M. Hildebrandt, J.-B. Mosset, A. Stoykov :: NUM :: Paul Scherrer Institut

Neutron detector based on ZnS:^{6}LiF scintillator read out with WLS fibers and SiPMs

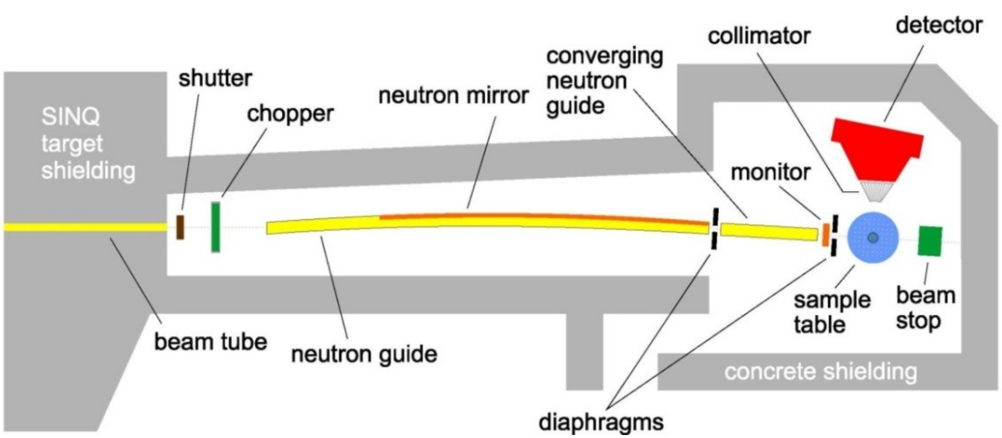
ESS HEIMDAL Detector Workshop, Villigen PSI, 14.03.2016

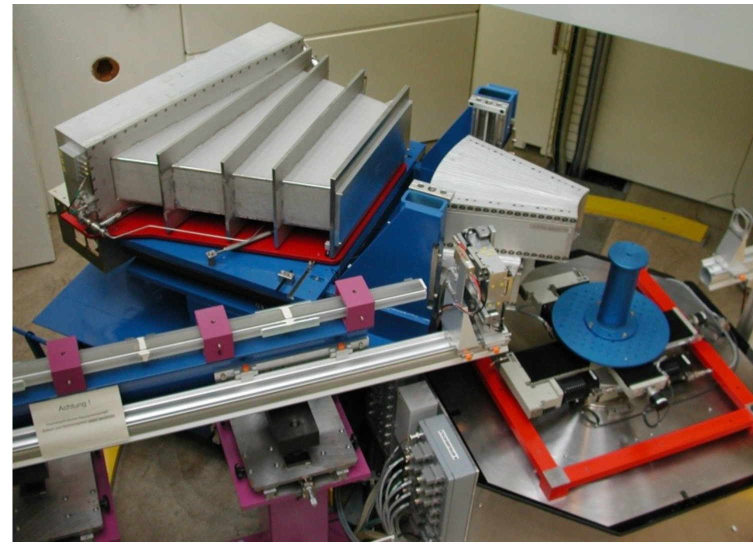
Framework

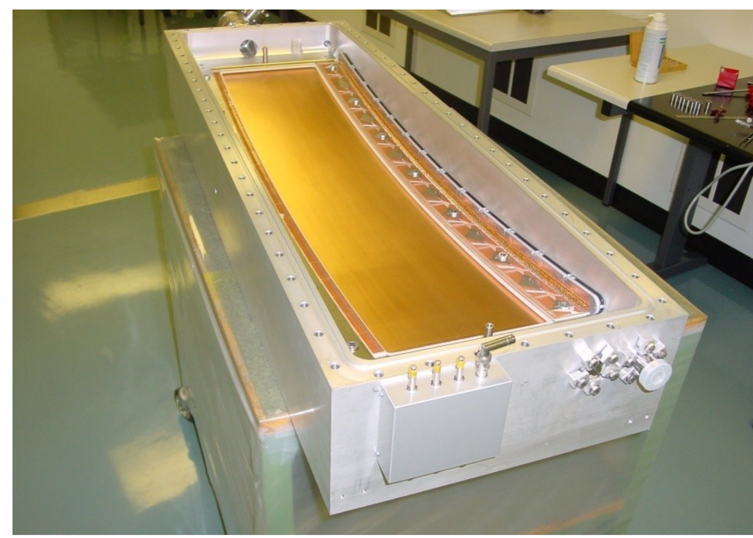
POLDI neutron beam line at SINQ (PSI)
- time-of flight neutron diffractometer
- strain scanner
  --> residual stress
  --> in-situ deformation sutdies

current detector
- Single 3He wire chamber
- 1-dimensional position sensitive
- in operation since 2001

program for the upgrade of the neutron detection started in 2013







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Framework

POLDI upgrade program: add a second detector

- oppositely placed to the current one
- same level of performance
- same geometry

Goal of the upgrade
simultaneous measurement of axial and transverse strain components during in-situ deformation studies

detector requirements

sensitive area	(1 x 0.2) m^2
radius of curvature	2 m
number of channels	400
channel width / height	2.5 mm / 200 mm
neutron spectrum	1 – 5 Å
detection efficiency	≥ 65 % @ 1.2 Å
time resolution	≤ 2 µs
sustainable count rate	4 kHz / channel
quiet background rate	< 0.003 Hz / channel
gamma sensitivity	$< 10^{-6}$

Helium-3 shortage
--> Duplication of the current detector not possible

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ZnS(Ag)/^{6}LiF scintillator

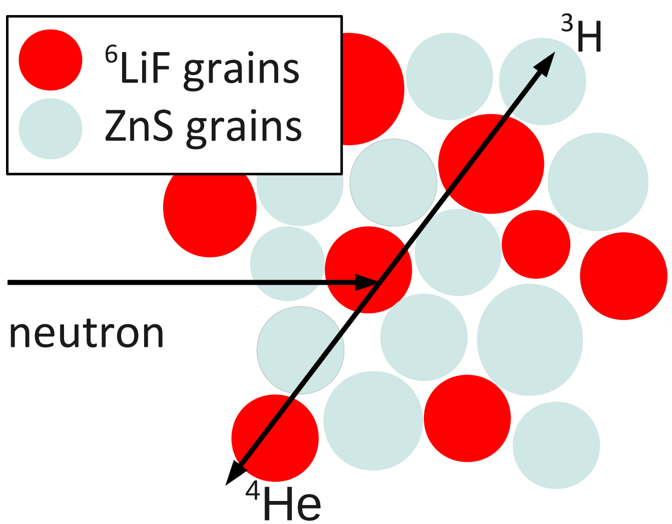
ZnS/^{6}LiF scintillator is a mixture of:

- ^{6}LiF powder (grain Ø ≈ 10 µm)
- ZnS powder (grain Ø ≈ 10 µm)
- Plexiglas (as a binder material)

neutron absorption:

^{6}Li + ^{1}n → ^{3}H + ^{4}He + 4.79 MeV

(σ = 940·λ / 1.8 barn ([λ] = Å)



ND2:1 scintillation screen (Scincator)

Mass ratio ZnS:^{6}LiF	2 : 1
Density	2.2 g/cm^3
^{6}Li atoms density	1.4 x 10^{22} atoms/cm^3
att. coeff. at 1.2Å	1 mm^{-1}
Emission peak	450 nm
ZnS light yield	160'000 photons / n
transparency	0.4 mm is almost opaque
thickness	0.25 mm, 0.45 mm

luminescence

Time interval	0-1µs	0-10µs	0-80µs
Emitted photons	25%	60%	90%

ZnS:^{6}LiF is the unique commercially available scintillator that is suitable for the POLDI requirements.

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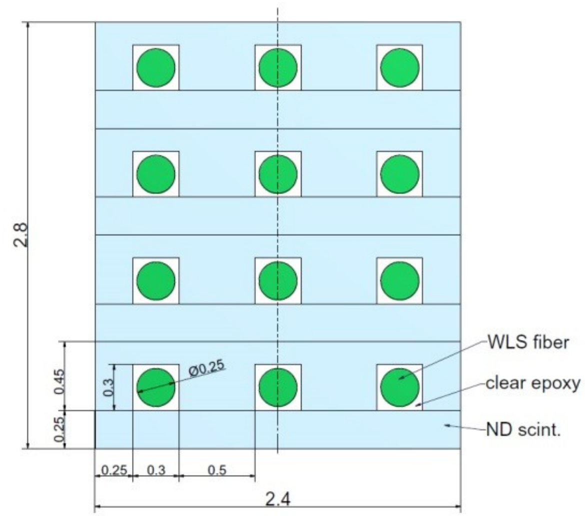
Single channel detection unit

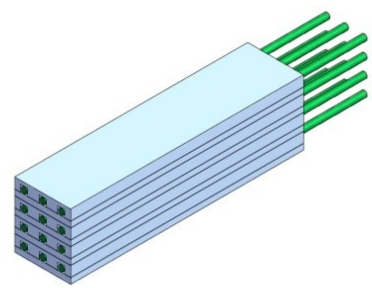
Approach: stack together several thin scintillation screens and collect their scintillation light with WLS fibers uniformly distributed in the detection volume.

