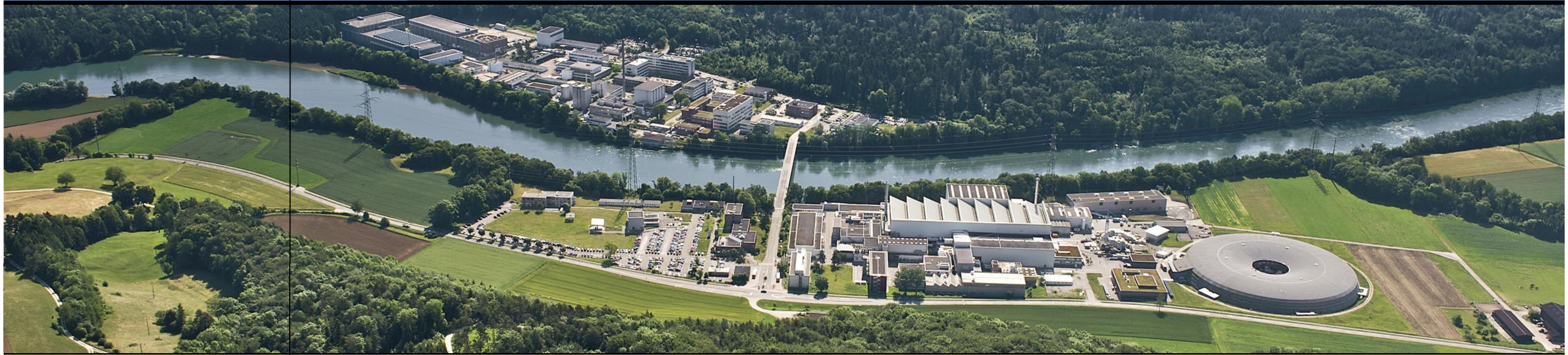


Wir schaffen Wissen – heute für morgen

Alexey Stoykov, Jean-Baptiste Mosset, Malte Hildebrandt

1. Use of Silicon Photomultipliers in ZnS:^{6}LiF scintillation neutron detectors

1. Options for the HEIMDAL NPD detector

ZnS:^{6}LiF scintillator

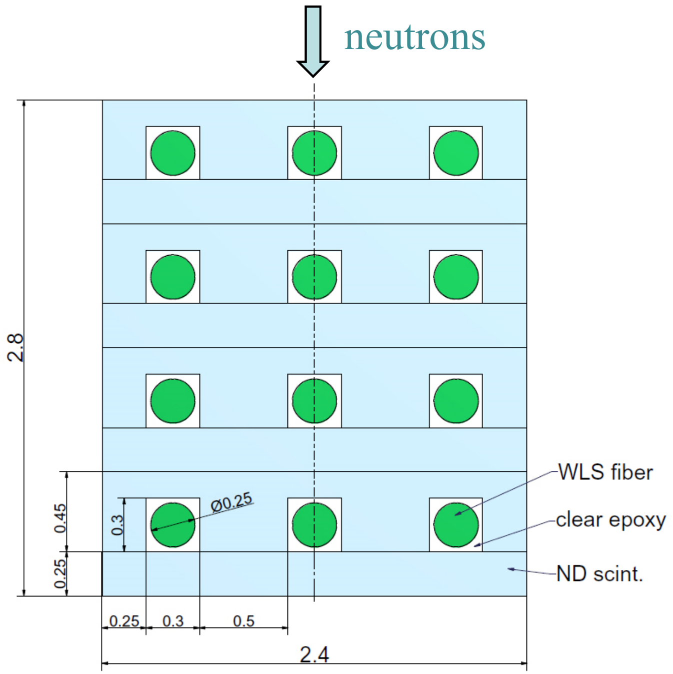
- high light yield (160’000 photons/neutron)
- non-transparent
  - light collection is poor and non-uniform
  - the number of detected photons is small, its distribution is broad
- long emission time (25% photons in 1 µs … 60% in 10 µs)
  - to avoid multiple triggers an artificial dead time is necessary
    - short dead times (down to 1 µs) are possible at the expense of rejecting weak signals → reduced trigger efficiency

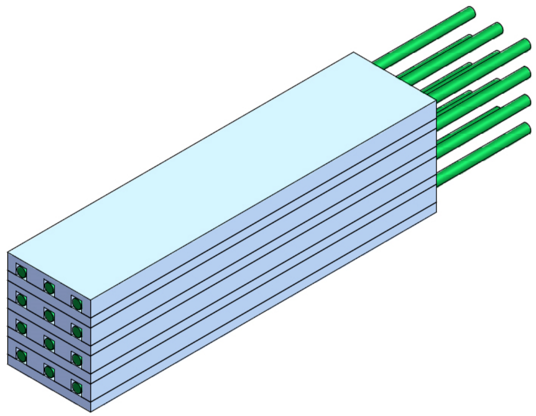
SiPM

- single-photon counting capability
- high photon detection efficiency (PDE ~ 40%)
- compact, robust, non-expensive
- low operation voltage
- insensitive to magnetic fields
- high rate of dark counts (thermal generation)
  - ~ 100 kHz/mm^2 at RT, increases with T
  - increases with accumulated radiation damage
  - weak signals can not be extracted from the background of dark counts → sets additional limit on trigger efficiency

Light collection

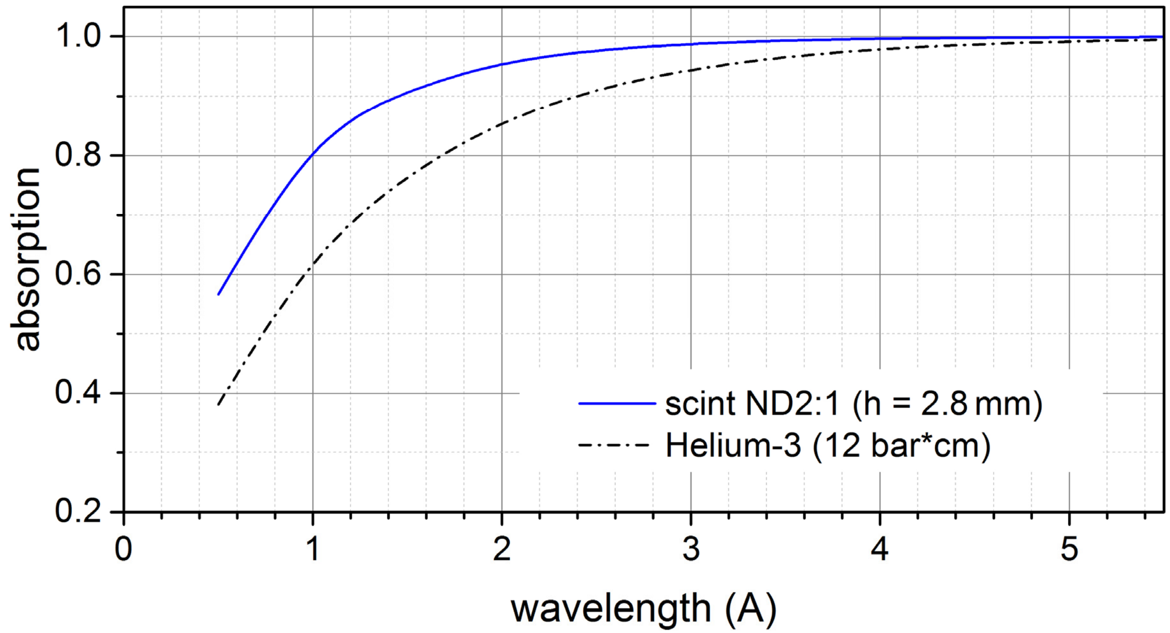
High light collection is essential – requires special pixel design !!!





