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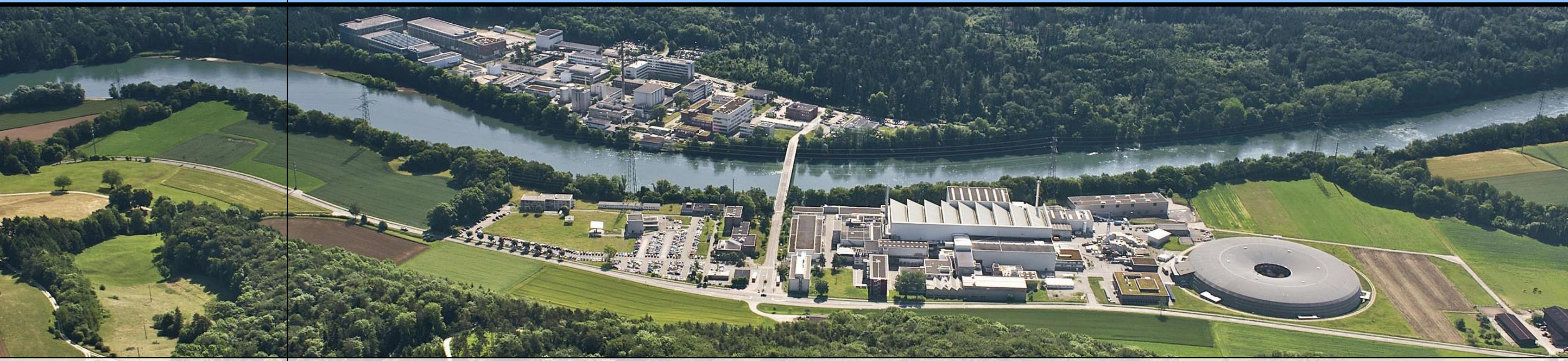

Wir schaffen Wissen – heute für morgen

A.Stoykov, J.-B.Mosset, U.Greuter, M.Hildebrandt, N.Schlumpf

Use of SiPMs in ZnS:^{6}LiF scintillation neutron detectors

ZnS:^{6}LiF scintillation detectors of thermal neutrons

- widely used in the neutron scattering experimental technique
- currently the only real alternative to the 3He gas detectors

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- 1D or 2D spatial resolution
- number of detection channels: $10^3 – 10^4$
- covered area: 1 – 10 m^2

Thermal neutrons: $E = 1 – 100$ meV ($\lambda = 1 – 6$ Å)

Detection:

1. conversion into charged particles (triton + alpha) through the nuclear absorption reaction on the ^{6}Li isotope (neutron converter):

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

2. detection of the products in the ZnS(Ag) scintillator

ZnS:^{6}LiF scintillator

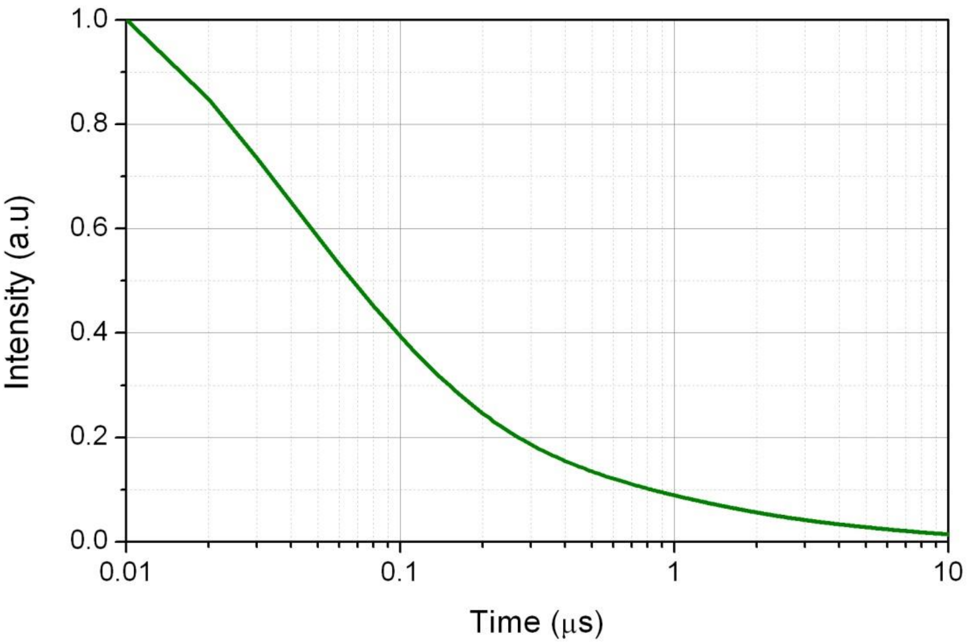
Neutron detection screens from
Applied Scintillation Technologies
http://www.appscintech.com

	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	1.5
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%

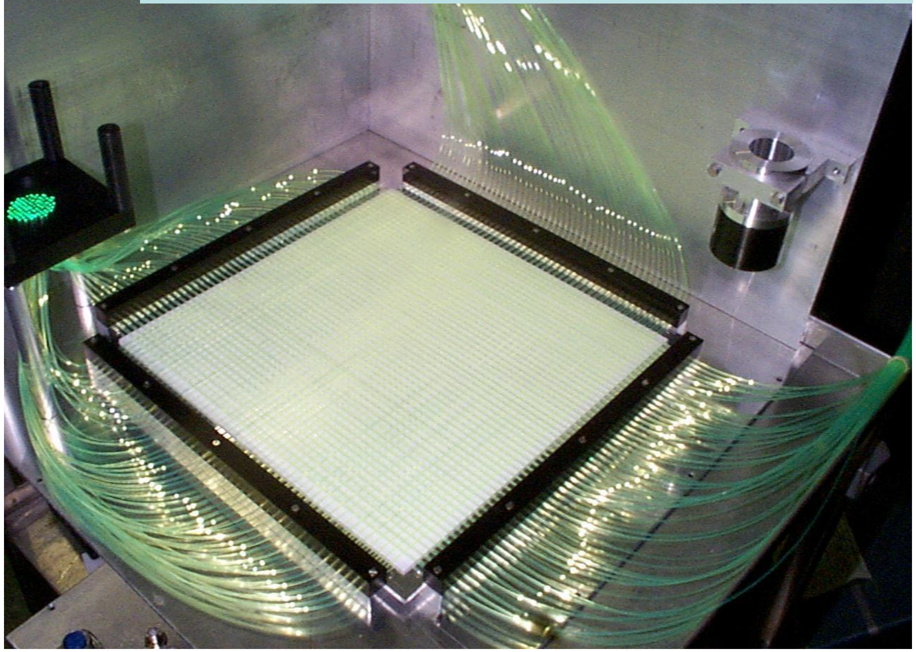
Detector design 1 (clear fibers + PMTs)

- V-shape (or Venetian blind) arrangement of the scintillator stripes to increase the neutron path through the scintillator and thus the probability of its absorption
- light collection through clear fibers
- channel coding by sharing the light between several PMTs (restricts the number of PMTs)

No way for using SiPMs, large-area photosensor is required!

Detector design 2 (WLS-fibers + MaPMTs)

From talk of T.E.Mason on “Neutron detectors for material research”



- light collection by 1D(2D) arrays of WLS fibers
- light detection by MaPMTs

Direct (without design change) replacement of MaPMTs by SiPMs is possible,
but the dark count rate of the SiPM has to be substantially reduced → requires deep cooling.

