PAUL SCHERRER INSTITUT

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Neutron detectors based on ZnS:Ag/^{6}LiF read out with WLS fibers and SiPMs

SINE2020 WP9 Industry Day, PSI, 13.06.2017

Content

The development of a 2D thermal neutron detector – which is our work within SINE2020 WP9 – is based on our recent work on a 1D detector.

→ content of the talk:
- technical details of 1D thermal neutron detector
- approaches for 2D thermal neutron detector

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- approaches for 2D thermal neutron detector

Motivation for PSI Approach – The Big Picture

The neutron detection system is based on:

- ZnS:Ag/^{6}LiF scintillation screen
  - established technology, appropriate properties
  - but: opaque, long emission time
    → small number of photons spaced out in time
- wavelength shifting (WLS) fibre
  - efficient, high and uniform light collection
    → less fibres, no ”light sharing”, no coding

The new approach includes:

- Silicon Photomultiplier (SiPM)
  - fast, single photon counting capability
  - small
  - insensitive to magnetic fields
  - cheap
    → each detection element coupled to single SiPM
  - but: cross talk, dark counts
    → influence on neutron signal extraction

> SiPMs are used everywhere, except in neutron scattering instrumentation!

- digital signal processing system
  - analyse temporal distribution of SiPM pulses
    → neutron signal extraction

Neutron Detection Unit

ND2:1scintillation screen (Scintacor)

- 0.25 mm and 0.45 mm
- grooves machined in 0.45 mm screen

WLS fibres: Kuraray Y11(400)M

- Ø = 0.25 mm
- embedded in grooves of scintillator

Eljen EJ-500 optical epoxy

detection unit

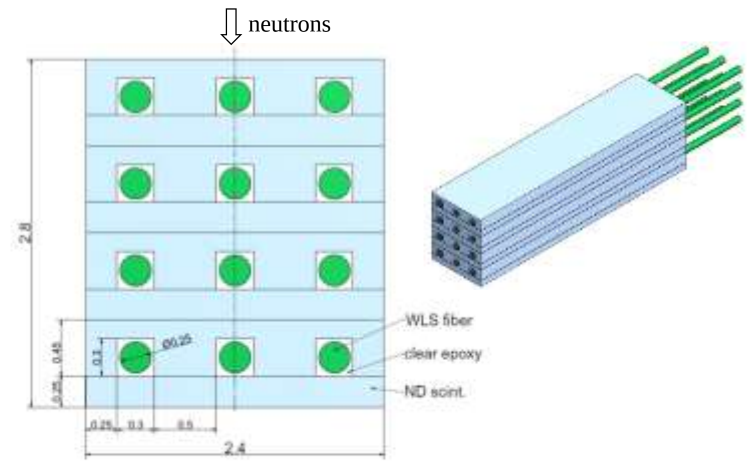
- front end: fibres polished and mirrored
- rear end: 12 fibres glued in plexigas block, polished and connected to SiPM

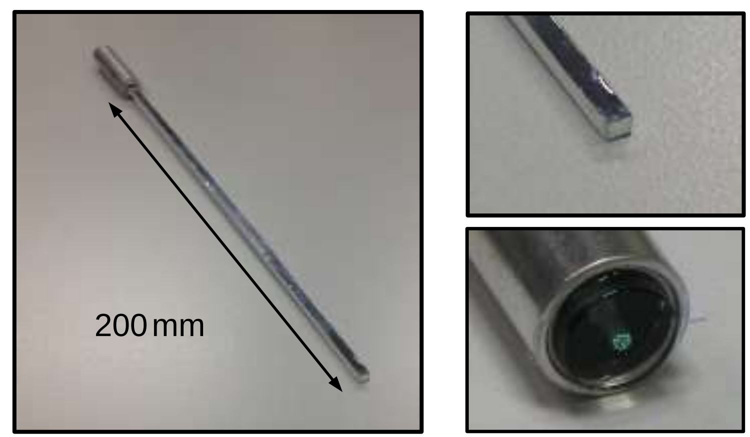
detection unit with 4 layers

- neutron absorption probability > 80 % @1.2 Å
- intrinsic time resolution < 1 μs

→ efficient and uniform light collection
→ less fibres, no "light sharing", no channel coding compared to clear fibre and PMT readout

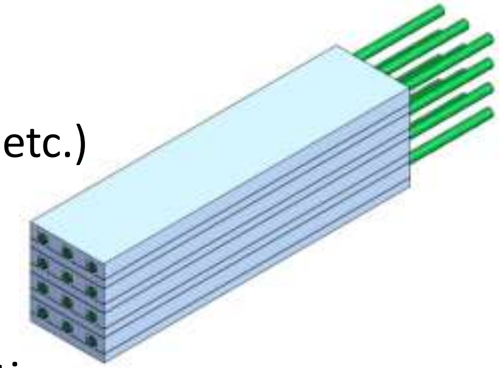
<u>1-channel, 4-layer (full-length) unit</u>



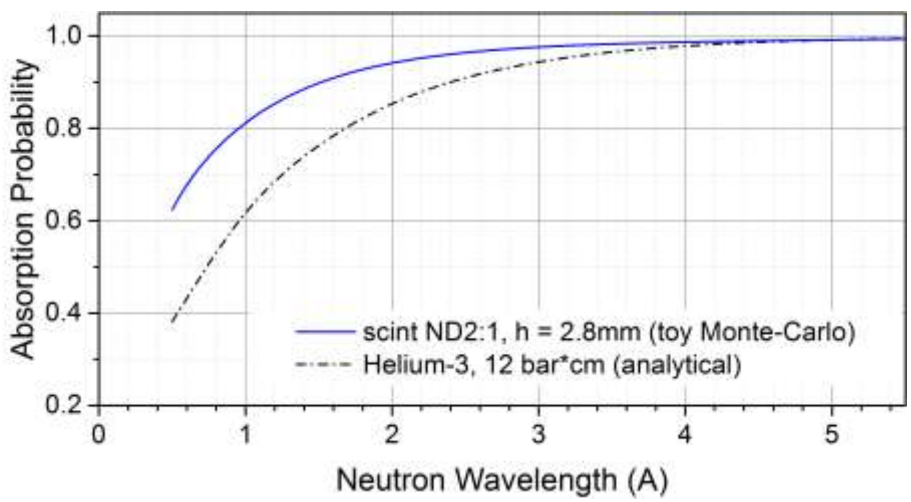


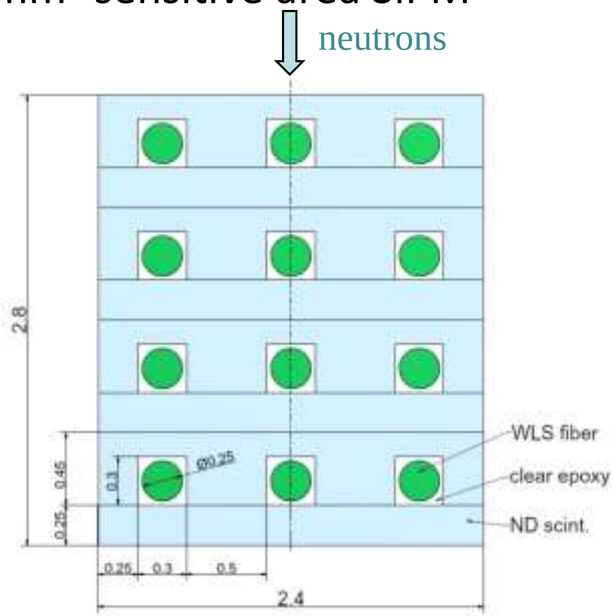
→ this unit represents elementary building block of full-size detector

Neutron Detection Unit

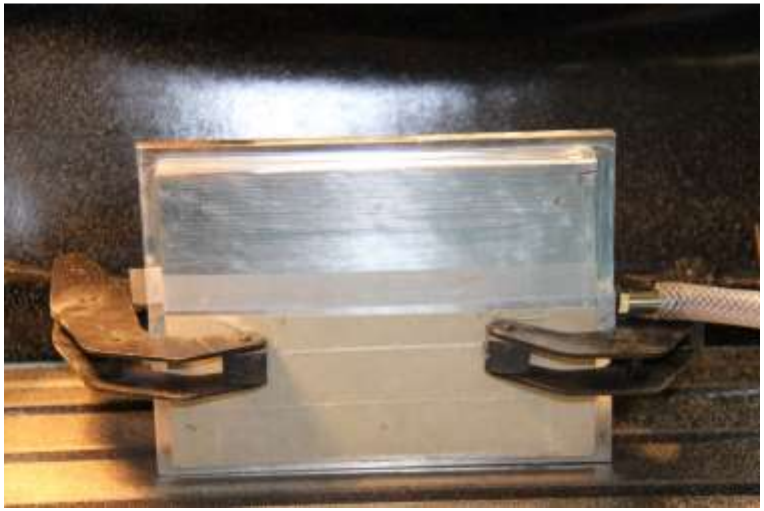


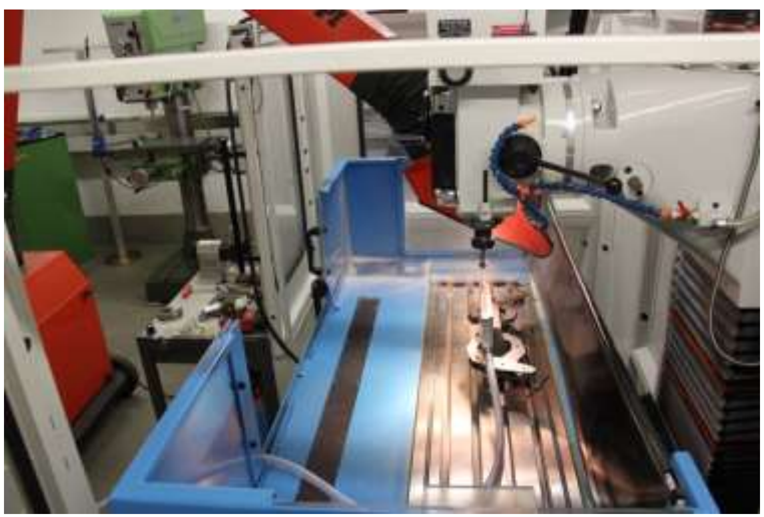
- efficient, high and uniform light collection is essential!
  → requires dedicated design of detection unit (bar, pixel, etc.)
- example: 1D neutron detection unit for strain scanning
  neutron diffractometer POLDI at PSI
  - within $(2.4 \times 200)\,\text{mm}^2$ channel: optimized light collection using 12 WLS-fibers (Ø 0.25 mm) embedded and uniformly distributed in "scintillation volume", thickness 2.8 mm
  - each channel / unit readout by individual $(1 \times 1)\,\text{mm}^2$ sensitive area SiPM
  - high neutron absorption probability achievable

