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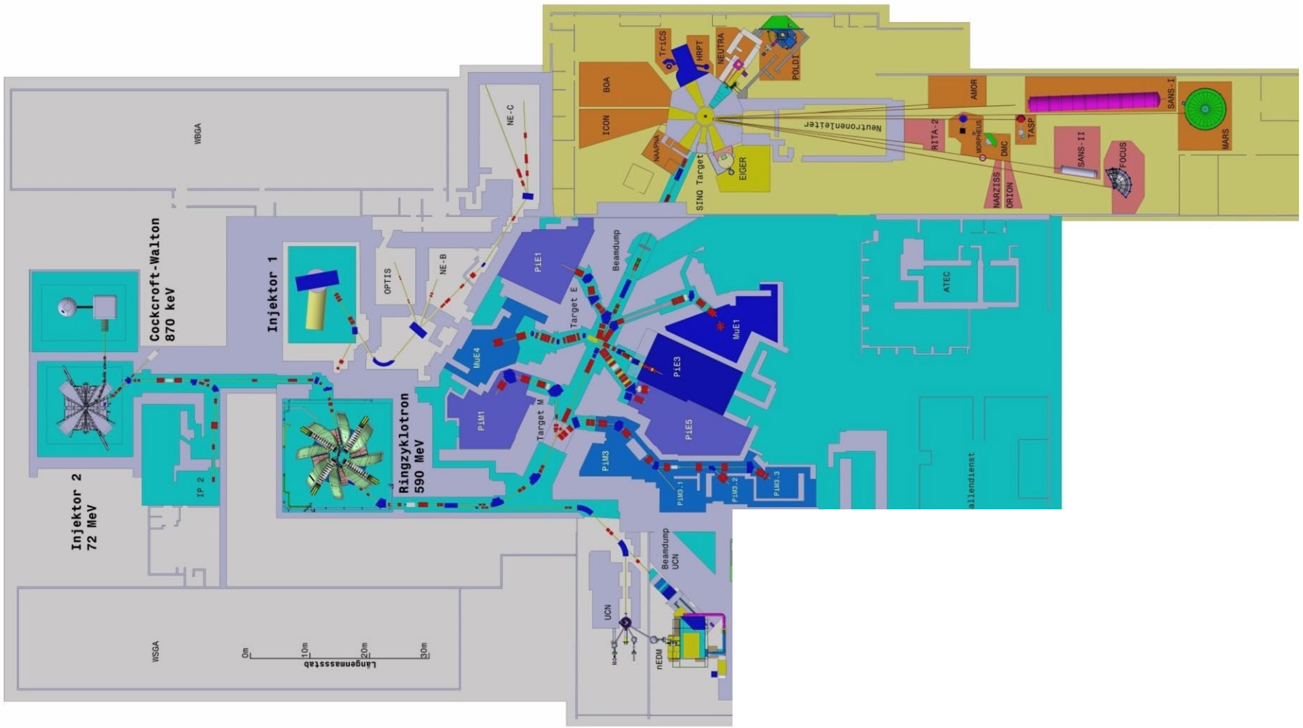
Malte Hildebrandt :: Laboratory for Particle Physics :: Paul Scherrer Institute

Detectors used at CHRISP and SINQ – insights in different technologies

BRIDGE Workshop, PSI, 18.-20. October 2023

CHRISP & SINQ



WBGA
NE-C
TriCS
HRPT
NEUTRA
POLDI
BOA
ICON
NAAPNA
SINQ Target
EIGER
Neutronenleiter
AMOR
SANS-I
MARS
RITA-2
MORPHEUS
TASP
DMC
SANS-II
FOCUS
NARZISS
ORION
Cockcroft-Walton
870 keV
Injektor 1
OPTIS
NE-B
PiE1
Beamdump
Target E
MuE1
ATEC
MuE4
PiE3
PiM1
Target M
PiE5
Ringzyklotron
590 MeV
PiM3
PiM3.1
PiM3.2
PiM3.3
IP 2
Injektor 2
72 MeV
Beamdump
UCN
nEDM
WSGA
0m
10m
20m
30m
Längenmassstab

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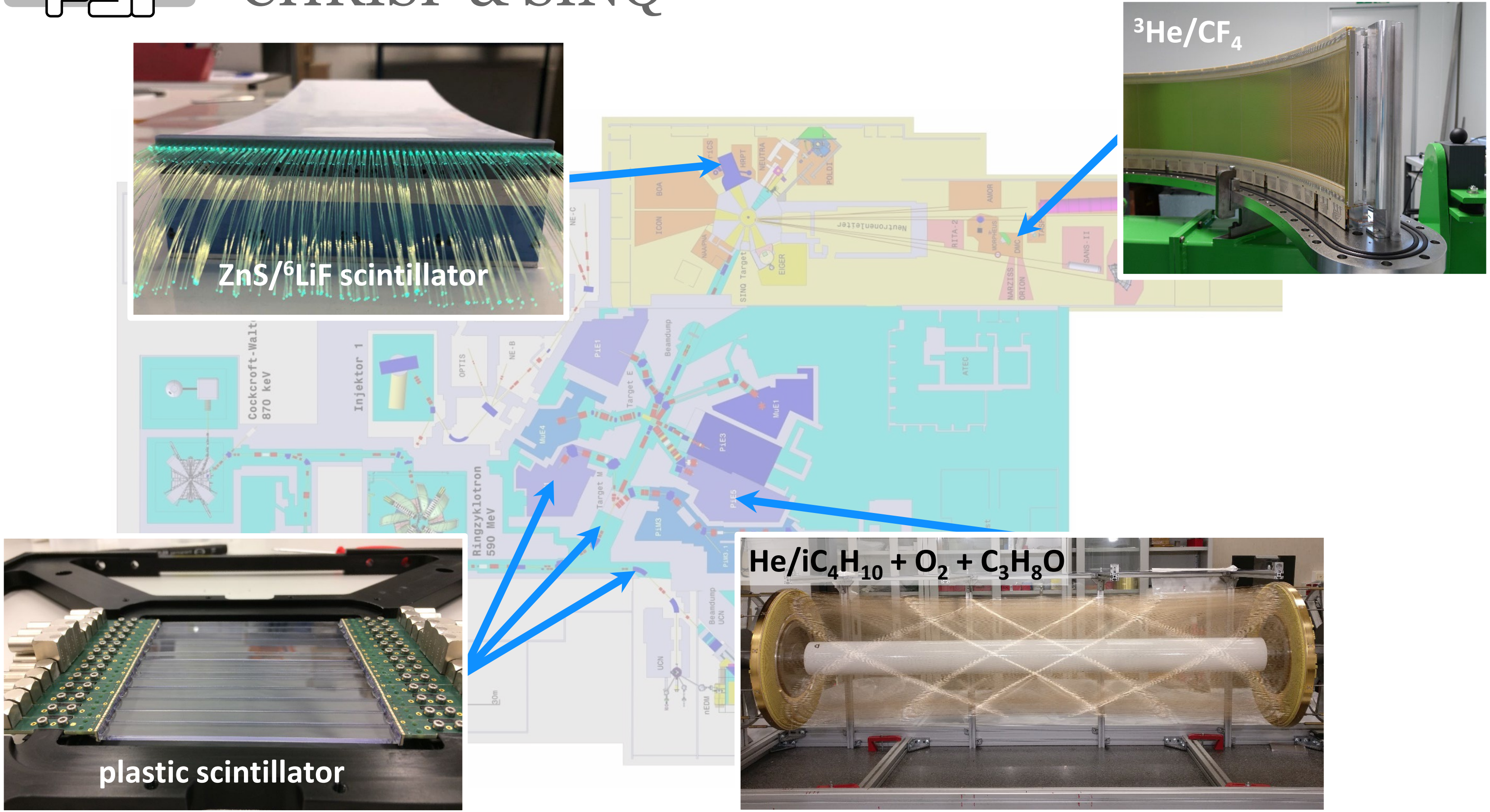
CHRISP & SINQ



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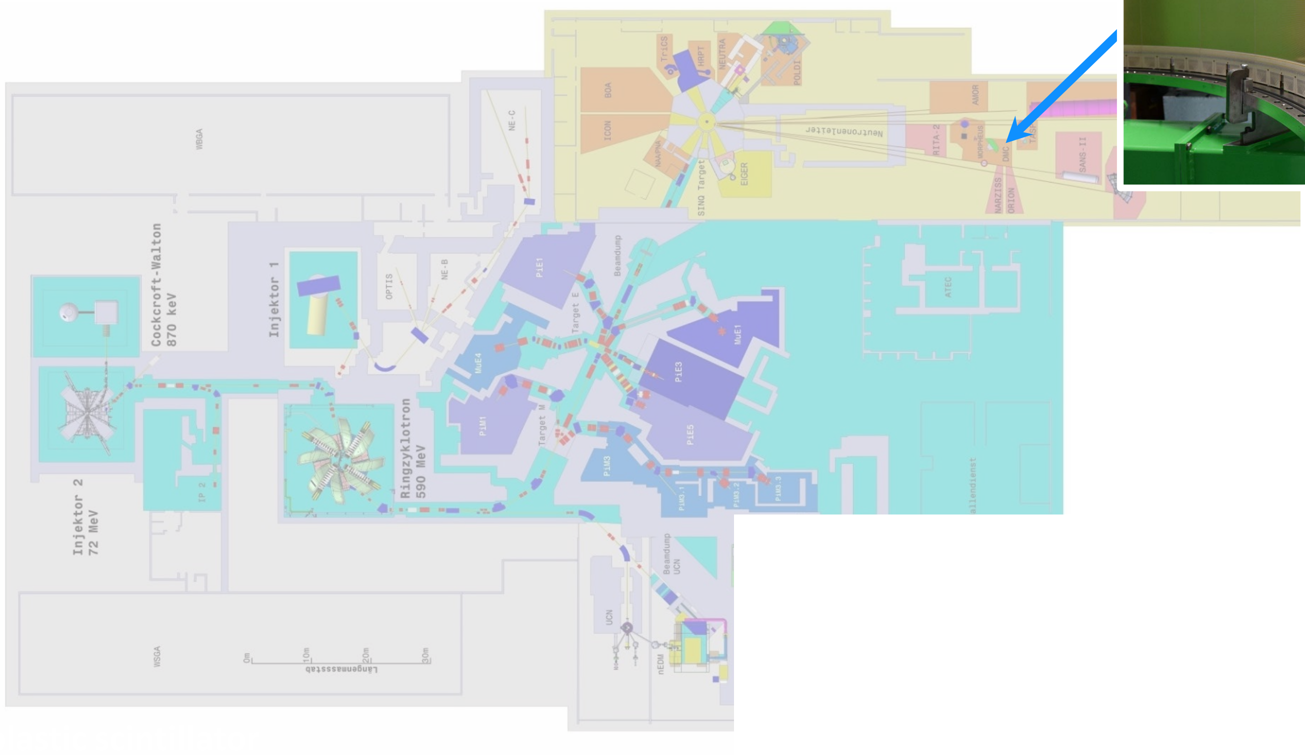
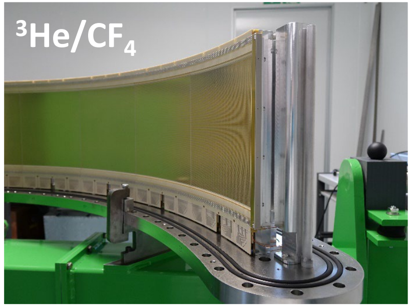
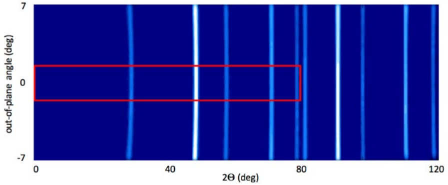
CHRISP & SINQ