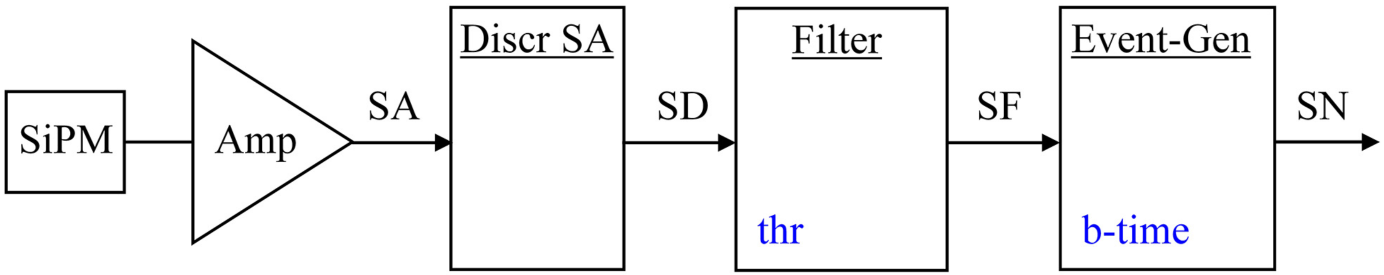
Pixel design for POLDI time-of-flight diffractometer:

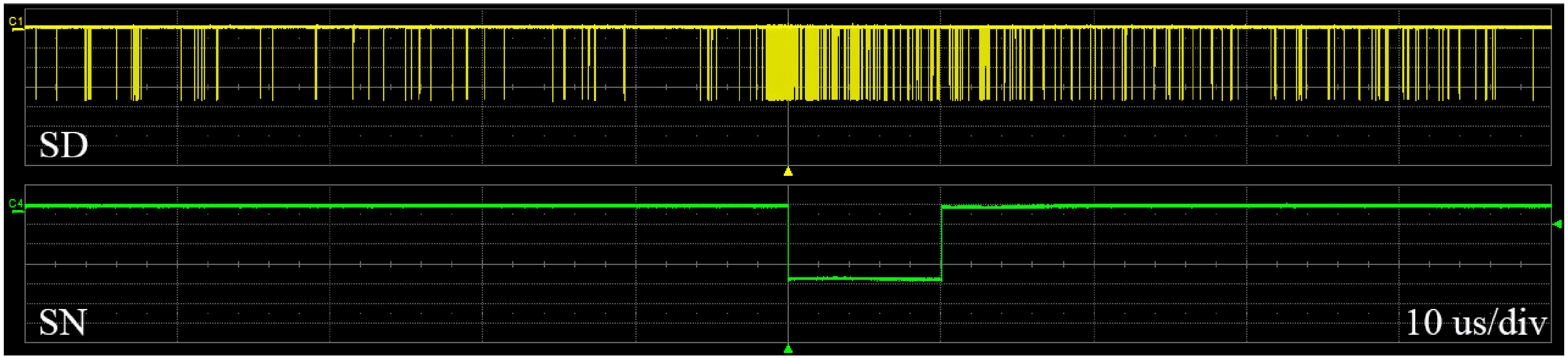
- optimized light collection with ø0.25mm WLS-fibers uniformly distributed over scintillation volume
- one pixel is readout by a 1mm^2 active area SiPM
- no problems in achieving high neutron absorption probability (here 80% at 1Å)



Signal processing

Neutron events are detected as an increase of the density of the single-cell SiPM signals





SA: amplified single-cell SiPM signals (detected photons, dark counts, afterpulses, cross-talk)

SD: standardized single-cell SiPM signals (detected photons, dark counts, afterpulses)

SF: neutron event + multicount events (number of detected photons above threshold – thr)

SN: neutron event (multicount events removed by setting an artificial dead-time – b-time)

Performance figures

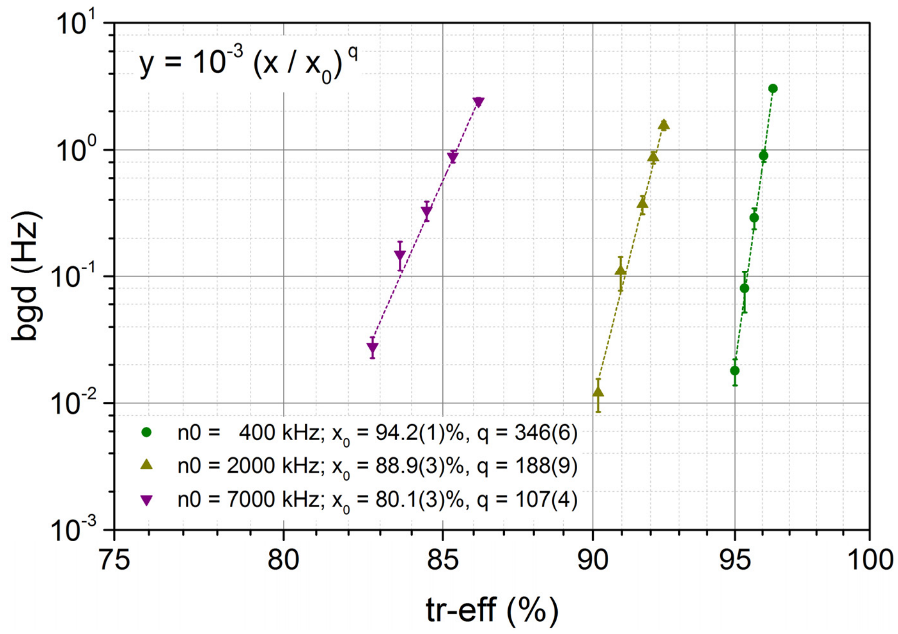
Neutron detection efficiency at 1Å (5Å), %	68 (85)	60 (75)
• absorption probability at 1Å (5Å), %	80 (100)	
• trigger Efficiency [(a)], %	85	75
Background count rate, Hz	$< 10^{-3}$	
Gamma-sensitivity (at 1.3 MeV)	$< 10^{-7}$	
Multi-count ratio	$< 10^{-3}$	
Dead time, μs	10	1
Sustainable neutron count rate (n-max), kHz [(b)]	20	200
Sustainable SiPM dark count rate (n_0-max), MHz [(c)]	4	4

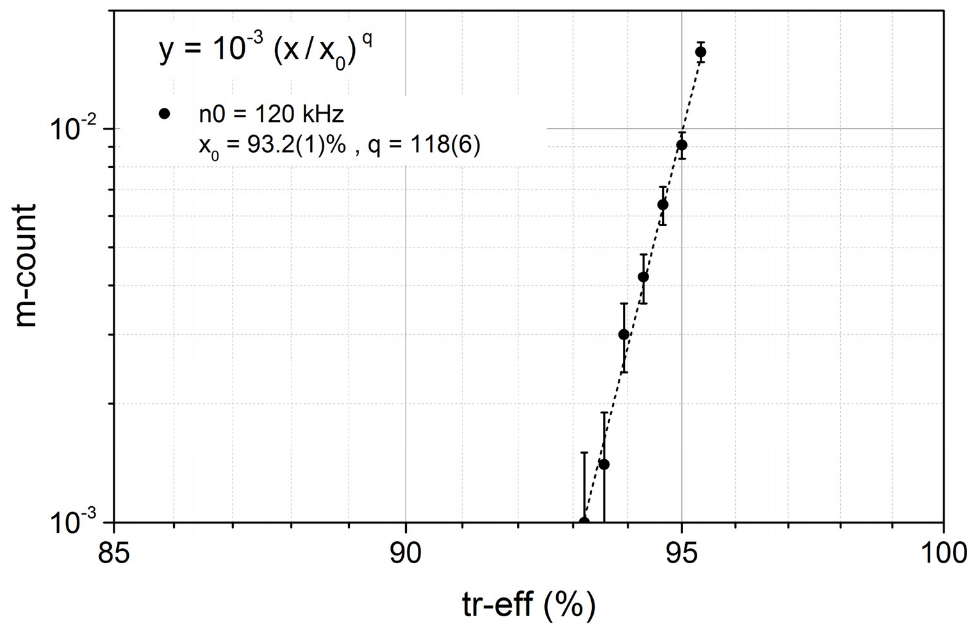
a) to fulfill BGM-conditions at chosen dead-time