The necessity to cool SiPMs will add to the complexity and to the price of the detector, which might otweigh all the advantages expected from their usage.

Our goal: a WLS fiber based detector readout by SiPMs operated at room temperature.

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ZnS:^{6}LiF detectors: typical parameters

Detection efficiency at 1Å, %	40 – 50
• neutron absorption probability at 1Å, %	50 – 60
• trigger efficiency, %	70 – 90
Background count rate, Hz	$< 10^{-3}$
Gamma-sensitivity (probability to detect 1.2 MeV γ from ^{60}Co source)	$< 10^{-6}$
Dead time, µs	5 – 20
Multi-count ratio, % (mean number of triggers per event – 1)	< 1

Problematic to fulfill simultaneously with a SiPM operated at RT (dark count rate ~ 1 MHz)

<u>To be able to use SiPMs at RT we need</u>:

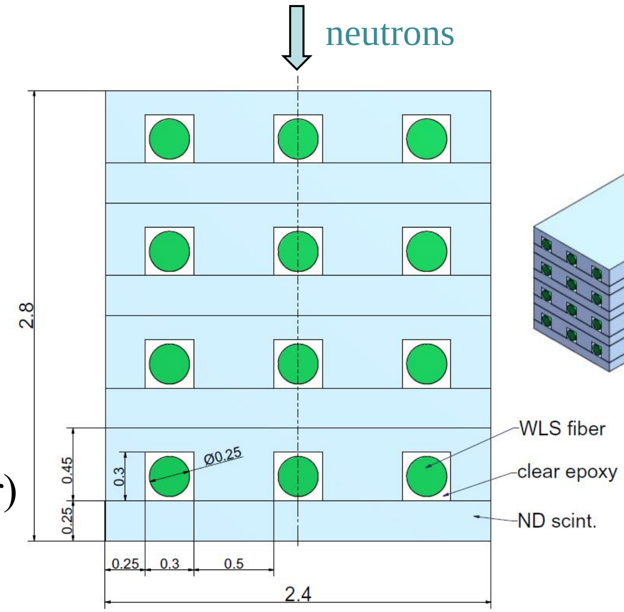
1. a much better light collection from the scintillator (at least a factor of 10)
2. a signal processing system capable to reliably identify the neutron signals against the high background of the SiPM dark counts

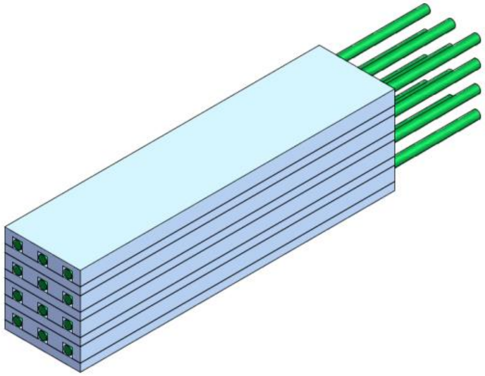
Single-channel detection unit (pixel in a multichannel detector)

- 2.4 x 2.8 x 50mm
- effective absorption volume = 0.83
- 12 fibers Y11(400)M, Ø = 0.25mm
- neutron absorption probability: ~ 80% at 1Å

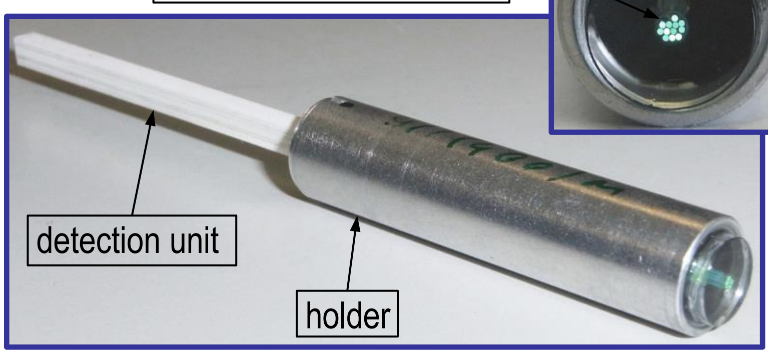
- readout with $1x1mm^2$ SiPM

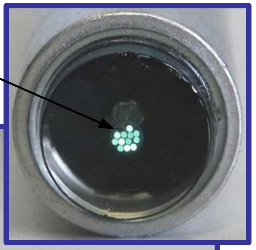
  via "optical expander" (Ø1.2x5mm clear fiber)

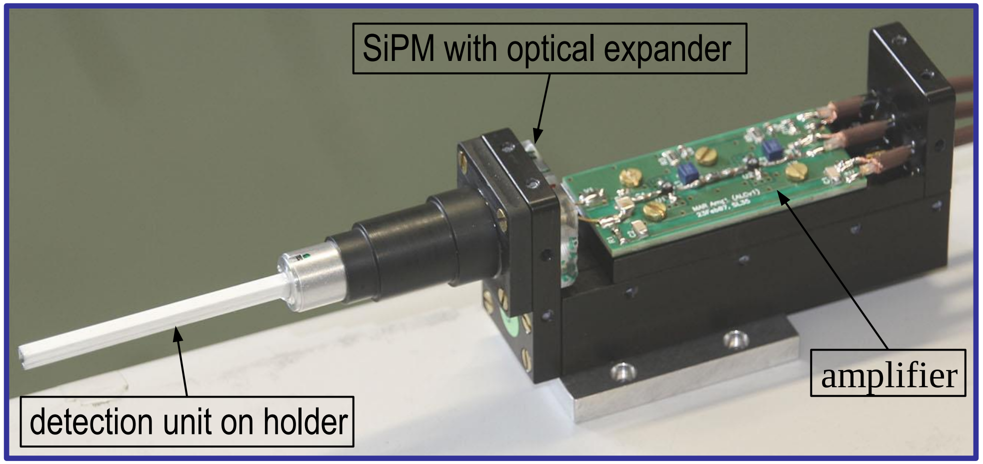




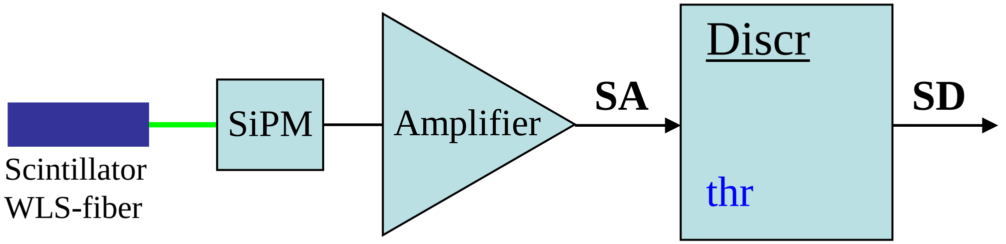
Single-channel prototype detector for current measurements