New DMC Detector @ SINQ

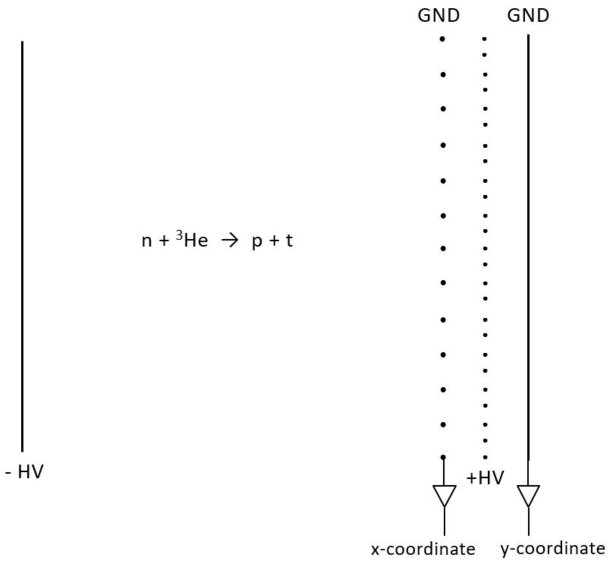
- common project FRM2/TUM (ErwiN) & PSI (DMC)
  (ILL left after prototype phase)
- DMC: cold neutron diffractometer for powder & single-crystal applications
- detector requirements
  - continuous, horizontal coverage ≥ 130°
  - vertical coverage ≥ 14° (200mm)
  - resolution in x and y of ~0.1°
  - efficiency 75% @ 1.8 Å
  - global rate capability ~2 MHz
  - time resolution ~µs
- realisation
  - BNL-type, high-pressure ^{3}He-MWPC
  - 6.5 bar ^{3}He + 1.5 bar CF_4
  - 9 wire segments
  - anode wires (pitch 1.6 mm), cathode strips (pitch 1.6 mm)

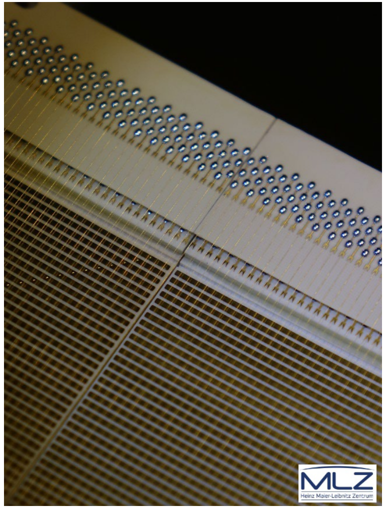


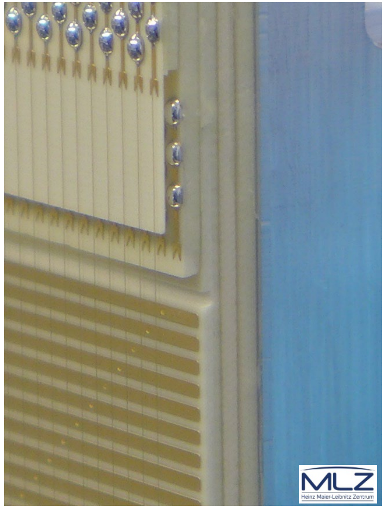
^{3}He-MWPC-based thermal Neutron Detector

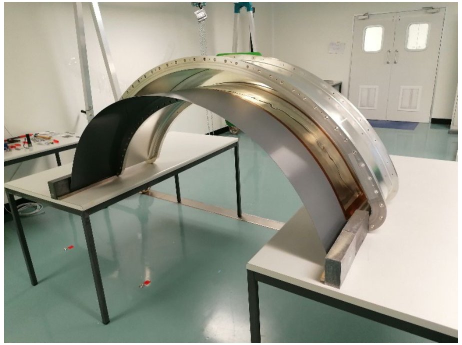
detector principle

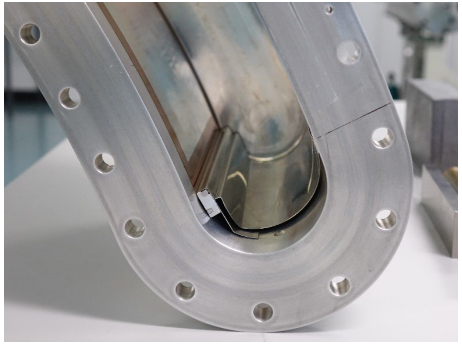
- n + ^{3}He → p + t
- high pressure ^{3}He-CF_4 mixture
- conversion volume
- amplification, detection (MWPC)



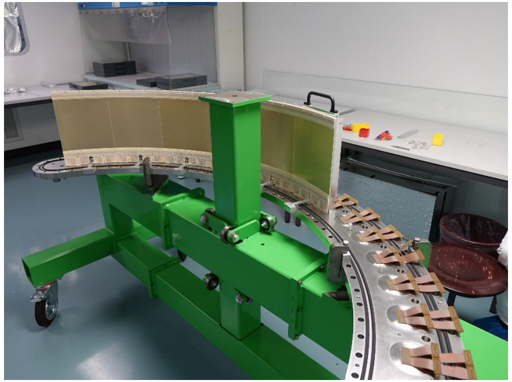
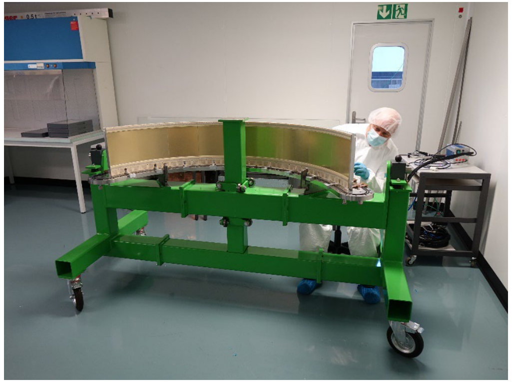
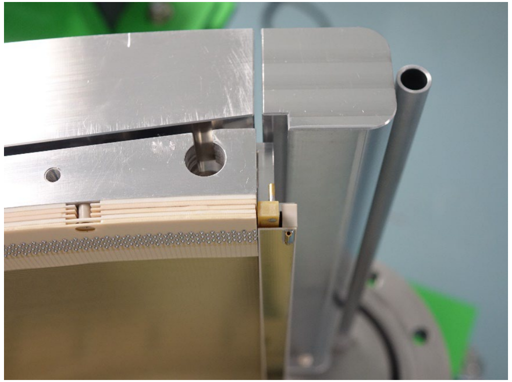
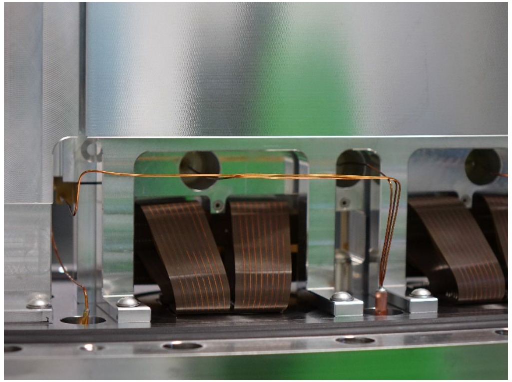
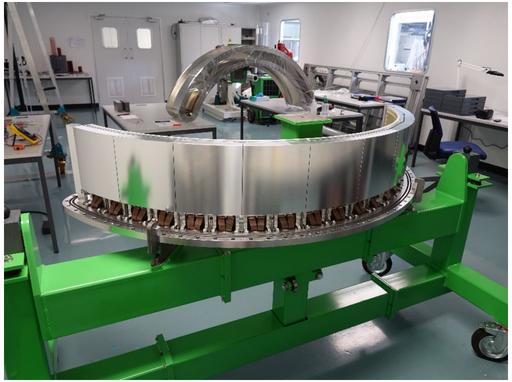








^{3}He-MWPC-based thermal Neutron Detector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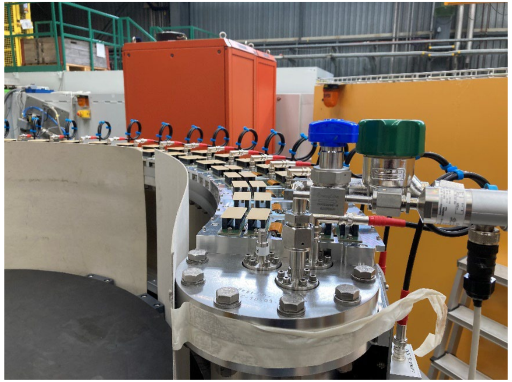

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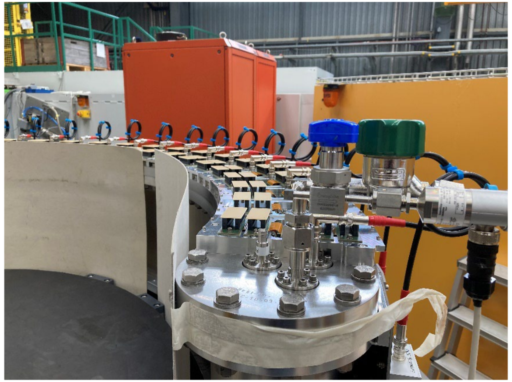
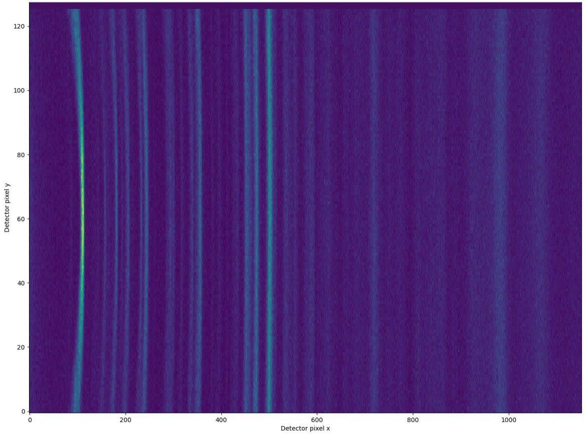
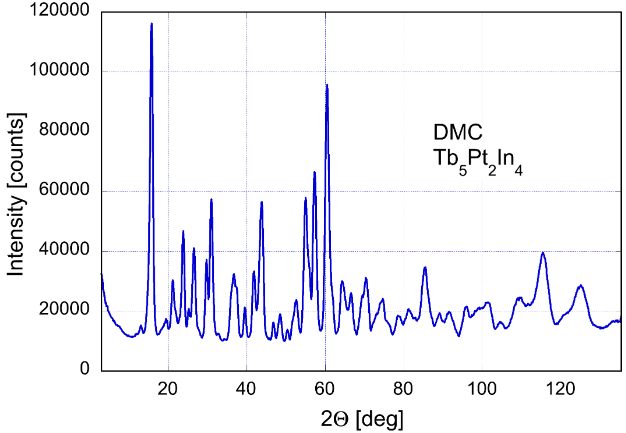




