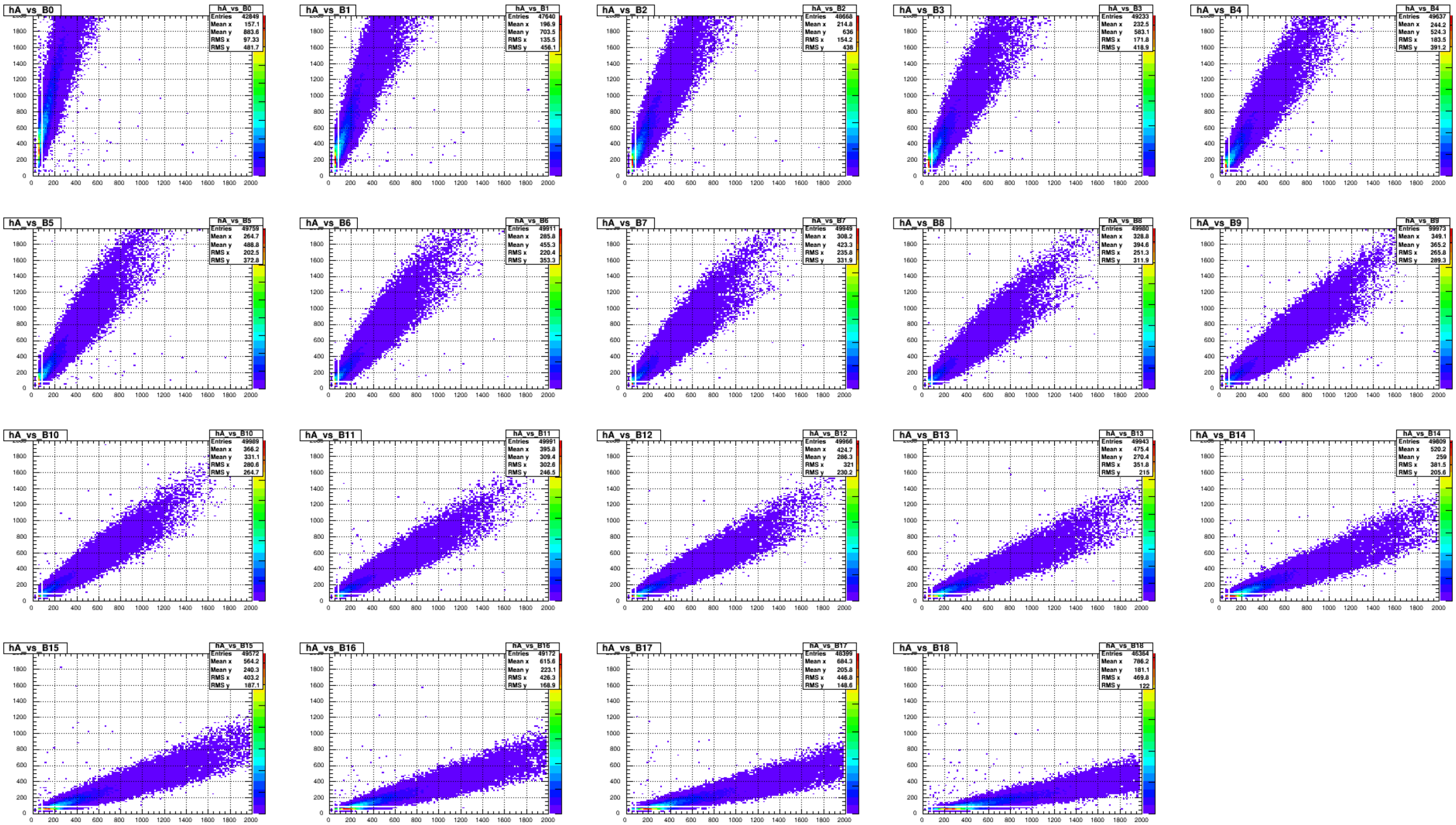
(amplitude unit is mV)