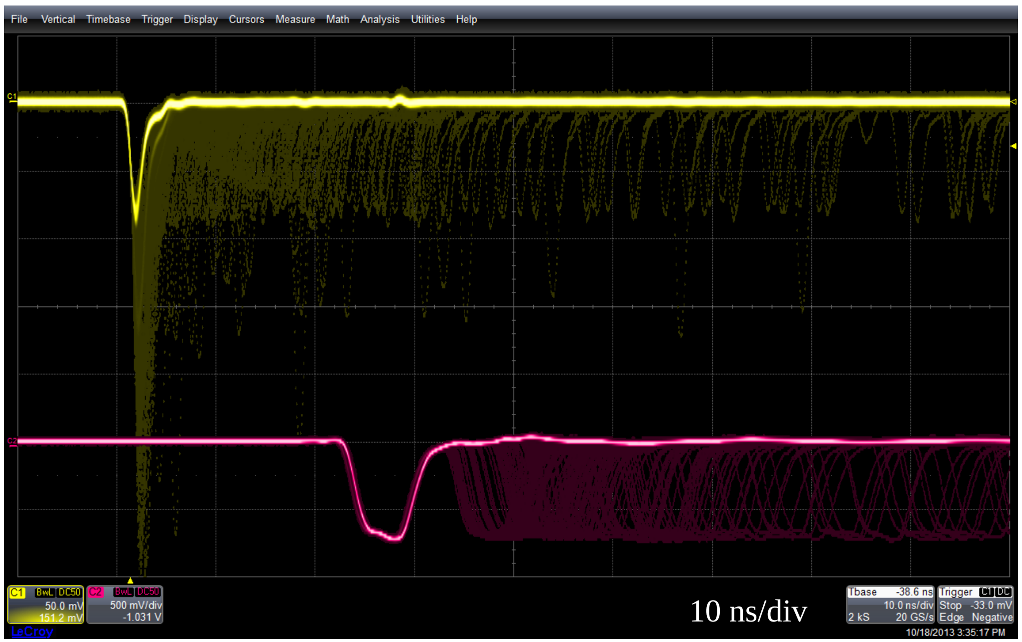






Signal processing (step 1): analog → digital





SA-signal

SD-signal

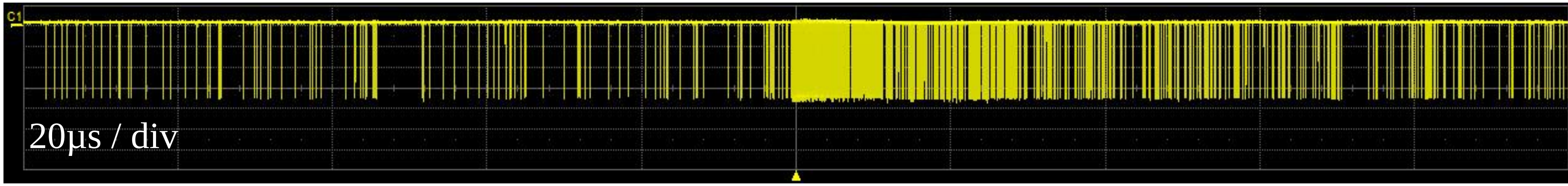
MPPC S12571-025C, 1x1mm

ΔU = 2.5V at RT, n0 ~ 100 kHz

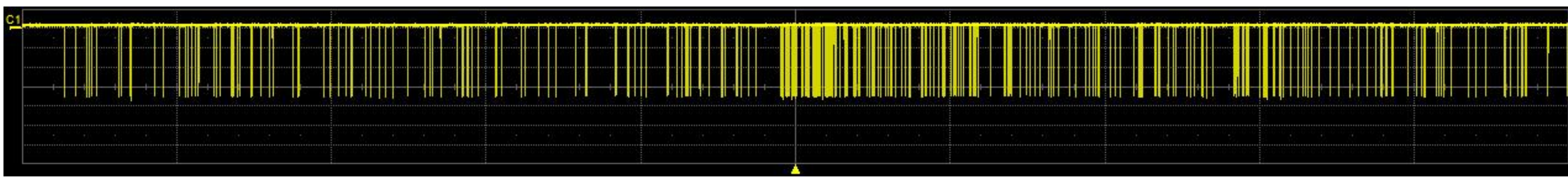
Independent of how many SiPM cells fire at the same time, only one SD-pulse is generated per one primary electron. Cross-talk is completely removed, further signal processing is independent of the used SiPM type.

Trains of SD-pulses

Neutron event 1: SD = 305 (pulses in first 10µs)



Neutron event 2: SD = 79



dark counts ~10^6 1/s

trigger efficiency < 10^{-9}

background count rate < 10^{-3} 1/s

signal begins here

trigger efficiency 70 – 90%

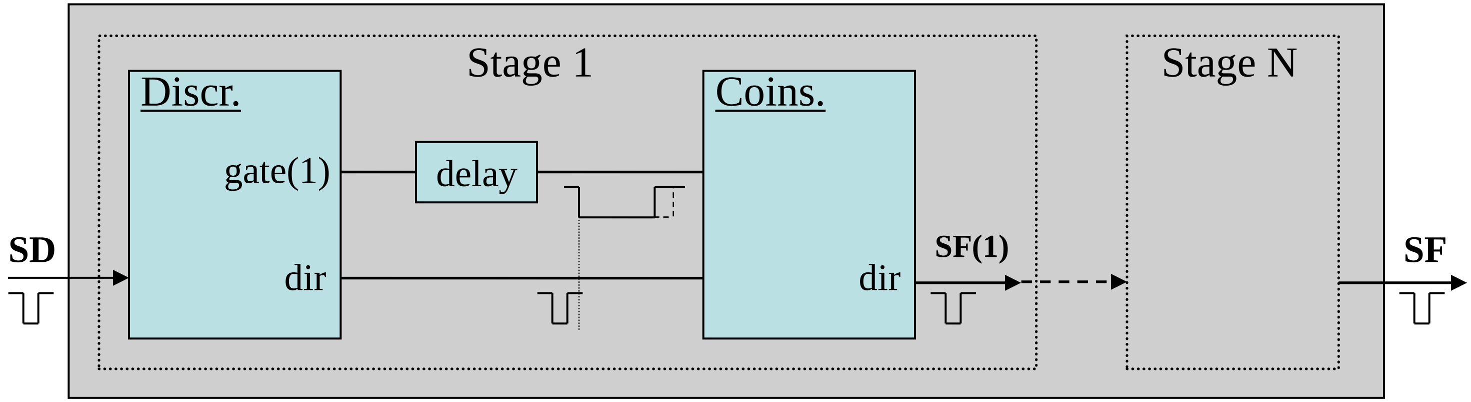
afterglow photons + dark counts

trigger efficiency < 10^{-2}

multi-count ratio < 1%

Removal of dark counts / Signal extraction

Multistage single-pulse elimination filter (high-pass pulse density filter)



SD – input pulse sequence

SF – subsequence of SD passing the filter

gate(i) – width of the self-coincidence gate for stage(i)

N – number of stages

To pass the stage(i) a pulse of the input sequence should have a preceding pulse within the time interval gate(i). Pulses not satisfying this condition are removed.