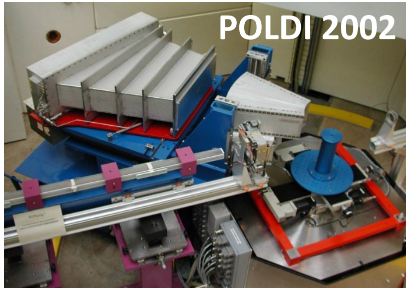


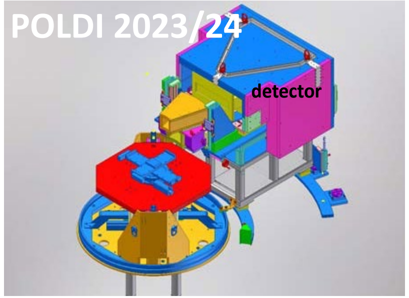
CHRISP & SINQ

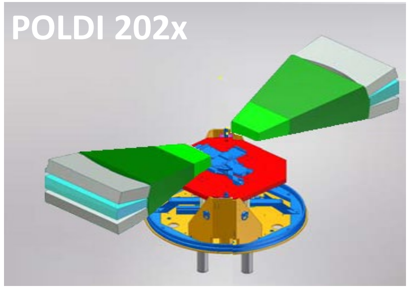

ZnS/^{6}LiF scintillator
SINQ Target
Neutronenleiter
BOA
ICON
HRPT
NEUTRA
POLDI
EIGER
AMOR
RITA 2
TASP
SANS-I
SANS-II
FOCUS
MARS
NARZISS
ORION
DMC
Cockcroft-Walton
870 keV
Injektor 1
Injektor 2
72 MeV
Ringzyklotron
590 MeV
OPTIS
NE-B
NE-C
PiE1
PiE3
PiE5
MuE1
MuE4
PiM1
PiM3
Target E
Target M
Beamdump
UCN
nEDM
ATEC
WSGA
IP 2
0m
10m
20m
30m
Längenmassstab

New POLDI Detector @ SINQ

- ongoing upgrade program PSI and CDT Ltd., Heidelberg
- POLDI: time-of-flight neutron diffractometer for strain measurements
- detector requirements
  - continuous, horizontal coverage ≥ 30°
  - vertical coverage ≥ ± 3.2° (200 mm)
  - horizontal resolution / channel width 2.5 mm
  - efficiency 65% @ 1.2 Å
  - global rate capability ~kHz / channel
  - time resolution ≤ 1 μs
- realisation
  - ZnS/^{6}LiF-based scintillator read out with WLS fibres and SiPMs
  - prototype developed at PSI in 2013-2017
  - former postdoc moved to CDT Ltd.







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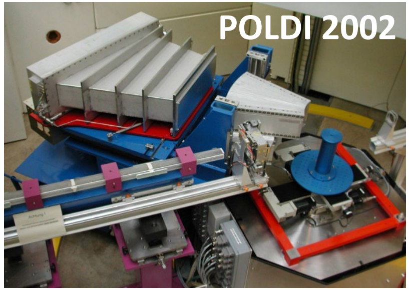
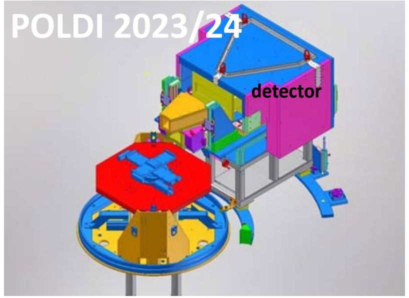
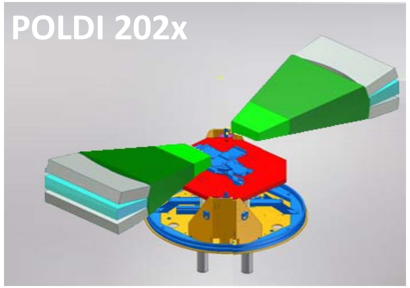
* first ZnS detector for neutron scattering @ PSI
* first SiPM in neutron scattering instrumentation worldwide

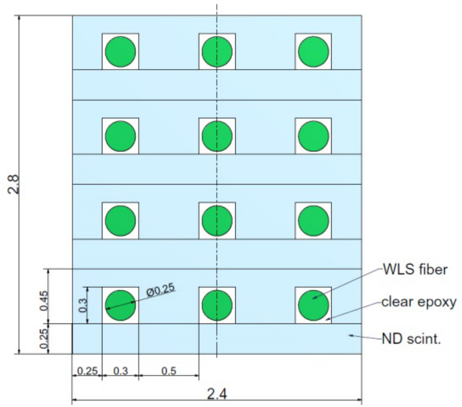


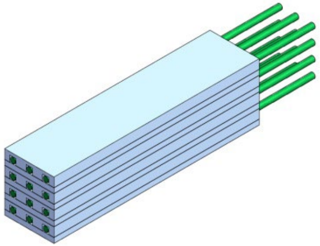


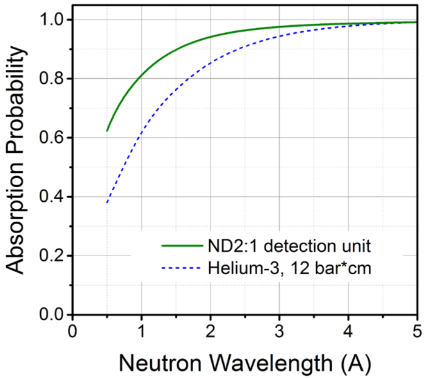


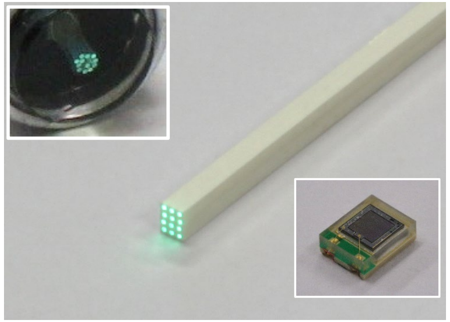
ZnS/^{6}LiF-based thermal Neutron Detector @ PSI

- detection principle
  - n + ^{6}Li → t + α
  - scintillation light from ZnS
- ND2:1 Scintillation screen (Scintacor)
  - non-transparent, 0.25 mm and 0.45 mm thickness
  - grooves machined in 0.45 mm screen
- WLS fibres Kuraray Y11(499)M
  - ∅ = 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 bundled and coupled to SiPM
- detection unit with 4 layers
  - ε_{abs} > 80% @ 1.2 Å , intrinsic time resolution < 1 μs