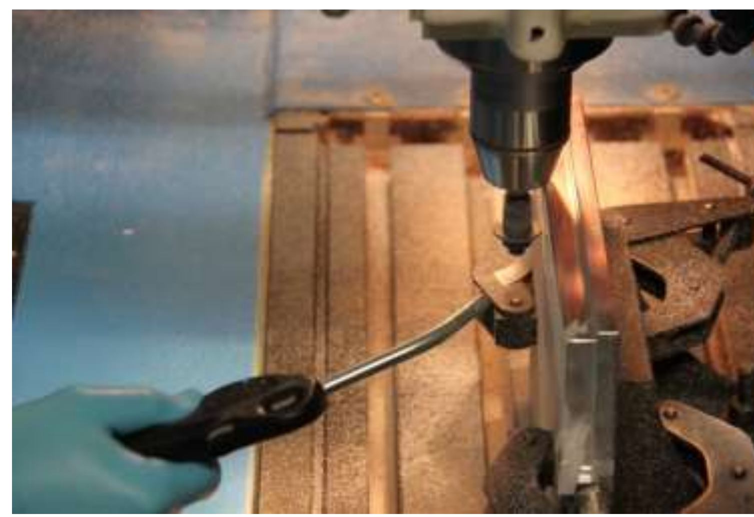




Machining of Scintillator







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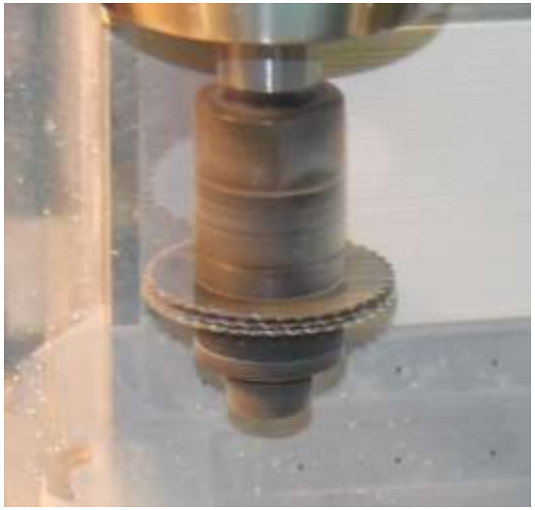
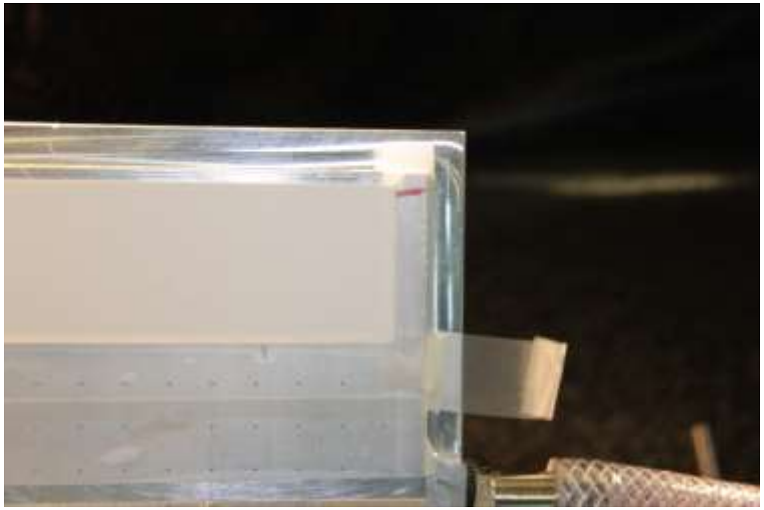
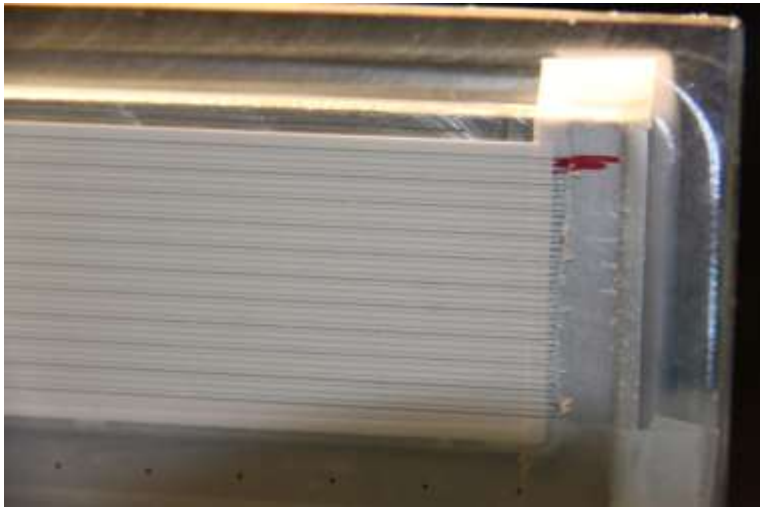
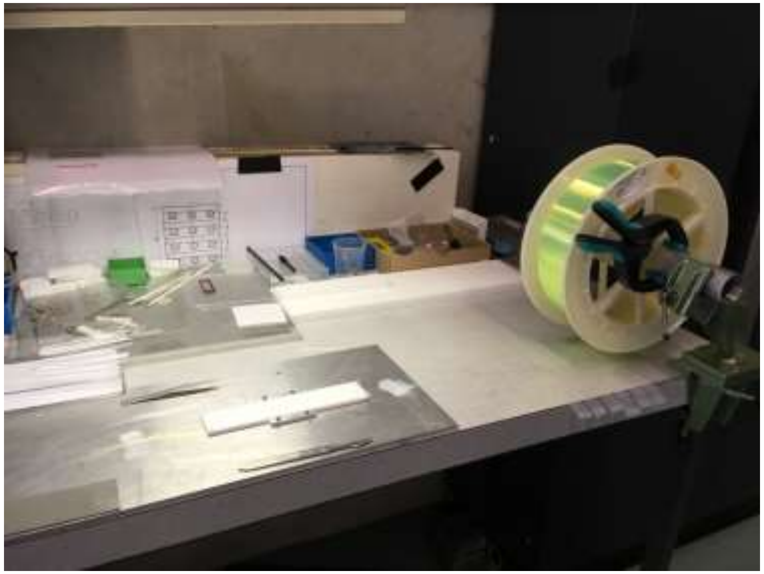
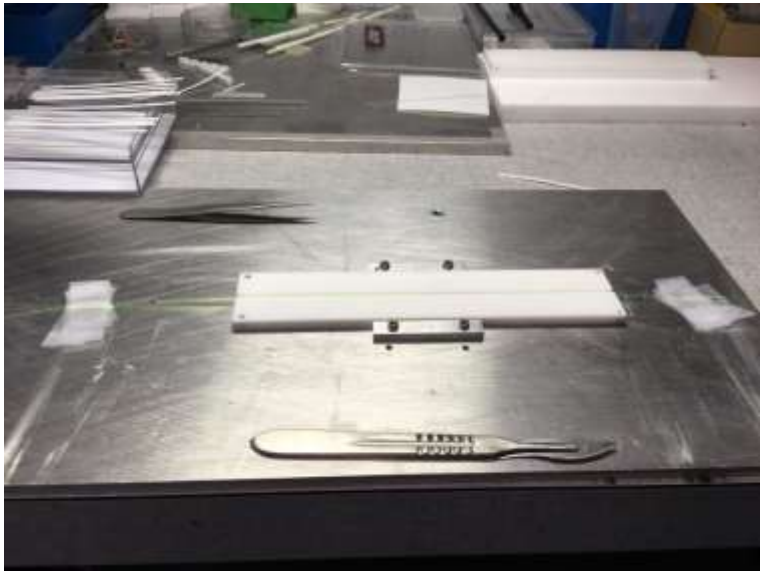
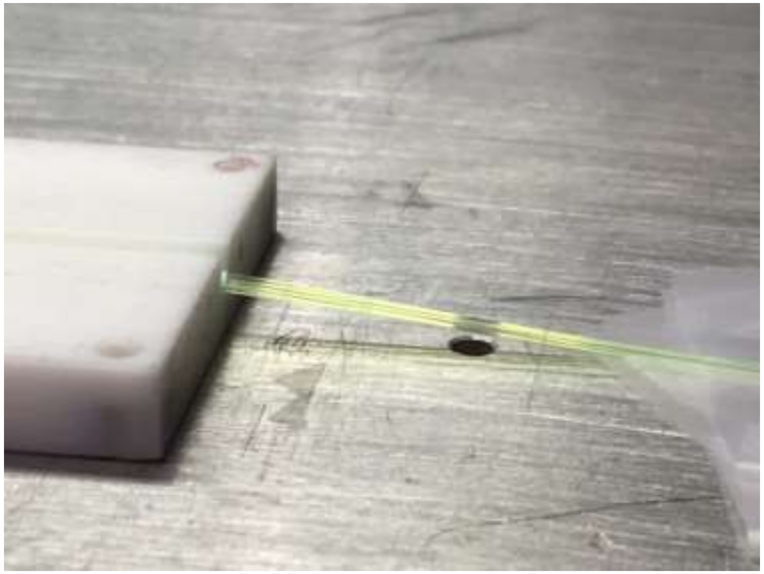
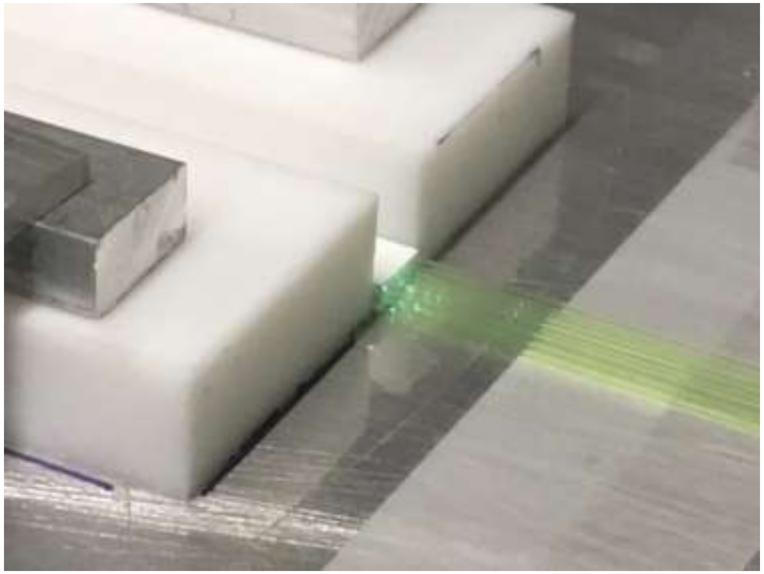






Manufacturing of Detection Unit

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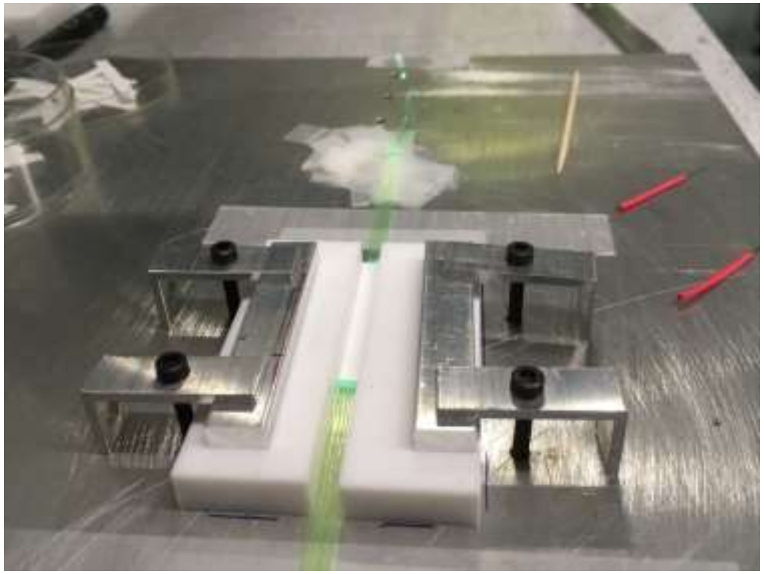