--> efficient and uniform light collection

--> high neutron absorption probability

1-channel: 4 layers and 12 fibers





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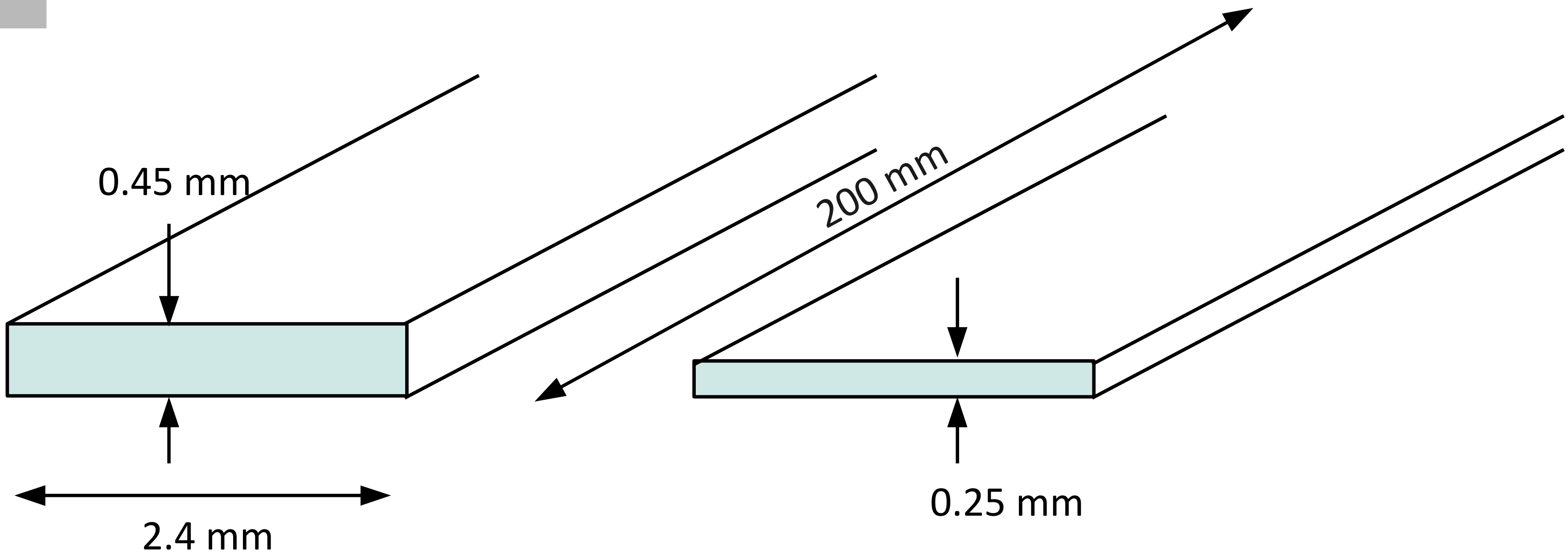
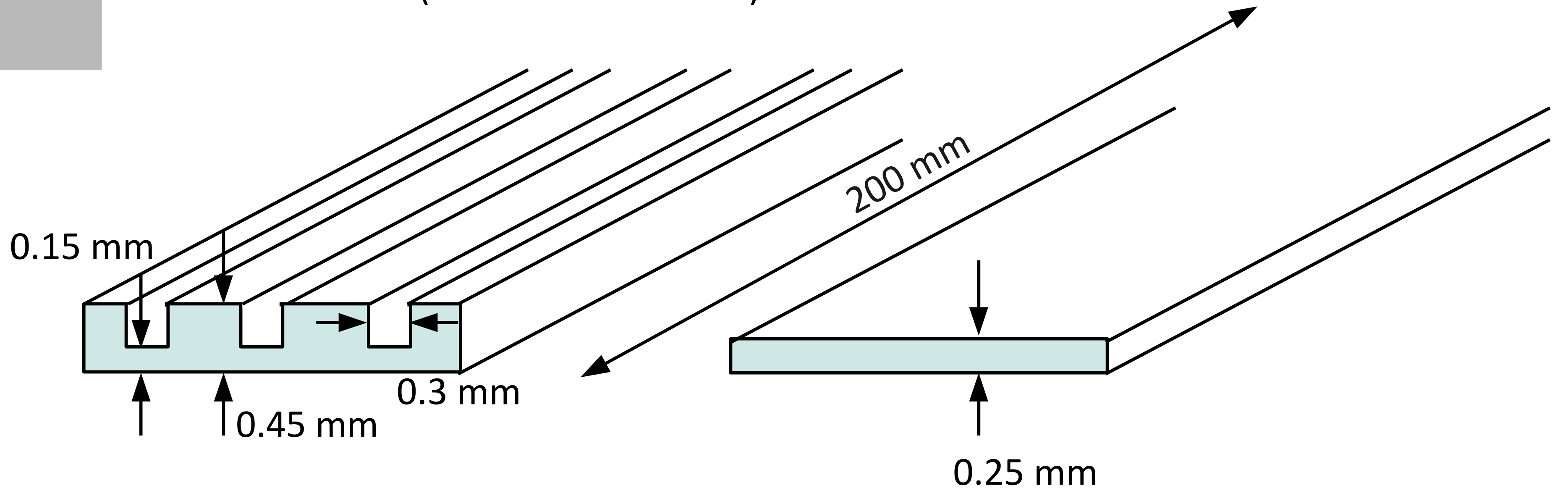
Manufacturing of a single channel detection unit

1st step: cut 0.25 and 0.45 mm thick strips of 2.4 x 200mm²



Manufacturing of a single channel detection unit

2nd step: machine grooves in the 0.45 mm thick strips
(with a train of saws)



Remark: Now, Scintacor also delivers scintillator sheets with grooves.
(the manufacturing is not a problem since the scintillator sheets are cast)

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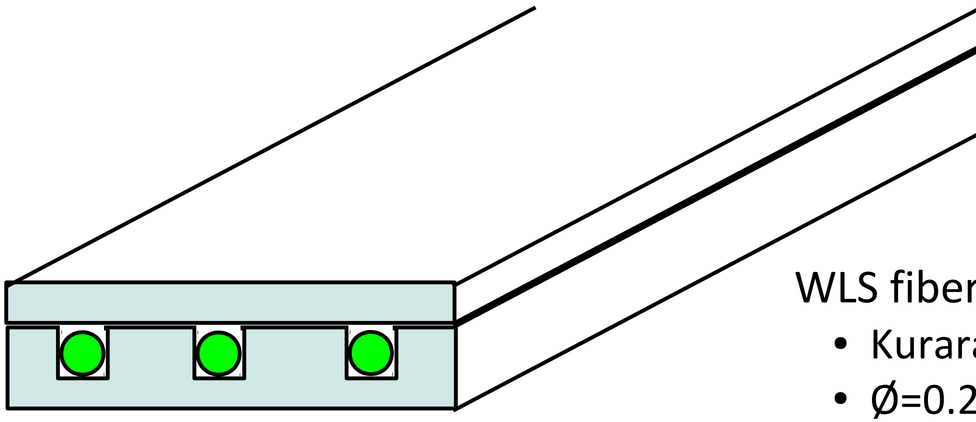
Manufacturing of a single channel detection unit

3rd step: glue WLS fibers in the grooves as well as a 0.25mm thick strip on the top



WLS fibers

- Kuraray Y11(400)M
- Ø=0.25mm

Eljen EJ-500 optical epoxy

4th step: glue 4 sandwiches on the top of each other

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Single channel detection unit

ND2:1 layers
- w/o grooves, 0.25mm
- w/ grooves, 0.45mm

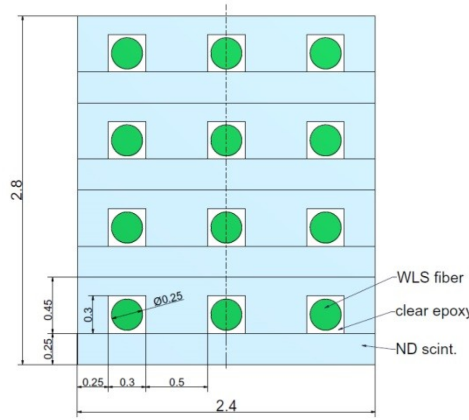
WLS fibers
- Kuraray Y11(400)M
- Ø=0.25mm
- embedded in scintillator grooves

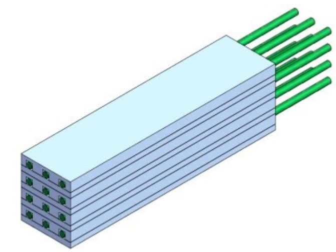
Eljen EJ-500 optical epoxy

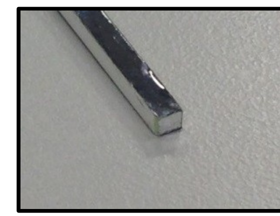
detection unit
- front end: fibers polished and mirrored
- rear end: fibers glued in a plexiglas block, polished and coupled to a SiPM
- efficient and uniform light collection
- with 4 layers:
  - → neutron absorption of 82% @ 1.2 Å
  - → intrisic time resolution < 1 µs

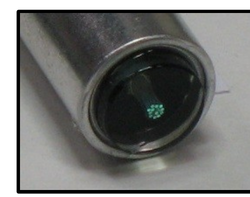
This unit represents an elementary building block of full-size detector.