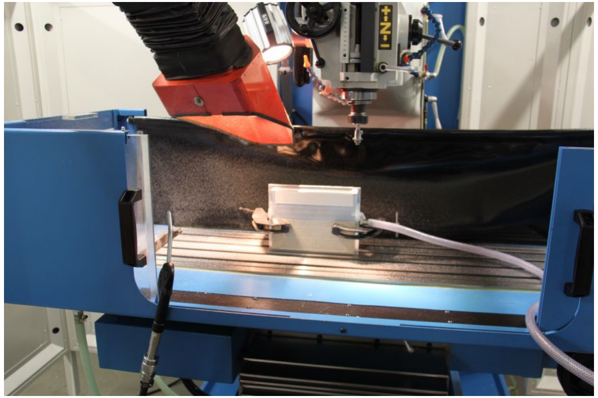


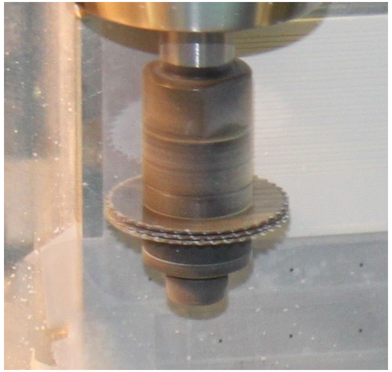


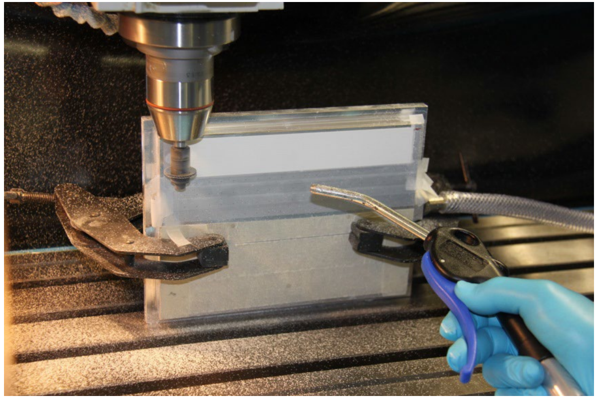


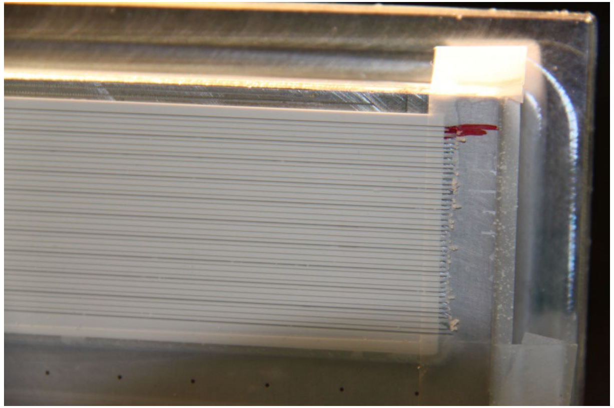


Manufacturing Prototype @ PSI









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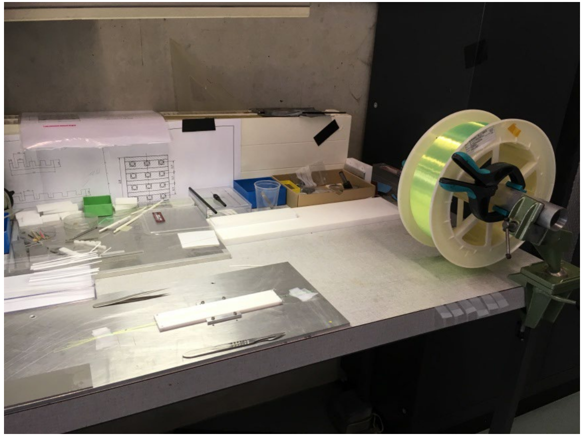
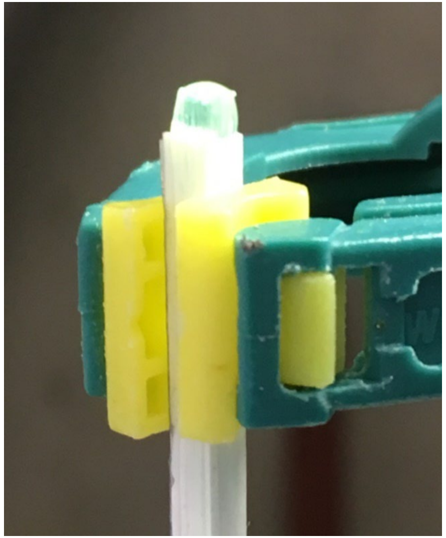
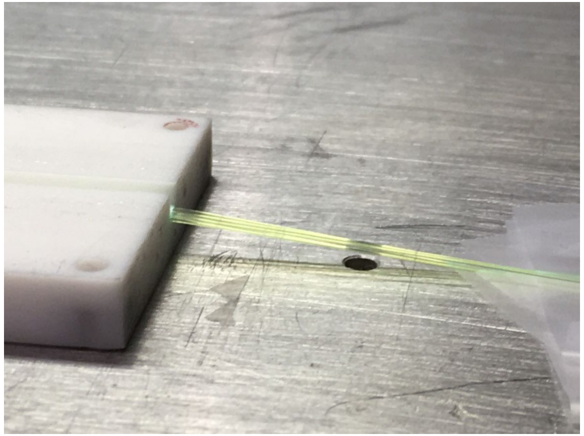
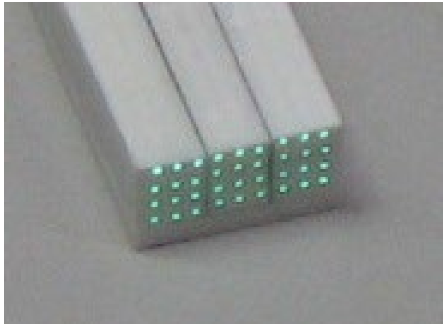
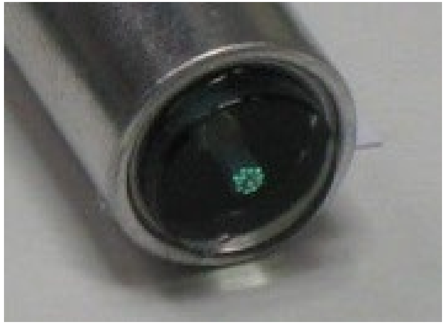


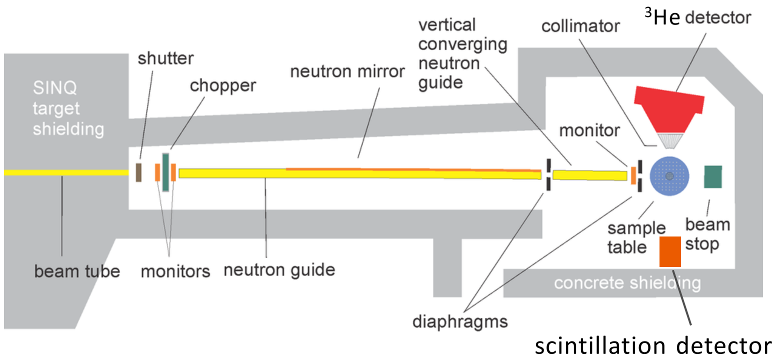


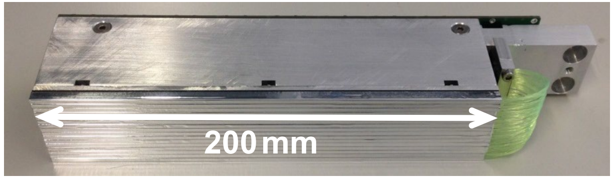


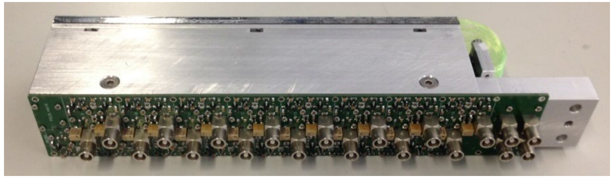




ZnS/^{6}LiF-based thermal Neutron Detector @ PSI







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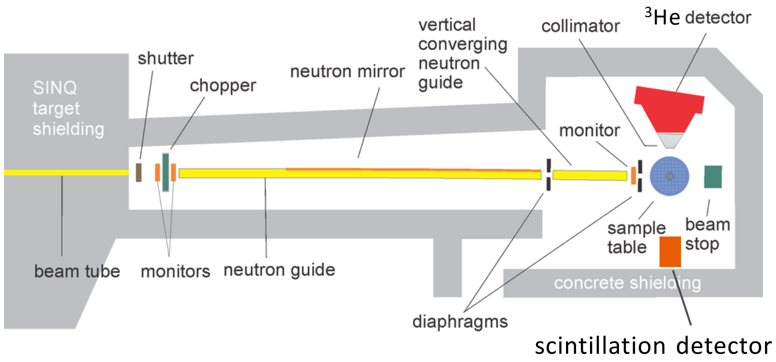
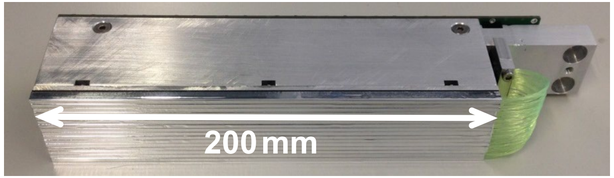
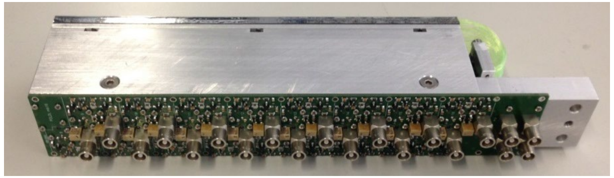
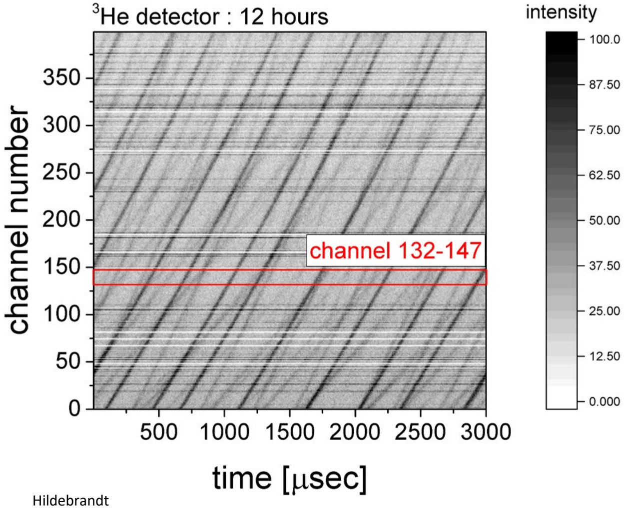
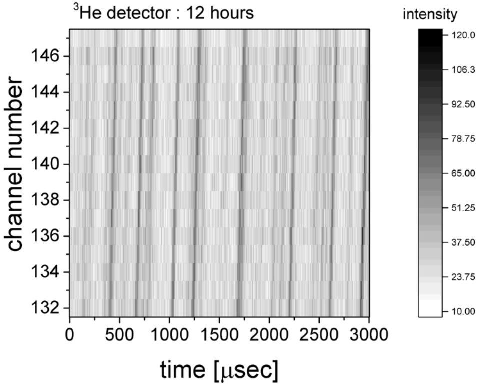
ZnS/^{6}LiF-based thermal Neutron Detector @ PSI

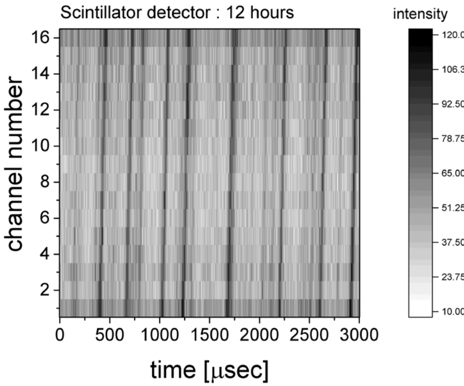












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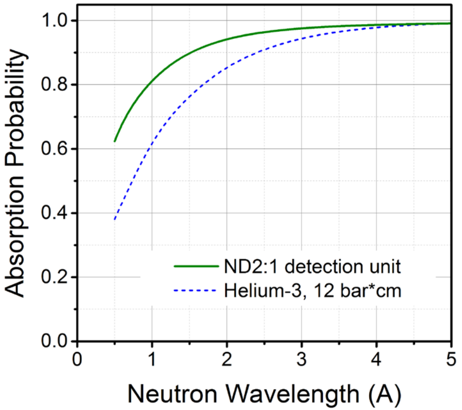
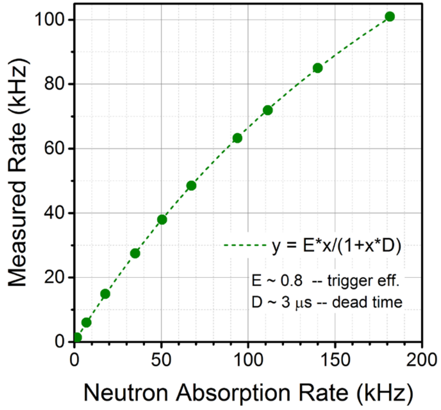
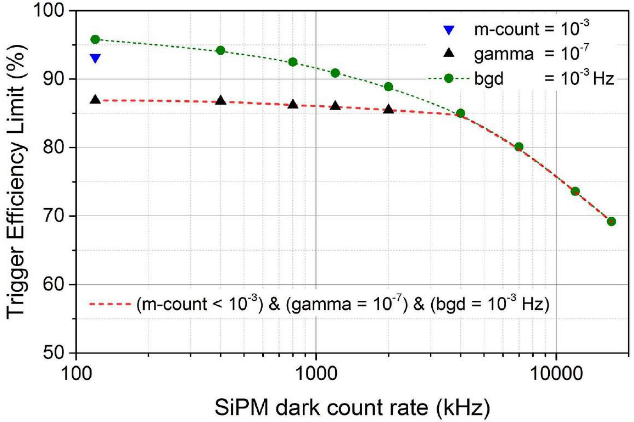
$ZnS/^6LiF$-based thermal Neutron Detector @ PSI