Dark counts suppression at gate(1) = gate(2) = … = gate(N):

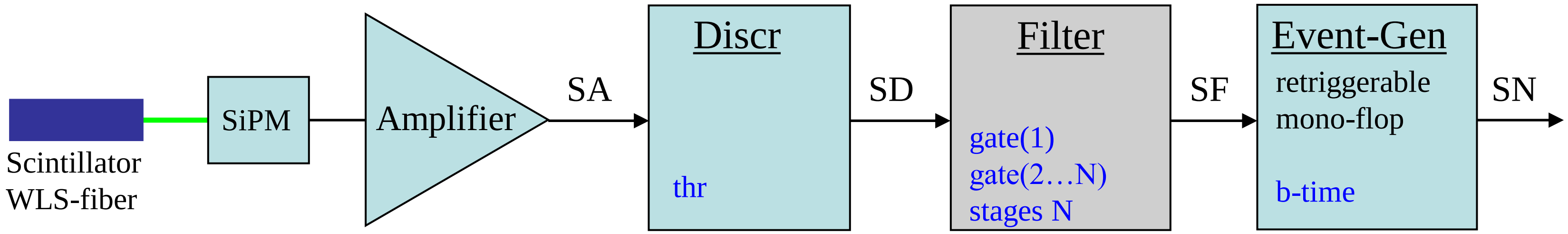
bgd = n0 (1 – α) α^N , α = Δ n0, Δ = gate(1) + SD-pulse width, n0 – SiPM dark count rate

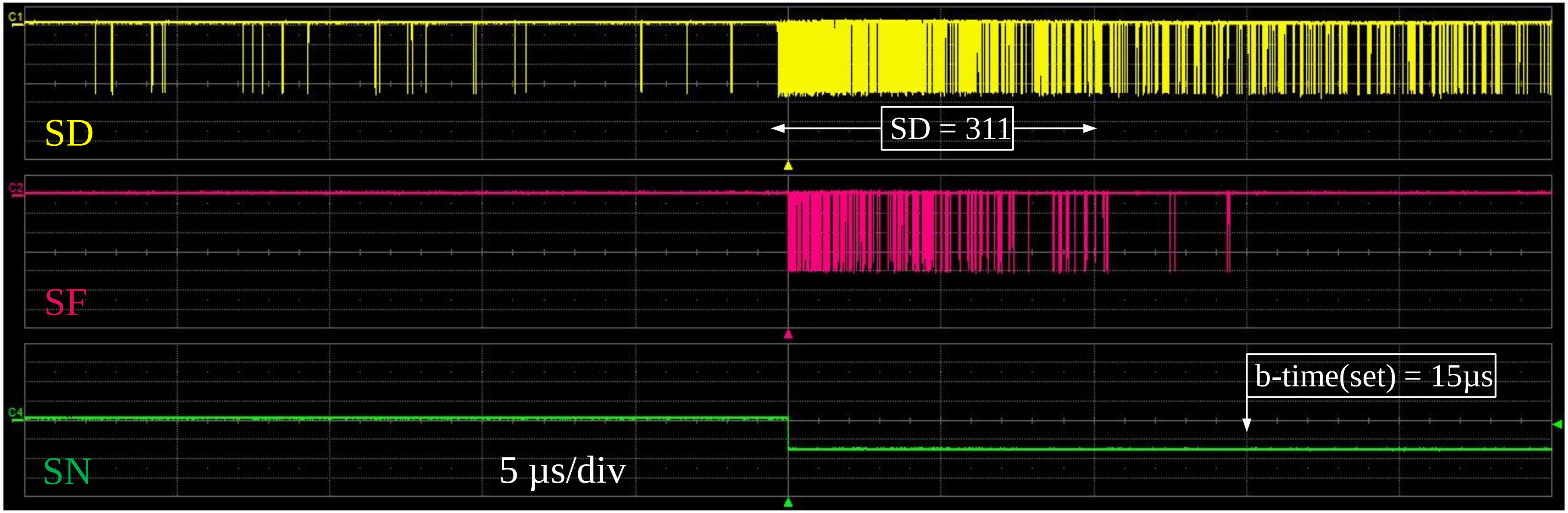
Practical choice of gates: gate(1) << gate(2) = … = gate(N)

-- dark count suppression almost as above, mainly determined by gate(1)

-- better transmission of neutron signals

Signal-processing: full chain





A retriggerable mono-flop as event generator ⇨ "blocking time" is automatically adjusted to the strength of SF-signal.

Further measurements with the following settings ⇨

parameter	thr	gate(1), ns	gate(2…N), ns	stages N	b-time, µs
value range	0.5 A_{1e}	20 – 80	500	4 – 12	5 – 100

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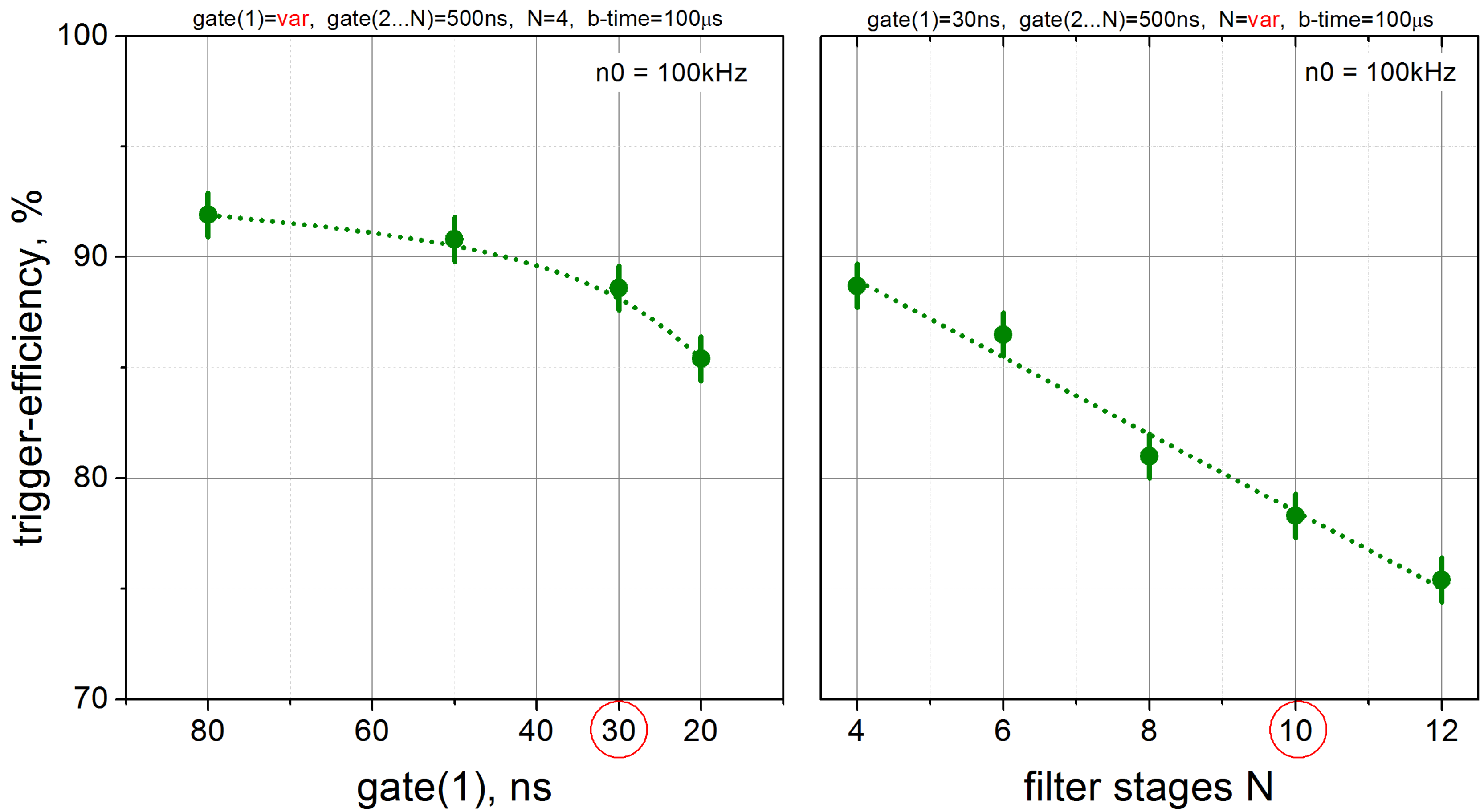
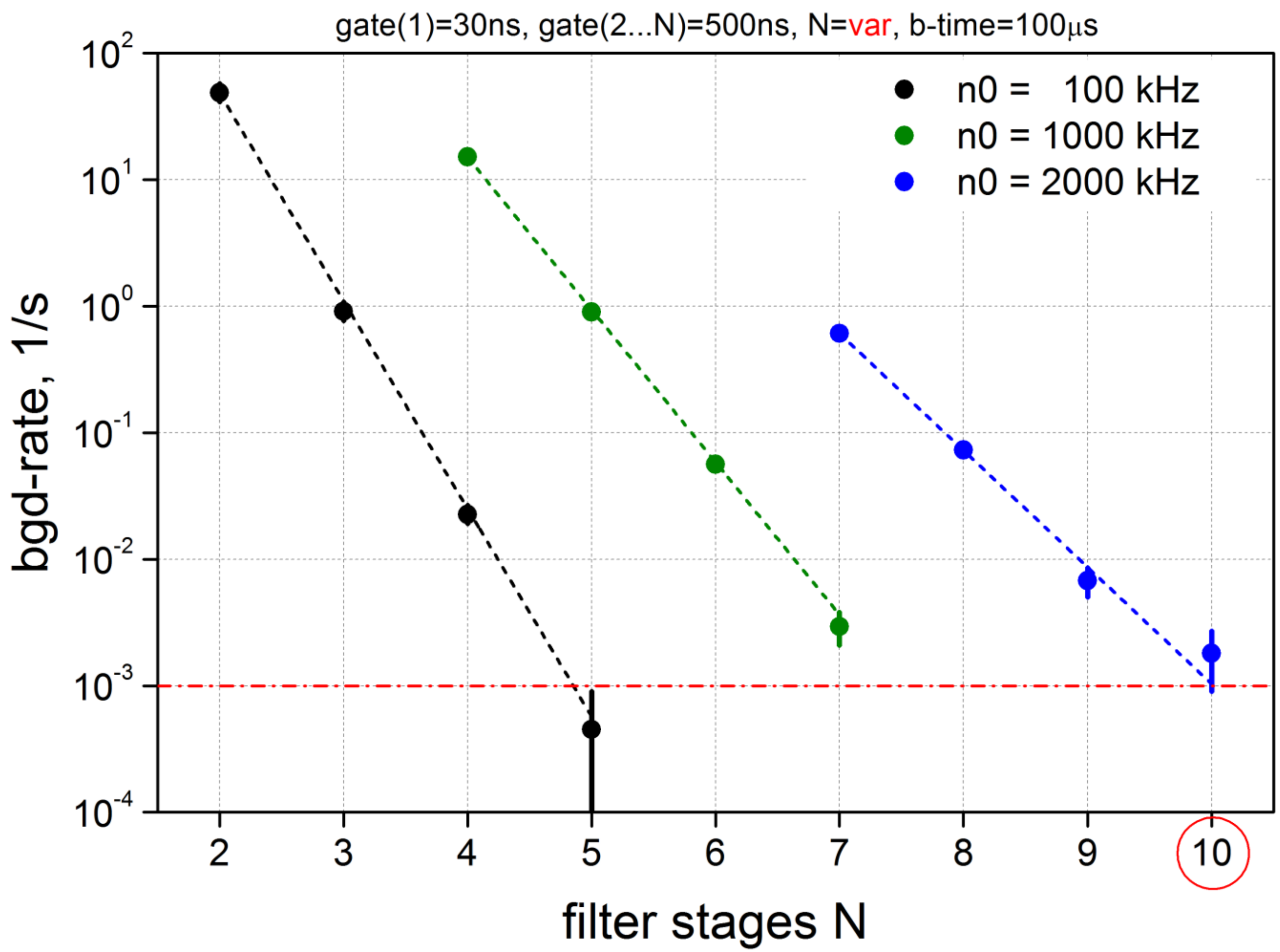
Measurements with prototype detector: trigger efficiency