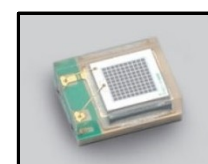
1-channel: 4 layers and 12 fibers











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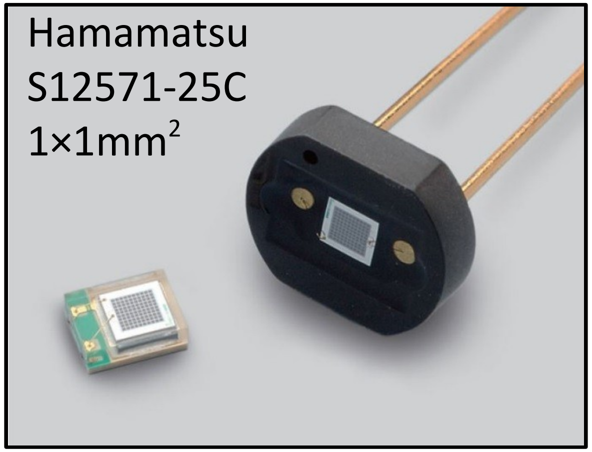
Silicon photomultiplier (SiPM)



advantages for this application

- high PDE ~35% @ 500 nm (<25% for PMT)
- insensitive to magnetic fields
- compact
- low cost ~30 CHF
- excellent single photon counting capability

drawbacks for this application

- dark counts ~ 100 kHz
- cross talk ~ 20 %
- afterpulses ~2 %

} Initial concern: contribute to signal fluctuations during long integration times

- increase of the dark count rate due to accumulated radiation damage
  - → irradiation test in POLDI beamline with 1x1 mm^2 SiPM: increase of ~ 90kHz/year
  - → measurements with non-irradiated SiPM and LED induced additional "dark count rate" up to 17 MHz

Optimization of the light collection efficiency

crosstalk artificially suppressed with the "digitization" of the SiPM signals

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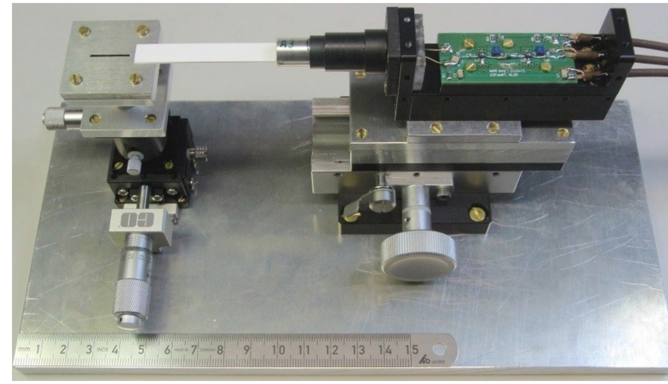
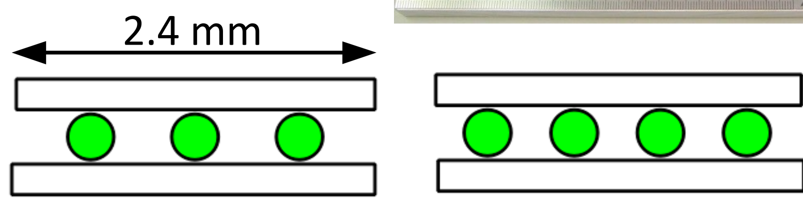
Test of different structures for the sensitive volume



bottom side of the prototypes irradiated with an α-source

Design of the existing detectors based on ZnS/^{6}LiF screens read out with WLS fibers (air gap)

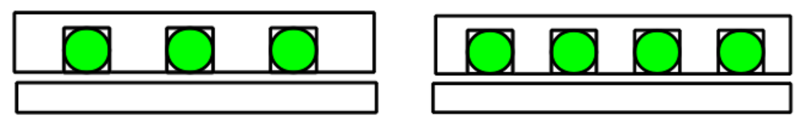


0.81 **0.87**

Relative number of detected photons

1 **1.06**

New PSI approach (with embedded fibers)



prototypes with embedded WLS fibers:
- provide 20% more light (good optical coupling between fibers and scintillator)
- are easier to produce

it is not worth to use 4 WLS fibers:
- little increase of light collection
- more dead space
- more hydrogen (scattering)

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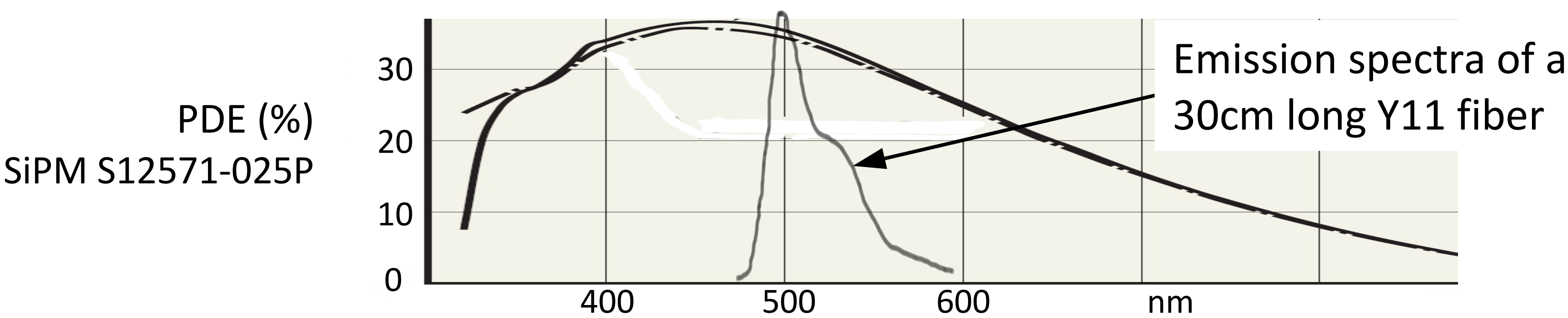
Test of different WLS fibers and SiPMs combinations

	number of photo-electrons in 10 μs		
Fiber Type	**Hamamatsu** S12571-025P	**Ketek** PM1175-B72T89S-Q3	**AdvanSiD** ASD-RGB3S-P-40
Y11(400)M	113	113	97
Y11(200)M	95	100	80
Y7(400)M	107	107	102
Y8(400)S	102	102	101
BCF91A	79	85	73
BCF92	57	63	56
F201B	62	69	61
F203B	64	69	67

Our choice: Y11(400)M from Kuraray + SiPM S12571-025P from Hamamatsu



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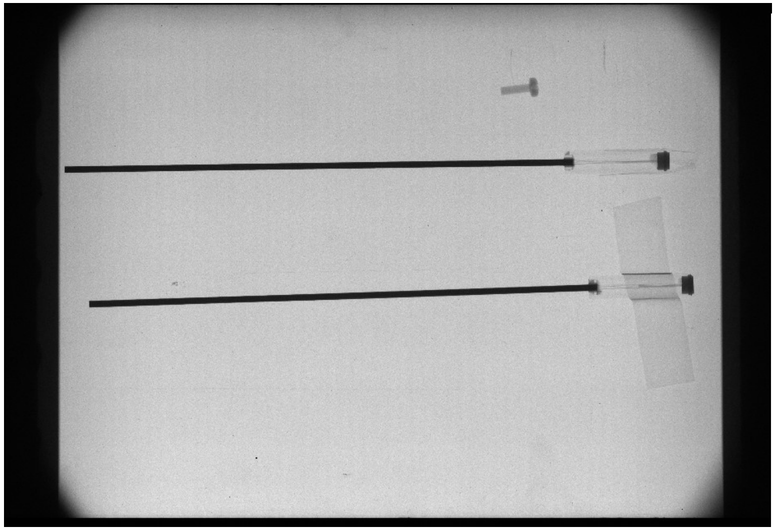
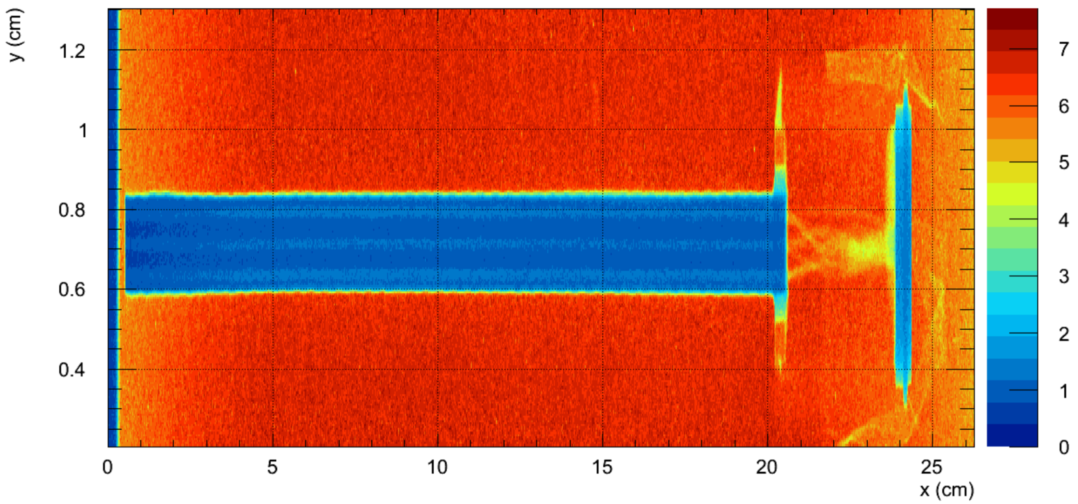
Uniformity of the neutron absorption efficiency