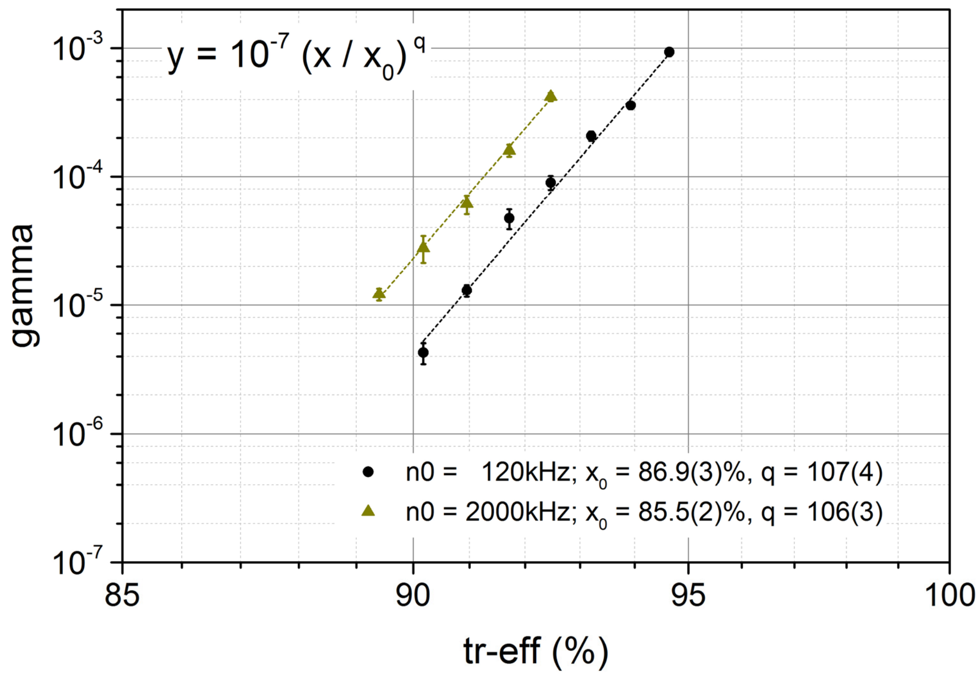
b) to ensure event loss ≤ 20%; verified up to n-max = 40 kHz (dead-time ≈ 5μs)

c) SiPM dark count rate up to which: E – constant, B – ok

BGM vs. Trigger Efficiency (b-time = 10µs)



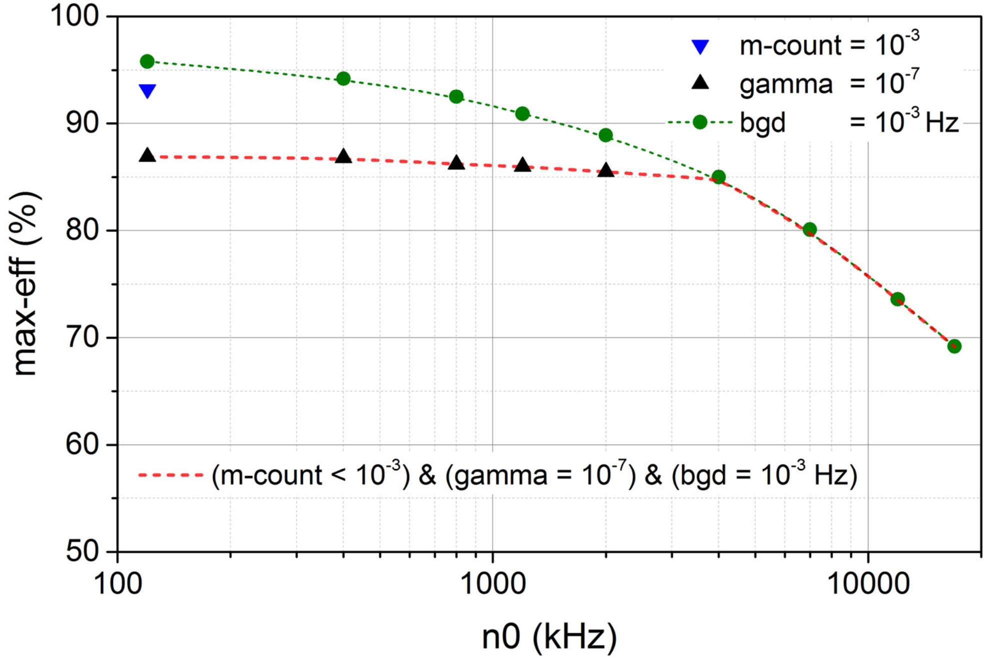




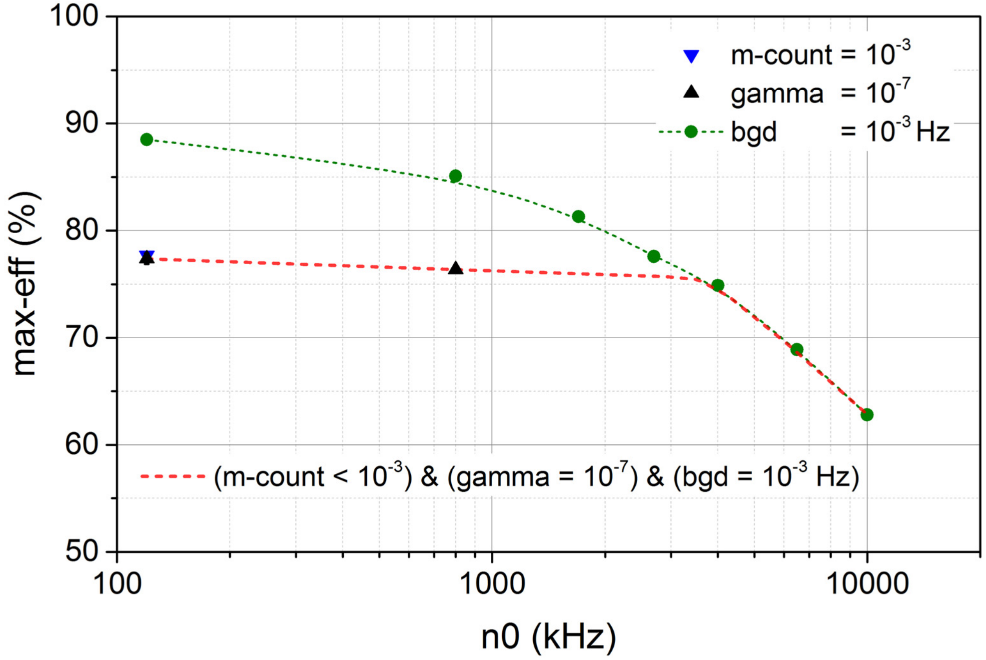
- strong dependence of **BGM**-parameters on **tr-eff** (high power index q)
- factor of **10** improvement by only **2%** reduction of tr-eff

BGM-limit on Trigger Efficiency (effect of **b-time**)

sh-time = 2µs, b-time = 10µs



sh-time = 0.25µs, b-time = 1µs



- For high-rate applications (neutron count rates up to 100 kHz) **sh-time** can be lowered to 0.25µs (**b-time** = 1µs). The required reduction of the trigger efficiency is about **10%**.

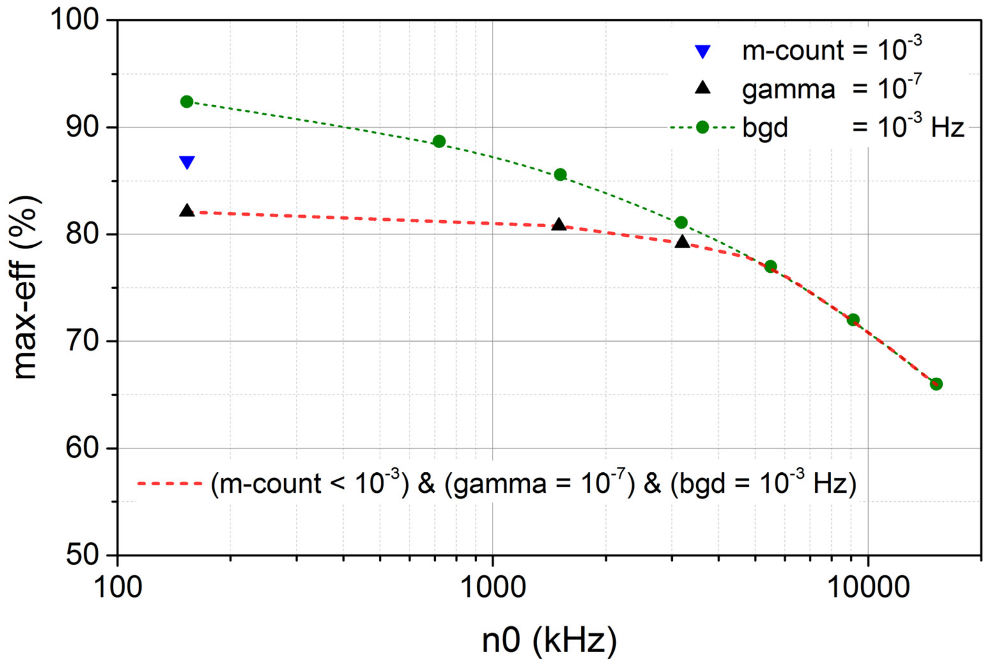
Sustainable dark count rate of the SiPM (**n_0-max**) –
dark count rate up to which: tr-eff = const, B-condition fulfilled