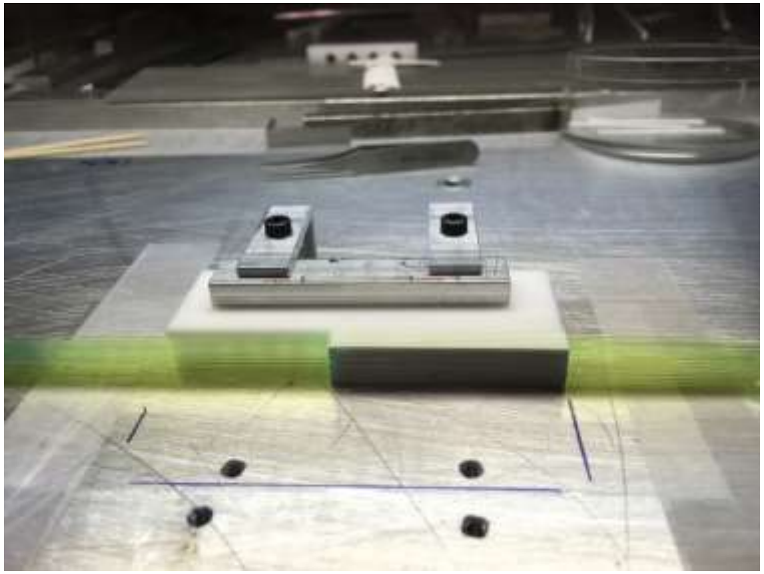

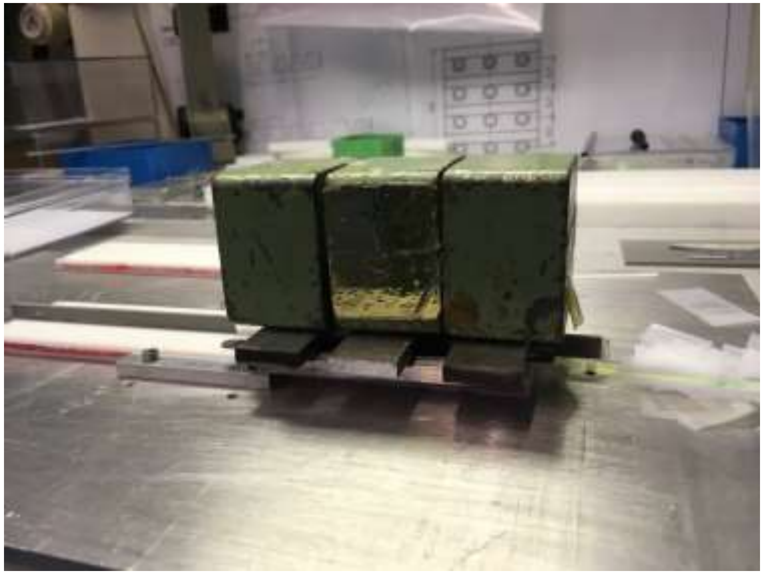

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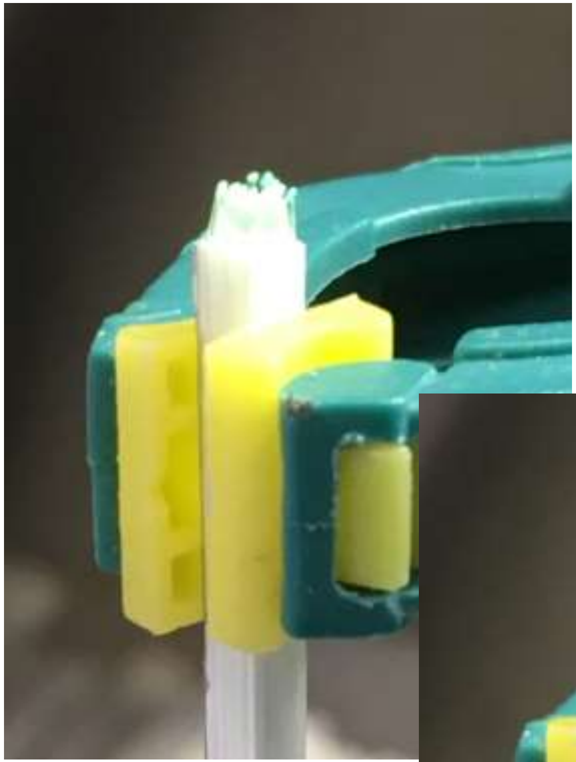
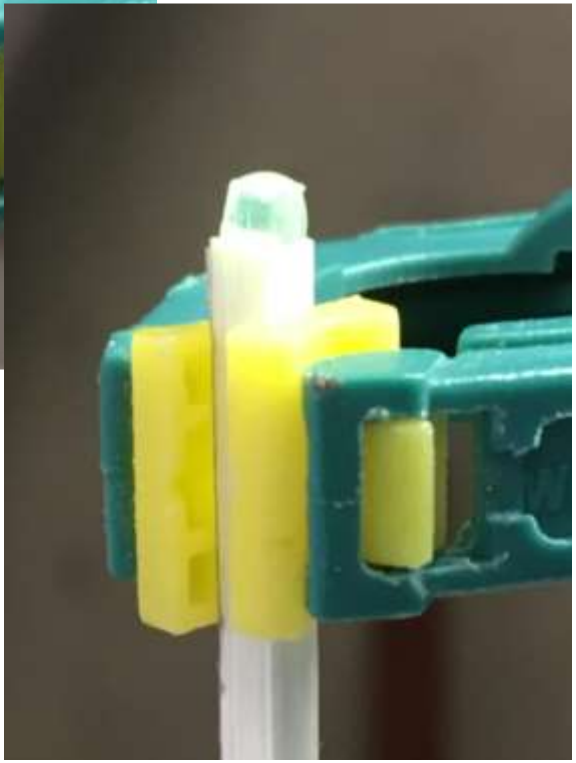
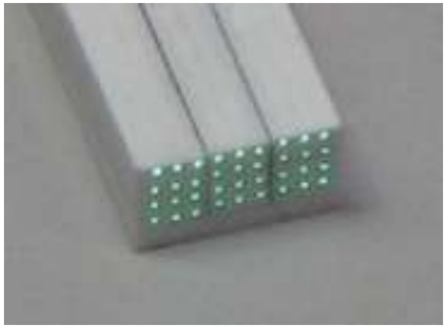
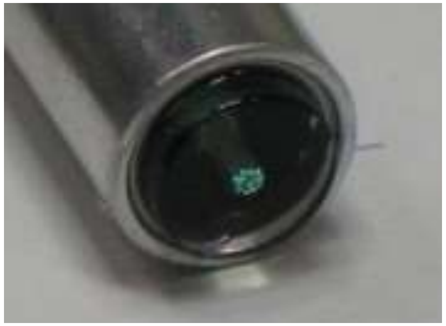
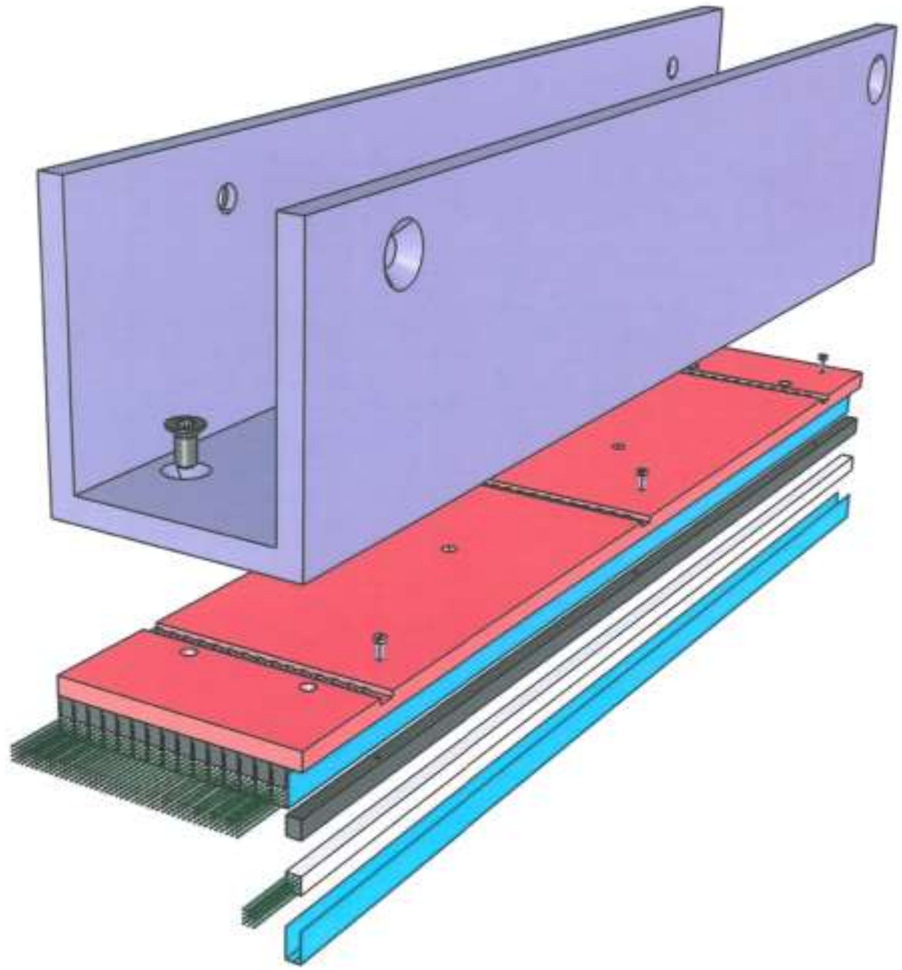








16-Channel Module



SiPM

- properties:
  - single-photon counting capability
  - high photon detection efficiency PDE ~40 % (at emission wavelength of WLS fiber)
  - low operation voltage
  - high gain: 10^5 to 10^6
  - compact, robust, non-expensive
  - insensitive to magnet fields

hamamatsu S13360-1350 1.3×1.3 mm²

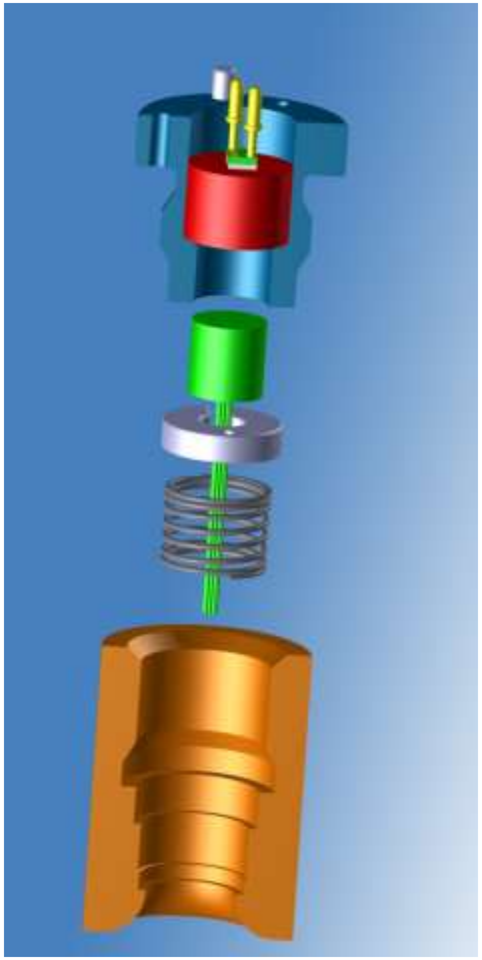
- drawback: (thermal) dark counts:
  - ~80 kHz/mm² at room temperature
  - increasing with raising temperature
  - increasing with accumulated radiation damage

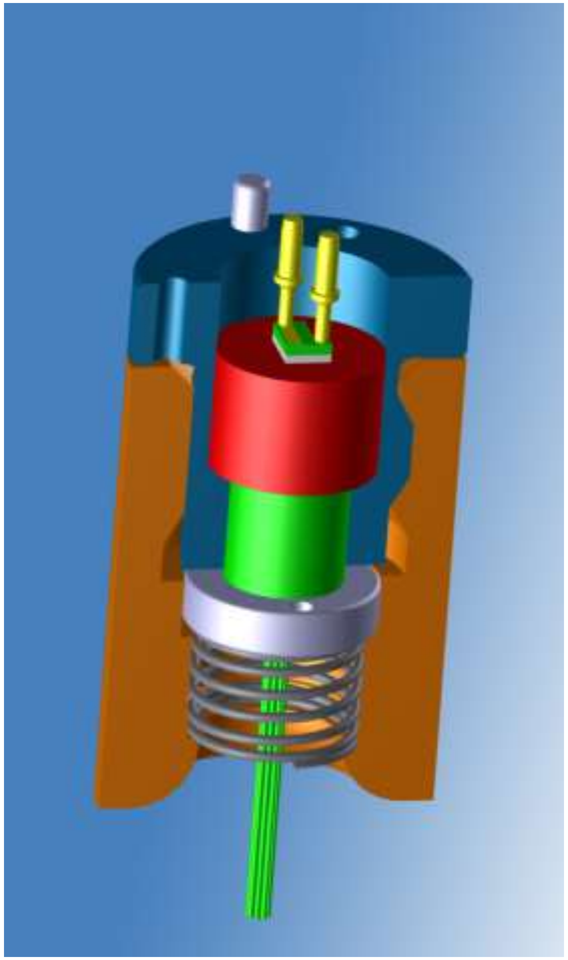
→ weak signals might not be extracted from dark count background