neutron radiography of 2 single channel 20 cm long detection unit performed with an imaging plate in the NEUTRA beamline in SINQ

- each strip is segmented into 20 1cm wide regions
- calculation of the relative StDev over the 40 regions
  --> StDev / mean = 0.6 %

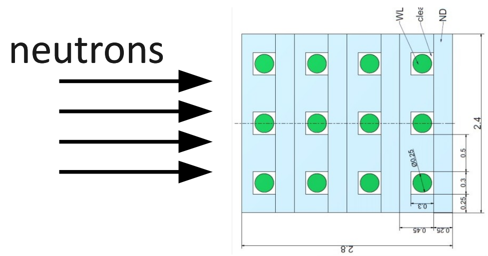


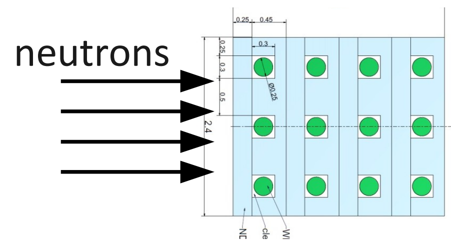


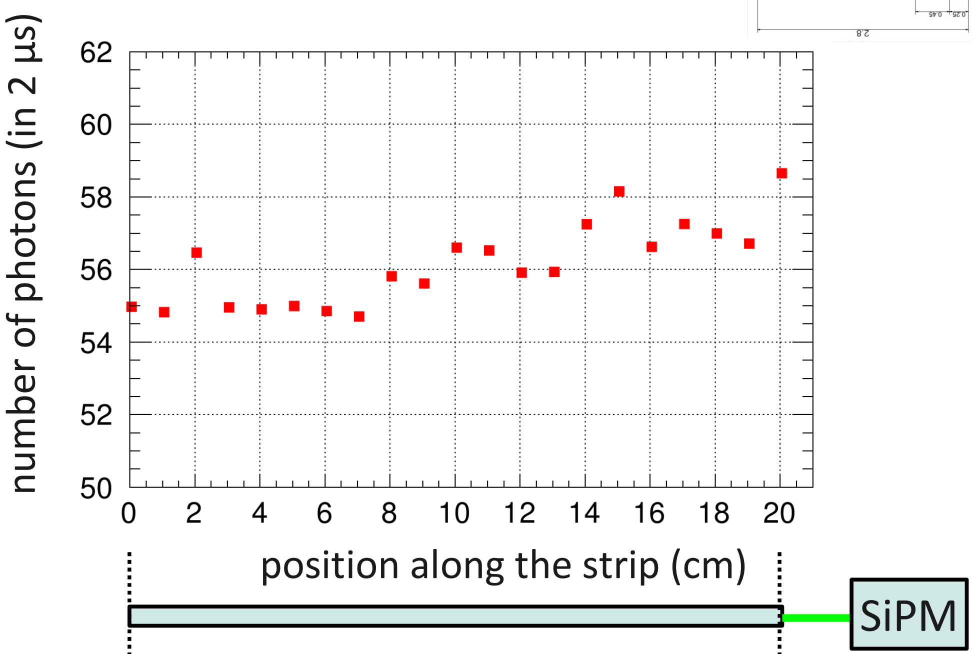
Uniformity of the trigger efficiency along the 20cm long layered assembly

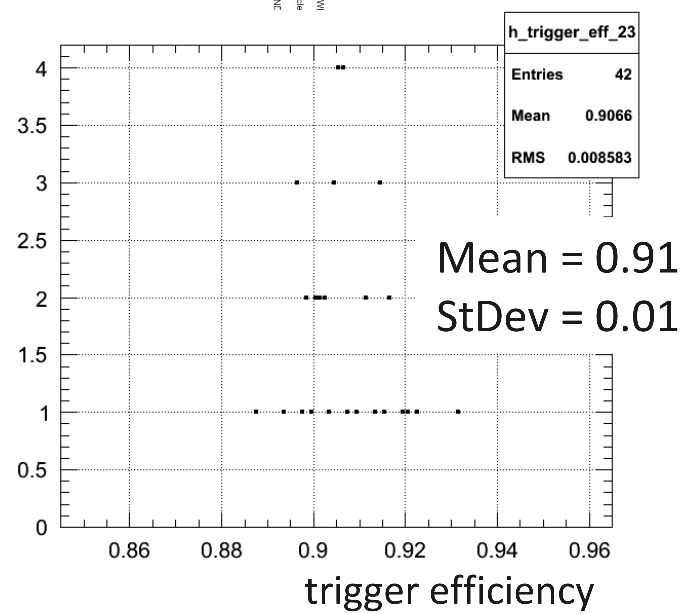
Measurement in the ORION beamline

- scintillator strip scanned from one extremity to the other with a 1cm step
- beam size set to 1mm (direction of the strip) x 5mm
- Neutron wavelength = 2.2 Å --> 74% of the neutrons are absorbed in the first 2 sandwiches
  --> 2 scans are performed: top side facing the beam, bottom side facing the beam

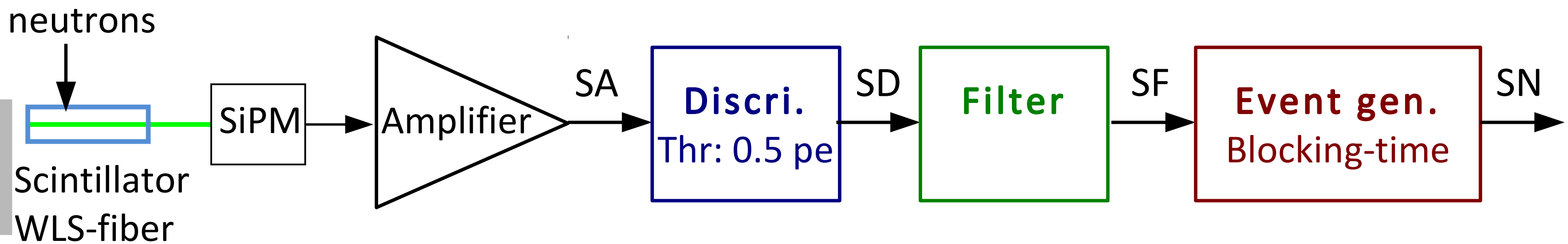






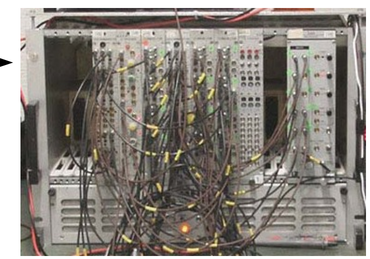


Signal processing System



- leading edge discriminator --> one SD pulse generated, independant of number of fired cells --> suppression of SiPM crosstalk due to "digitization" of SiPM pulses

- filter (examples)
  (1) consecutive delayed self-coincidence on SD-pulse sequence →
    - our initial approach
    - can be implemented with a NIM electronics
    - has been used for the detector development
    - no differentiation --> rather large dead time --> effective thr. depends on dark count rate