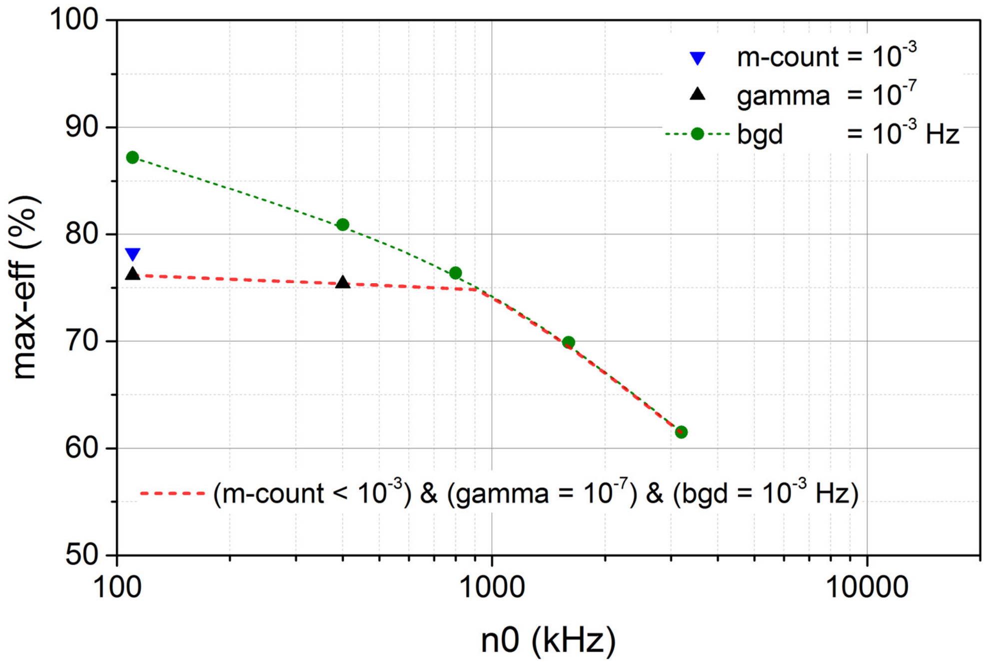
n_0-max = 4 MHz at b-time = 10µs (1µs), tr-eff = 85% (75%)

BGM-limit on Trigger Efficiency (effect of N_{phe})

N_{phe} – number of detected photons (photoelectrons) in 10µs

N_{phe} = 160 … (sh-time = 1µs, b-time = 5µs) … **N_{phe} = 80**





n_0-max = 6.5 MHz … (at tr-eff = 75%) … n_0-max = 0.9 MHz

Reduction of N_{phe} by a factor of 2 leads to only 5% reduction of the maximum possible trigger efficiency, but to a factor of 7 reduction of **n_0-max** and, accordingly, the SiPM **lifetime**.

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SiPM lifetime

Detector operation time during which the dark count rate of the SiPM (n_0), increasing as a result of radiation damage, reaches its sustainable value **n_0-max**.

SiPM lifetime depends on:
- operation temperature (T)
- blocking time (b-time)
- trigger efficiency (tr-eff)
- B-condition

Example of POLDI (1.3 x 1.3 mm^2 active area SiPM) – preliminary estimate:
- for non-irradiated device: n_0 = 100 kHz at 25 ^{o}C (1 MHz at 50 ^{o}C)
- n_0 increase with irradiation: ≤ 170 kHz/year at 25 ^{o}C (≤ 850 kHz/year at 50 ^{o}C)

T, ^{o}C	b-time, µs	tr-eff, %	B, Hz		n_0-max, MHz	SiPM lifetime, years
25	10 (1)	85 (75)	10^{-3}		4	≥ 23
50	…	…	…		…	≥ 3.5
25	10 (1)	80 (70)	10^{-3}		7 (6)	≥ 40
50	…	…	…		…	≥ 6

- keeping the detector at temperatures below 30 ^{o}C is advisable
- lowering tr-eff by 5% increases the lifetime 1.7 times

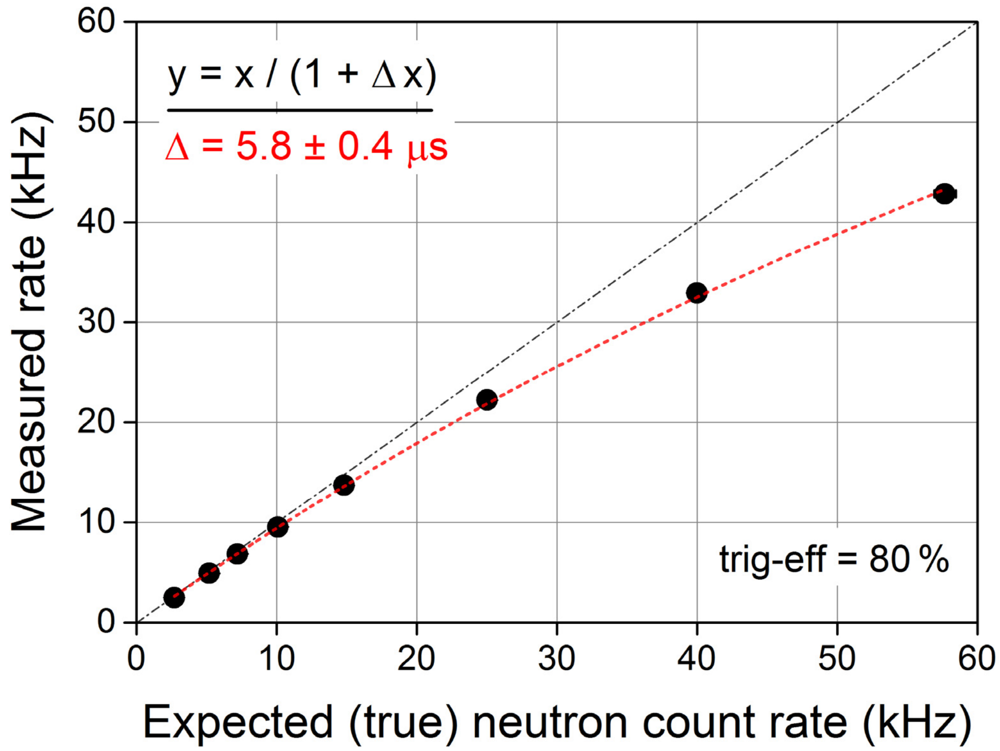
Sustainable neutron count rate (n-max)

Maximum true neutron count rate up to which:

- the detector performance is stable
- measured vs. true count rate follows the appropriate dead-time model
- dead-time related count losses ≤ 20%

➢ n-max = **40 kHz** at b-time = 4 µs (to be verified down to b-time = 1 µs)

➢ offset between the set (4 µs) and the measured values (5.8 µs) of the dead time to be verified