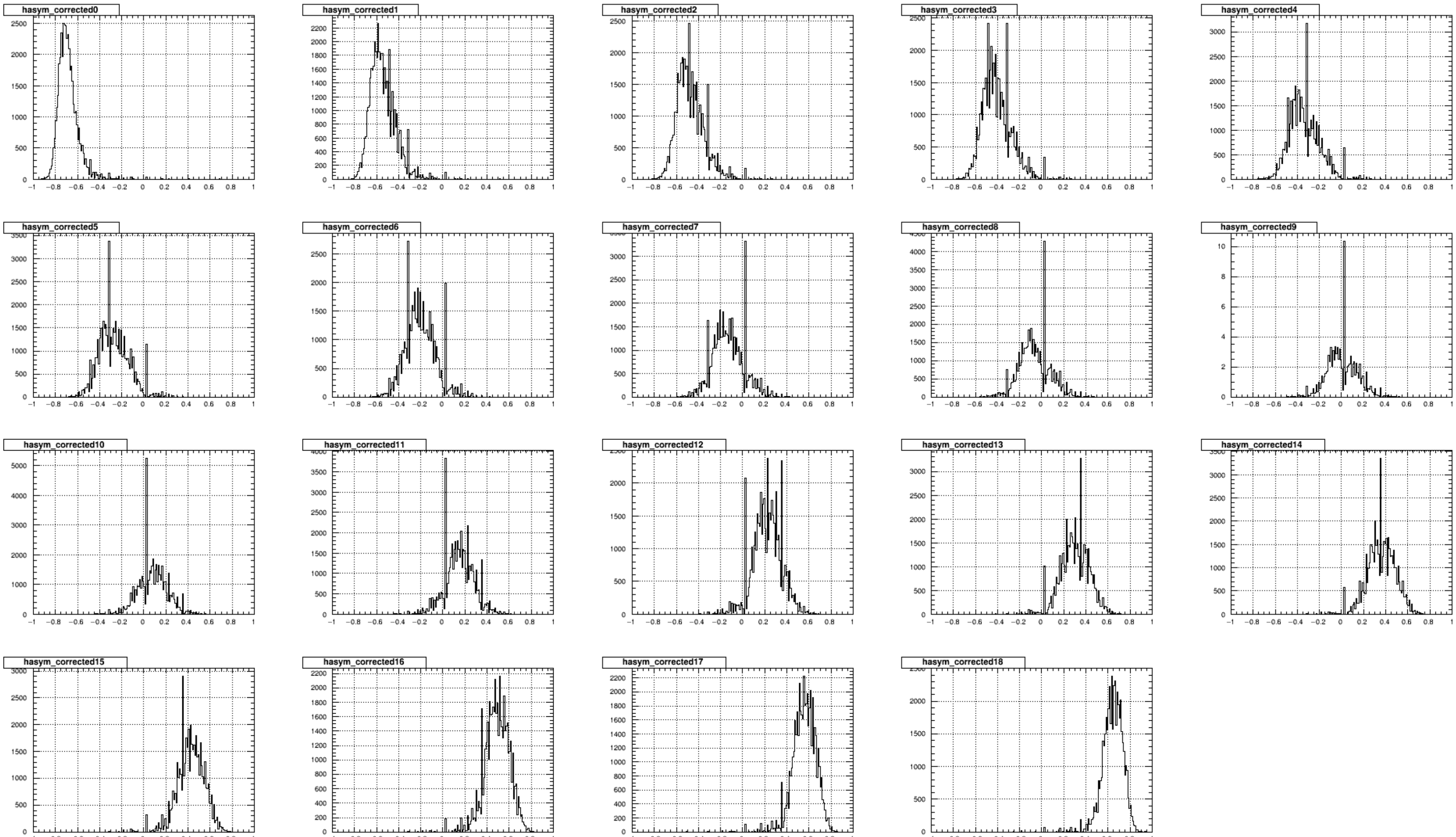
- At the central position, the first bins of the amplitude spectrum (before the discrimination threshold) are filled according to a linear extrapolation of the distribution.
- A polynomial function convoluted with a poisson distribution is fitted on this spectrum.
- All other spectra are fitted with the same function. Only an horizontal scale factor and a normalisation factor for the area are kept free.
- The trigger efficiency is calculated as :

$$trig.\ eff. = \frac{\int_{threshold}^{2000} f_{extrapolation}(A)\, dA}{\int_{0}^{2000} f_{extrapolation}(A)\, dA}$$