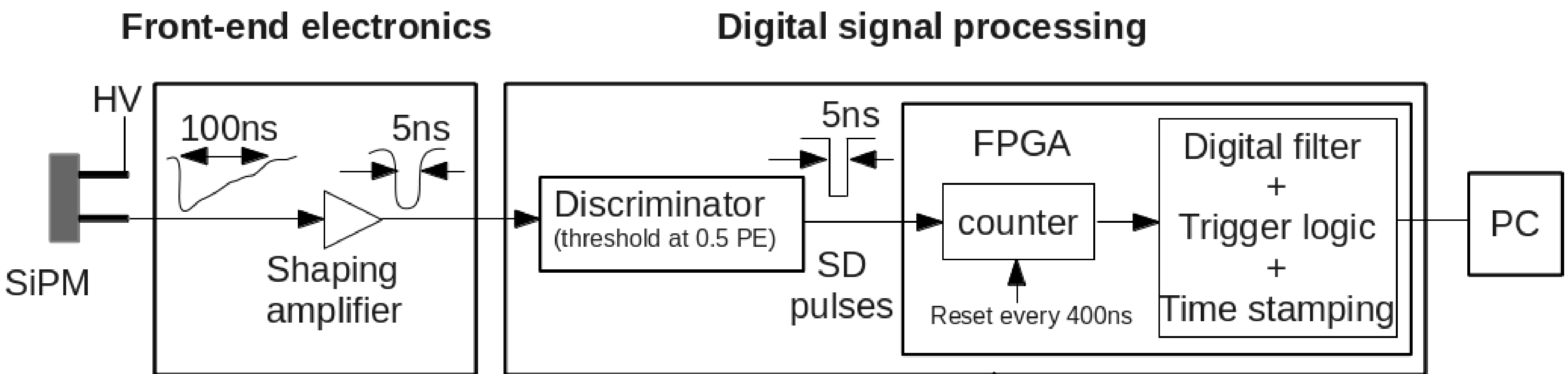


  (2) analog $CR\text{-}RC^4$
    - our currently used filter in the lab
    - more efficient and compact than filter (1)

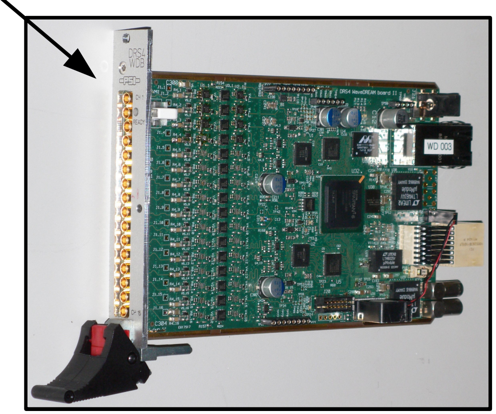
  (3) digital filter (moving sum, moving sum after differentiation, digital $CR\text{-}RC^4$ etc ...)

- "Event generator" --> prevent multiple triggers on the same event due to after-glow photons --> trade-off between pulse-pair resolution (dead time) and multi-count ratio

Digital Signal processing for the new POLDI detector



- sampling of the density of SiPM counts every 400ns
- digital filtering of the sampled signal
- triggering conditions:
  - channel ready (after each trigger, blocking time to prevent multiple triggers)
  - filter output is maximum (time stamp)
  - Filter output higher than the threshold



Digital filter: moving sum after differentiation (MS+DI)
(requires very little computational ressources)

x_i = filter input, z_i = filter output

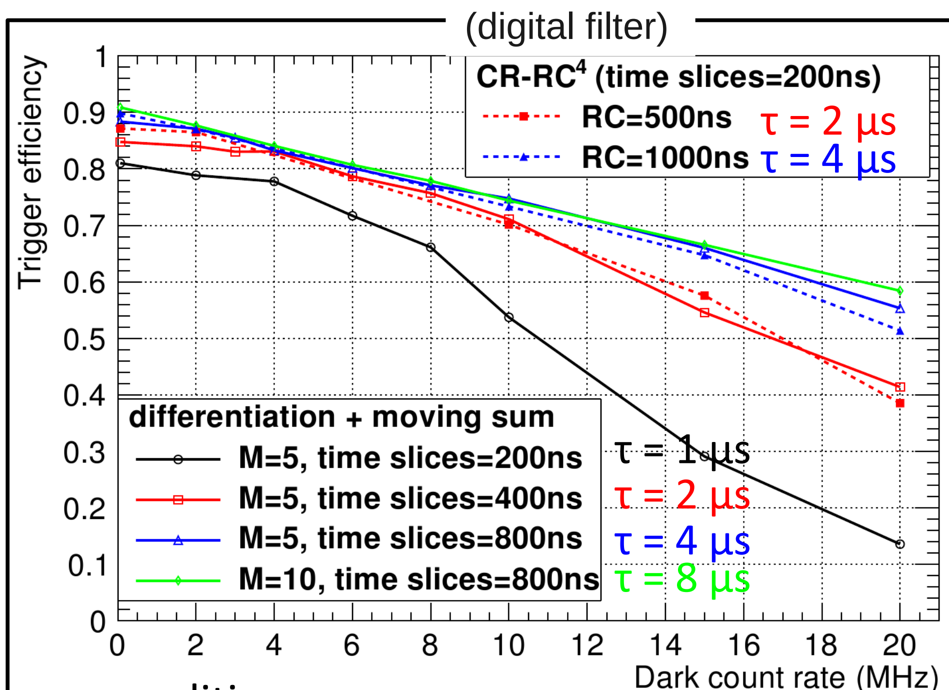
$z_i = z_{i-1} + y_i - y_{i-M}$ where $y_i = x_i - x_{i-M}$ (for M =5, the shaping time = 400 ns x 5 = 2 µs)

Performance evaluation of the digital SPS

- method
  - temporal sequence of SD pulses produced during the 80 μs following the neutron capture (real data)
  - 10'000 events
  - SiPM S12571-25C (1×1mm²)
  - SiPM dark rate = 64 kHz
  - neutron rate = 20 Hz
  - temporal sequences of dark counts are simulated and mergerd with the measured data

- gamma sensitivity measurements not yet performed with the MS+DI filter,

  BUT
  - the MS+DI filter is equivalent to the digital CR-RC⁴ filters which is equivalent to the analog CR-RC⁴ filter
  - Performance with the analog CR-RC⁴ filter have been measured in detail (see next slides)



- conditions
  - background rate < 0.001 Hz
  - prob. of multiple trigger < 0.001
  - protection window (~dead time) = 2 x shaping time (τ)

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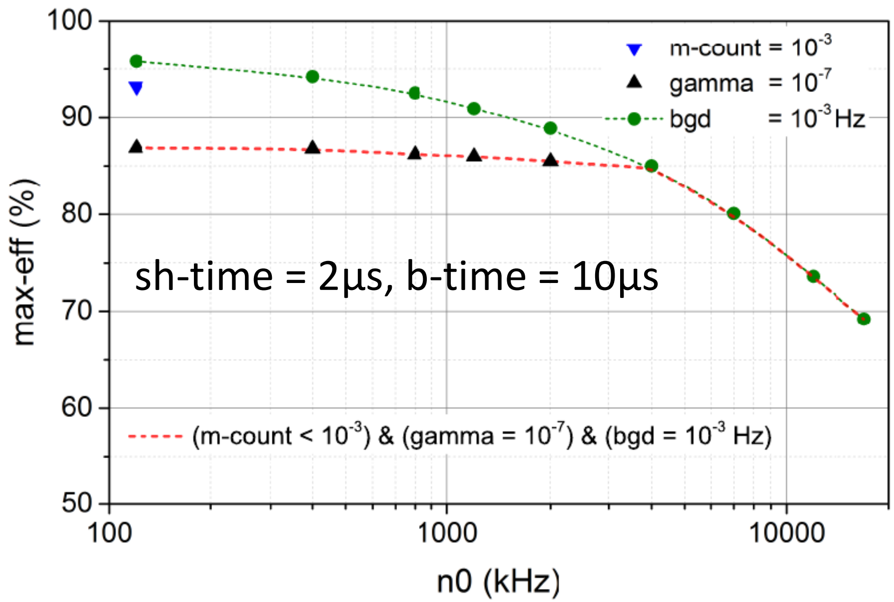
Maximum trigger efficiency

setup

- analog CR-RC^4 filter
- higher dark rate induced with constant light source
- Irradiation with ^{241}AmBe source

- single channel detection unit (200mm long layered assembly)
- SiPM S13360-1350PE (Hamamatsu) 1.3 mm x 1.3 mm, dark rate=100 kHz, overvoltage=4V, PDE=40% --> ~30% more photons than with SiPM S12571-25C (16-ch detection unit)



measurements shows that a decrease of 50% of the number of photons corresponds to a decrease of 5% of the max. trigger efficiency plateau

--> at a trigger eficiency of 81% and with SiPM S12571-25C, all boundary conditions are satisfied