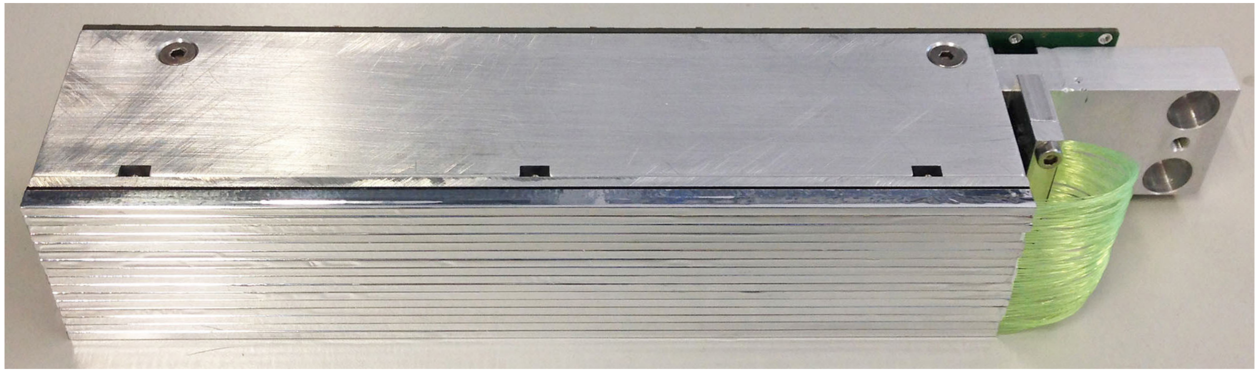


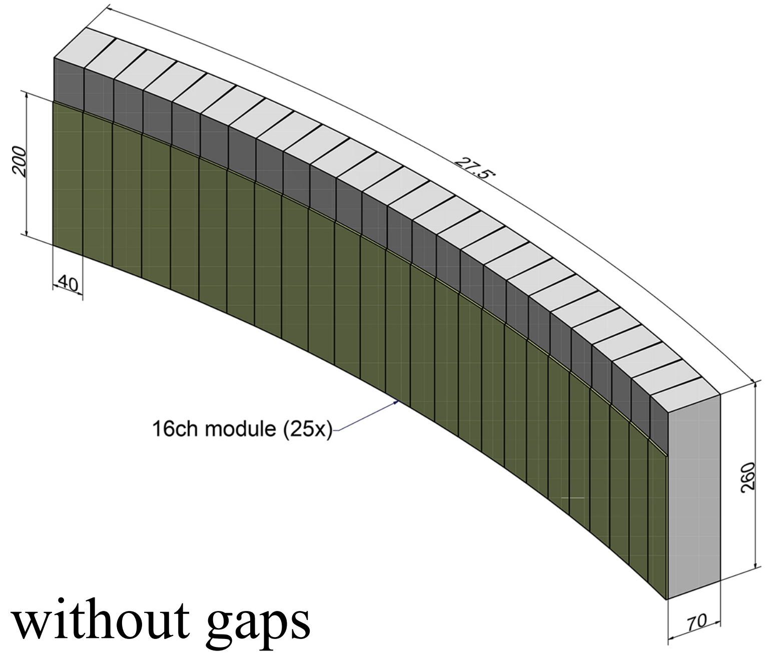
SiPM based ZnS:^{6}LiF detector: some facts to remember

- high light collection is essential – requires special pixel design
- high neutron detection efficiency (comparable with Helium-3 detectors)
- high count rate capability (expected up to 100 kHz)
- low gamma-sensitivity ($\leq 10^{-7}$)
- SiPM dark count rate $\mathbf{n_0}$ (100 kHz/mm^2 at RT; increases with accumulated radiation damage) should not exceed its sustainable value $\mathbf{n_0}$**-max** (typically 4 – 10 MHz). Small area SiPMs (1mm^2) should be preferably used.

1D detector

16ch module for the POLDI time-of-flight diffractometer





- 1D spatial resolution, arrangement in large panels without gaps
- channel pitch = 2.5mm, length = 200mm, absorption depth = 2.8mm
- channels produced and assembled separately (exchangeable)
- signals from each channel are converted and processed independently (maximum possible count rate capability)
- 1mm^2 active area SiPMs are used (longest possible ``life-time`` in radiation environment; > 10 years at POLDI)

2D detector – HEIMDAL NPD

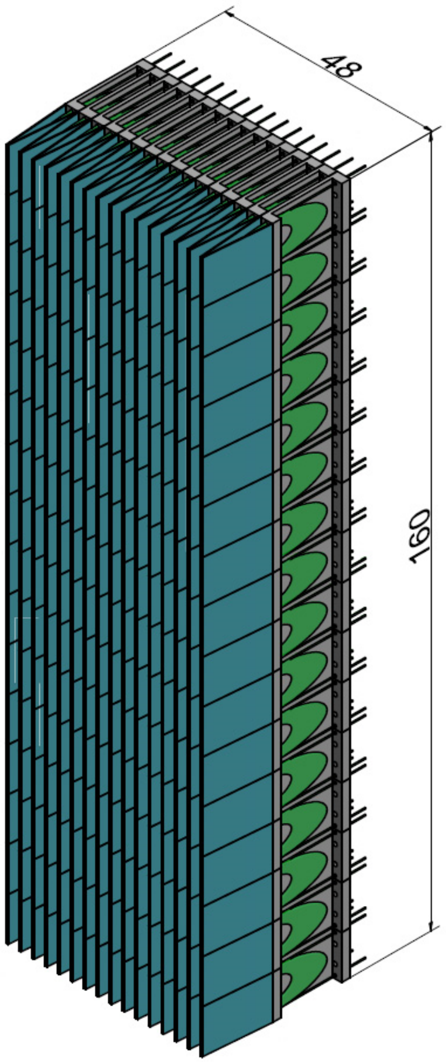
Parameter	request	SiPMs, no coding	SiPMs, XY(16x16)
Total area, m^2	4	• high cost of SiPMs • highly-integrated dedicated electronics • count-rate conditions reliably fulfilled	• low cost of SiPMs • count-rate capability to be confirmed (additional limit on XY resolving time)
Radius / Height, m	1.5 / 1.0		
Design	2D, gapless		
Pixel size, mm	3 x 10		
Total number of pixels	~ 140’000		
Wavelength range, Å	1 – 10		
Max. overall count rate, kHz/cm^2	10	150 [a]	10 [a,b]
Max. count rate on spot, kHz/cm^2	100 ?	150 [a]	100 [c]
Efficiency at 1Å / 5Å / 10Å, %	50 / 75 / 100	60 / 75 / 75	60 / 75 / 75
Max. time resolution (σ), µs	100 (40) ?	10 [d]	10 [d]
Cost, kEuro	4’000 [e]	1’100 – 2’200 [f]	140 – 280 [f]

(a) requires **n-max** = 50kHz per readout channel (feasible)
(b) requires XY resolving time $\Delta_{X\text{-}Y}$ = 300ns (feasibility to be verified)
(c) requires **n-max** = 30kHz per readout channel (ok);
at $\Delta_{X\text{-}Y}$ = 300ns max. affordable spot size = 5x5 pixels (request ?)

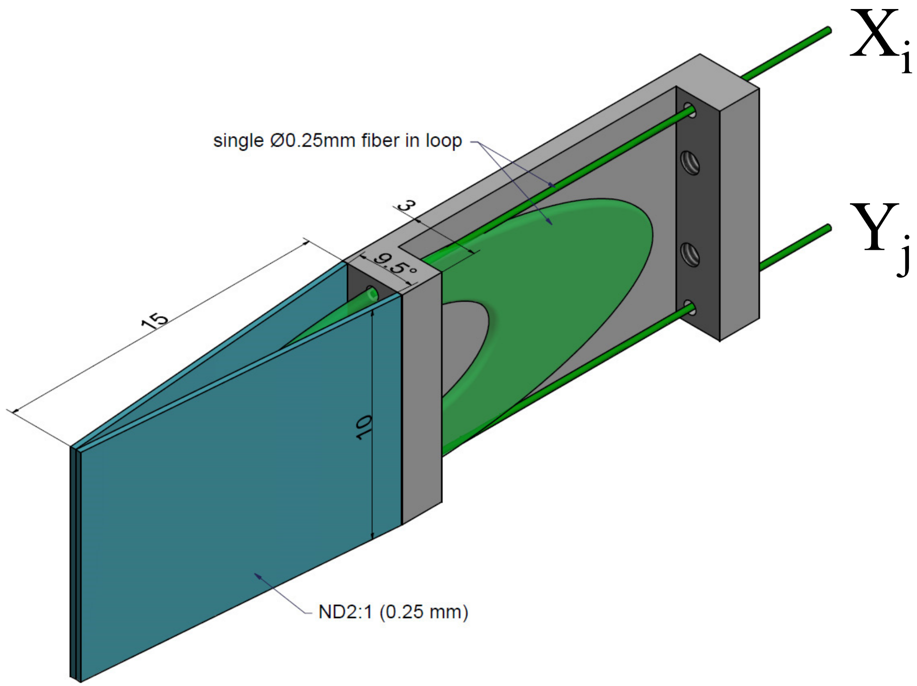
(d) uncertainty of neutron travel time (intrinsic time-res);
electronic time-res is much lower.
(e) full detector cost including mechanics
(f) only SiPMs (8 - 16 euro per 1x1mm^2 SiPM)

coding XY(16x16) – pixel design V1

detector head with 256 pixels
readout by 32 SiPMs (1x1 mm^2)