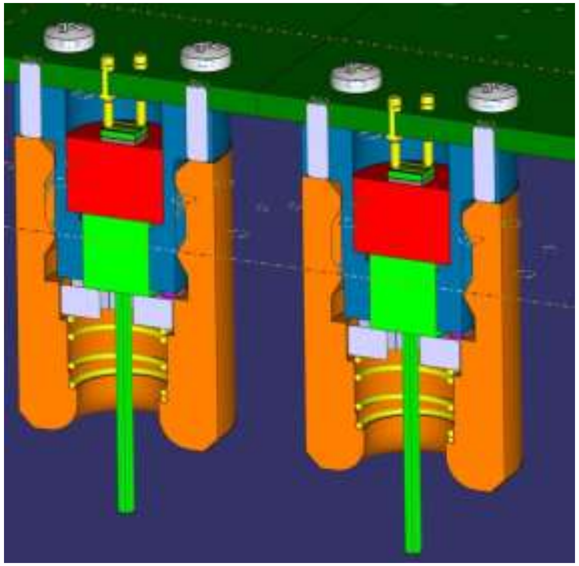
→ additional limit on trigger efficiency

postpone technical discussion on SiPM requirements to next meeting with participation of Hamamatsu

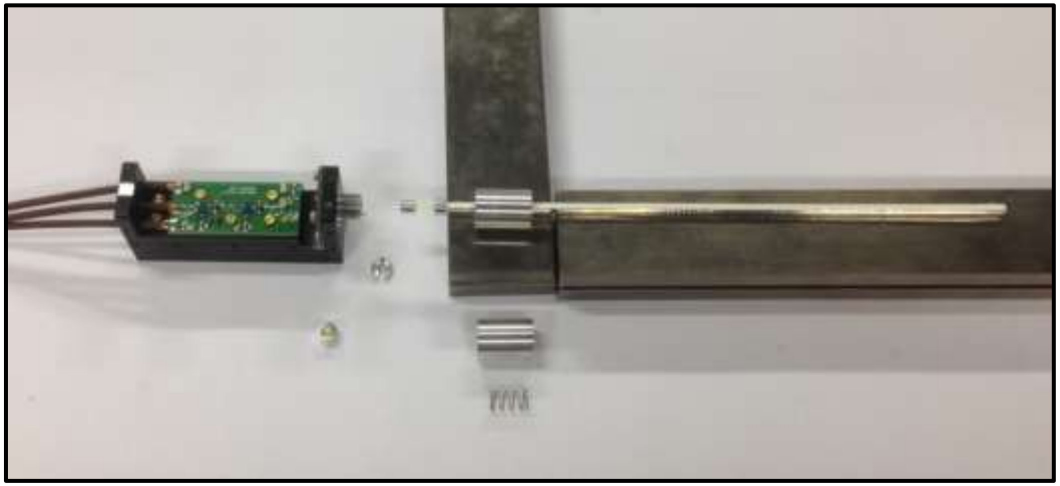
Electrical & Optical Coupling of SiPM

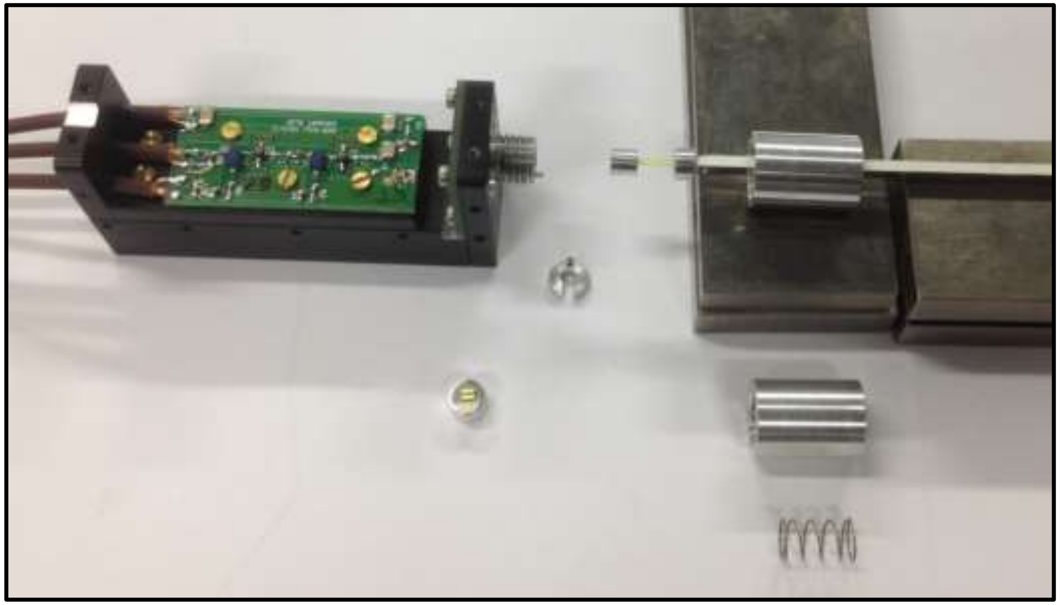




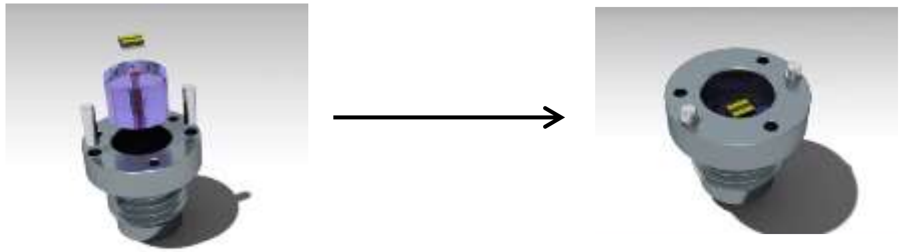


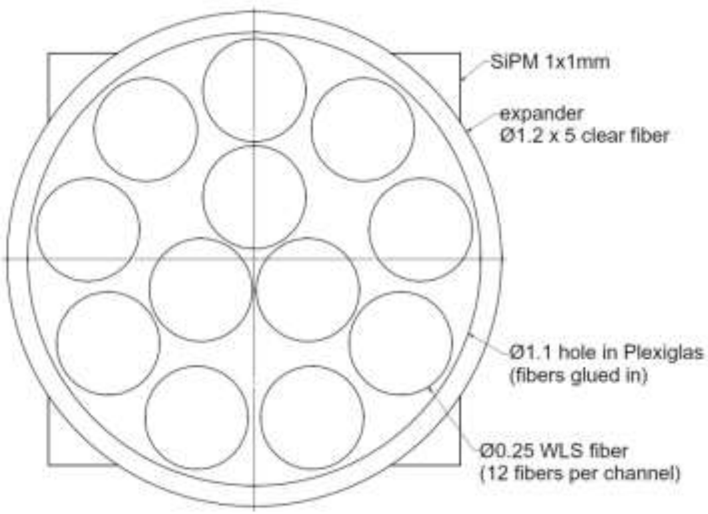
Optical Coupling of SiPM

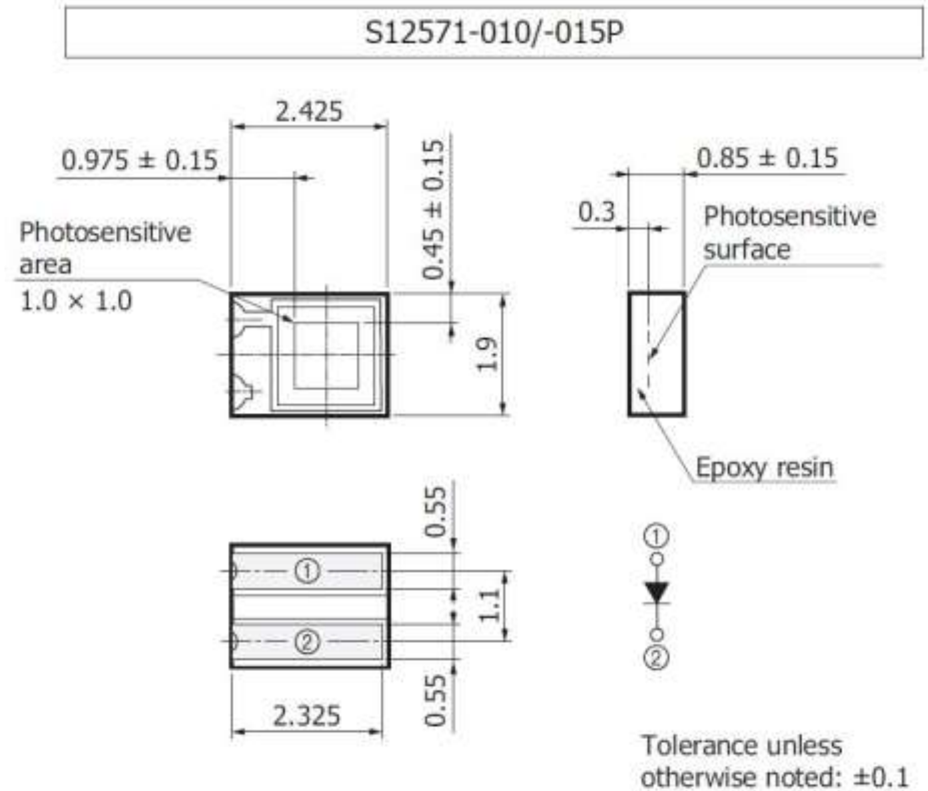




Alignment of SiPM







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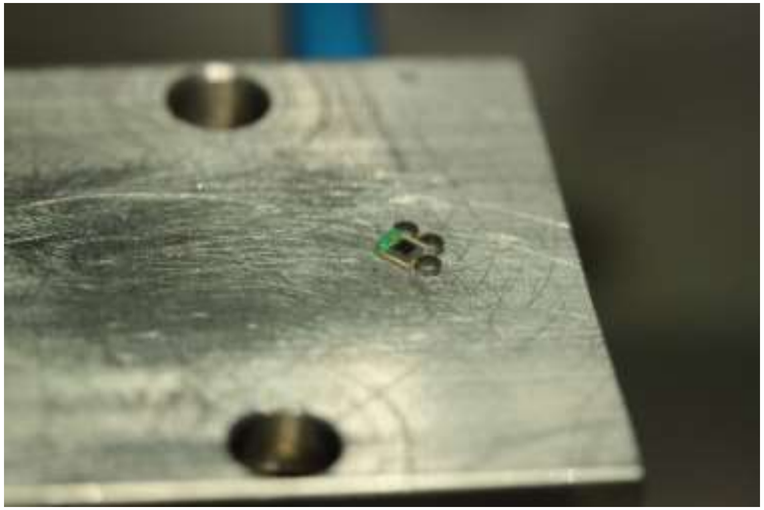