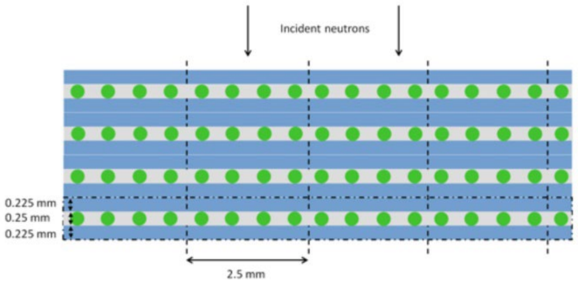
- achieved detector performance
  - 1D, gapless, individual pixel readout
  - individual long pixels (2.5 mm, 200 mm)
  - detection efficiency at 1 Å — 60 %
    - absorption probability — 75 %
    - trigger efficiency — 80 %
  - background count rate — $\leq 10^{-3}$ Hz
  - gamma-sensitivity (^{60}Co)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

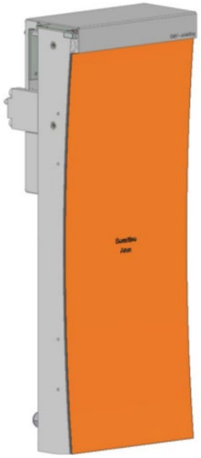


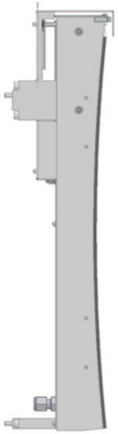


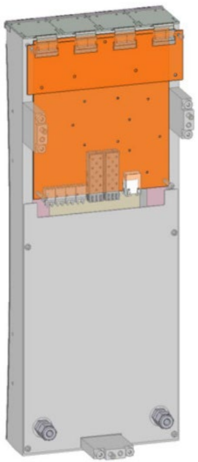


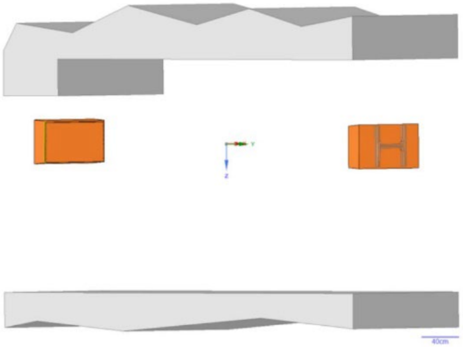
Full-Size Module Production @ CDT











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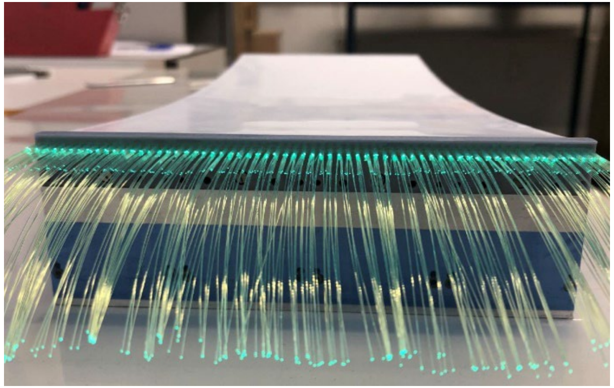

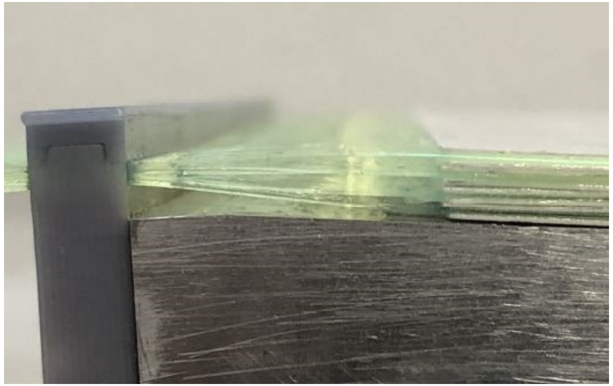

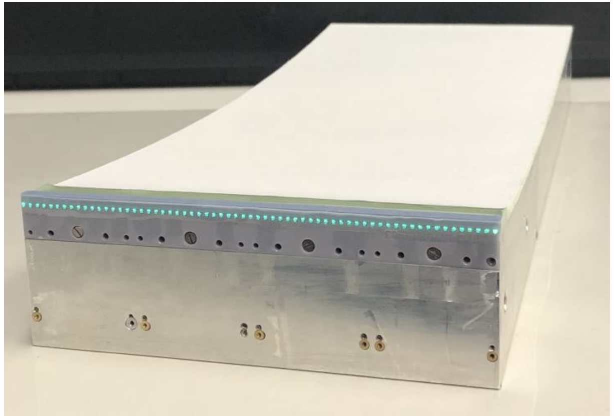

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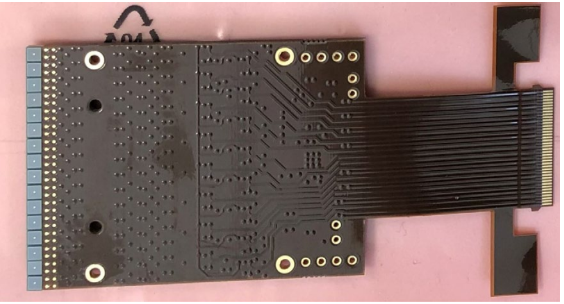
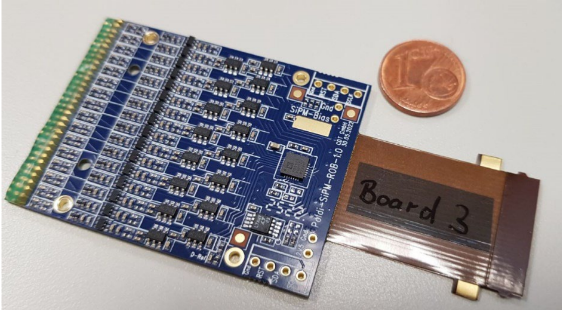
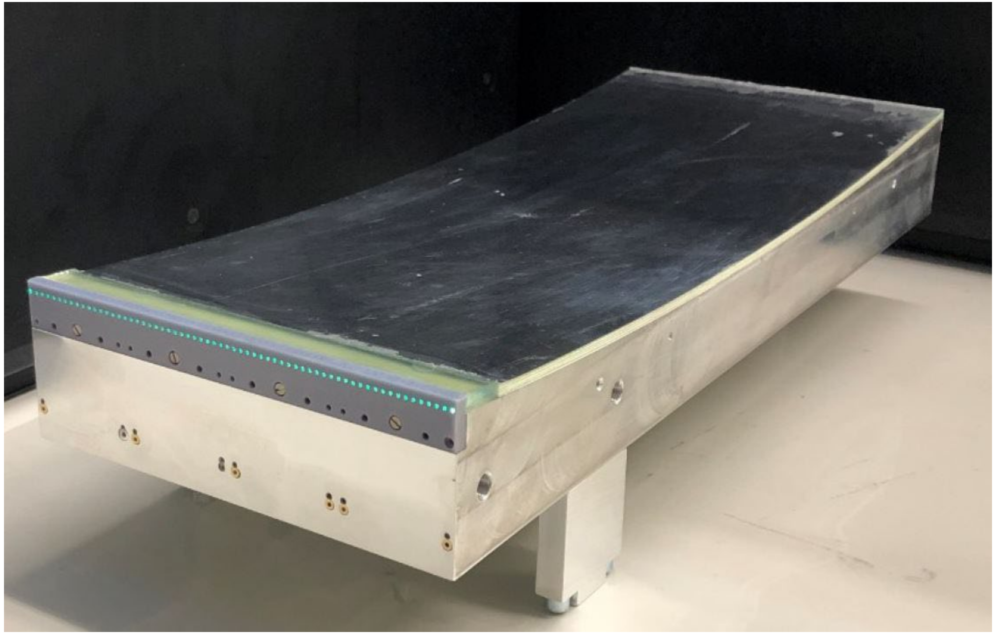
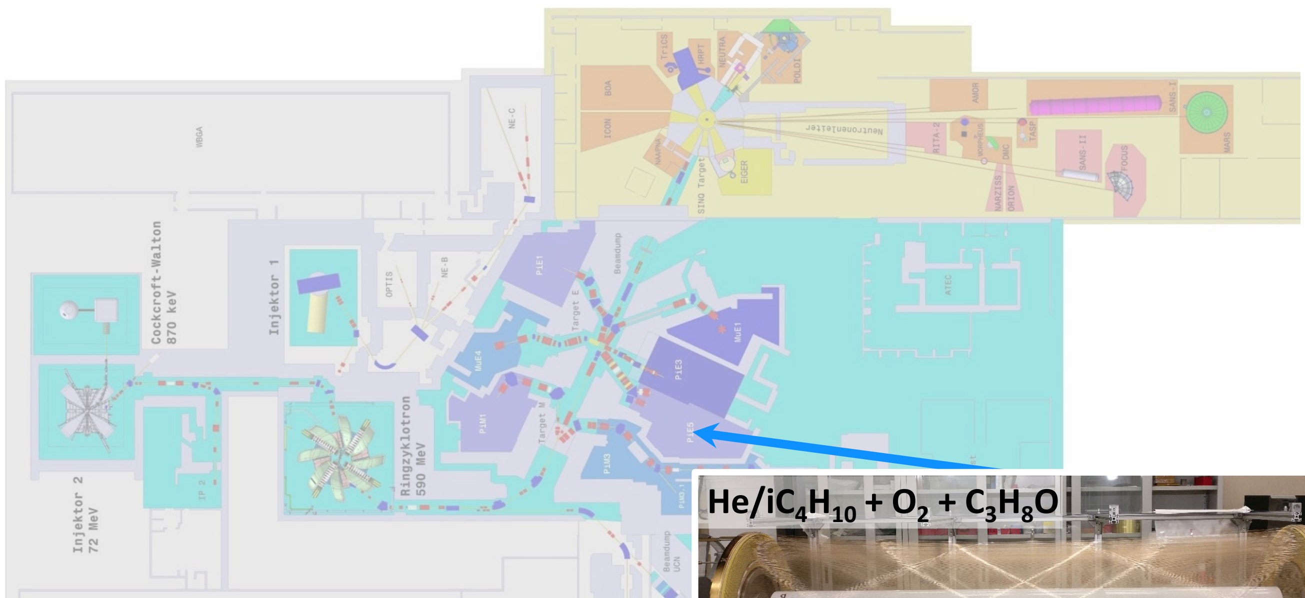
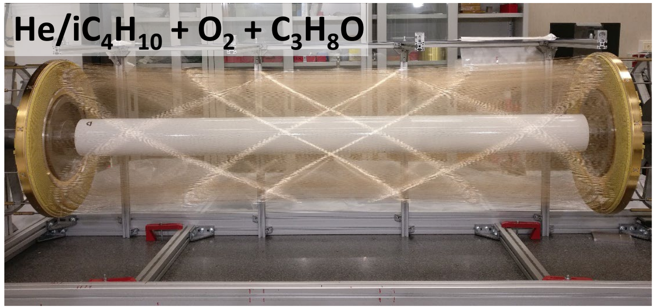