^{241}Am/Be neutron source in polyethylene moderator
-- neutron absorption rate in the test detector = 9.0 Hz -- trigger-efficiency = measured event rate / neutron absorption rate

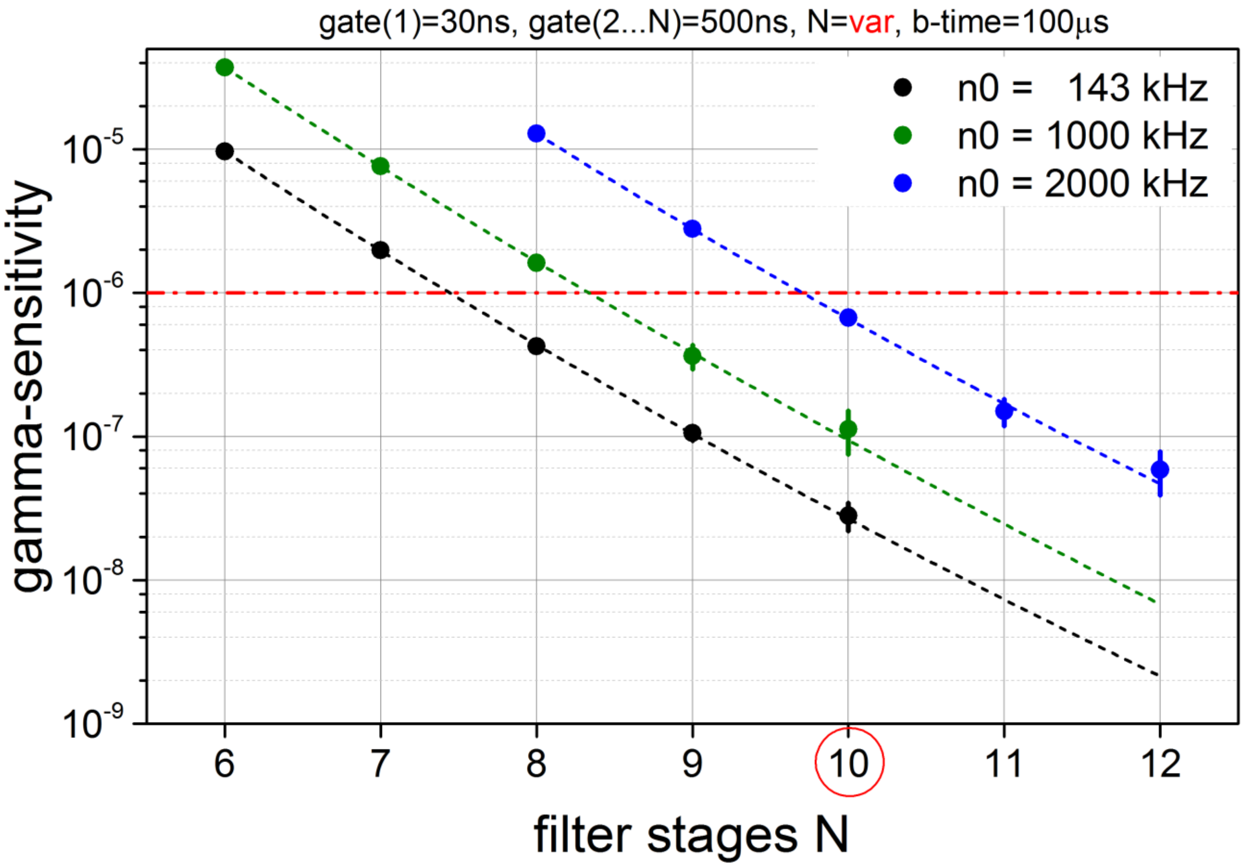
Filter operation point: gate(1) = 30 ns, N = 10
trigger efficiency ≈ 80%

Background count rate



At trigger-efficiency of ~ 80% the background count rate $\leq 10^{-3}$ Hz is guarantied up to the SiPM dark count rate of ~ 2 MHz.