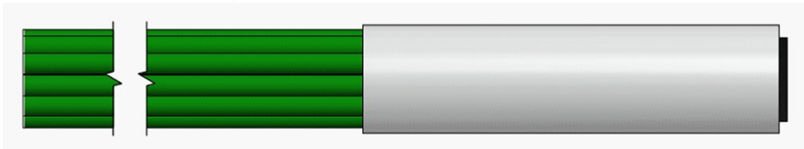
pixel **V1**
abs = 80% at 1Å
σ (μs) = 1.1 λ (Å)



light transport to photosensor

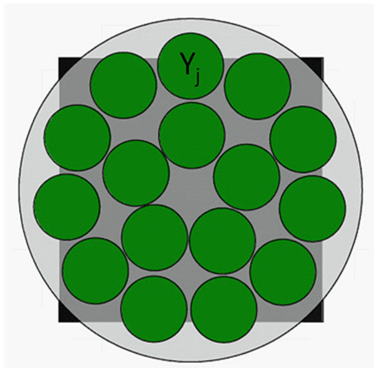
fiber bundle X_i
16 WLS-fibers ø0.25mm

expander X_i
clear fiber ø1.3mm

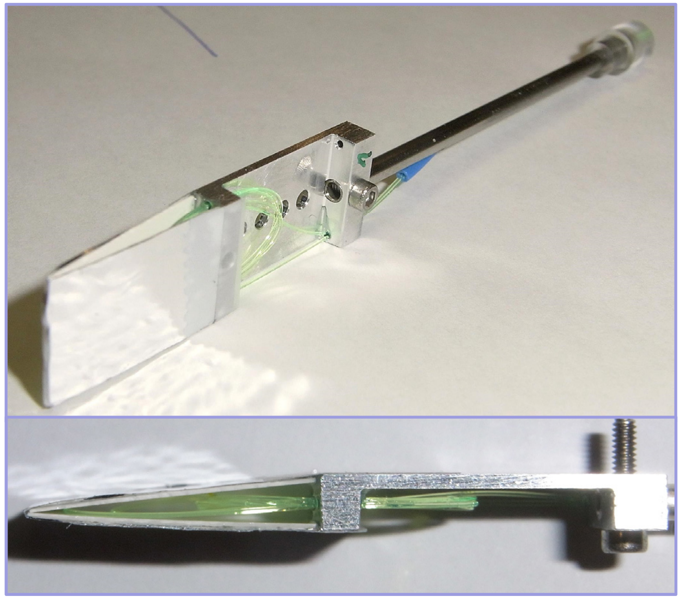


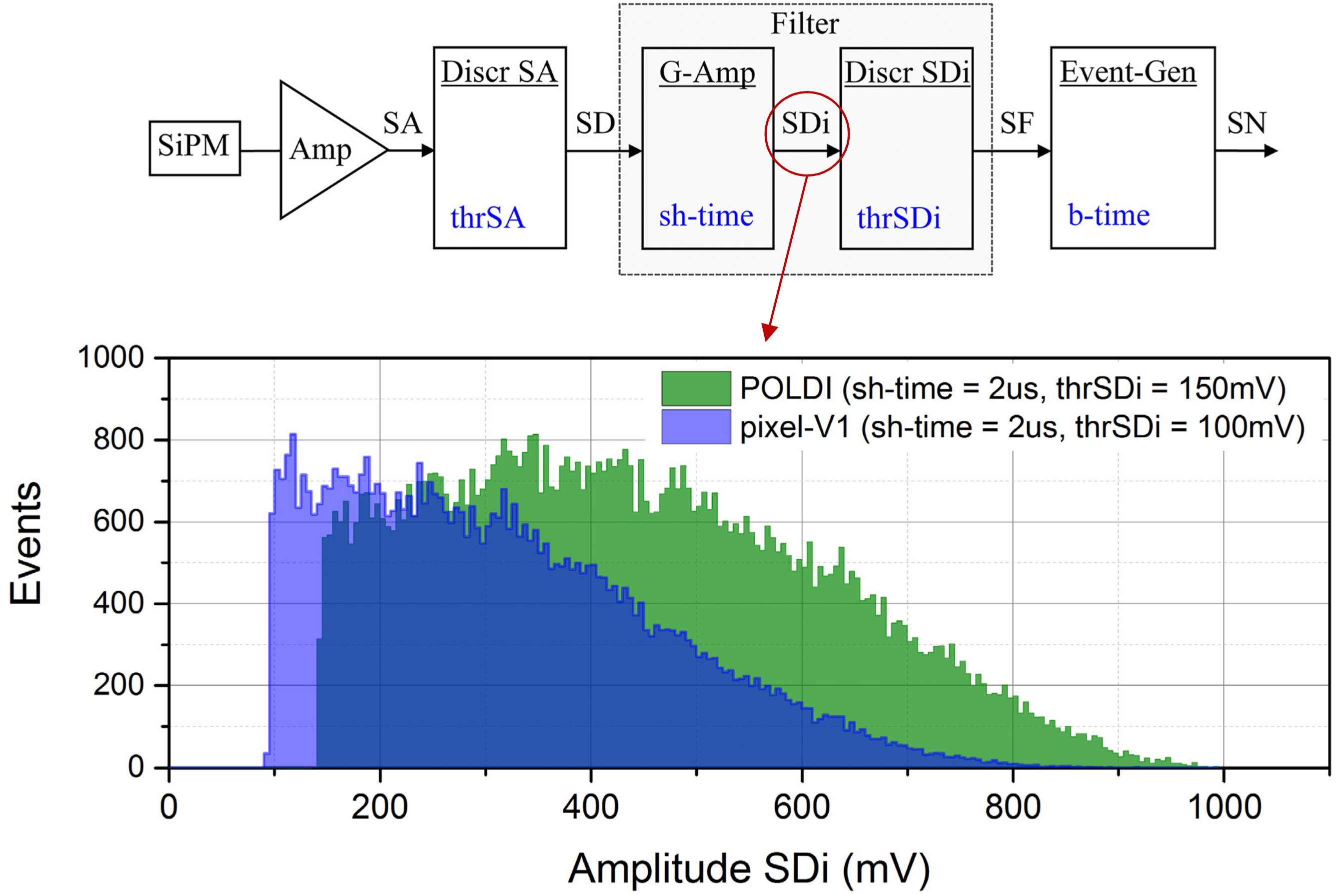
Light Collection (LC) = 0.75

sensor X_i
1x1mm SiPM



pixel V1 – fist tests

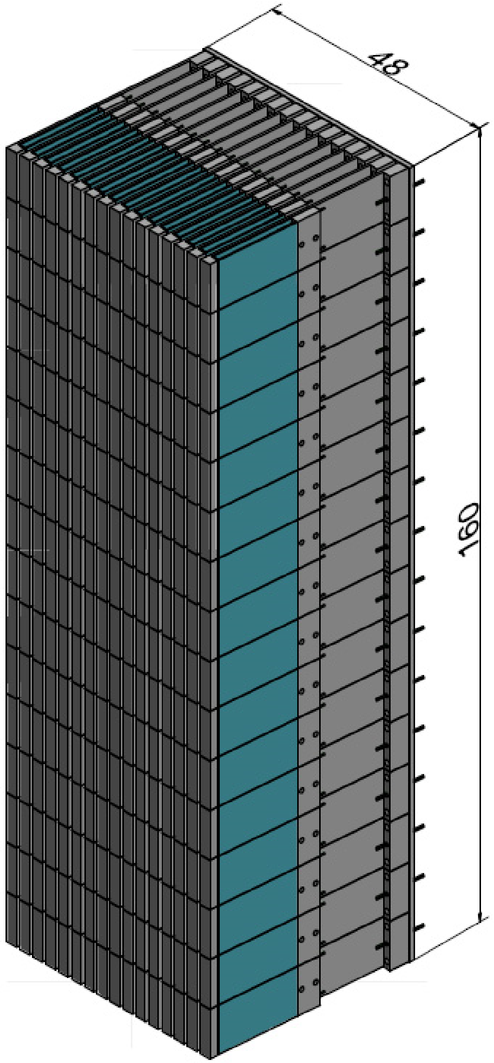




