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Approaches for a 2D Neutron detector based on ZnS:^{6}LiF readout with WLS fibers and SiPMs

SINE2020 WP9 Detector Meeting, Abingdon, 14.01.2016

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:
- reminder of 1D thermal neutron detector
- ideas / approaches for 2D thermal neutron detector

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Framework - 1

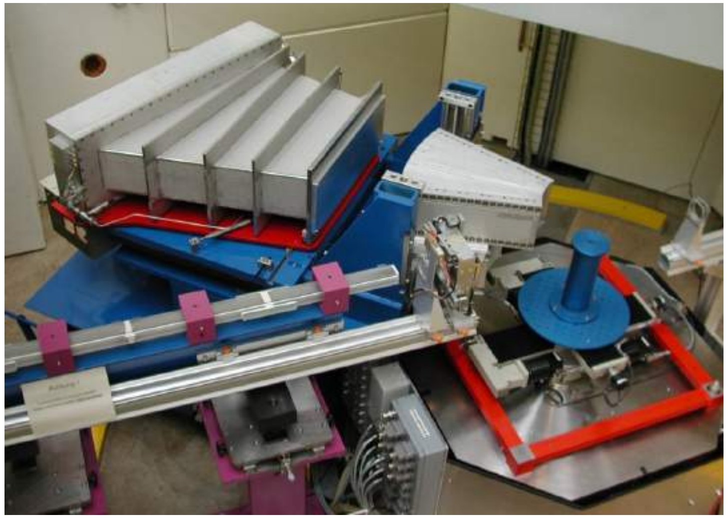
POLDI neutron beam line at SINQ (PSI)

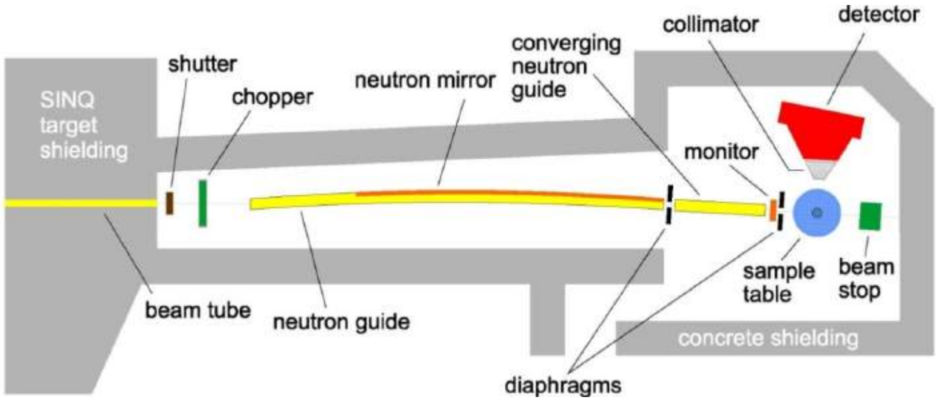
- time-of-flight neutron diffractometer
- strain measurements: accurate determination of lattice spacings

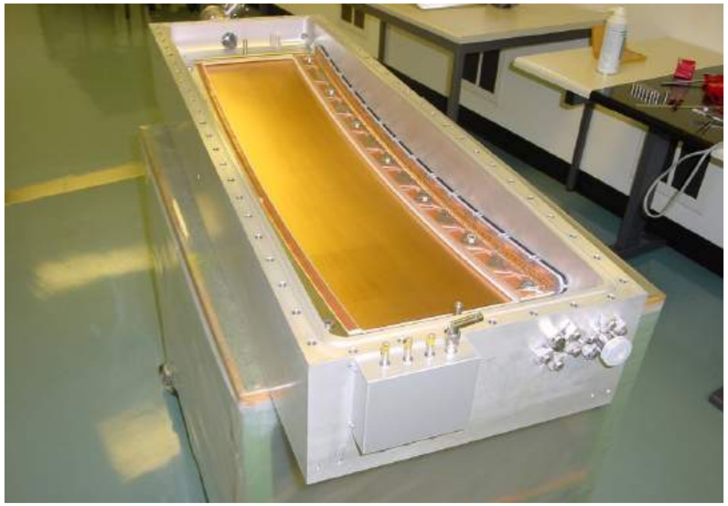
current detector

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

→ upgrade program started in 2012







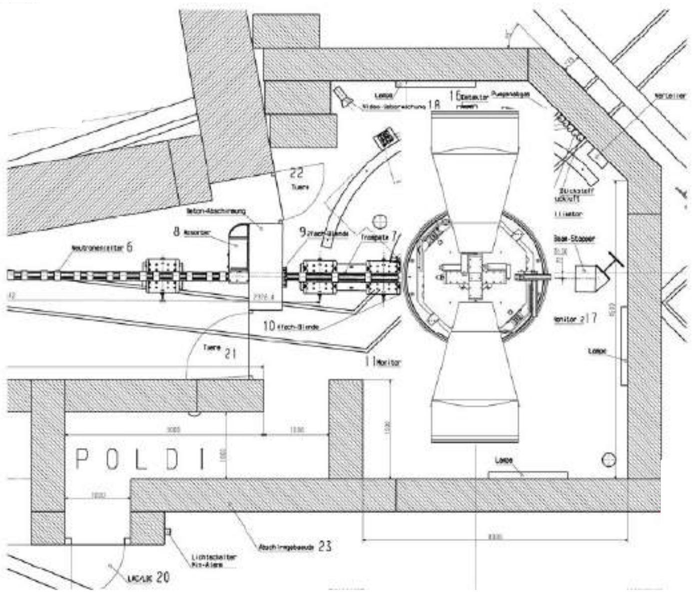
Framework – 2

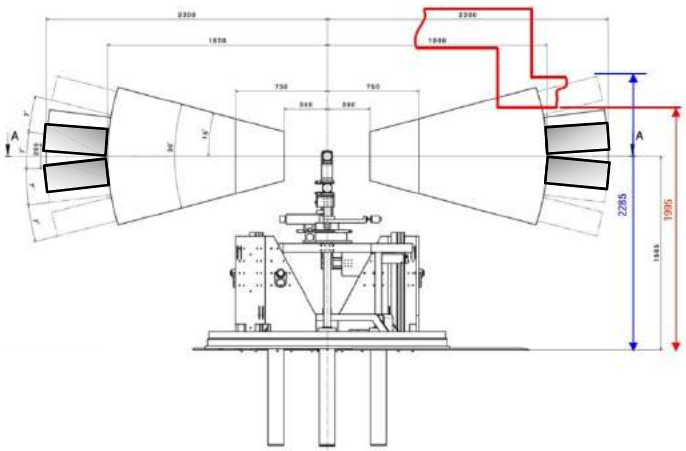
POLDI upgrade program

- 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





Motivation for PSI-Approach –The Big Picture

The neutron detection system is based on:

- ZnS:Ag/^{6}LiF scintillation screen
  - no Helium-3
  - established technology, appropriate properties
  - but: opaque, long emission time
    → small number of photons spaced out in time
- wavelength shifting (WLS) fibres
  - 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
    → signal fluctuations in analog integration
- 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

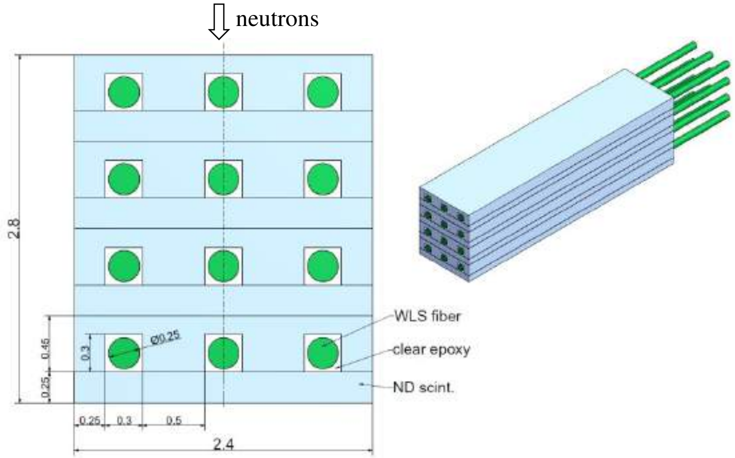
- front end: fibres polished and mirrored
- rear end: 12 fibres glued in plexigas block, polished and connected to SiPM

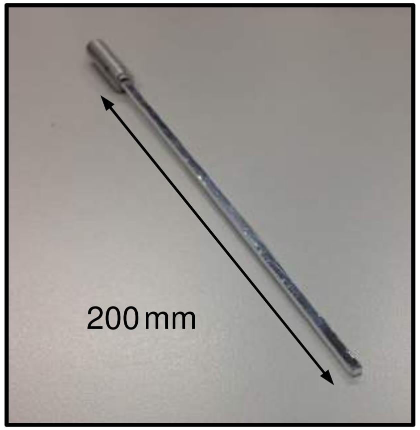
detection unit with 4 layers

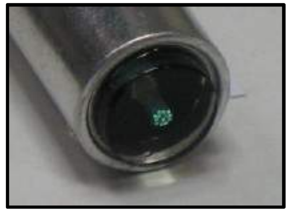
- neutron absorption probability > 80 % @1.2 Å
- intrinsic time resolution < 1 μs

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

1-channel, 4-layer (full-length) unit





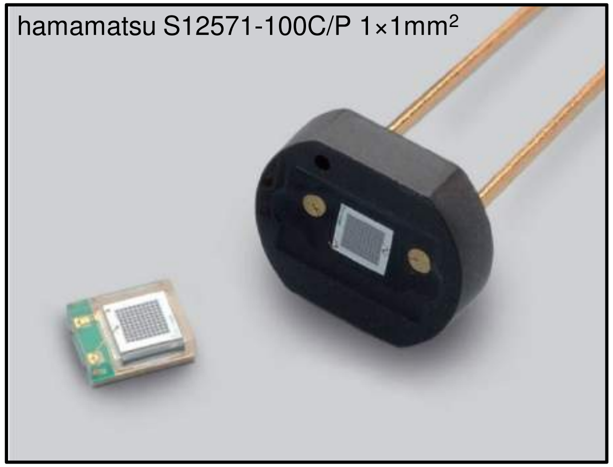


> → this unit represents elementary building block of full-size detector

Silicon Photmultiplier (SiPM)

properties

- opto-semiconductor device with excellent **single photon counting capability**
- PDE ~35 % (at emission wavelength of WLS fibres)
- high gain: 10^5 to 10^6
- fast response and very good time resolution
- operation: low voltages (≤100 V), room temperature
- **insensitive to magnetic fields**
- **compact**
- sensitive areas, e.g. (1×1) mm^2, (3×3) mm^2, with pixel sizes (10×10) mm^2 to (100×100) mm^2



drawbacks

- dark counts ≥100 kHz/mm^2
- cross talk ~20 %
- afterpulses ~1-2 %

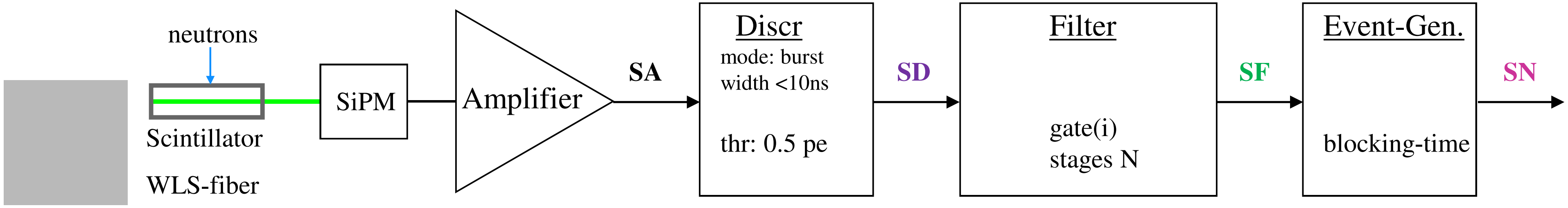
initial concern: contribute to signal fluctuations during long integration times

dark count rate might increase due to accumulated radiation damage

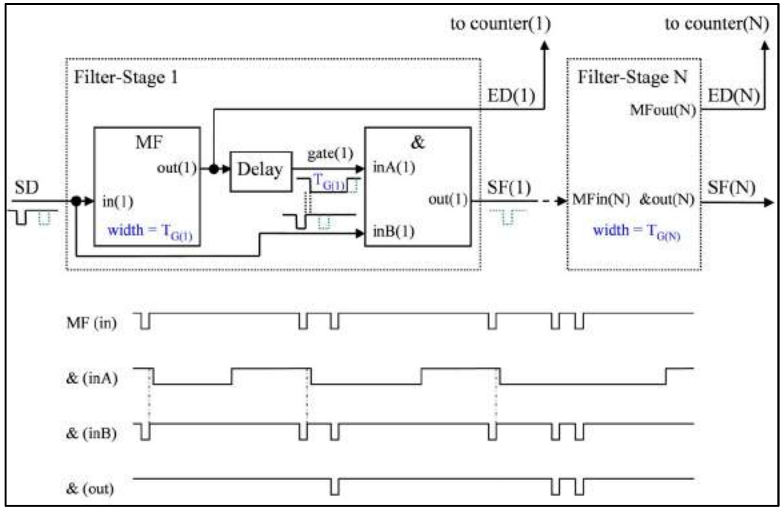
→ irradiation test in POLDI beamline with (1×1) mm^2 SiPM: increase of ~90 kHz/year