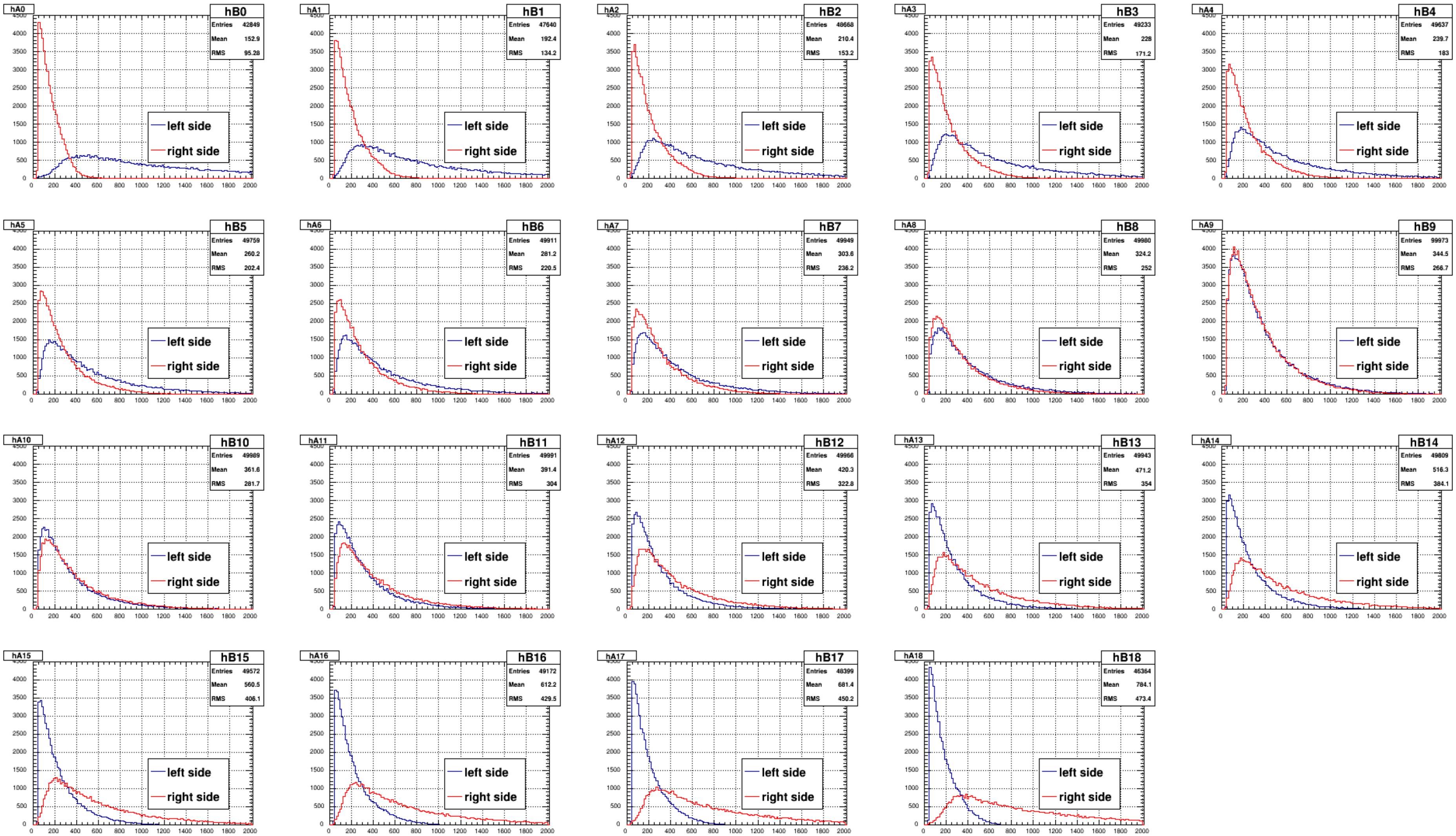
Annex: 8-fiber prototype, correlection plot



Annex: 8-fiber prototype, asymmetry spectra



Annex: 8-fiber prototype, amplitude spectra
(readout gain ~ 5mV/photon)