Gamma-sensitivity



^{60}Co source (γ-energy ~ 1.2MeV)
calibration with 2x2x15mm LYSO crystal

-- absorption probability ≈ 0.1

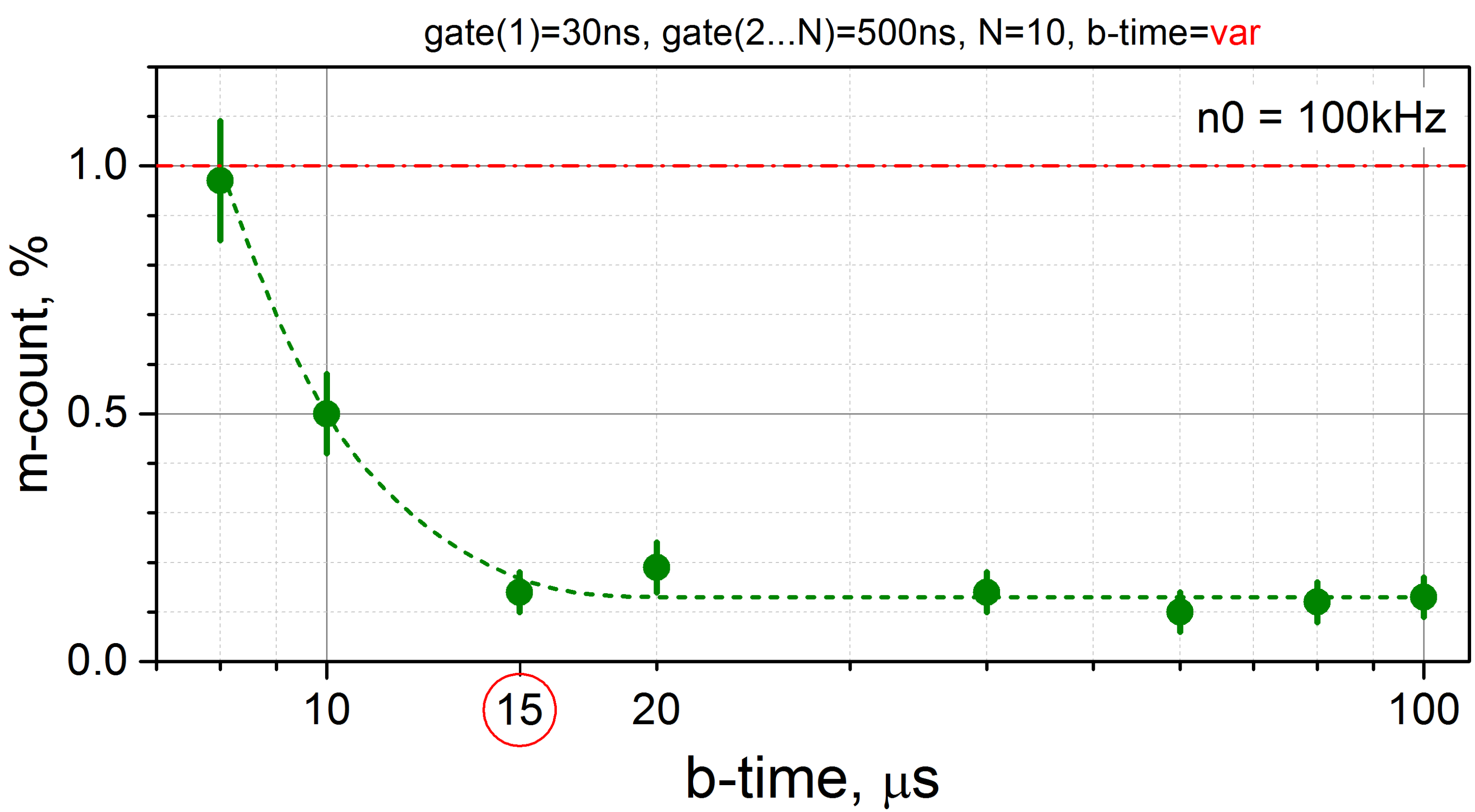
-- measured γ-rate ≈ 10^3 1/s

⇩

γ-flux through test detector ≈ 10^4 1/s

At trigger-efficiency of ~ 80% the gamma-sensitivity $\leq 10^{-6}$ is guarantied up to the SiPM dark count rate of ~ 2 MHz.

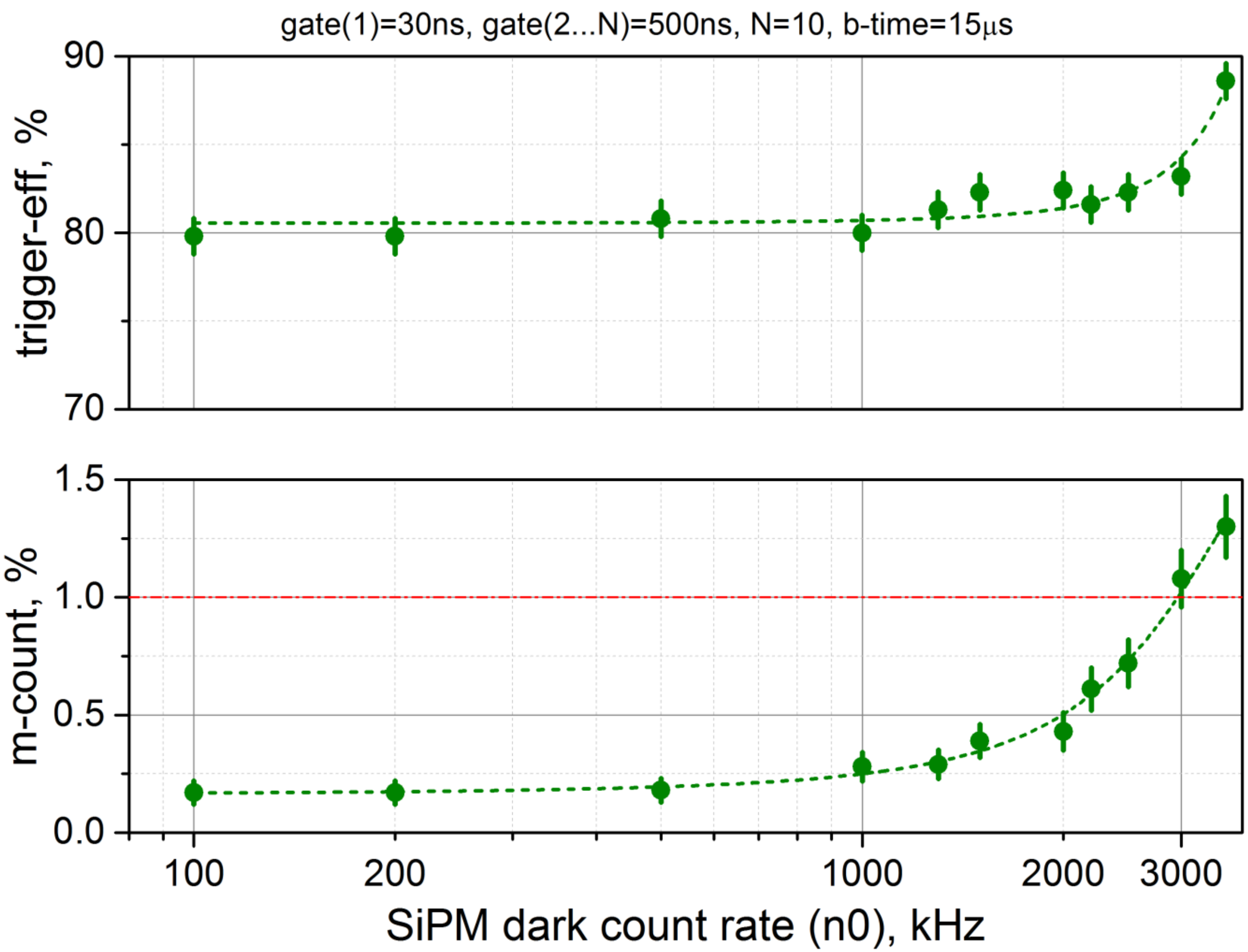
Multi-count ratio vs. blocking time



b-time (set) = 15µs → b-time (measured mean value) ≈ 20µs	
retriggerable mono-flop as event generator → b-time (true) ≥ b-time (set)	