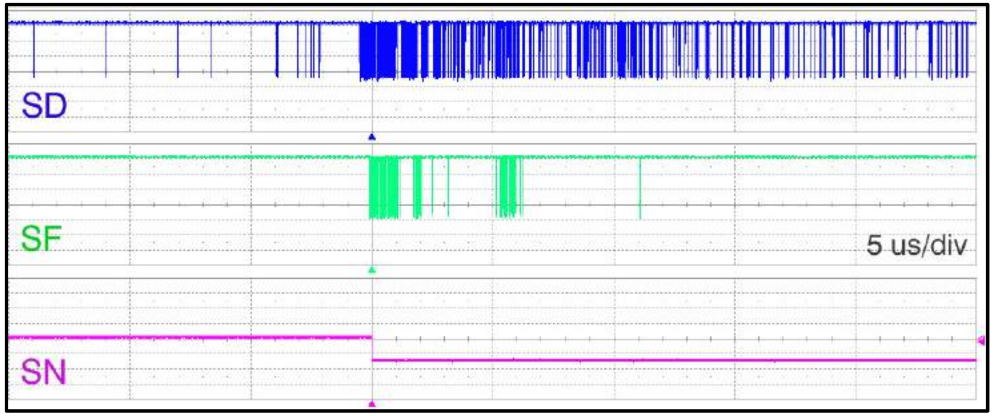
→ measurements in lab:
- non-irradiated (3×3) mm^2 SiPM with dark count rate of 1 MHz corresponds to: (1×1) mm^2 with 0.1 MHz + ~10 y operation
- non-irradiated (1×1) mm^2 SiPM with 0.1 MHz dark count rate with LED induced additional ”dark count rate”

Signal Processing System



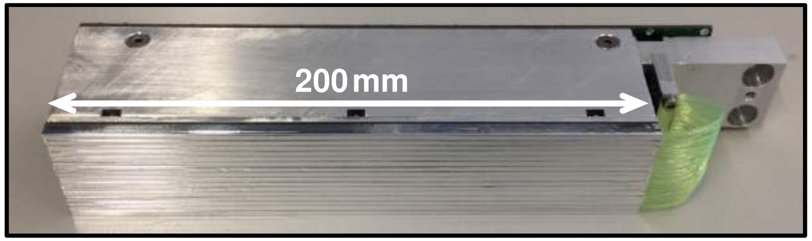
- leading edge discriminator
  - one SD puls is generated, independent of number of fired SiPM cells
  - suppression of SiPM cell-to-cell cross-talk due to ”digitization” of SiPM pulses
- filter (examples)
  - consecutive delayed self-coincidence on SD-pulse sequence
    → scalable, multi-stage filter
  - moving sum
  - moving sum after differentiation
  - CR-RC^4
- ”event generator”
  - elimination of late after-glow photons
  - puls-pair resolution vs multi-count ratio

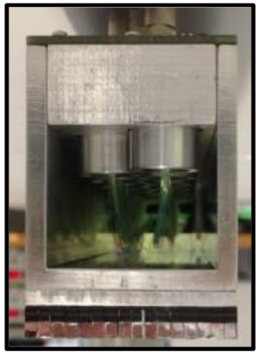


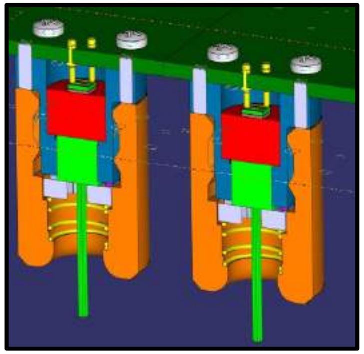


16-Channel Module

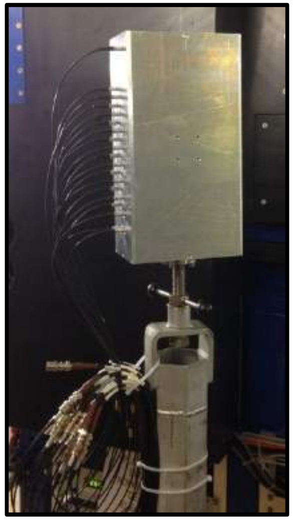
- 16-channel detection unit





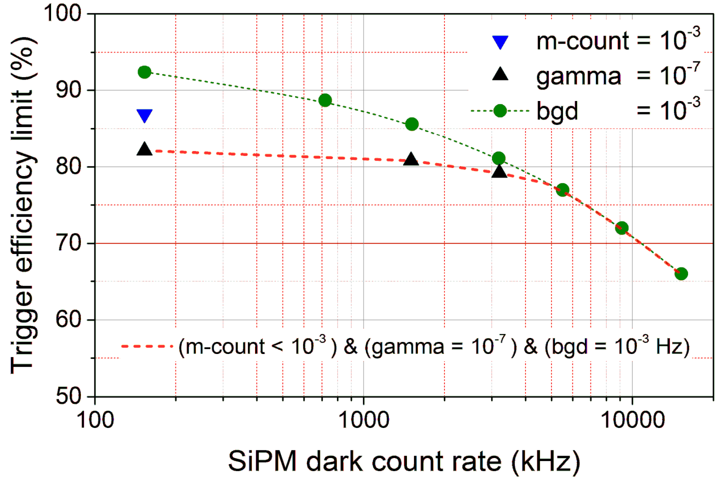


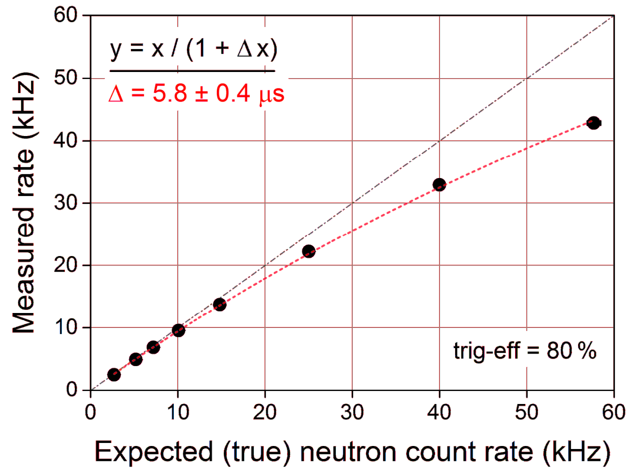
- setup in POLDI experimental area at SINQ