Boundary condition limiting the trigger efficiency

- gamma sensitivity in the plateau region
- Background rate after the knee

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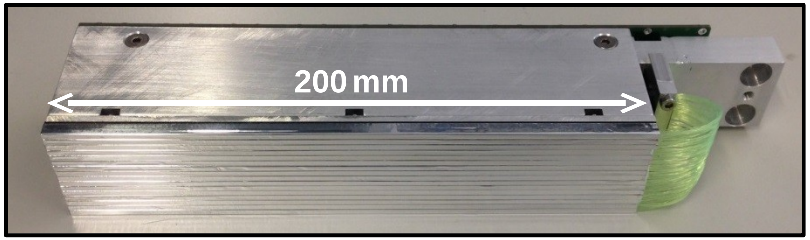
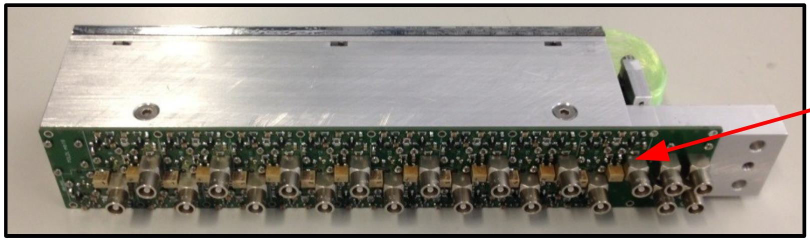
The 16-ch detection unit

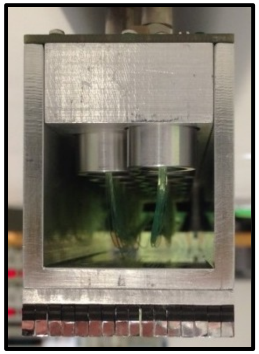
- 16-channel detection unit

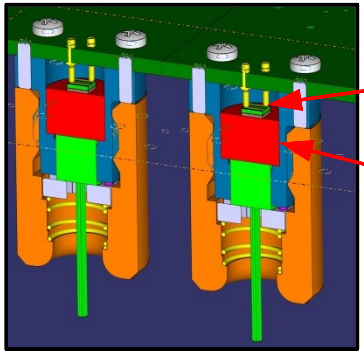


- each channel mounted individually
  --> possibility of replacement

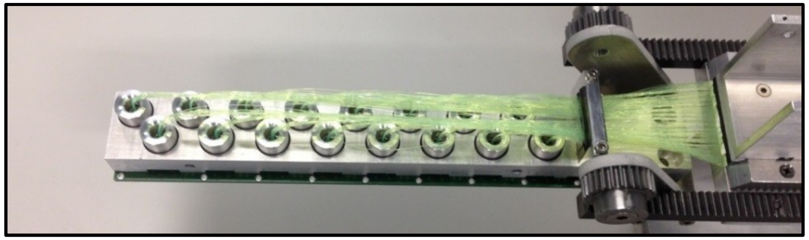


- passive thermistor circuit on each HV line
  -->compensation for temperature variations
  (SiPM overvoltage stabilization)



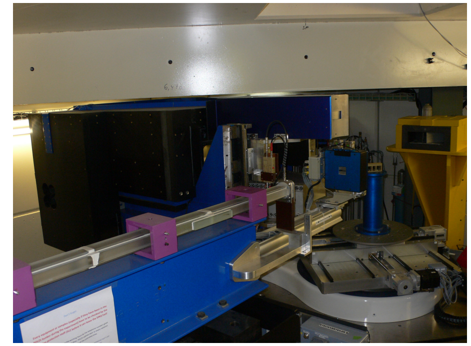


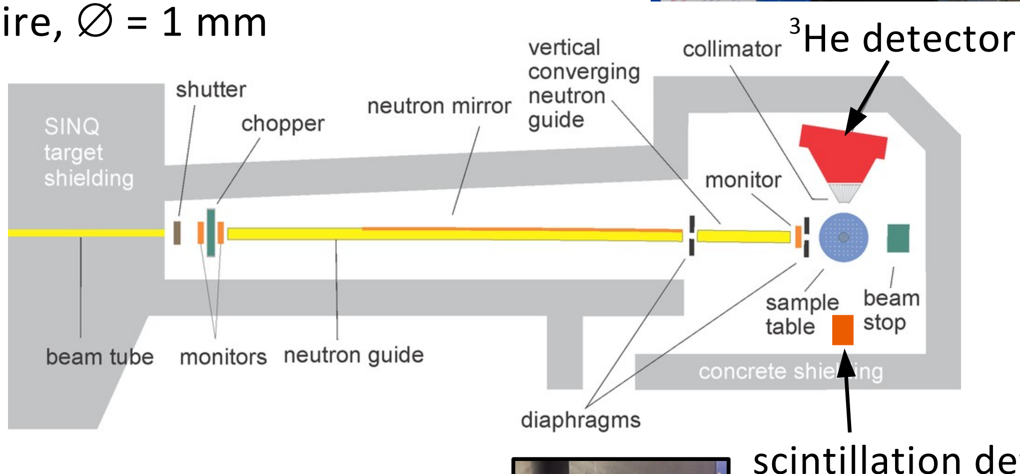
- SiPM connected with spring contacts
  --> possibility of replacement
- to ensure uniform illumination of the SiPM, coupling of WLS fiber bundle to SiPM through a 2mm long clear fiber Ø=1.2 mm

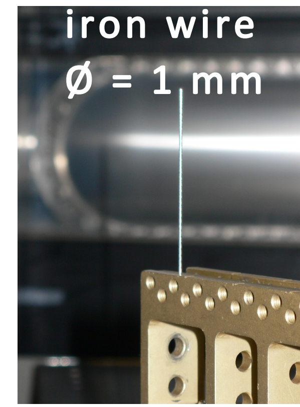


Measurement setup in POLDI

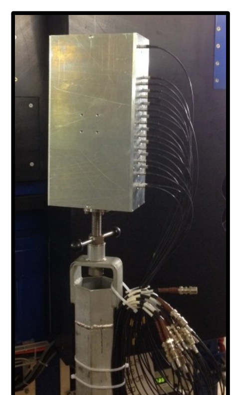
- setup
  - 400-channel ^{3}He detector without collimator
  - 16-ch scintillator module
    - at 90° scattering angle
    - 2 m away from sample
    - shielded with borated polyethylene plates
  - sample: iron wire, ∅ = 1 mm







- condition
  - DAQ of two detectors synchronized
  - Same reset signal from chopper
  - Threshold set at 20 photons (81% trigger efficiency)
  - Shaping time 2 μs



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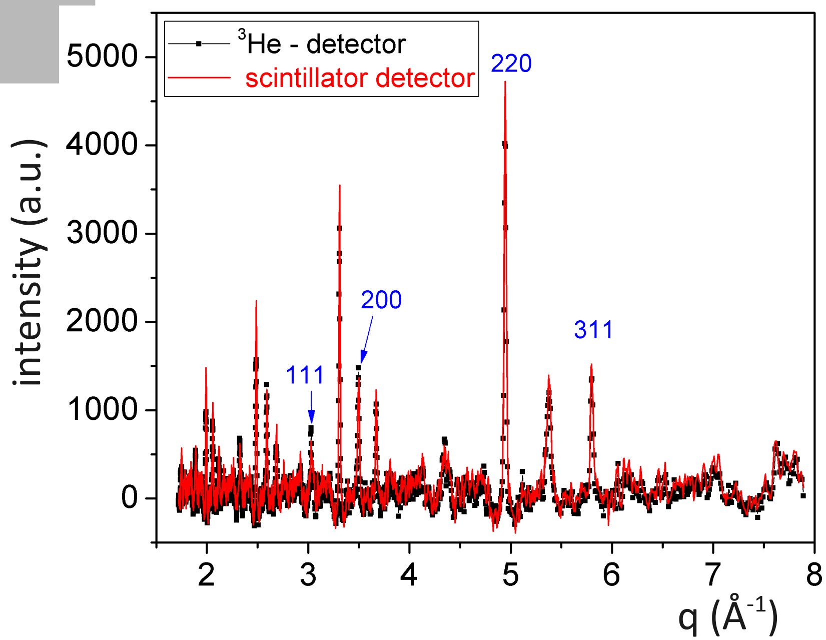
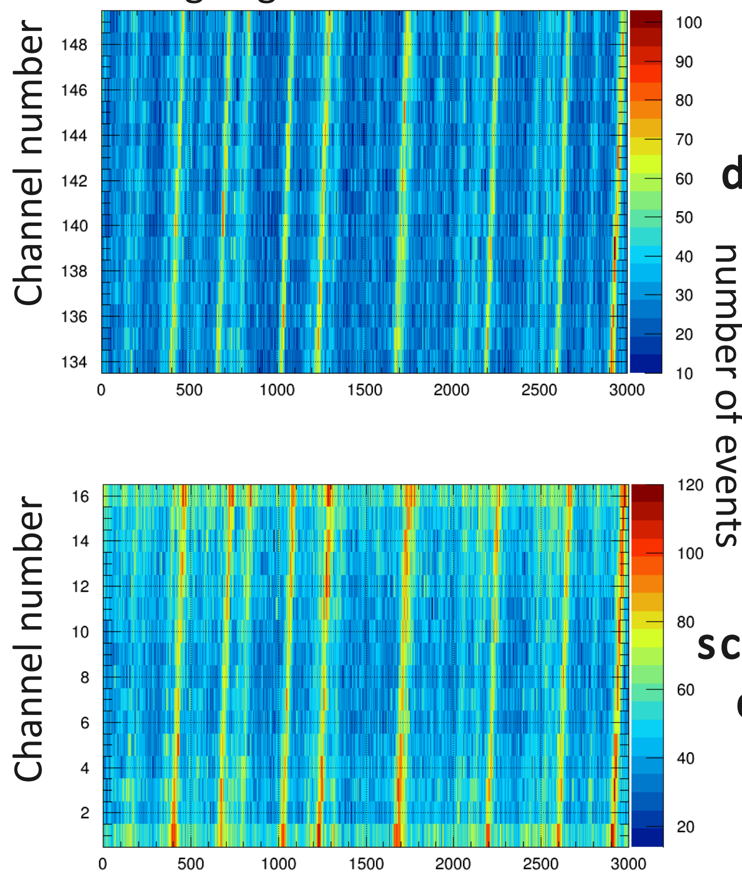
Direct comparison of POLDI performance with ^{3}He and scintillation detectors