The multi-count ratio < 1% is reliably guarantied with the true blocking time of ~ 20µs.

Multi-count ratio, efficiency vs. SiPM dark count rate



Practically no change of the detector performance up to the SiPM dark count rate of ~ 2 MHz.

Summary 1

We proved the feasibility of using Silicon Photomultipliers operated at room temperature for individual readout of detection channels in multichannel neutron detectors utilizing $ZnS{:}^{6}LiF$ scintillation screens.

The problem of the high dark count rate of the SiPM is solved by substantially improving the light collection from the scintillator and by developing an efficient algorithm based on the time-domain filtering for separating the signals from the dark counts.

With a single-channel prototype detector we achieved very good performance characteristics up to 2 MHz SiPM dark count rate.

Summary 2

We are convinced, that the use of SiPMs in ZnS:^{6}LiF scintillation detectors for application in the neutron scattering experimental technique will open on the one hand new possibilities in designing this kind of detection systems, and on the other hand a new field for the large-scale application of SiPMs.

Measurement setup

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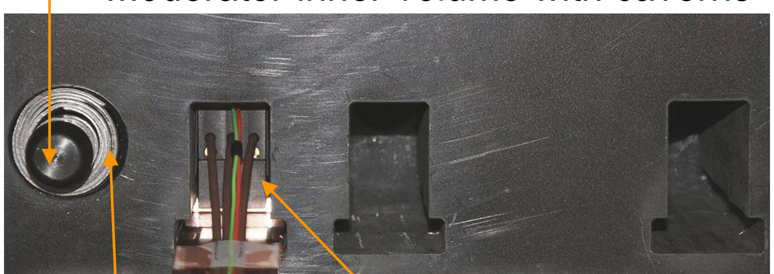
^{241}Am/Be neutron source on polyethylene holder