Results and Conclusion

- achieved detector performance
  - 1D, gapless, individual pixel readout
  - individual long pixels (2.5 mm, 200 mm)
  - detection efficiency at 1 Å — 60 %
    - absorption probability — 75 %
    - trigger efficiency — 80 %
  - background count rate — $\leq 10^{-3}$ Hz
  - gamma-sensitivity (^{60}Co) — $\leq 10^{-7}$
  - multi-count ratio — $\leq 10^{-3}$
  - dead time — $\approx 6\ \mu s$
  - max. neutron count rate — ≈ 50 kHz





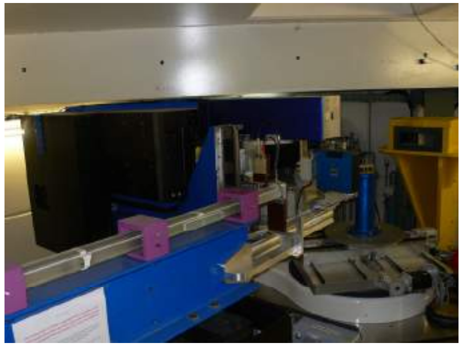
- status of POLDI project:
  - scalable detector design
  - FPGA-based, scalable readout electronics
  - → POLDI detector requirements achieved

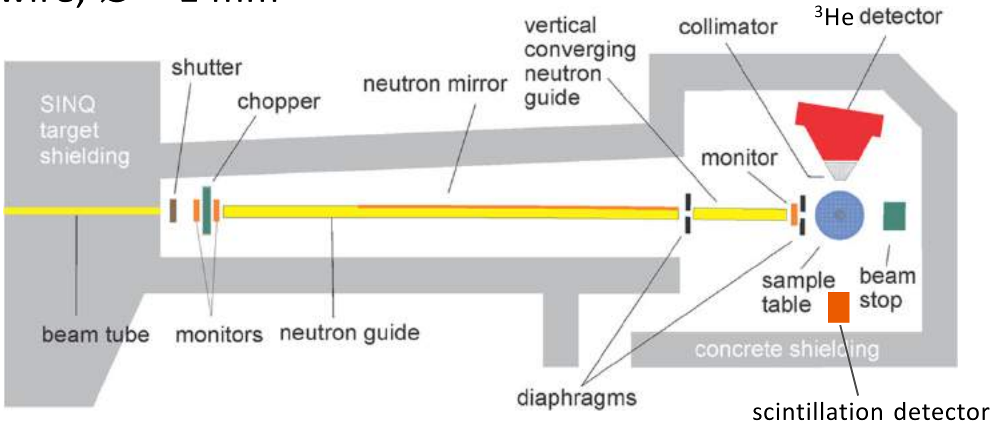
- to do:
  - tools/procedures for mass production, detector housing, engineering & area layout, etc.

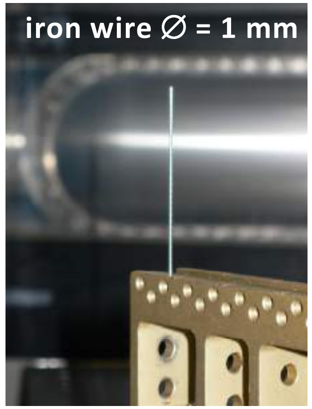
→ POLDI Upgrade and realisation of detector modules postponed due to reduced priority

Measurements in POLDI - 1

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



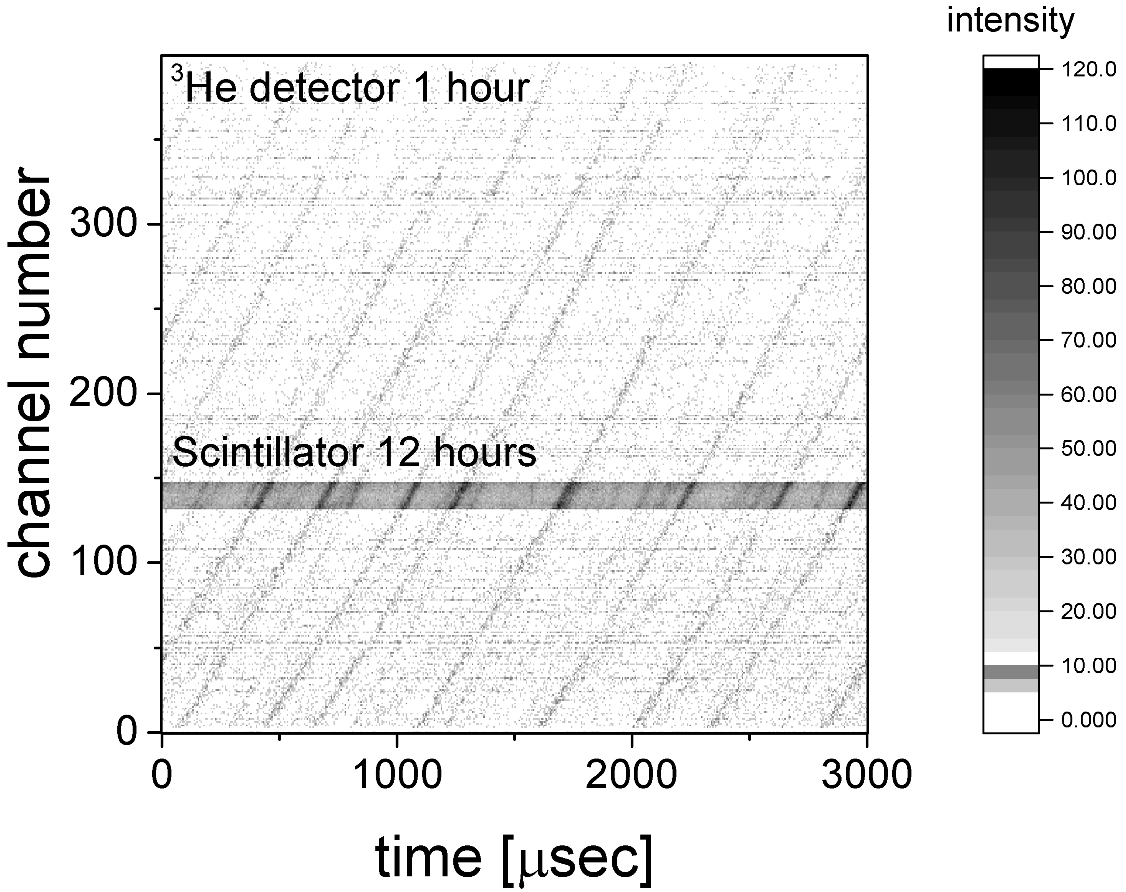




- condition
  - DAQ of two detectors synchronised
  - same reset signal from chopper