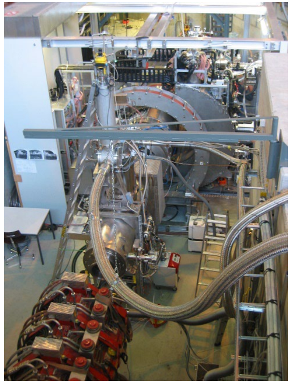
CHRISP & SINQ

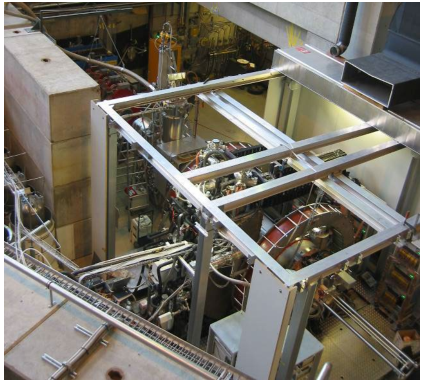

Cockcroft-Walton
870 keV
Injektor 1
Injektor 2
72 MeV
Ringzyklotron
590 MeV
SINQ Target
Neutronenleiter
WSGA
WBGA
UCN
nEDM
Beamdump

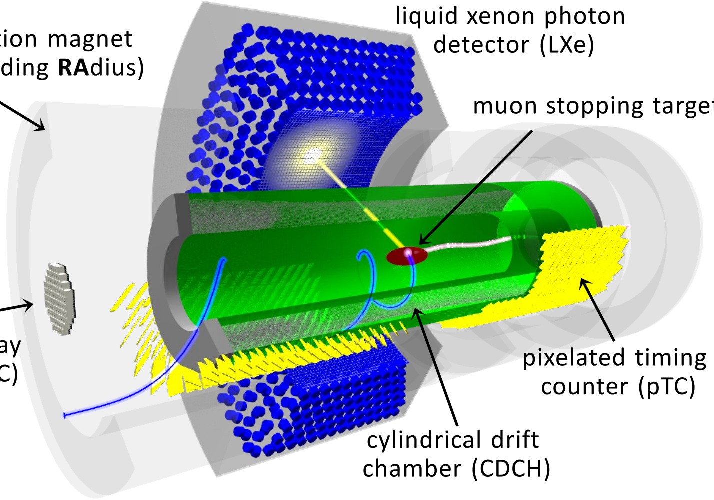

$He/iC_4H_{10} + O_2 + C_3H_8O$

MEG II Experiment @ PSI

- search for cLFV decay $\mu \rightarrow e + \gamma$
- located at CHRISP facility @ Paul Scherrer Institute
  - p-cyclotron: 590 MeV, 2.4 mA
  - πE5: most intense DC low-momentum μ-beam with $O(10^8\ \mu/s)$
- dedicated detector design
  - to measure the observables characterising the $\mu^+ \rightarrow e^+\ \gamma$ event: E_γ, E_e, $t_{e\gamma}$, $\vartheta_{e\gamma}$, $\varphi_{e\gamma}$
  - to reject background







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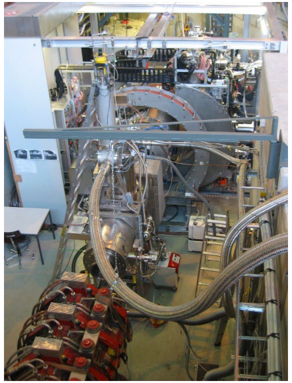
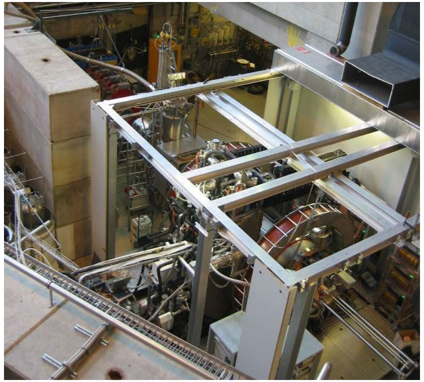
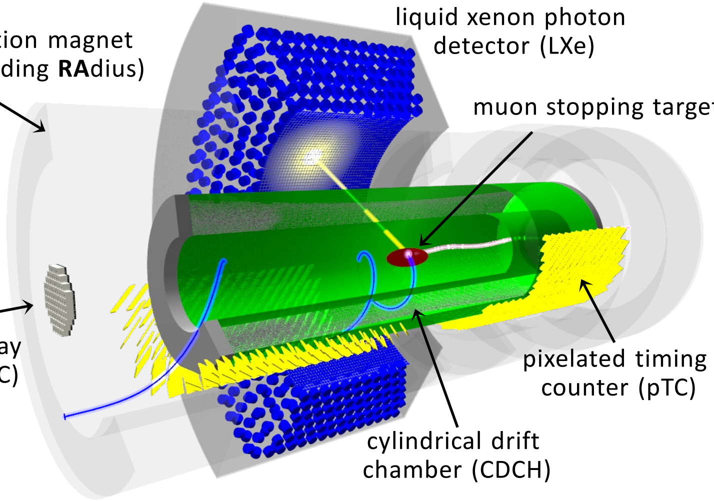






- MEG: analysis of full data sample 2009-2013

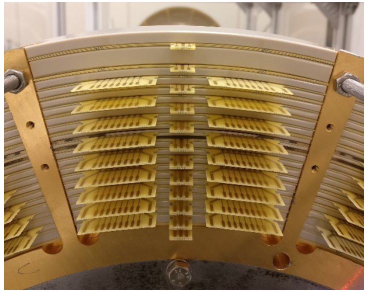
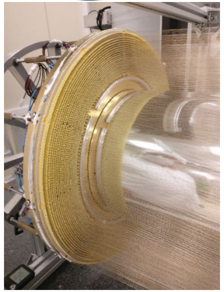
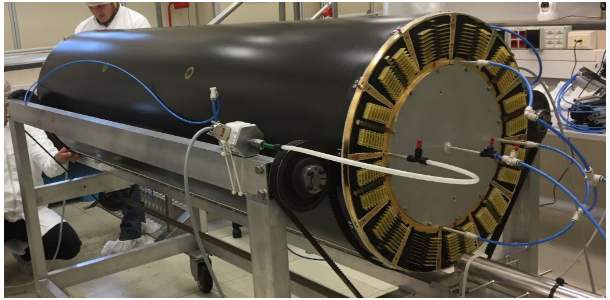
  $$\mathrm{BR}(\mu^+ \rightarrow e^+ \gamma) < 4.2 \cdot 10^{-13} \quad (90\%\ \mathrm{CL})$$

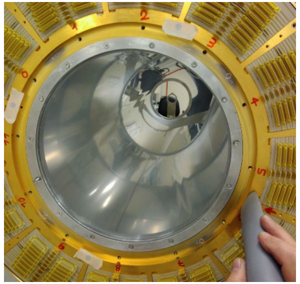
- MEG II: analysis of data sample 2021

  → talk by Toshi Mori, Friday 09:00

Cylindrical Drift Chamber @ MEG II

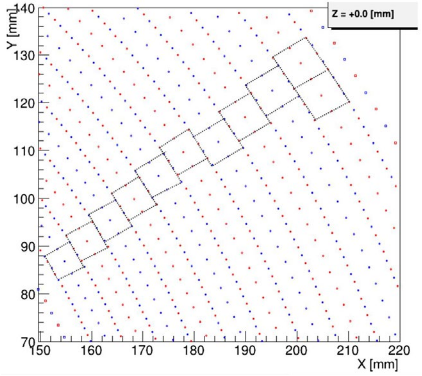
- designed to measure 52.8 MeV e^+ (achieved $\sigma_E \approx 90$ keV)
  - single volume detector
  - high transparency towards Timing Counter
  - low multiple scattering contribution
    $1.58 \cdot 10^{-3}$ X_0 along e^+ track
  - operated in B-field, 0.5 - 1.26 T
- mechanics
  - length = 200 cm, ∅ = outer = 60 cm
  - sensitive region 17 cm < $r_{sensitive}$ < 29 cm
    corresponding to the bending radius of 52.8 MeV/c e^+ in magnet
  - carbon fibre support structure (1.8mm thick) consisting of two half shelfs
  - endplates with stacked PCBs and PEEK spacers
  - thin aluminized Mylar foil to separate sensitive volume with wires and inner part with μ beam and stopping target

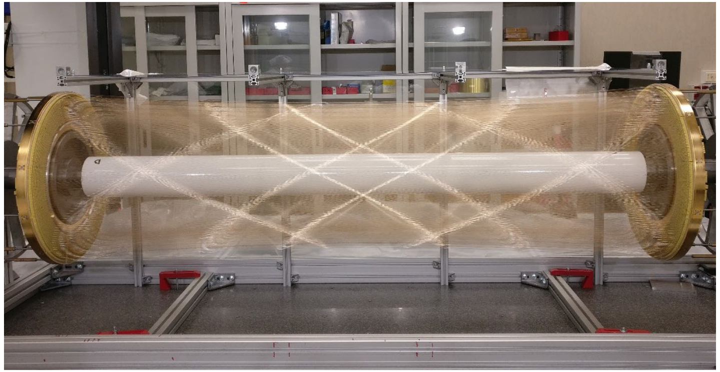






Cylindrical Drift Chamber @ MEG II

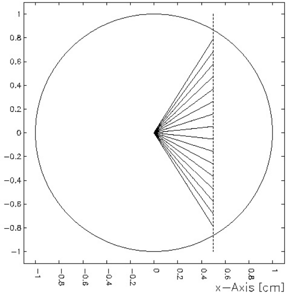
- wiring
  - stereo-angle geometry (6.0° to 8.5°)
    → hyperboloid volume
  - 9 concentric drift cell layers, 2 guard wire layers
  - (approximately) squared drift cell size
    $\pm z_{max}$: 6.7 mm (inner) – 8.7 mm (outer)
    z = 0: 5.8 mm (inner) – 7.5 mm (outer)
  - 20 μm gold-plated W wires
    40 μm, 50 μm silver-plated Al wires
    → 1728 + 9408 + 768 = 11 902 wires with 272 kg
- readout
  - stereo angle geometry
  - high rate environment: >1 MHz per cell (innermost layer)
  - double-sided readout for charge division and signal time propagation difference (DRS4)
- in operation since 2019