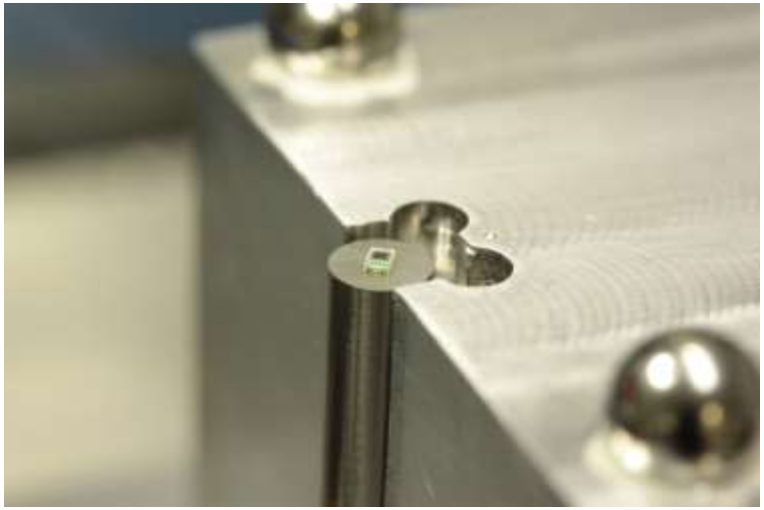

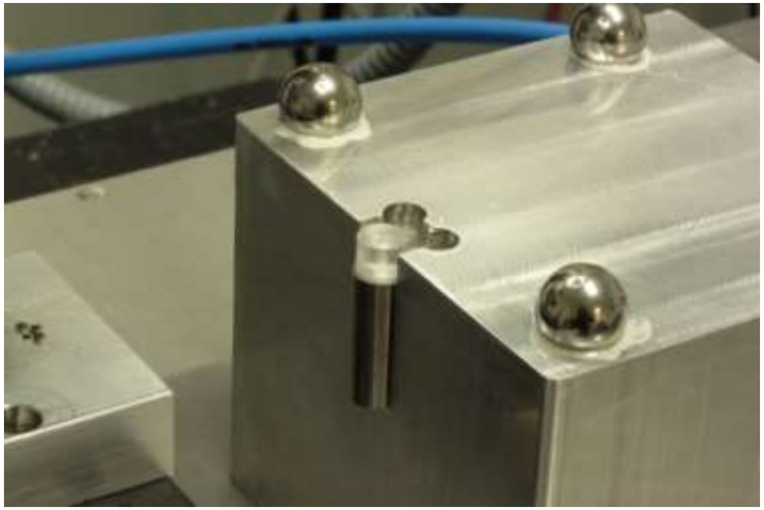

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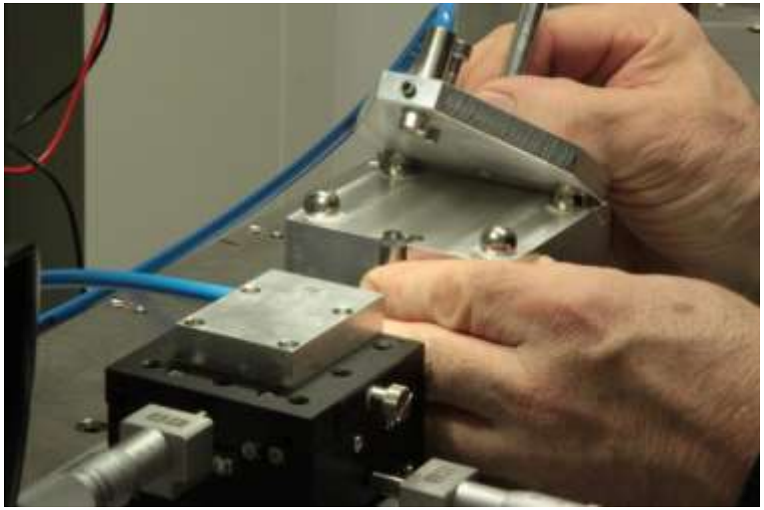
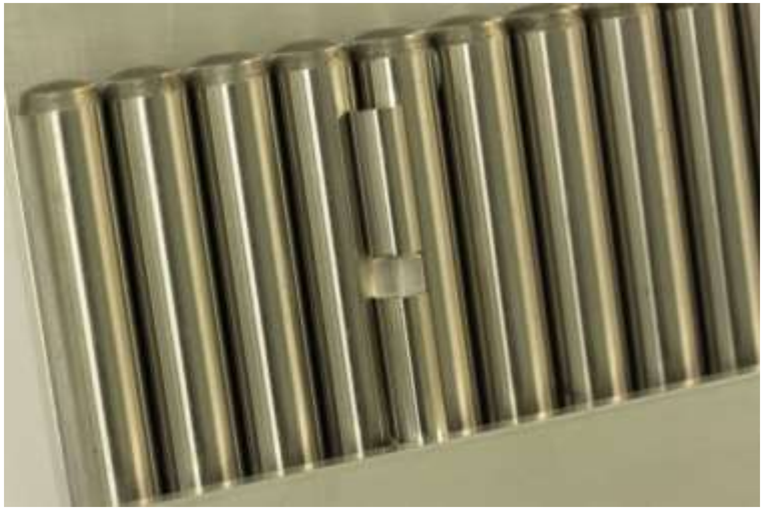
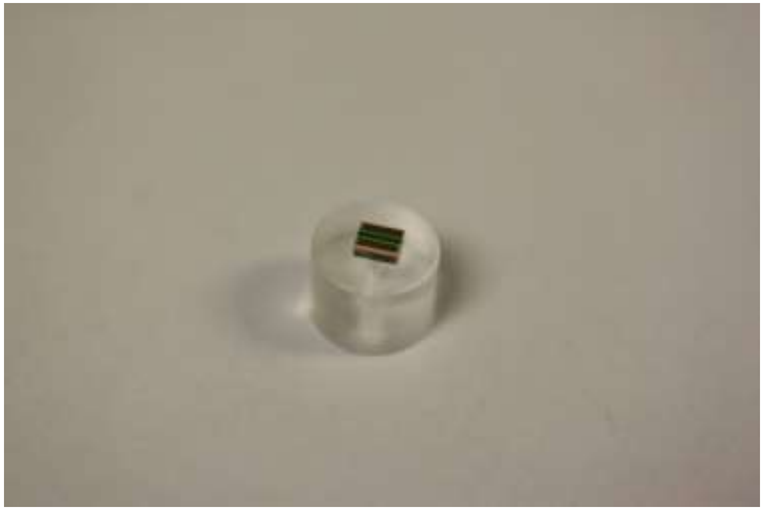
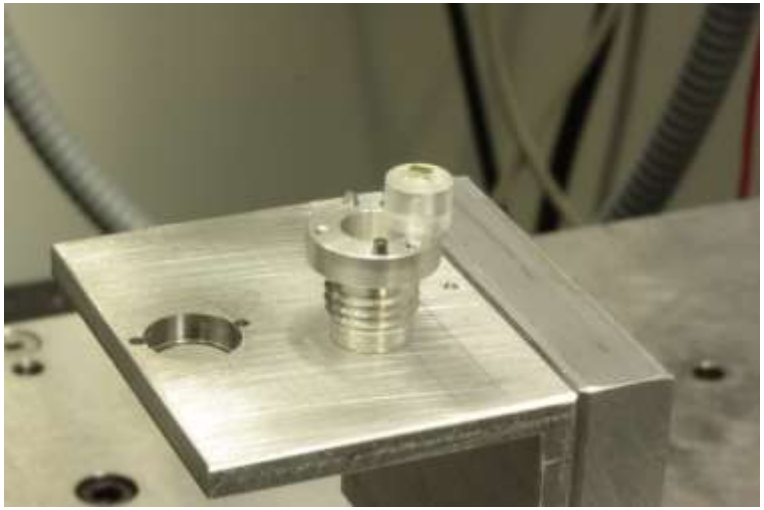
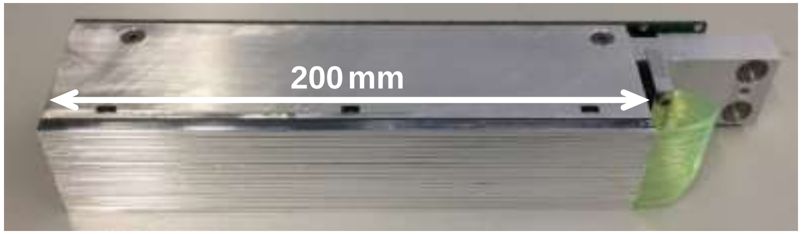