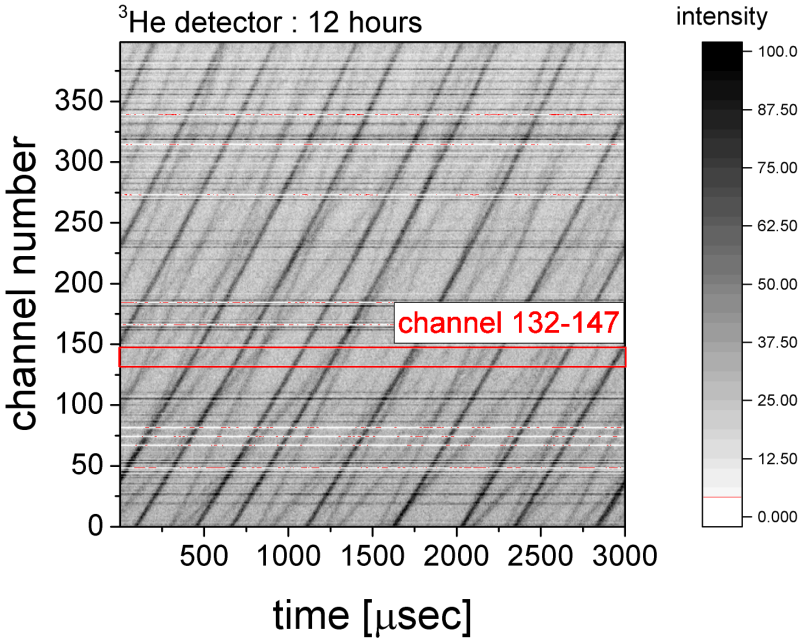
Measurements in POLDI - 2

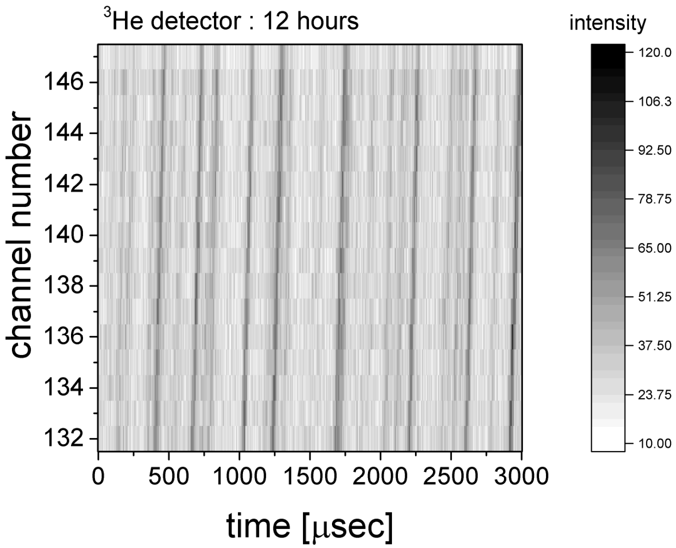
- channel vs time (raw data), both detectors superimposed

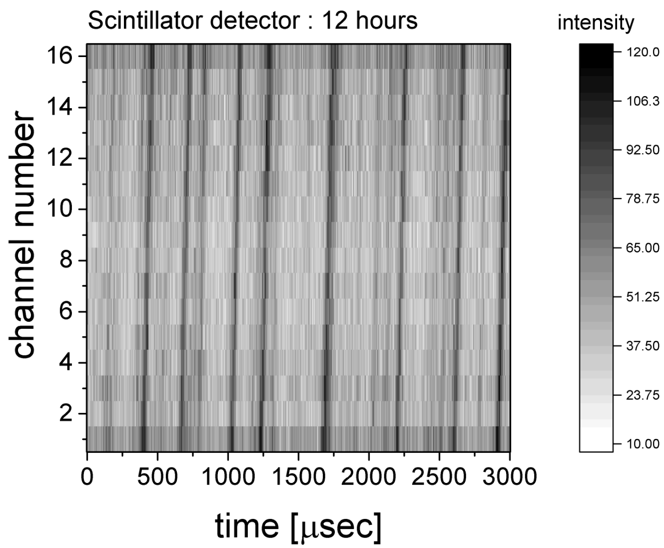


Measurements in POLDI - 3

- channel vs time (raw data)