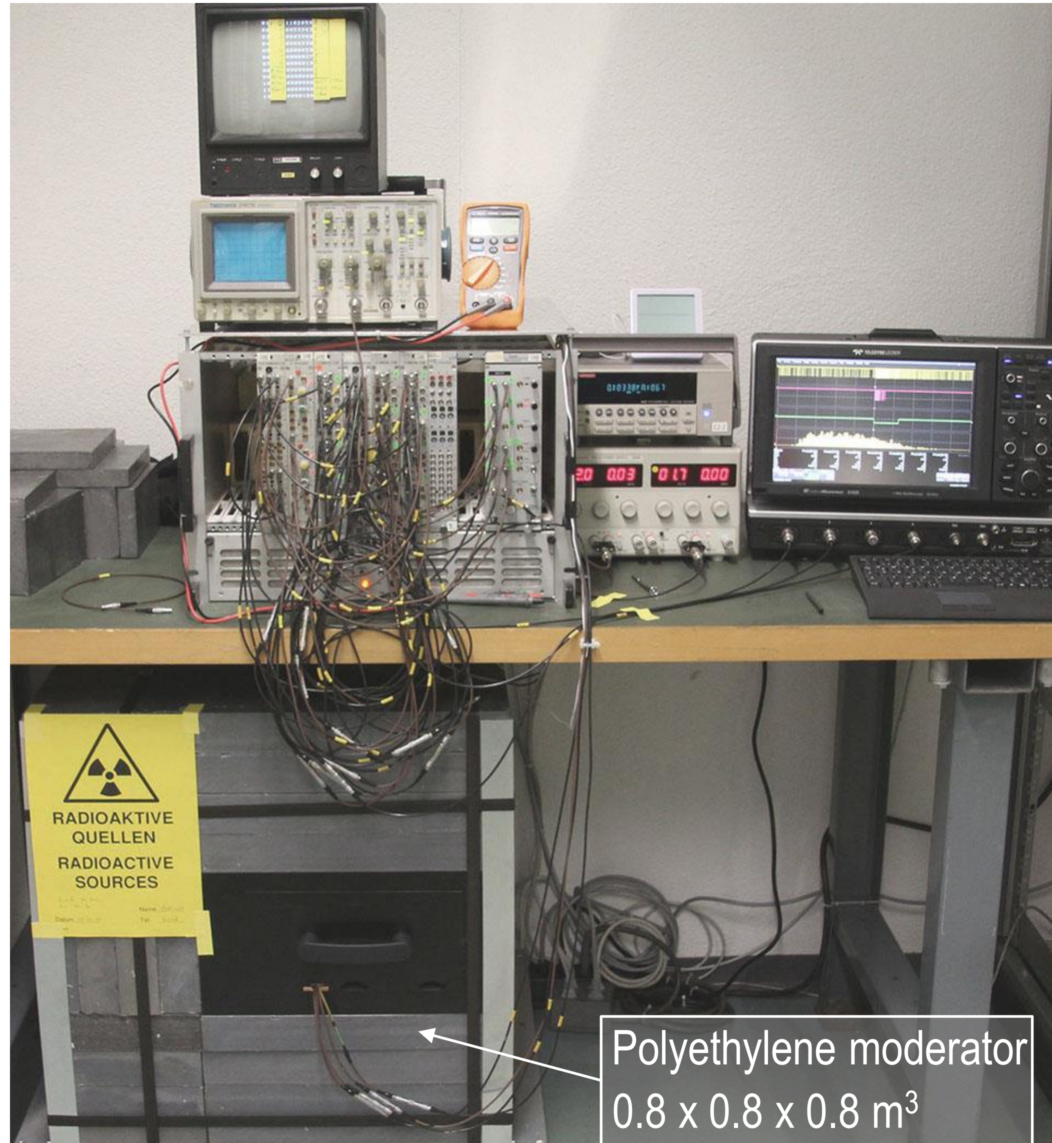
$2 \cdot 10^4$ fast neutrons / s

Moderator inner volume with caverns

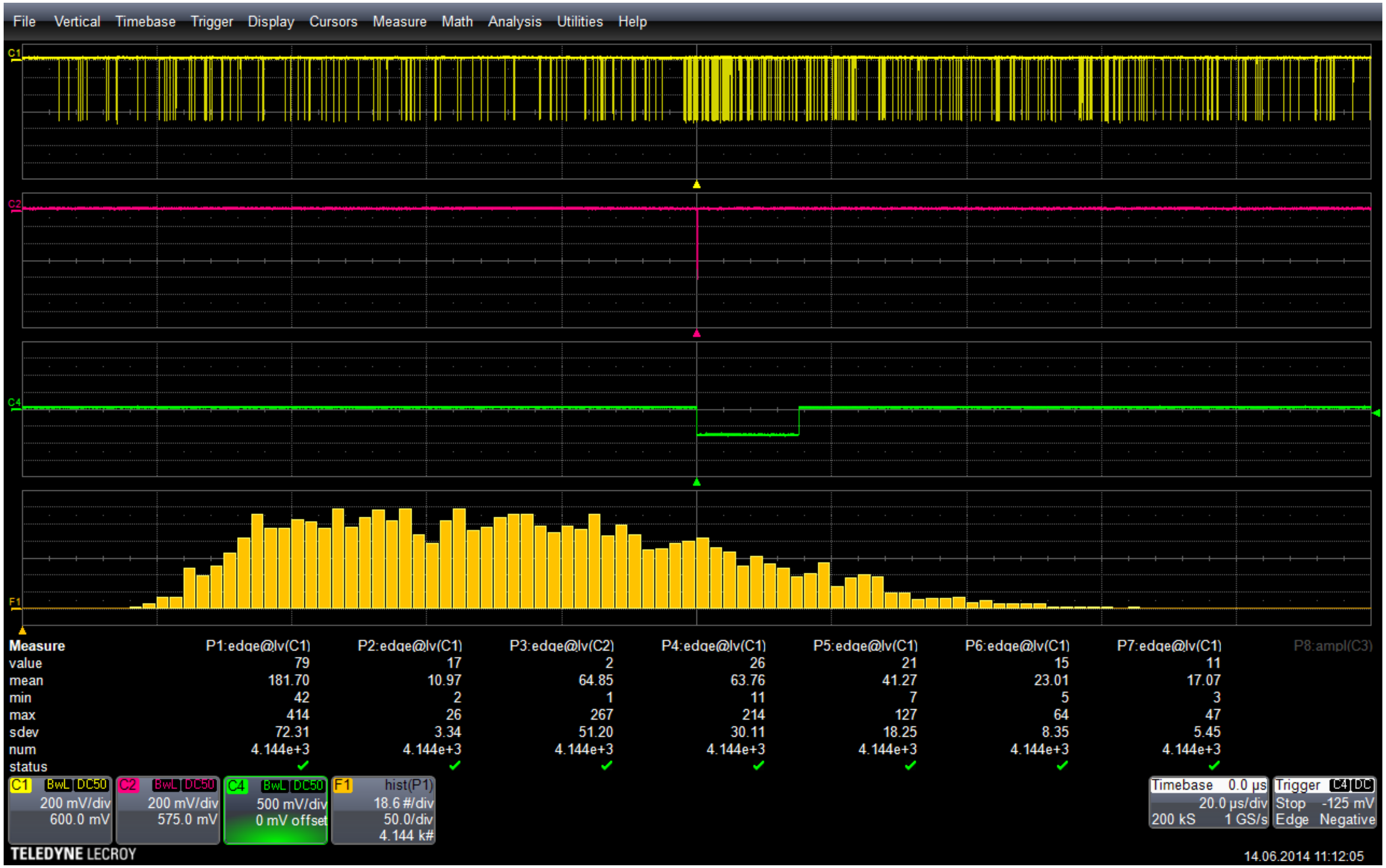


Pb-shielding

Detector module



DSO event detection panel



SD

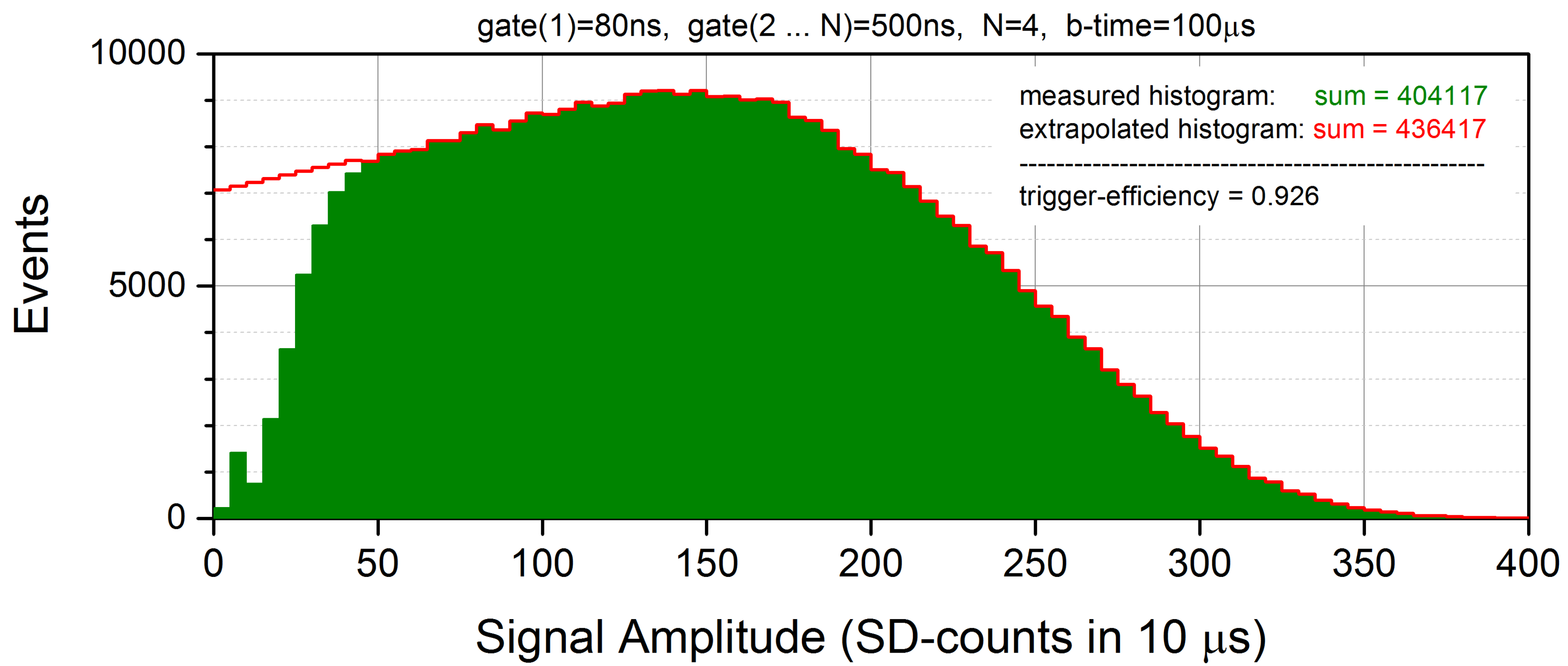
SF

SN

Histogram:
SD-counts
in (0 – 10 µs)

Parameter	P1	P2	P3	P4	P5	P6	P7
Window, µs	(-90, -80)	(0, 10)	(0, 10)	(10, 20)	(20, 30)	(50, 60)	(90, 100)
Description	SD-counts	SD	SF	SD	SD	SD	SD

Calibration (neutron absorption rate)



-- trigger efficiency by extrapolating the SD-amplitude spectrum to zero amplitude: 0.926 -- measured event rate: 8.3 Hz
neutron absorption rate in the scintillator: 9.0 Hz

Thermal neutron (1 – 100 meV)

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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

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

$^{6}Li + {}^{1}n \rightarrow {}^{3}H + {}^{4}He + 4.79$ 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: $1.5 \cdot 10^{22}$ cm^{-3}

Attenuation length at 1Å

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

ND2:1 : **0.13 cm**