Correlation function for 16 channels



- only 4 peaks correspond to Bragg peaks (the others are artefacts due to the limited number of channels used)
- perfect agreement concerning peak positions
- equivalent or slightly better POLDI resolution with the scintillator detector

selection of the 16 channels having the same scattering angle as the scintillation detector



^{3}He detector

scintillation detector

time elapsed between last chopper reset and detection time (ms)

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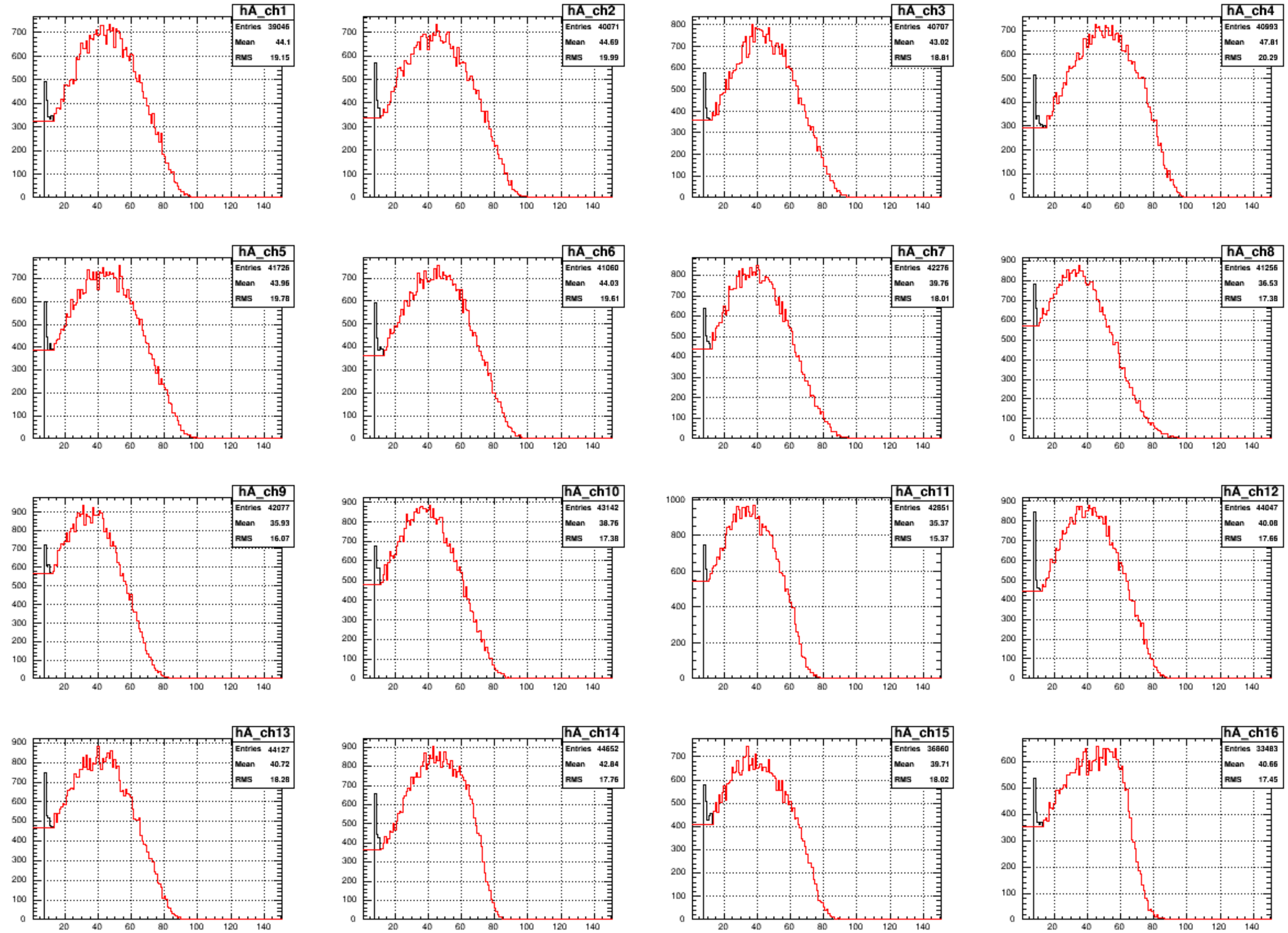
Channel-to-channel uniformity



Trig efficiency @ 20 PE:

Mean = 0.81
Std dev / Mean = 4%
Min = 0.74
Max = 0.86

Measurement perform at a low threshold (8 pe)
with a large protection window (200µs)

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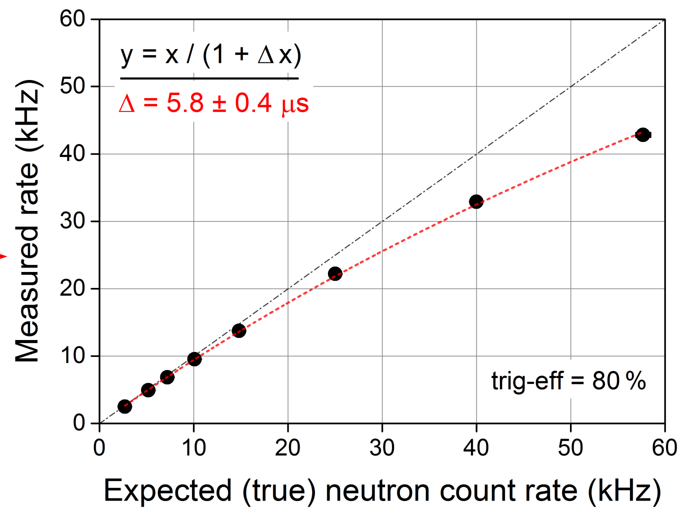
Results and conclusion

- **achieved performance of the 16-ch detection unit**
  - 1D, gapless, individual pixel readout
  - individual long pixels (2.5 mm, 200 mm)
  - detection efficiency at 1.2 Å 68%
    - absorption efficiency 84%
    - trigger efficiency 81%
  - background count rate ≤ 10^{-3} Hz/ch
  - gamma sensitivity (^{60}Co) ≤ 10^{-7}
  - multi-count ratio ≤ 10^{-3}
  - time resolution ≤ 1 µs
  - effective dead time ≈ 6 µs
  - max neutron count rate ≈ 50 kHz

Up to a SiPM dark count rate of 4 MHz (more than 20 years of operation)



- **status of POLDI project:**
  - scalable detector design
  - FPGA-based, scalable readout electronics

  → POLDI detector requirements achieved

- **to do**: tools/procedures for mass production, detector housing, engineering & area layout, etc.

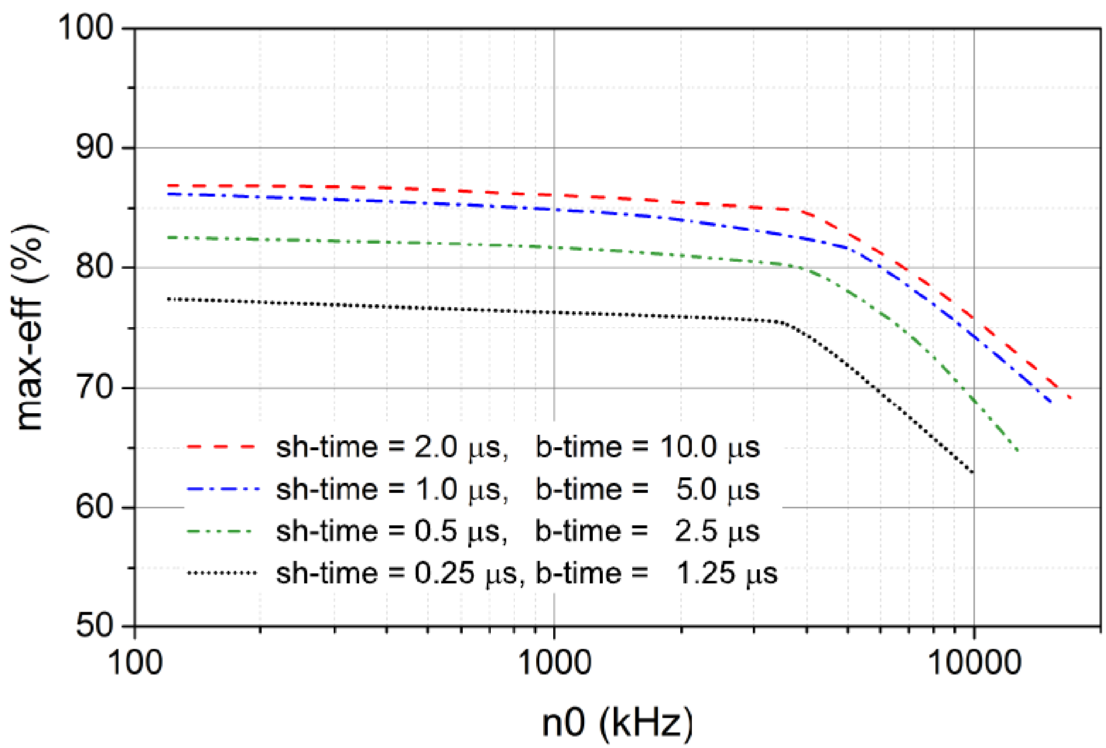
  → POLDI Upgrade and realization of detector modules postponed due to reduced priority