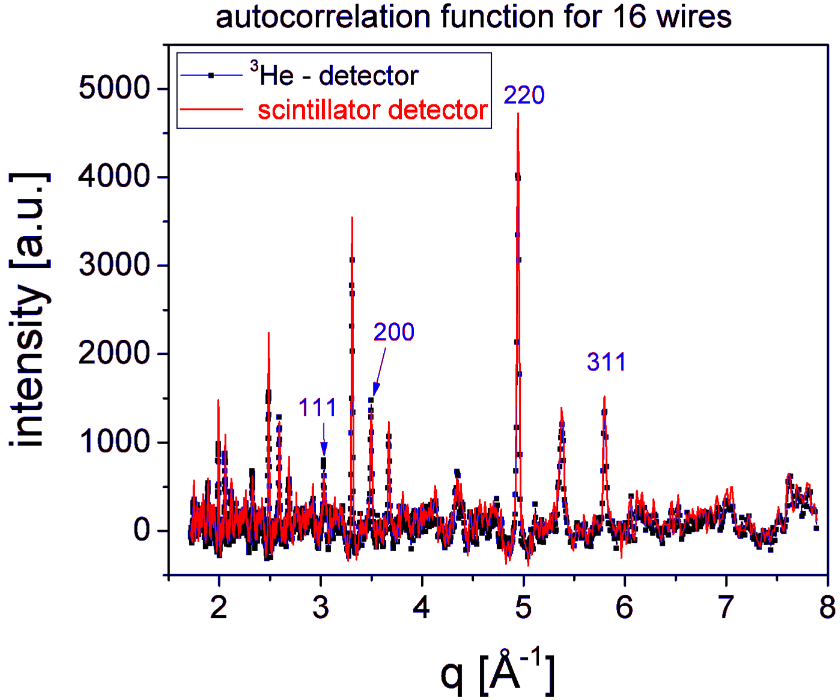


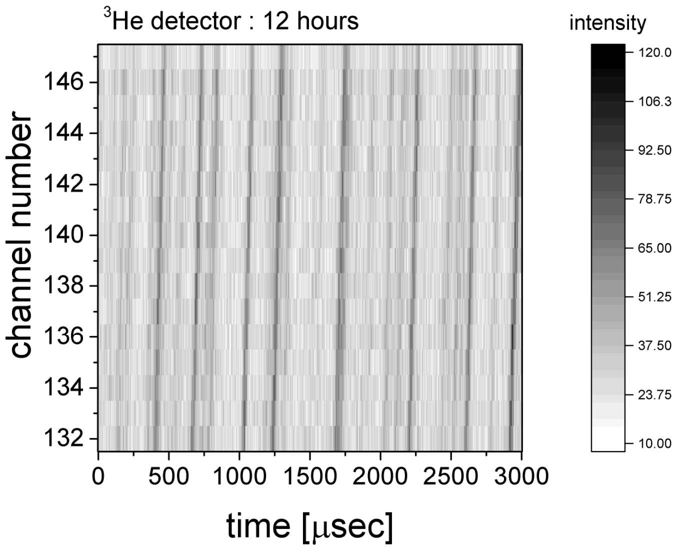


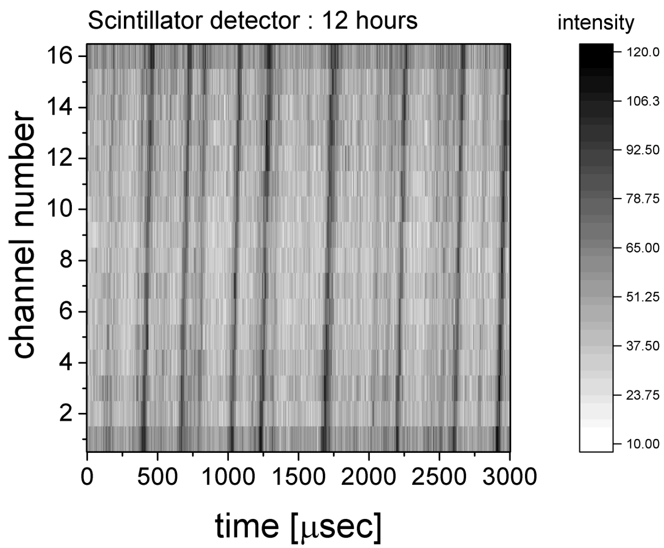


Measurements in POLDI - 4

- autocorrelation function







Content

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→ content of the talk:

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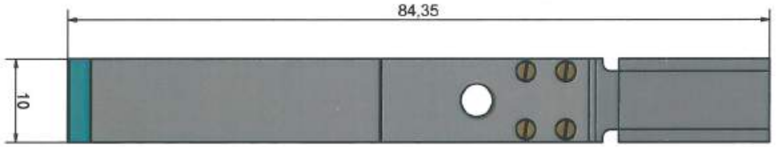
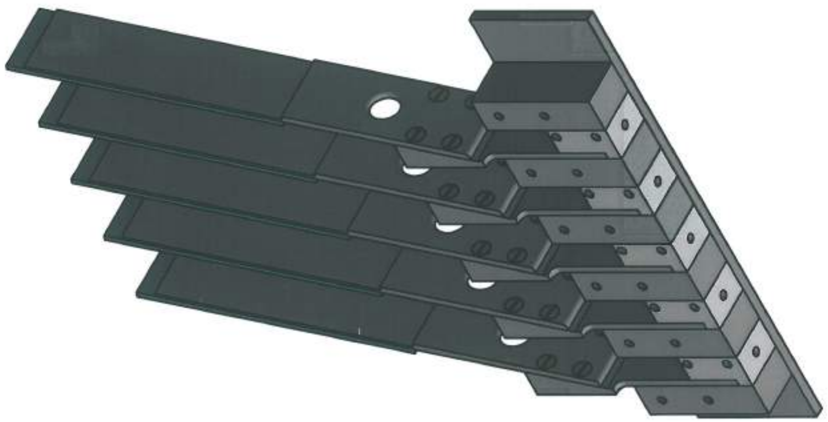
Pixelated 2D Detector

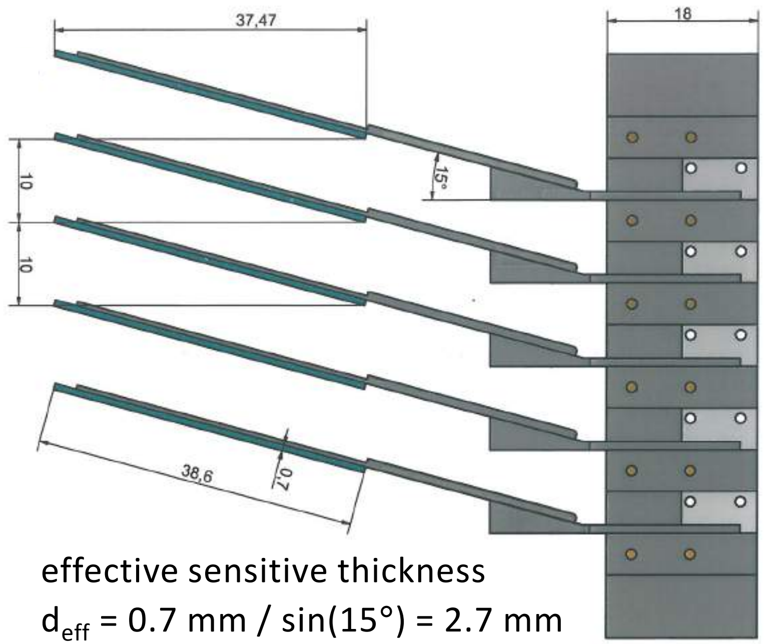
- pixelated 2D detector
  - 2D, gapless, individual pixel readout
  - individual pixel size down to 2.5 mm × 2.5 mm (?)
  - detector performance of 1D POLDI design (except for time-of-flight uncertainty)