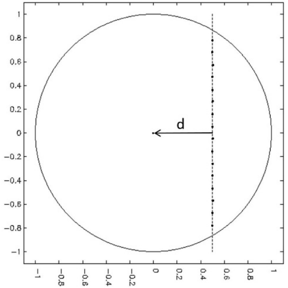


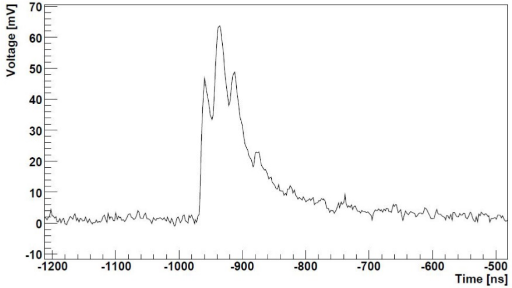


Filling Gas and Cluster Counting Technique

- He/iC_4H_{10} (90/10), admixture of 0.5 % O_2, 1.5 % isopropyl alcohol
  - ~13 e^-/cm (n_p dominated by w_{He} = 41 eV) → large spacing between individual clusters

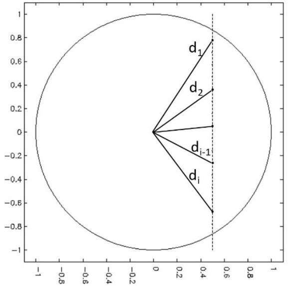


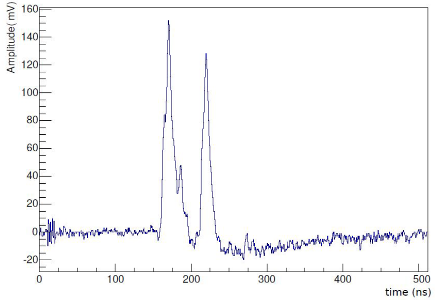




- "traditional" procedure
  - high and dense primary ionisation

- cluster counting technique
  - increased number of supporting points along particle trajectory
  - improved track fitting accuracy and momentum determination





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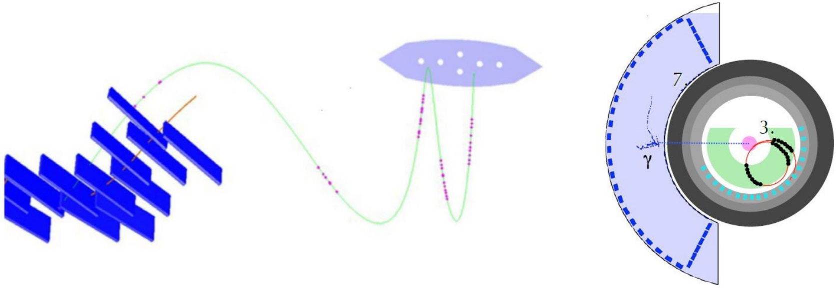
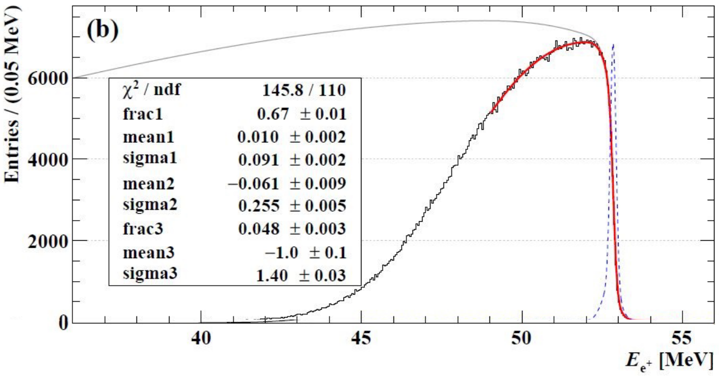
- “traditional” procedure
  - high and dense primary ionisation

- cluster counting technique
  - increased number of supporting points along particle trajectory
  - improved track fitting accuracy and momentum determination

- performance (resolution σ)
  - energy ~90 keV (@52.8 MeV)
  - angular ~7.4 mrad in θ, ~4.1 mrad in ϕ





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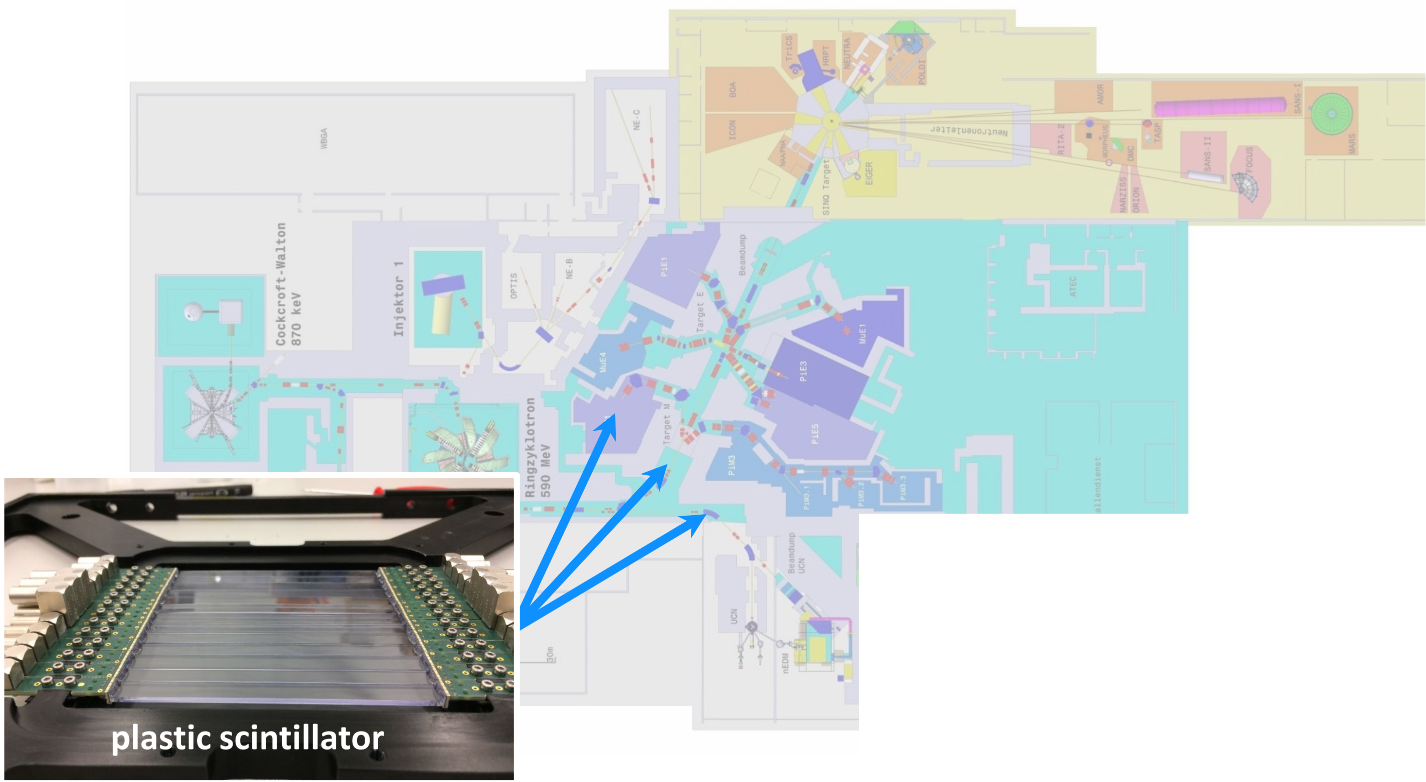
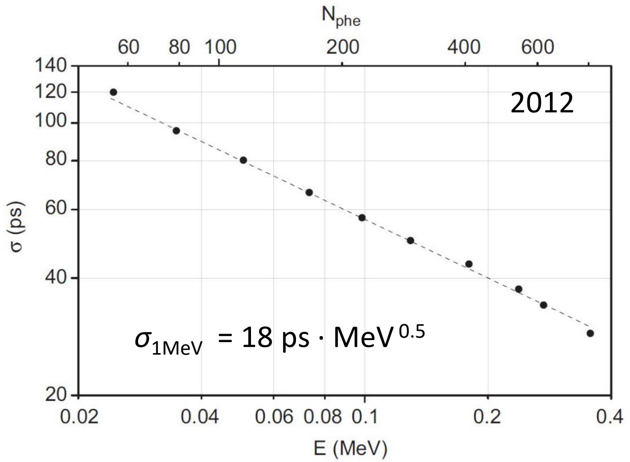


Fast Timing Plastic Scintillator Detectors

- trigger: need of fast timing detectors in μSR technique

- 2012: NIM A 695 (2012) 202-205
  - scintillator BC422 $(3\times3\times2)$ mm^3
  - SiPM Hamamatsu MPPC S10362-33-050, (3×3) mm^2
  - constant fraction discriminator

  → $\sigma_{timing} = \sigma_{1MeV} / E^{0.5}$ with $\sigma_{1MeV} = 18$ ps · $MeV^{0.5}$



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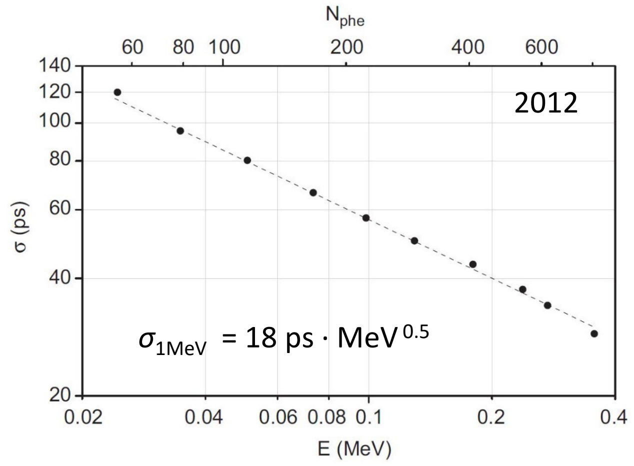
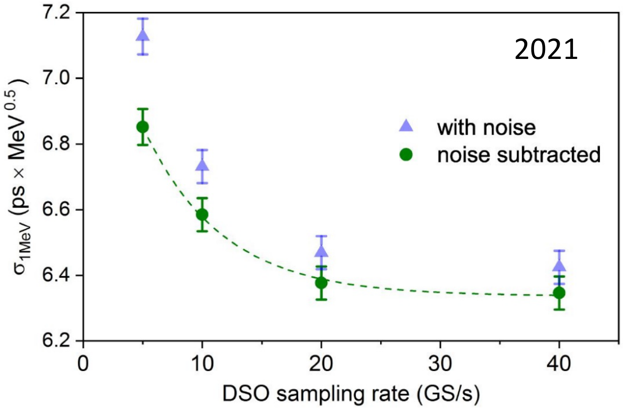