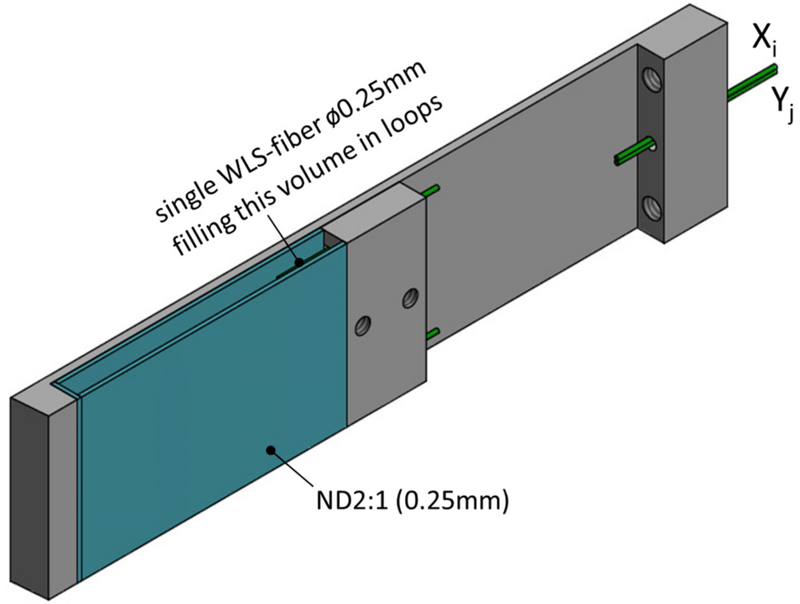
- for the first try – quite acceptable performance
- light collection needs to be improved by a factor of **≥ 2**
- potential for the optimization is present

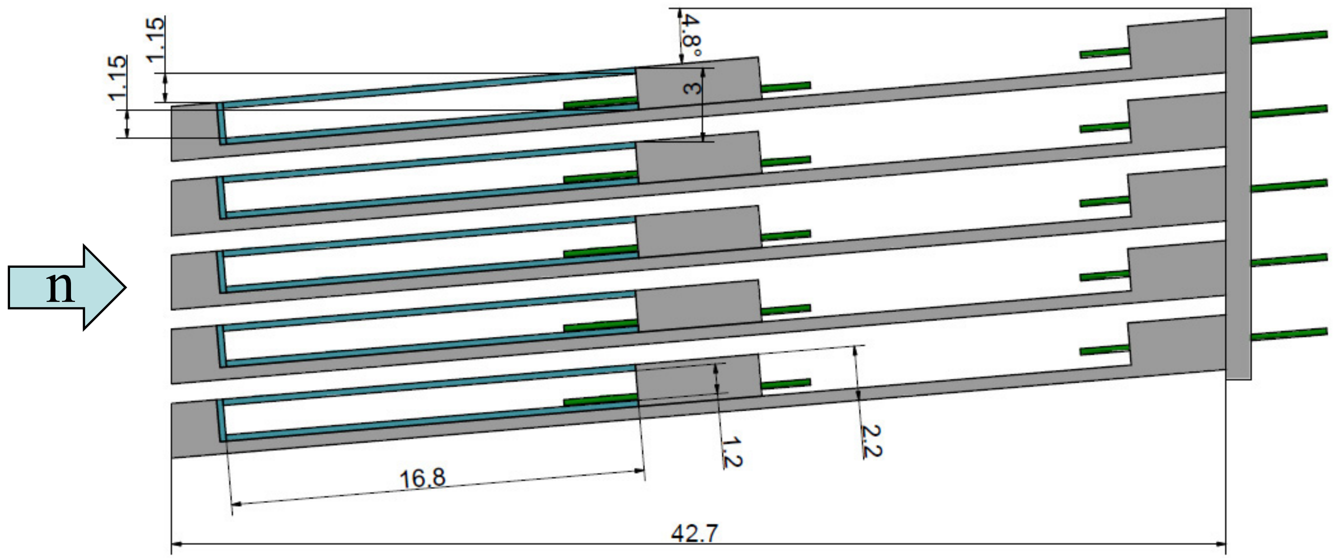
pixel design V2

detector head with 256 pixels
readout by 32 SiPMs (1x1 mm^2)



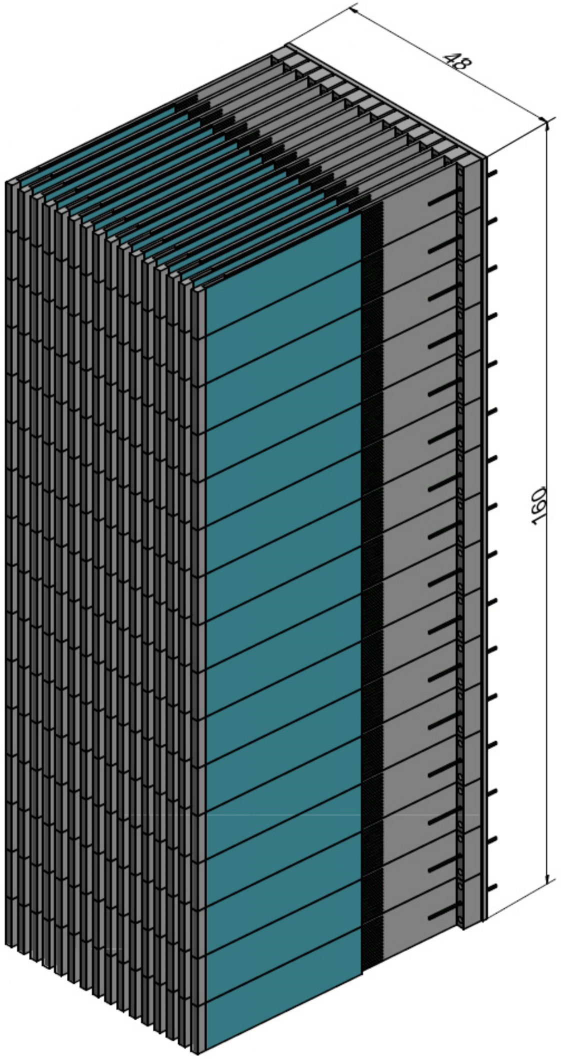
pixel **V2**
abs = 80% at 1Å σ (µs) = 1.1 λ (Å)