- but:
  - large number of individual channels (WLS fibers, SiPMs)
  - complex mechanics
  - ”thick” (in n-flight direction) → not ”interchangeable” with 1inch ^{3}He tube

possible design for (10×10) mm^2



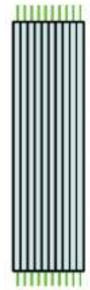




effective sensitive thickness

d_{eff} = 0.7 mm / sin(15°) = 2.7 mm

2D – Light Sharing



- geometrical design
  - 2D, gapless (horizontal), individual long pixels with two-side readout
    → 2^{nd} coordinate via light sharing/pulse-amplitude analysis
- light sharing approach
  - proportionality between $N_{detectedphotons}$ and signal amplitude essential
    → photon counting approach for POLDI (maybe) not suitable due to 10 ns dead time
  - SiPM, high pixel density, short recovery time (like for POLDI)
  - transimpedance amplifier (like for POLDI) followed by semi-gausian CR-RC^4 filter
  → to avoid saturation in photon detection
- simple modelling
  - common formulas: $I = I(x, I_{01}, L_{att1}, I_{02}, L_{att2})$,
    $N_{photons,\ left\ or\ right} = I_0 \cdot att_{l\ or\ r}(x, I_{01}, L_{att1}, I_{02}, L_{att2}) \cdot PDE$
    $Asymmetry = Asymmetry(N_{photons,left}, N_{photons,right})$

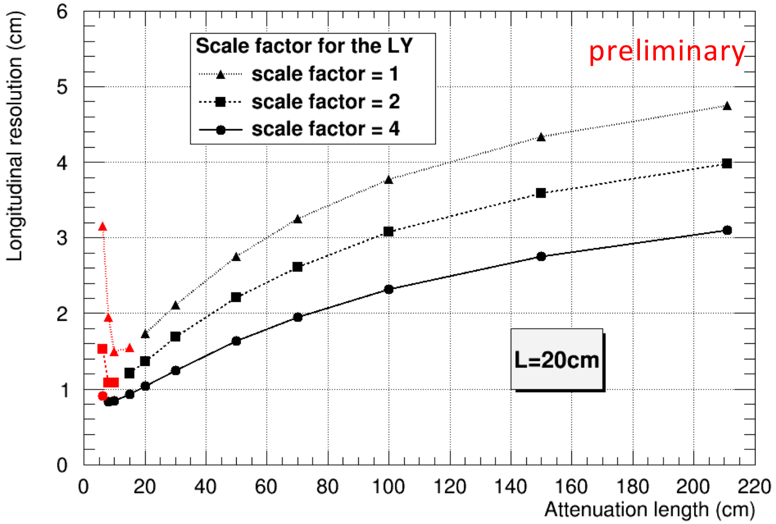
    I_0: average number of photons trapped in fiber within first 2 μs
- input parameters
  - distribution I_0 (determined from own measurements)
  - short attenuation length L_1 = 12.7 cm (literature*)
  - relative amplitude between short and long attenuation lengths (own measurements)

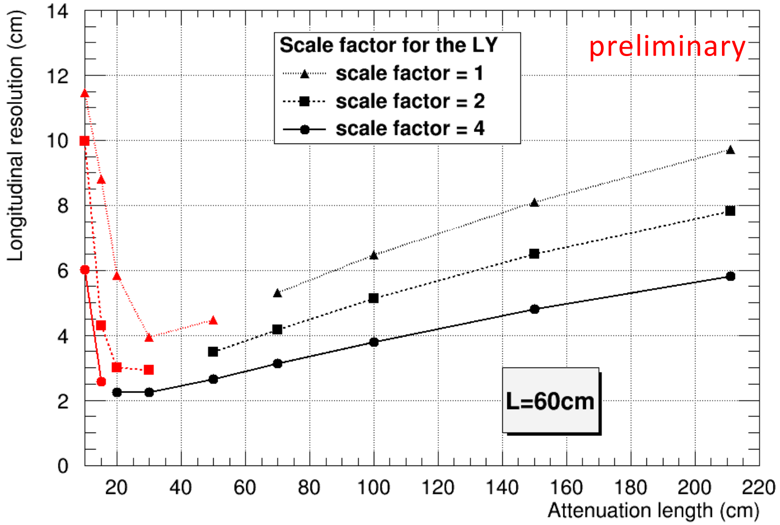
* M.David *et al.*, Comparative Measurements of WLS Fibers, CERN Documents Server, ATL-TILECAL-94-034

Light Sharing – Simple Modelling

- free parameters
  - long attenuation length L_2 (condition for L_1: L_1=12.7 cm if L_2>L_1, L_1=L_2 otherwise)
  - scaling factor for light yield I_0

→ achievable longitudinal resolution depends mainly on:
- light yield
- attenuation length of WLS fiber





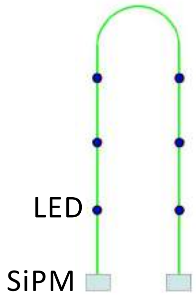
▲ ■ ● : average $\varepsilon_{trigger}$ along detection unit >80% and variations of $\varepsilon_{trigger}$ along detection unit <10%

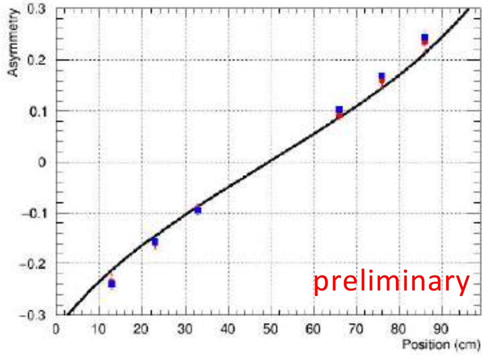
→ to do /necessary:
- WLS fibers with short attenuation length
- modified design of detection unit (WLS fibers inside scintillator) to increase light yield

Light Sharing – First Tests of Simple Modelling

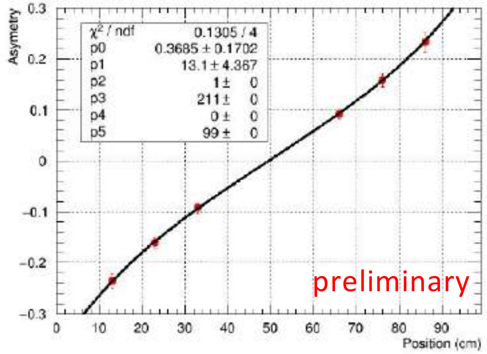
- pure (non-doped) WLS fiber, Kuraray Y-11(400), 250 μm, multi-cladding
- 1m long
- illuminated with LED