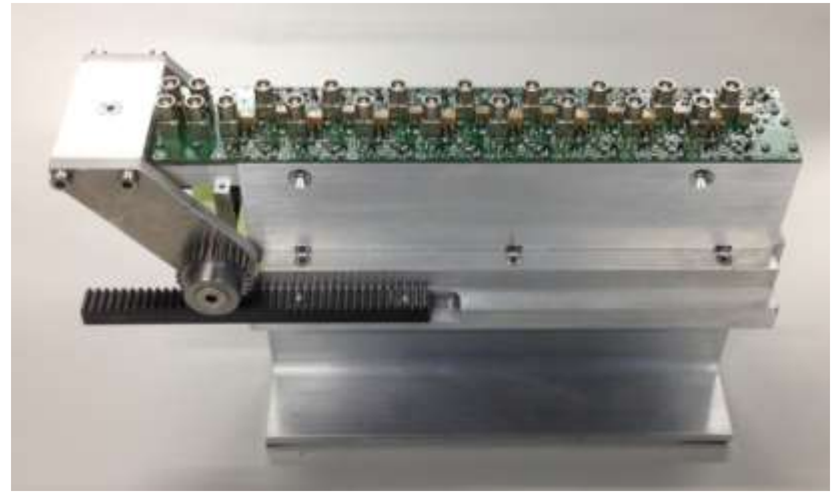


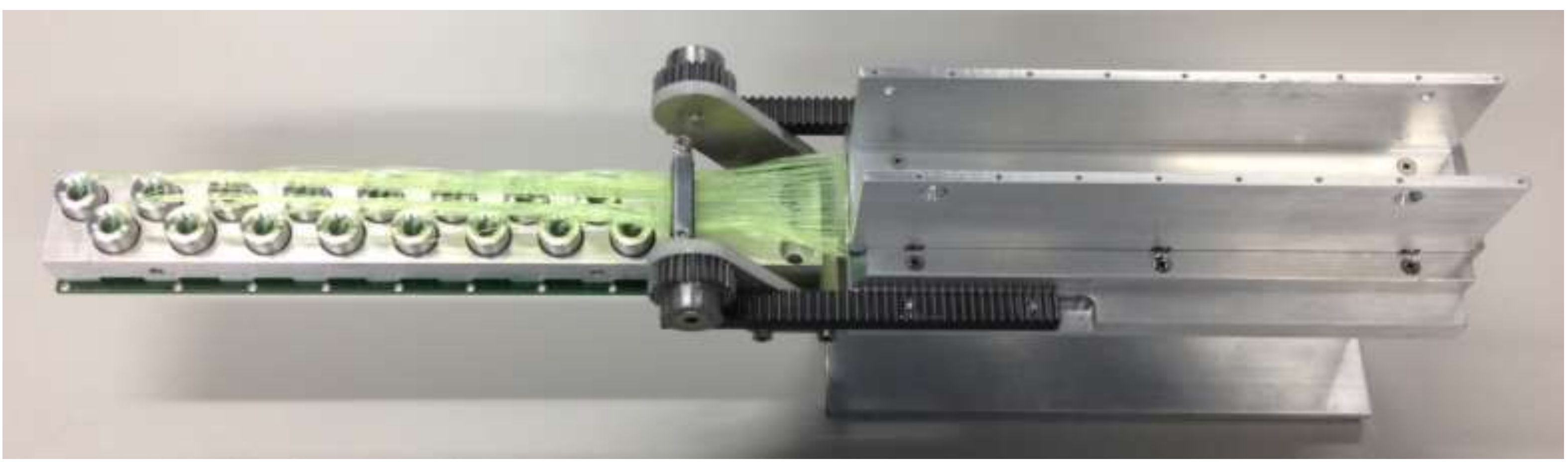




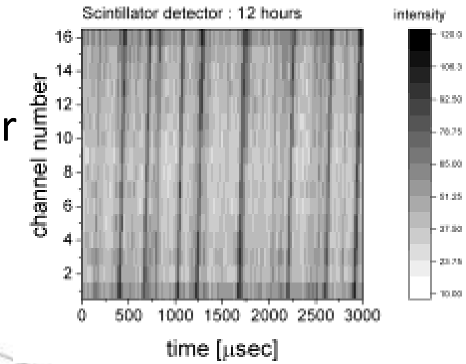
Mechanics of 16-Channel Module



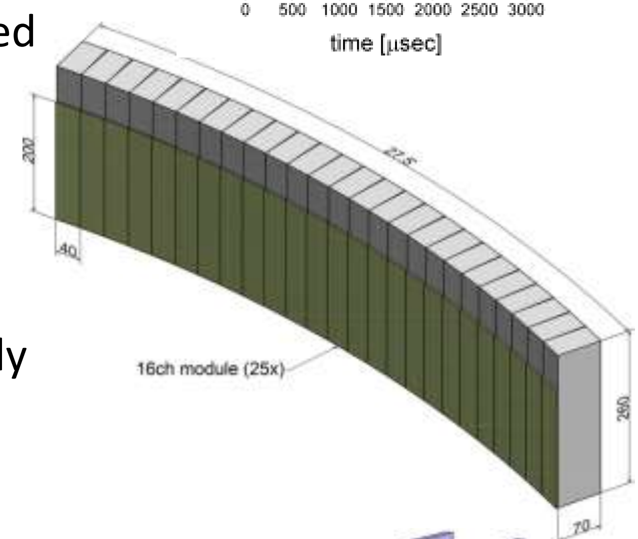




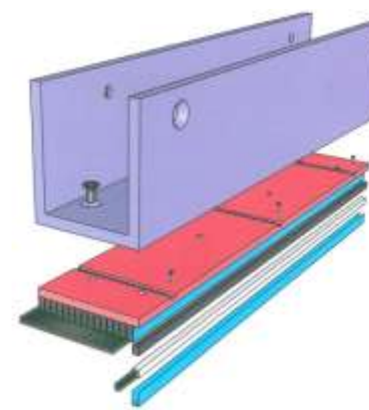
1D Detection Module



- 16ch module for POLDI time of flight neutron diffractometer
  - 1D resolution $(2.5 \times 200)\,\mathrm{mm}^2$, gapless arrangement in large detector banks
  - channels individually manufactured & assembled
    → single detection units exchangeable
  - $(1 \times 1)\,\mathrm{mm}^2$ SiPM can be used for single channel
    → longest life-time in radiation environment
    ~10 years at POLDI and room temperature
  - signals from each channel processed individually
    → maximum possible count rate capability

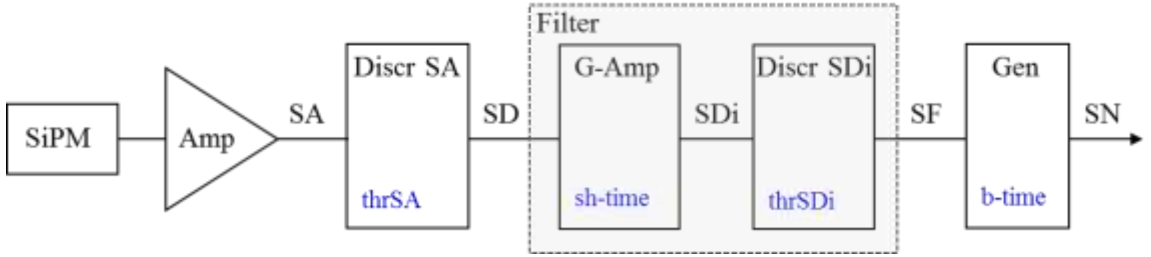


references: [1] J.-B. Mosset *et al.*, NIM A 845 (2017) 494-498
[2] A. Stoykov *et al.*, IEEE TNS 63 (2016) 2271

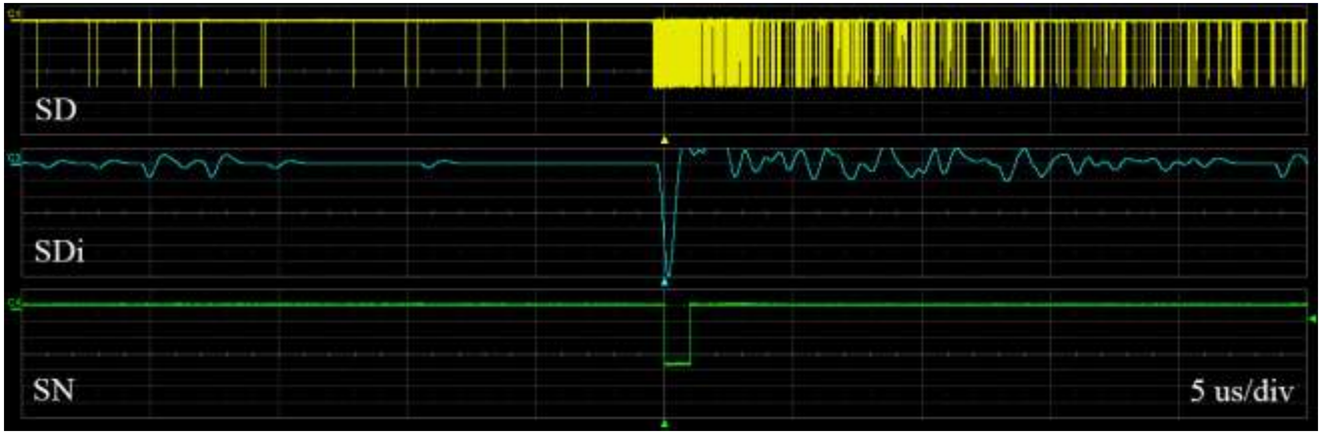


Signal Processing

- based on analysis of temporal distribution of single-cell SiPM signals
  → neutron events detected as an increase of the density of single-cell SiPM signals
- blocking times can be much shorter than emission time of scintillator



- FPGA-based solution
- scalable



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)

Performance (1 D Detector)

measured with Hamamatsu MPPC S13360-1350PE (1.3 x 1.3 mm^2)

Neutron detection efficiency at 1Å (10Å), %	65 (80)	55 (70)
… absorption probability at 1Å (10Å), %	80 (100)	
… trigger Efficiency [(a)], %	80	70
Background count rate, Hz/ch	$< 10^{-3}$	
Gamma sensitivity (with ^{60}Co)	$< 10^{-7}$	
Multi-count ratio	$< 10^{-2}$	
Dead time [(b)], µs	6	1.5
sustainable neutron count rate [(c)], kHz/ch	< 17	< 70
sustainable SiPM dark count rate [(d)], MHz	< 6	< 6
SiPM lifetime [(e)], years	> 10	> 10

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

(b) dead-time ≈ 6 · sh-time (with appropriate blocking time: b-time ≈ 4 · sh-time)

(c) to ensure the dead-time caused event losses ≤ 10%

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

(e) detector operation time until SiPM dark count rate reaches its sustainable value; in POLDI radiation environment: dark count increase ≈ 100kHz/mm^2/year at RT

Content

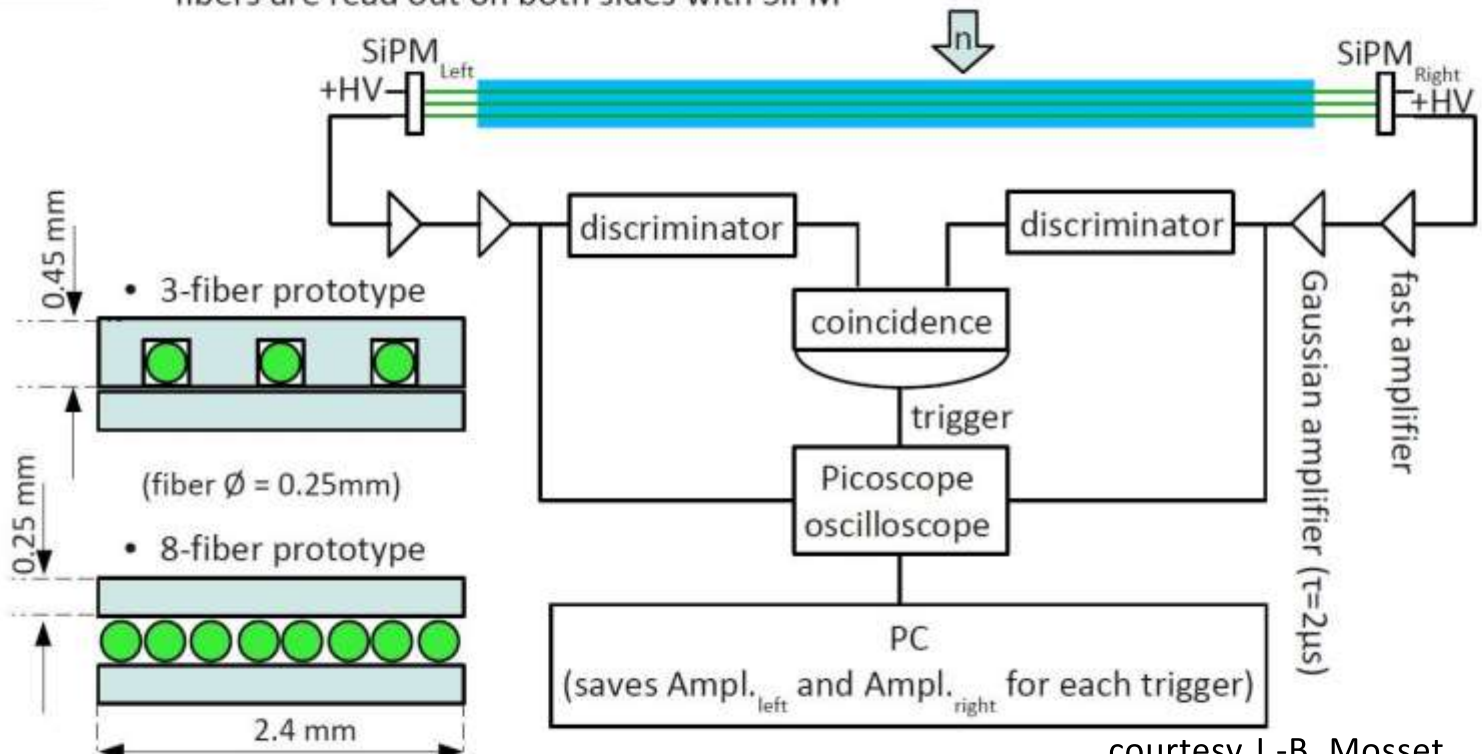
The development of a 2D thermal neutron detector – which is our proposal within SINE2020 WP9 – is based on our recent work on a 1D detector.

→ content of the talk:

- technical details of 1D thermal neutron detector
- approaches for 2D thermal neutron detector

2D – Light Sharing Approach

- ZnS:^{6}LiF detection unit
  - sensitive area (2.4 × 200) mm^2
  - WLS fibers with short attenuation length (λ≈15cm) especially developed by Kuraray for this study (core doped with 2wt% PMMA)
  - fibers are read out on both sides with SiPM



courtesy J.-B. Mosset

WLS fiber:
- short attenuation length ($\lambda_{att} \approx L_{detection\,unit}$)
- homogeneous

2D – Light Sharing Approach

Conlusion

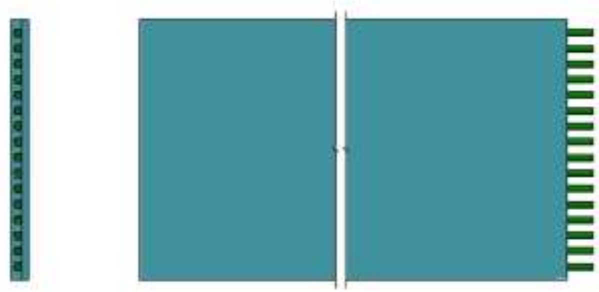
- The first kilometers of WLS fibers with a very short attenuation length of ~15 cm have been produced (Kuraray)
- Uniformity of the attenuation length of the fibers has to be improved
- Results concerning the light sharing approach are very encouraging
- Performances could meet the specifications of the ESS neutron diffractometers, in particular for Heimdal:

gamma sensitivity < 10^{-6}	OK
detection efficiency ≥ 65 % @ 1.2 Å	OK
spatial resolution horizontally: 3 mm	OK
spatial resolution vertically: 10 mm	OK (if standard deviation)
Local instantaneous peak count rate: 4 kHz/cm^2 (--> 24 kHz/strip)	OK with a 1µs shaping time: • Extendible dead time of ~6µs • 13 % losses • 2.4 % of events with a wrong reconstructed position due to pile-up
Area : 7m^2 (~10^4 sensitive strips)	Mass production seems realistic

courtesy J.-B. Mosset

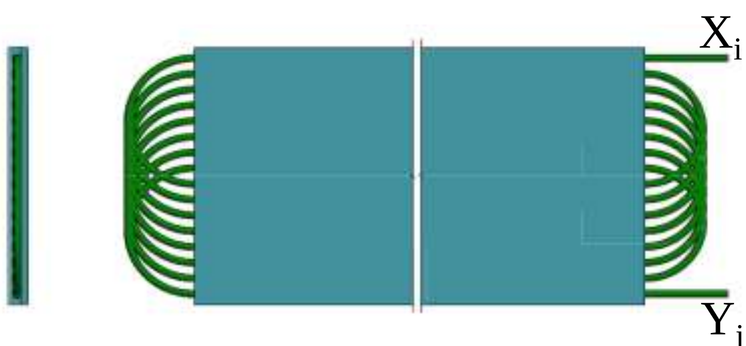
2D – Pixelated Design (2D gapless coverage)