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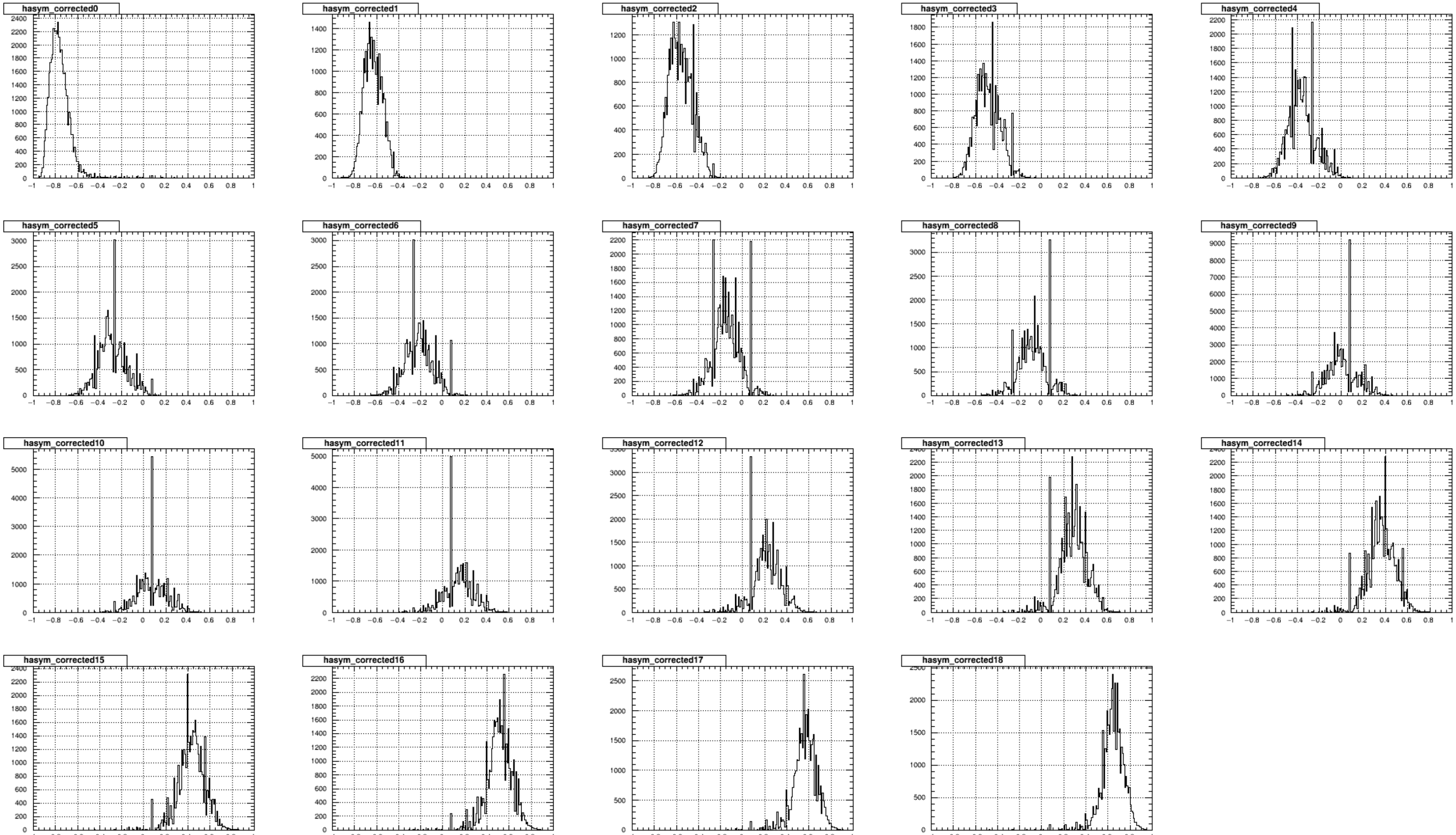
Annex: 3-fiber prototype, asymmetry spectra
(clean data)



Annex: 3-fiber prototype, amplitude spectra

(readout gain ~ 5mV/photon, clean data)