1) LED in DC mode
   nA meter



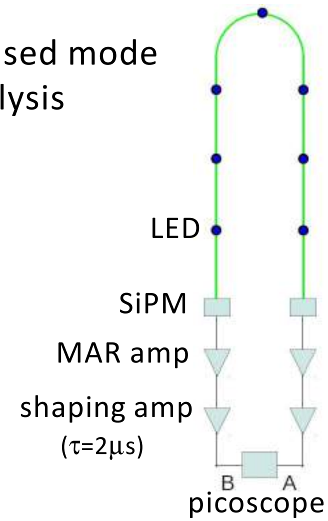


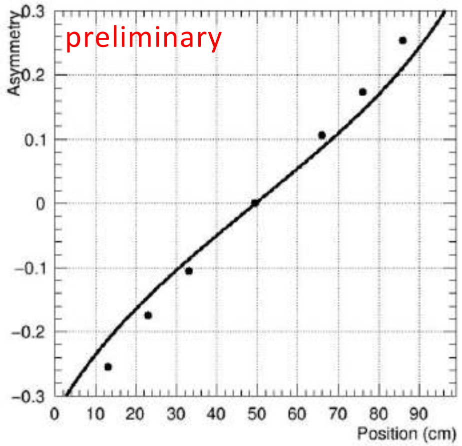
Estimated values for l1 and L1:
l1 = 0.23 ± 0.08
L1 = 12.7 cm



Experimental value for l1 and L1:
l1 = 0.37 ± 0.2
L1 = 13.1 ± 4.2 cm

2) LED in pulsed mode
   pulse analysis





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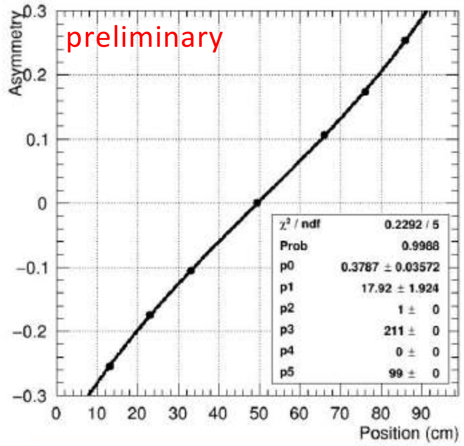


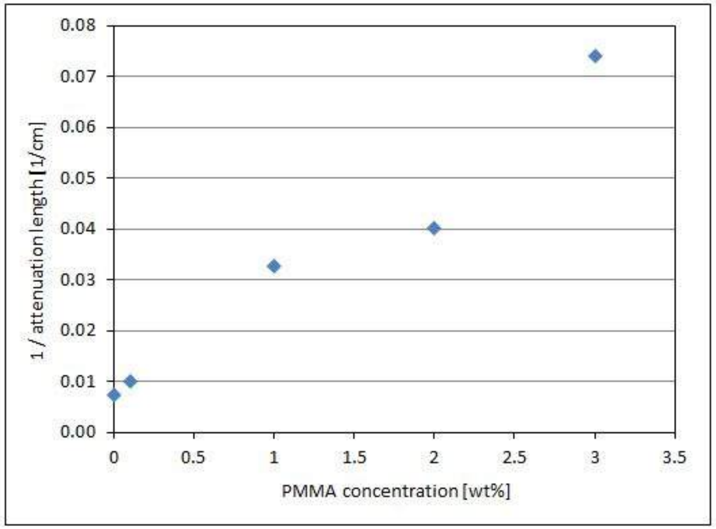
Experimental value for l1 and L1:
l1 = 0.38 ± 0.04
L1 = 18 ± 2 cm

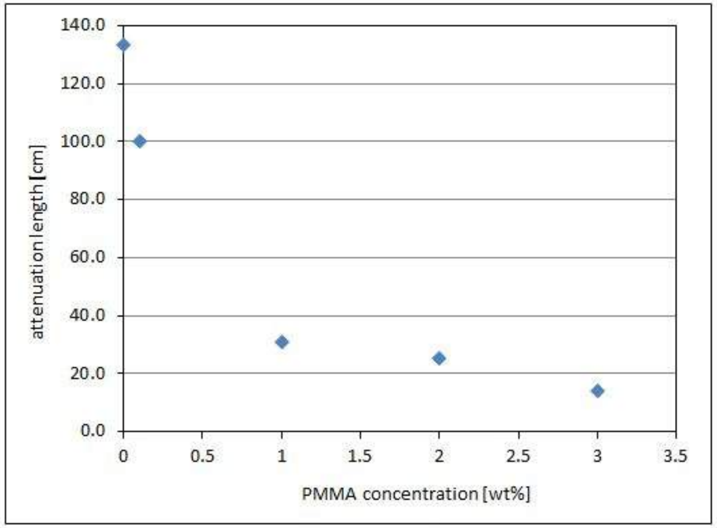
PMMA polymer doped WLS Fiber

- WLS fiber with reduced attenuation length
  - Kuraray WLS fiber Y-11(400), 250 µm, multi-cladding,
    attenuation decribed by two components: L1 = 12.7 cm, L2 = 211 cm
  - fiber core (polystyrene) doped with PMMA (polymethylmethacrylate) polymers as light scattering dopant
  - Kuraray: tests with 0.100 wt%, 1.00 wt%, 2.00 wt% and 3.00 wt%
    simple description: only one component λ

PMMA concentration C(wt%)	0	0.100	1.00	2.00	3.00
1/λ	0.00753	0.01002	0.03283	0.04020	0.07401
λ	132.9	99.8	30.5	24.9	13.5

delivered to PSI last week





Next Steps

- 1D 16-channel module
  - optimize filter of signal processing system
  - explore full potential of 16-channel module, if possible in combination with current ^{3}He detector
  - explore potential market, further applications

- 2D approach (within SINE2020)

  pixelated
  - design of detector concept with reasonable pixel size (HEIMDAL, BEER beam lines?)

  light sharing approach
  - tuning of "simple modelling", e.g. including paramters L_1 and I_{01}/I_{02} which were achieved in measurement with 1m (undoped) WLS fiber
    → redo simulation for expected longitudinal resolution as function of attenuation length (and scaled light yield)
  - extract longitudinal resolution from measurement with 1m (undoped) WLS fiber
  - new design for detection units with increased light collection
  - build new detection units with best matching WLS fiber (concerning attenuation length)

Team

detector

- **Jean-Baptiste Mosset**
  (partially payed by SINE2020)
- **Alexey Stoykov**
- **M.H.**

- **Dieter Fahrni**
- **Andi Hofer**

electronics

- **Urs Greuter**
- **Alexey Gromov**
- **Nick Schlumpf**

POLDI beamline scientist

- **Tobias Panzner**

Summary