V1a



V1b

V2



individual pixel readout scheme (V1a, V1b):

- ZnS:^{6}LiF scint. (0.45mm + 0.25mm thick strips)
- grooves in 0.45mm strips
- embedded WLS-fibers Ø = 0.25mm
- each pixel is readout by a single SiPM

coded pixel readout scheme (V2):

- ZnS:^{6}LiF scint. (0.45mm + 0.25mm thick strips)
- grooves in 0.45mm strip
- single embedded WLS-fiber Ø = 0.25mm
  - bending the fiber at T ≈ 60 ^{o}C
  - min. bending diameter ≈ 4.5mm

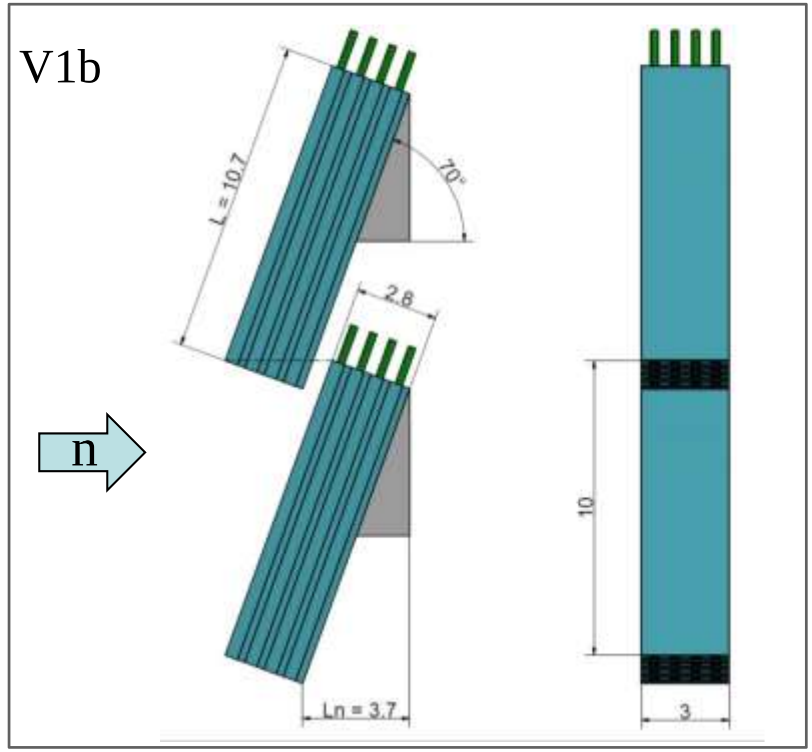
→ suitable for XY-coding
e.g. matrix of 10 $\times$ 10 pixels can be readout
with 20 SiPMs with $(1 \times 1)\,\mathrm{mm}^2$ active area

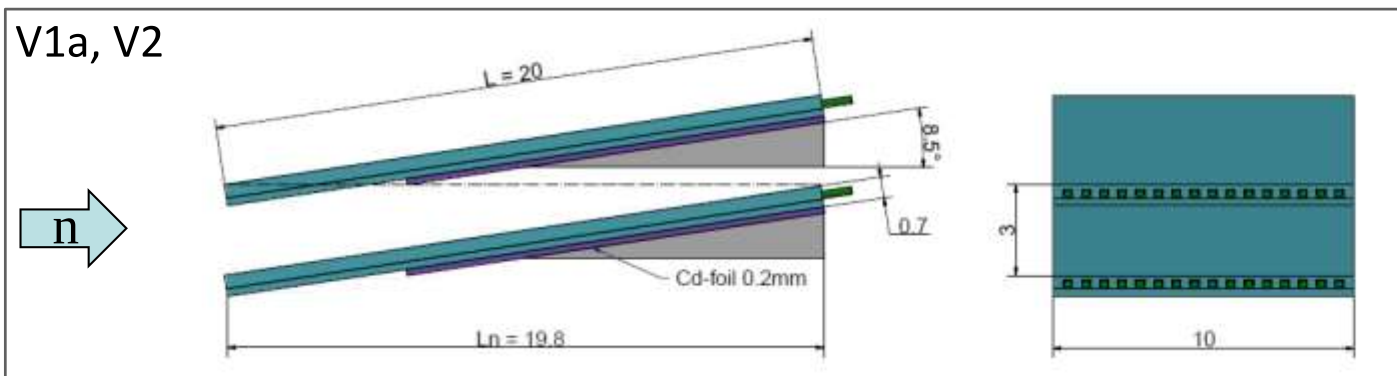
2D – Pixel Arrangements into Arrays

- tilted pixel arrangement to adjust:
  - arrangement of WLS fibers
  - "effective" pixel size
  - "effective" neutron path length in scintillator for neutron absorption probability according requirement

→ intrinsic time resolution:
  - uncertainty of neutron interaction time along length in neutron flight direction L_n
    σ_{int} [µs] ≈ 0.073 · L_n [mm] · λ [Å]

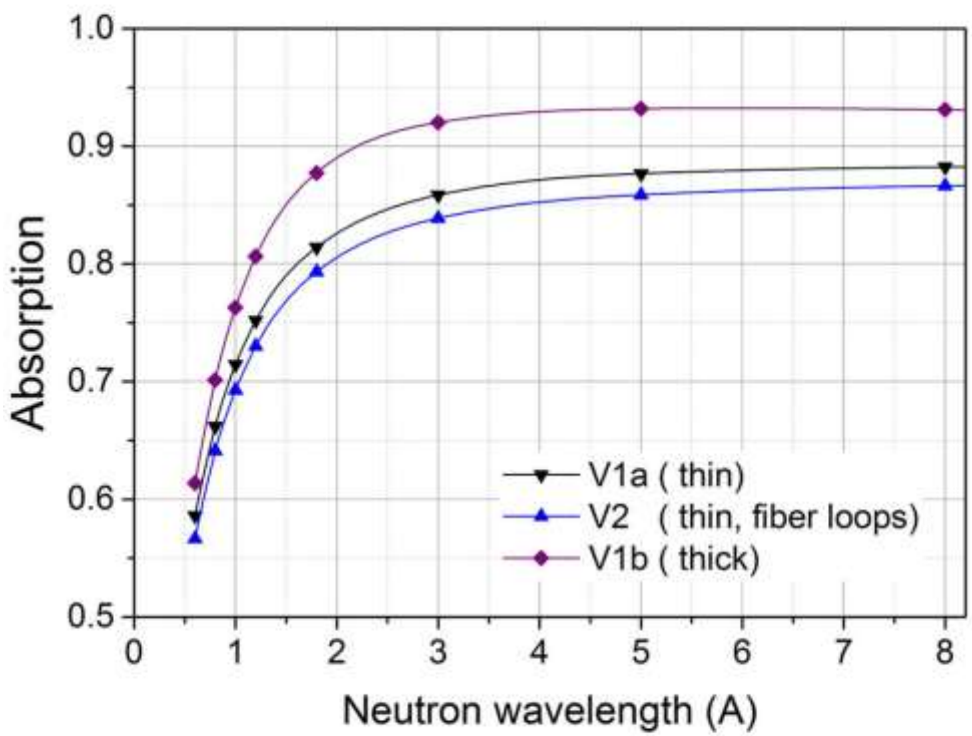
  → V1b: σ_{int}[µs] ≈ 0.3 · λ [Å]
  V1a, V2: σ_{int}[µs] ≈ 1.5 · λ [Å]



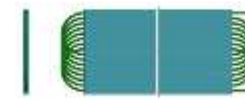


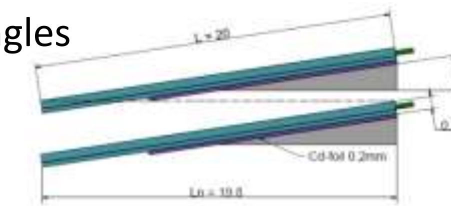
Neutron Absorption Probability (MC)

- due to scattering, some neutrons will be absorbed in "wrong" channel
  → leads to deterioration of spatial resolution
- pixel array, individual pixel size $(3 \times 10)\ \mathrm{mm}^2$
- to preserve good spatial resolution also at short wavelengths:
  - thick pixels at large tilting angles (pixels V1b)
  - additional absorbing plates in case of thin pixel at small tilting angles

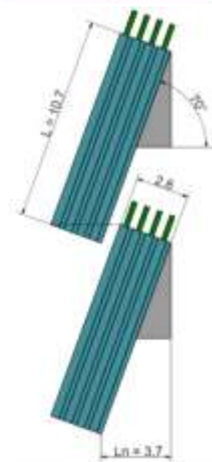



V1a


V2




V1b



Performance (2D Detector)

Pixel type	V1	V2
Readout type	individual	coded, M=10
Neutron detection efficiency at 1Å, %	**65**	**50**
… absorption probability at 1Å, %	80	80
… trigger efficiency, %	80	60
Background, Hz	10^{-3}	
Gamma sensitivity	10^{-7}	
Multi-count ratio	10^{-2}	
Dead time of readout channel Δ_d , µs	6	1.5
XY-coincidence resolving time Δ_c , µs	--	0.5
Max. local instantaneous peak rate, kHz/pixel (required for NPD detector at ESS ≈ 1 kHz/pixel)	**17**	**2.5**
Sustainable SiPM dark count rate, MHz	< 6	< 4
SiPM lifetime [a)], years	> 10 (needs to be confirmed on site)	

a) estimate for HEIMDAL NPD detector at ESS for global time-averaged neutron flux on sample = $2 \cdot 10^9$ 1/cm^2/s

Neutron Detector - PSI Approach

Requirements for materials and components:

- ZnS:Ag/^{6}LiF scintillation screen
  - high neutron absorption efficiency
  - high light yield
  - high transparency
- wavelength shifting (WLS) fibre
  - high "conversion" efficiency (c_{dye} vs λ_{att})
  - single-sided readout: long λ_{att}
    double-sided readout: $\lambda_{att} \approx L_{detection\,unit}$
    homogeneous
- Silicon Photomultiplier (SiPM)
  - high PDE
  - low dark count rate
  - low after pulsing
  - radiation hard (n, γ)
- manufacturing
  - optical coupling
  - SiPM exchangeable
    (depending of cost SiPM vs cost detection unit)
- digital signal processing system
  - FPGA-based
  - scalable