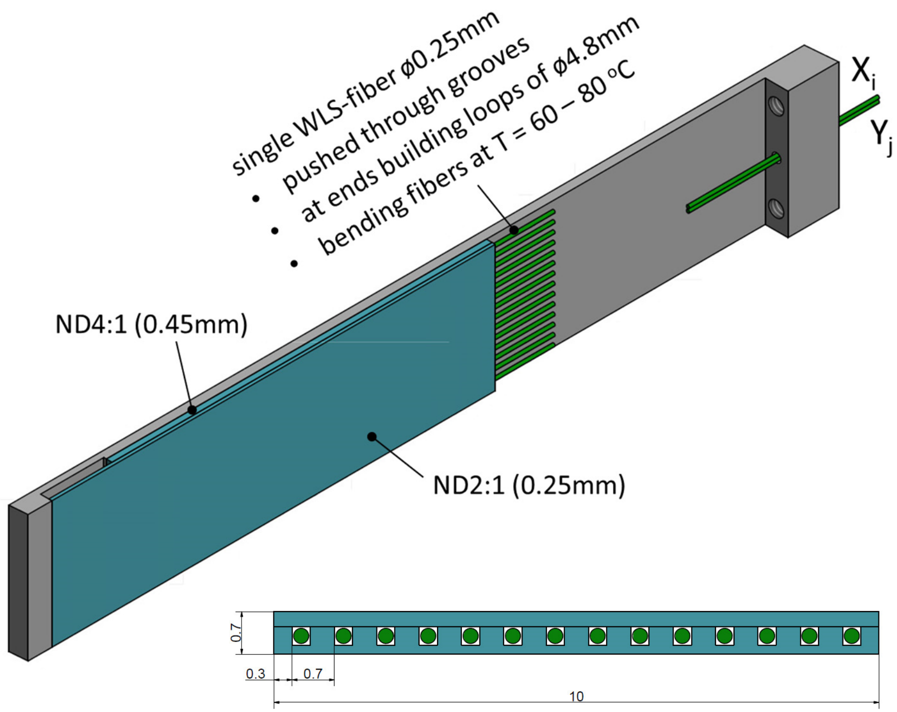


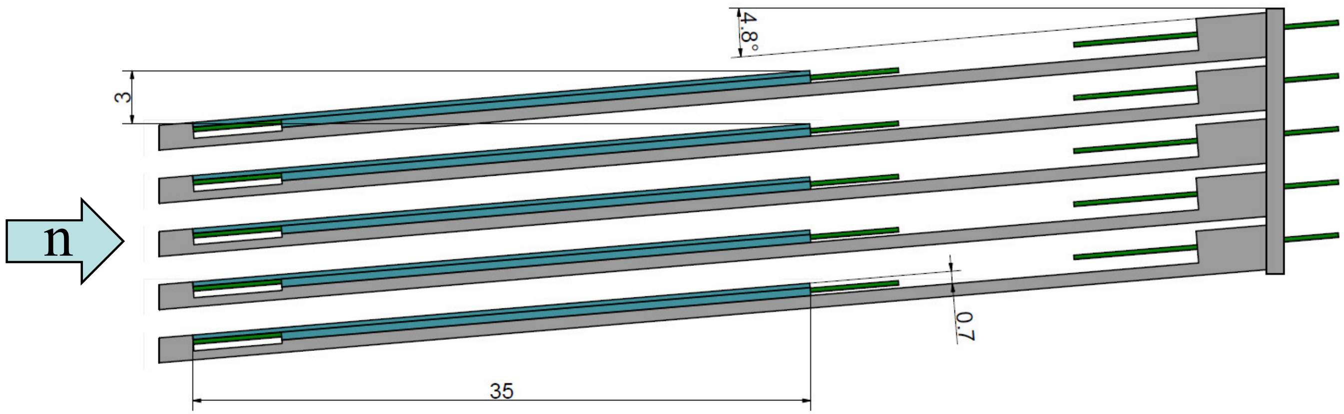
pixel design V3

detector head with 256 pixels
readout by 32 SiPMs (1x1 mm^2)



pixel **V3**
abs = 95% at 1Å σ (µs) = 2.5 λ (Å)





2D gapless detectors (summary)

- 2D large area detectors with gapless design and pixel dimensions down to 2.5 x 5mm seem to be feasible

- XY coding allows to keep the number of photosensors / readout electronic channels reasonably small
  - requirement on max. overall count rate sets additional limit on the XY-coincidence resolving time $\Delta_{X\text{-}Y}$

- both SiPMs and MaPMTs can be used as photosensors
  - with SiPMs one gets better performance at lower price, but in hard radiation environment MaPMTs should be preferred

Rate capability and the choice of XY-matrix dimension

Input parameters:

- max. overall count rate at "uniform" illumination – **3kHz / pixel** (HEIMDAL NPD)
- XY-matrix dimension – **M**
- max. event loss due to rejection of simultaneous "diagonal" events – **20%**

	M = 32	M = 16	M = 8
Total number of pixels	1024	256	64
Total number of "diagonal" pixels ($M^2 – 2M + 1$)	961	225	48
Max. rate of "diagonal" events, kHz	2880	675	144
Required X-Y coincidence resolving time ($\Delta_{X\text{-}Y}$), ns	70 [(a)]	300 [(b)]	1400
Use of ≈ 1mm² SiPMs possible (considering light collection)	no	yes	yes
Use of MaPMTs possible (considering form-factor, price)	yes	yes	no

(a) most probably not feasible (to be verified)

(b) feasibility to be verified

At spot illumination the total count rate in spot should not exceed the maximum count rate of "diagonal" events in the **M**atrix at uniform illumination **!!!**

Thermal neutron (1 – 100 meV)

backup slides

E [meV] = 81.82 / λ^2 [Å]

λ [Å] = 9.045 / $E^{0.5}$ [meV]

v [m/s] = 3956 / λ [Å]

E, meV	λ, Å	v, m/s	Δt(1cm), μs
81.8	**1.0**	3956	2.5
25.2	**1.8**	2197	4.5
2.3	**6.0**	659	15.7

Δt(1cm) – travel time in 1cm

Detection

$^3He + {}^1n \rightarrow {}^3H + {}^1p + 0.76$ MeV , $\sigma = 5333 \cdot \lambda / 1.8$ [barn]

$^6Li + {}^1n \rightarrow {}^3H + {}^4He + 4.79$ MeV, $\sigma = 940 \cdot \lambda / 1.8$ [barn]

Interaction probability

$\varepsilon = 1 - \exp(-N \cdot \sigma \cdot d)$

N [cm^{-3}] – density of absorbing atoms

σ [barn] – absorption cross-section

d – detector thickness

Density of absorbing atoms:

^{3}He: $2.7 \cdot 10^{19}$ $cm^{-3} \cdot atm^{-1}$

ND2:1 scint: $1.4 \cdot 10^{22}$ cm^{-3}

Attenuation length at 1Å

^{3}He (1 atm): **12 cm**

ND2:1 : **0.13 cm**

ZnS:^{6}LiF scintillator

Neutron detection screens from Scintacor (http://www.scintacor.com)

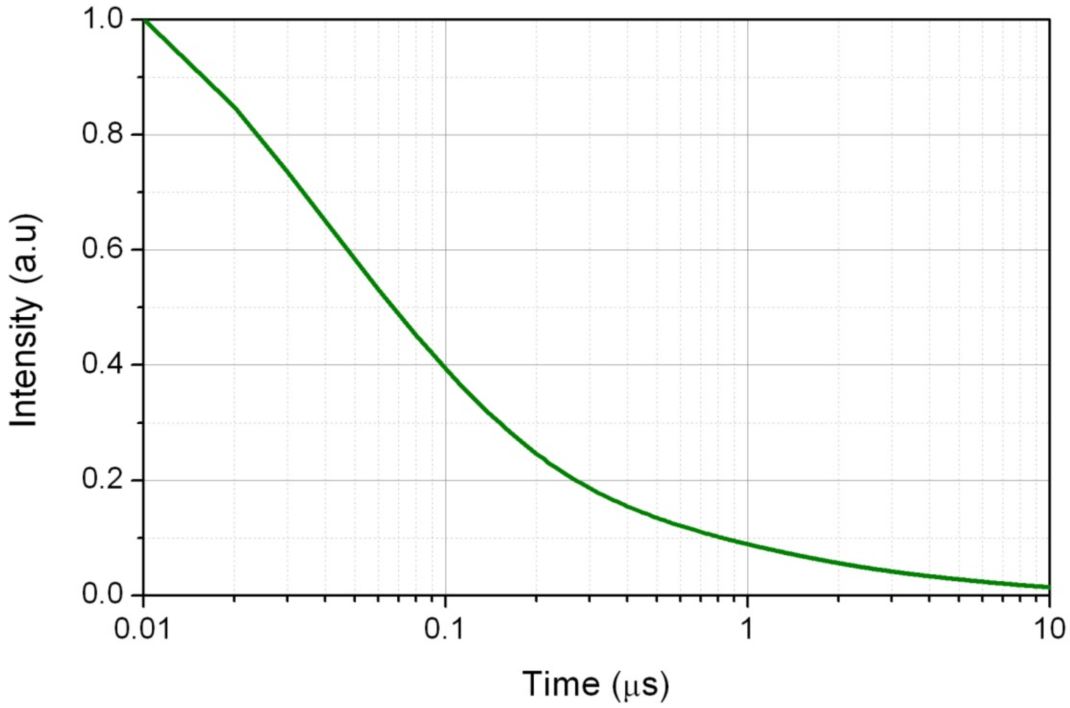
	ND4:1	ND2:1
Mass ratio ZnS:^{6}LiF	4:1	2:1
Density, g/cm^3	2.2	2.2
^{6}Li atoms, 10^{22} cm^{-3}	1.0	1.4
Thickness, mm	0.45, 0.25	
Emission max., nm	450	
Photons per neutron	160000	
Transparency	opaque	

- bright (+)
- non-transparent (-)
- usable thickness ≤ 0.5mm (-)
- scintillation process slow (-)

ND scintillator luminescence in response to neutrons

(from E.S.Kuzmin et.al., Journal of Neutron Research 10 (2002) 31)

Ampl	191	230	88	50	25	6	1.2
τ, μs	0.022	0.074	0.208	0.88	4.3	18.1	87.7



Time interval, μs	0 – 1	0 – 10
Emitted photons	25%	60%