Outlook – other filter parameters for other applications

measurement conditions

- analog CR-RC^4 filter
- higher dark rate induced with constant light source
- Irradiation with ^{241}AmBe source

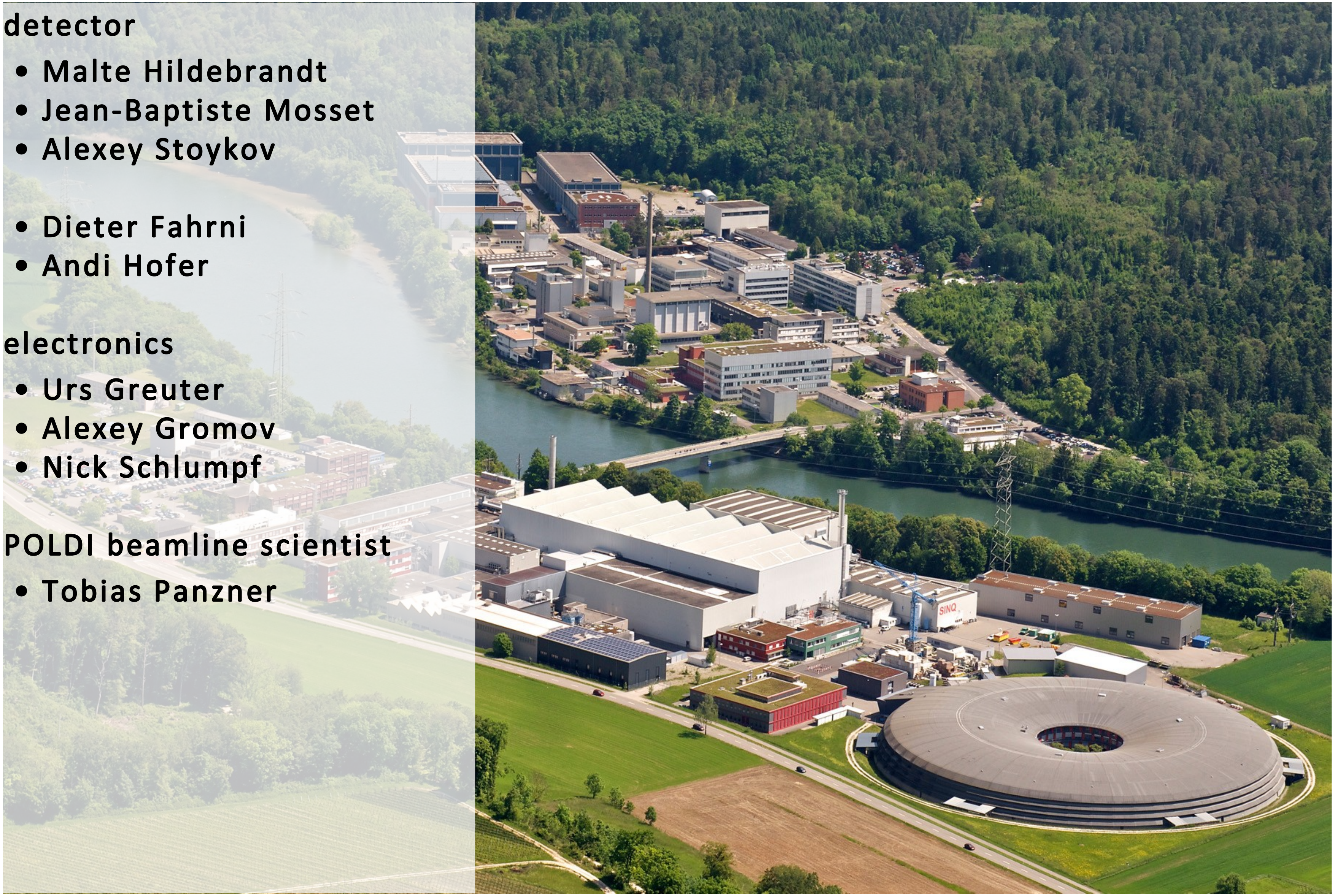
- single channel detection unit (200mm long layered assembly)
- SiPM S13360-1350PE (Hamamatsu) 1.3 mm x 1.3 mm, dark rate=100 kHz, overvoltage=4V, PDE=40%



boundary conditions

- multiple trigger prob < 0.001
- gamma sensitivity < 1E-7
- background rate < 0.001 Hz

Team



detector

- Malte Hildebrandt
- Jean-Baptiste Mosset
- Alexey Stoykov

- Dieter Fahrni
- Andi Hofer

electronics

- Urs Greuter
- Alexey Gromov
- Nick Schlumpf

POLDI beamline scientist

- Tobias Panzner

Backup slides

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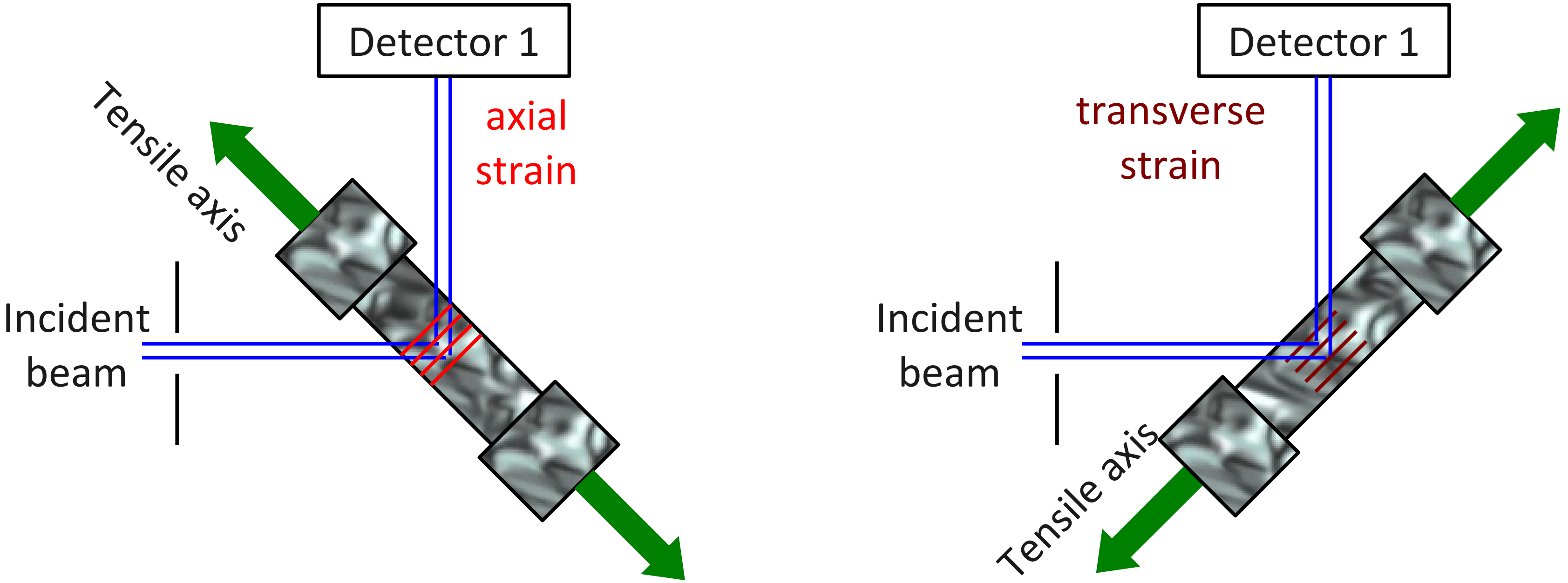
in-situ studies

with only one detector:
2 steps measurement with 2 different samples rotated by 90°



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In-situ studies

in-situ study with 2 detectors:
simultaneous measurement of axial and transverse strain components