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Summary

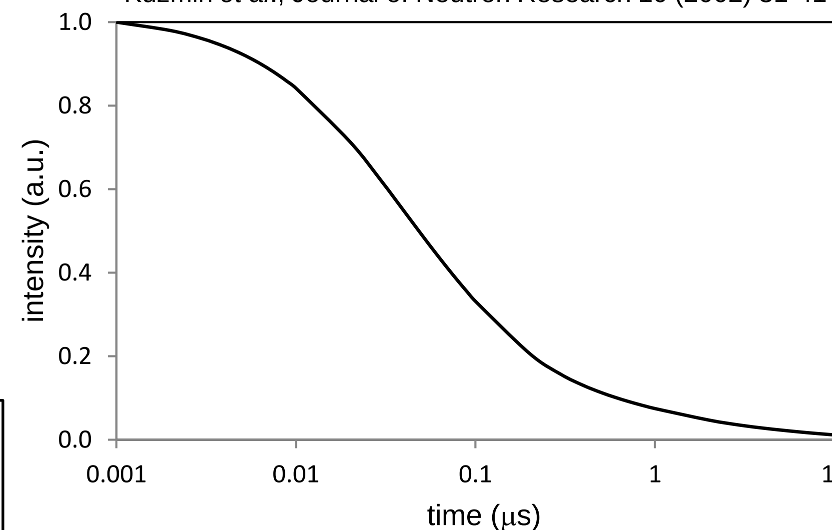
ZnS:Ag/^{6}LiF scintillator*

* e.g. Scintacor, scintillation screen ND 2:1

- neutron absorption: $^6\text{Li} + {}^1\text{n} \rightarrow {}^3\text{H} + {}^4\text{He} + 4.79$ MeV , $\sigma = 940 \cdot \lambda / 1.8$ barn ($[\lambda] =$ Å)
- high light yield: 160 000 photon / neutron
- non-transparent: collected light is
  - limited → small number of detected photons
  - non-uniform → large dynamic range of signals
- long emission time:
  - 25% photons within 1 μs
  - 60% photons within 10 μs

→ artificial dead time needs to be implemented in signal processing to avoid multiple triggers

Kuzmin *et al.*, Journal of Neutron Research 10 (2002) 31-41



requirements:
- high neutron absorption efficiency
- high light yield
- high transparency

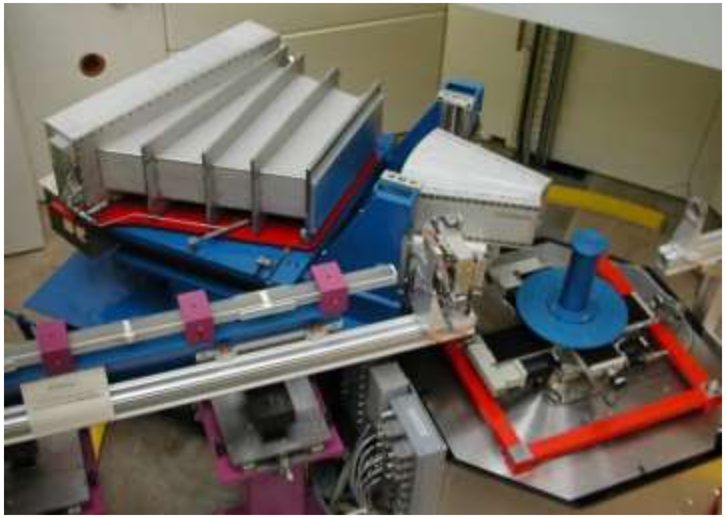
Framework - 1

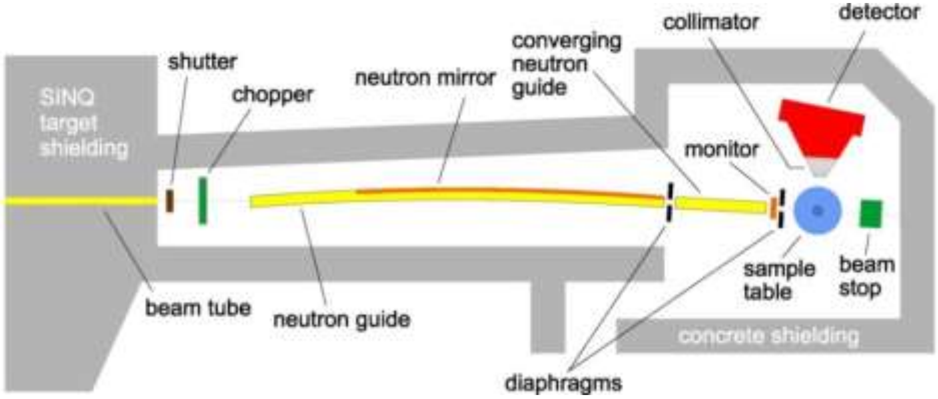
POLDI neutron beam line at SINQ (PSI)

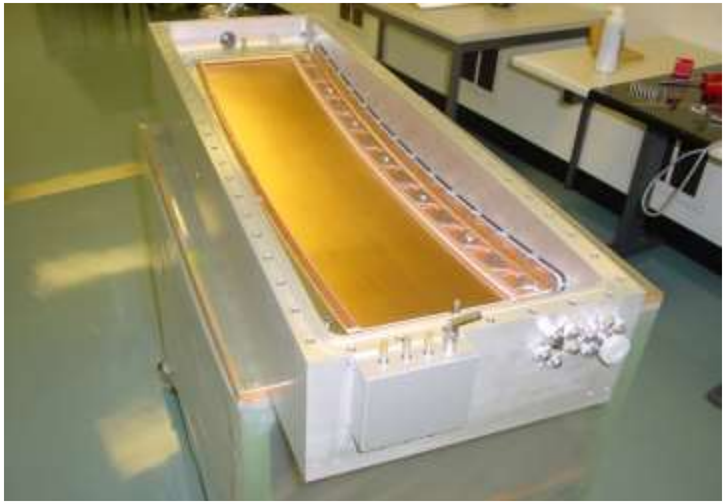
- time-of-flight neutron diffractometer
- strain measurements: accurate determination of lattice spacings

current detector

- single ^{3}He wire chamber (1-dimensional)
- in operation since 2001
  refurbishment 2012/13
  gas cleaning 2016/17



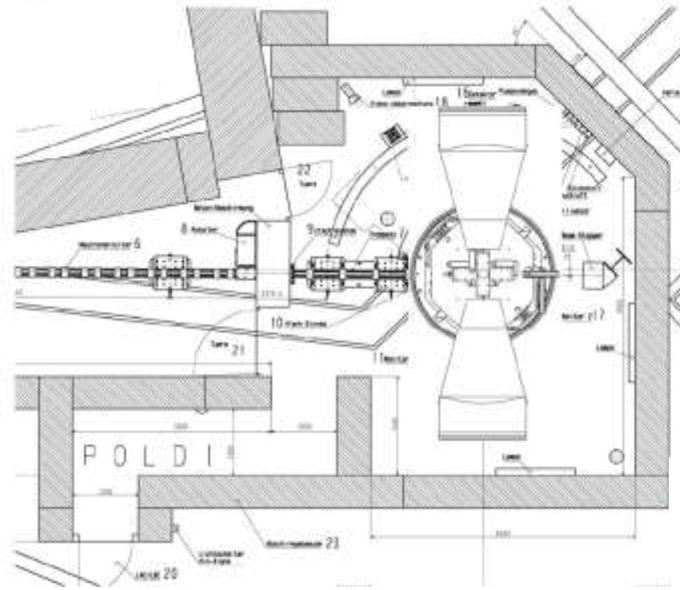




Framework - 2

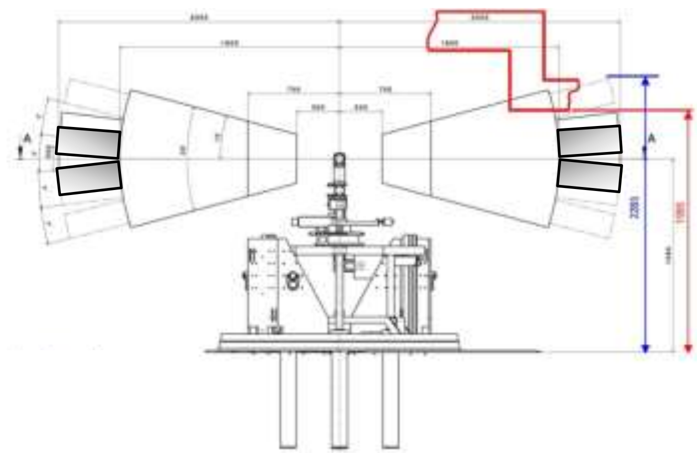
POLDI upgrade program ("on stand-by")

- two oppositely placed detector banks
- rather stringend spatial boundary conditions:
  → 2 modules on each side



detector requirements

detector modules	2 x 2
radius	2000 mm
channel width / height	2.5 mm / 200 mm
channels per module	400
size of one module	(1 x 0.2) m^2
neutron wavelength	1 - 6 Å
detection efficiency	≥ 65 % @ 1.2 Å
time resolution	≤ 1 μs
sustainable count rate (per channel)	4 kHz
gamma sensitivity	< 10^{-6}
quiet background rate (per channel)	< 0.003 Hz

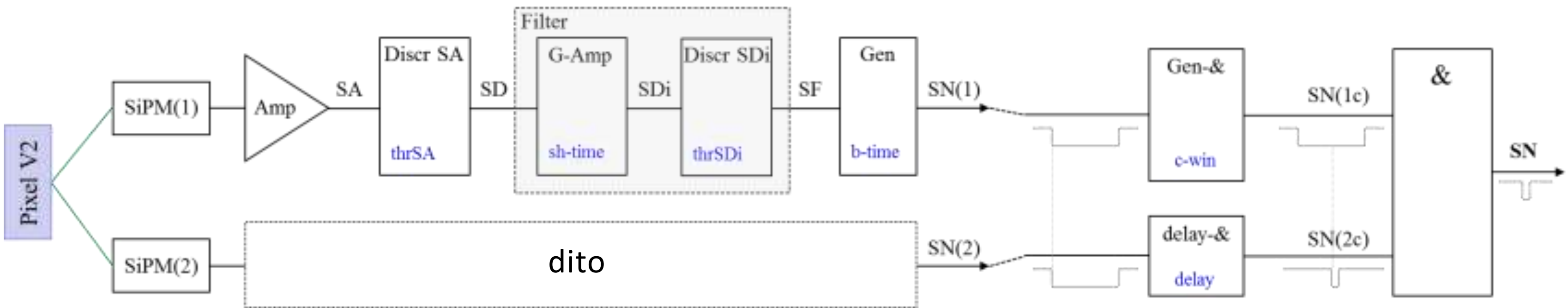


remark: our detector design (16-ch module) fulfils these requirements!

Signal Processing System

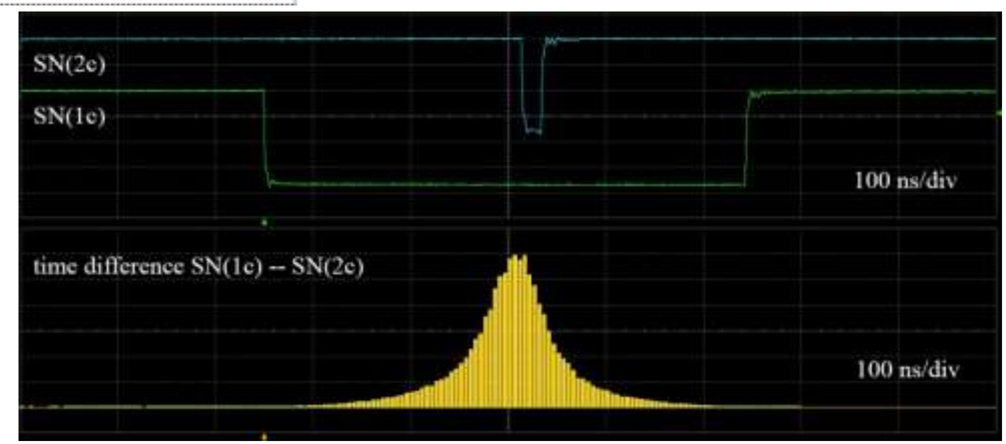
pixel design V1, direct readout:

- sh-time = 1 μs
- b-time = 4 μs
- $\Delta_d \approx 6$ μs



pixel design V2, coded readout:

- sh-time = 0.25 μs
- b-time = 1 μs
- $\Delta_d \approx 1.5$ μs
- $\Delta_c \approx 0.5$ μs



SiPMs (in all cases):
MPPC S13360-1350PE at ΔU ≈ 4V