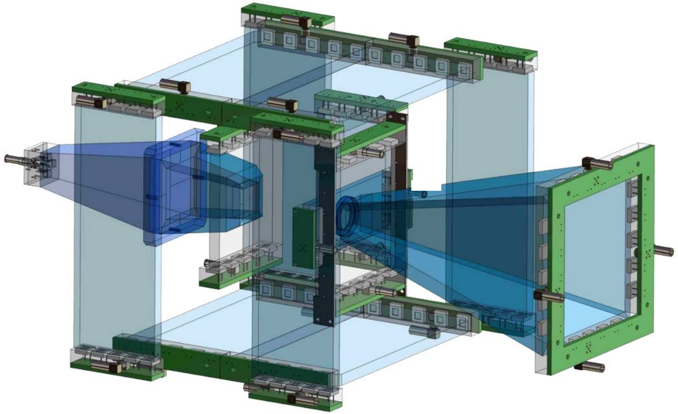
- 2021: IEEE TNS 68, 7 (2021) 1487-1494
  - scintillator BC422 (3×3×3) mm^3, EJ-232 (3×3×3) mm^3
  - SiPM Hamamatsu , Advansid, Ketek, all (3×3) mm^2, Broadcom (3.72×3.72) mm^2
  - constant fraction discriminator

  → BC422 & Broadcom SiPM: $\sigma_{1MeV} = 6.4\ ps \cdot MeV^{0.5}$

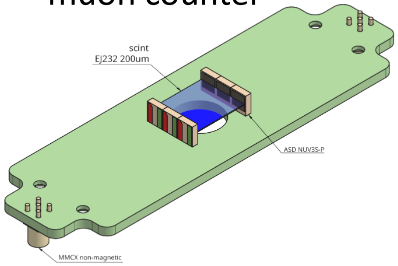


Fast Timing Plastic Scintillator Detectors

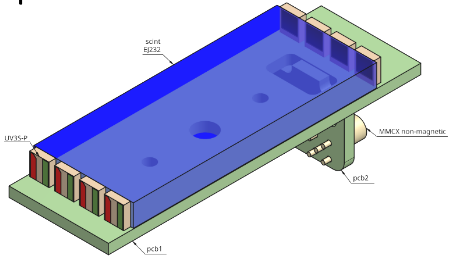
- fast timing μ, e detectors in μSR instrumentation



muon counter



positron counter



Fast Timing Plastic Scintillator Detectors

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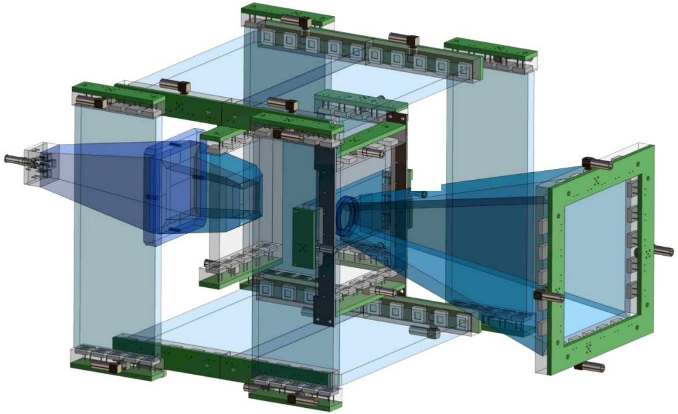
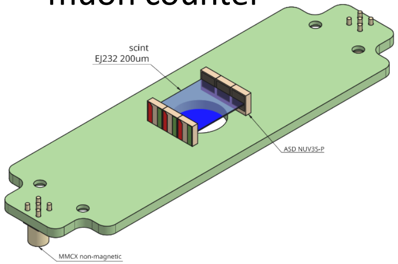
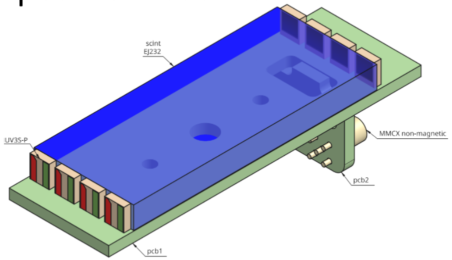


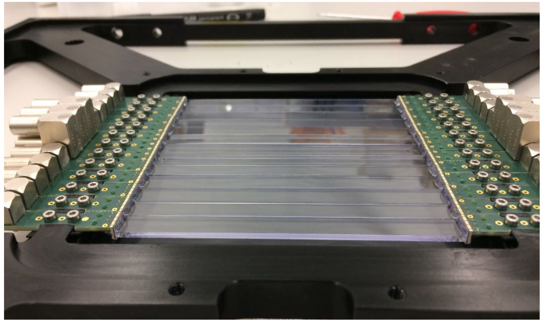
muon counter

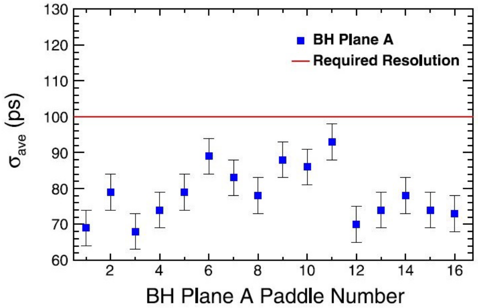


positron counter



- fast timing π, μ, e detectors in MUSE experiment

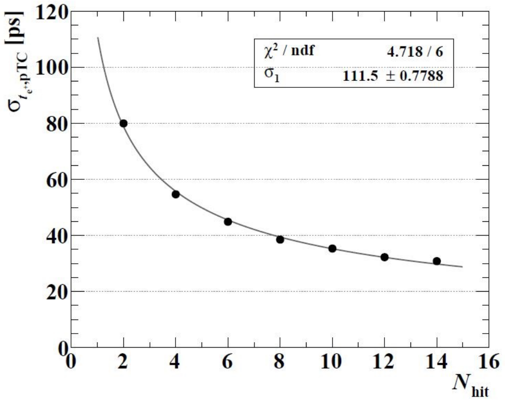


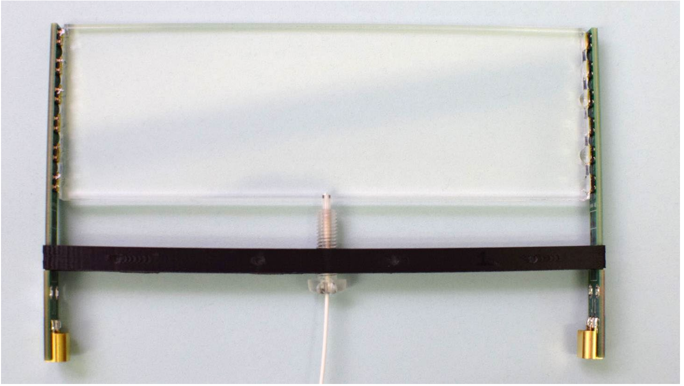


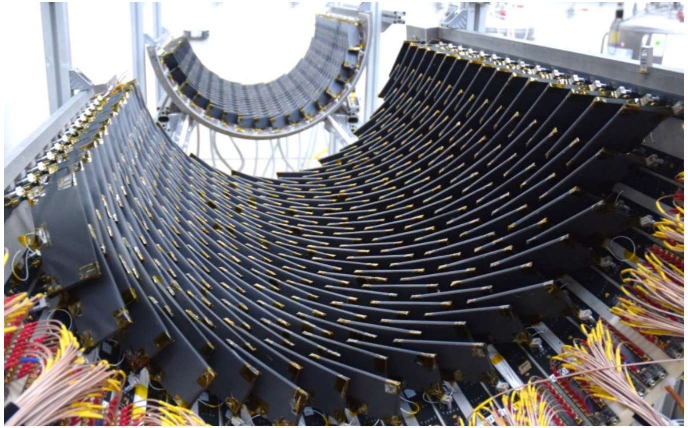
pixelated Timing Counter @ MEG II

- designed to measure timing of 52.8 MeV e^+ ($\sigma_t < 100$ ps)
  - 2× 256 plastic scintillator tiles, (120×40/50×5) mm^3
- scintillator tile
  - scintillator BC422
  - SiPM AdvanSiD (ASD-NUV-SiPM3S-P) (3×3) mm^2
    - each side 6 SiPMs in series
  - wrapped with
    - polymeric reflector foil (VIKUITI 3M Mirror Foil)
    - black TEDLAR foil
- performance

  $\sigma_t < 40$ ps

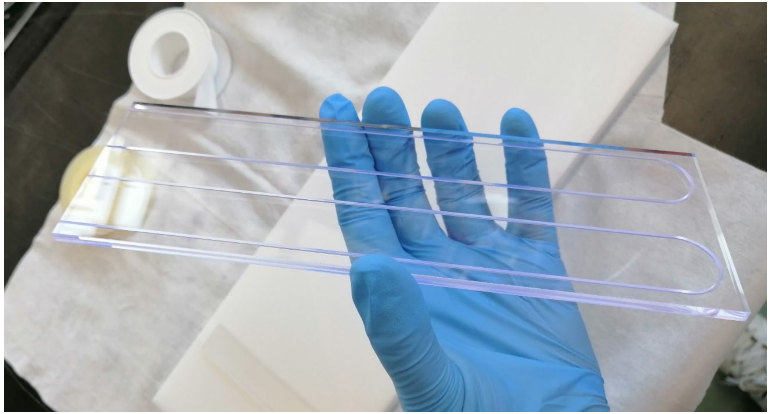
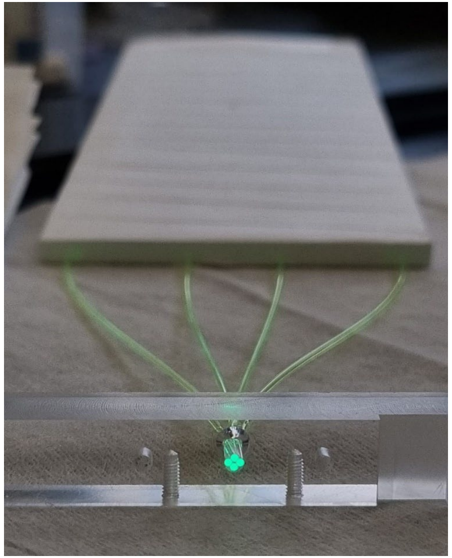
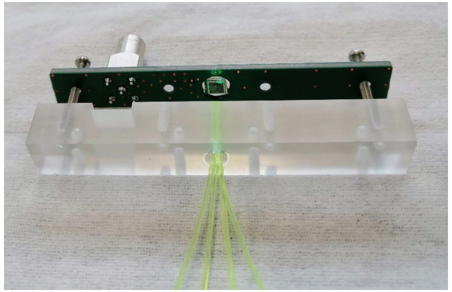






Plastic Scintillator Detectors with WLS Fibre

- embedded WLS fibres for light collection and guiding
- SiPM outside irradiated region, vacuum, etc.
- large area read out by single SiPM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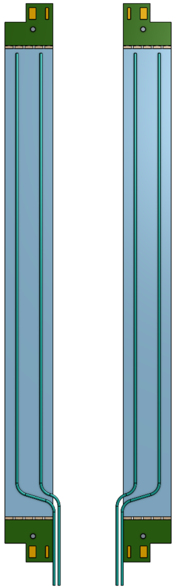

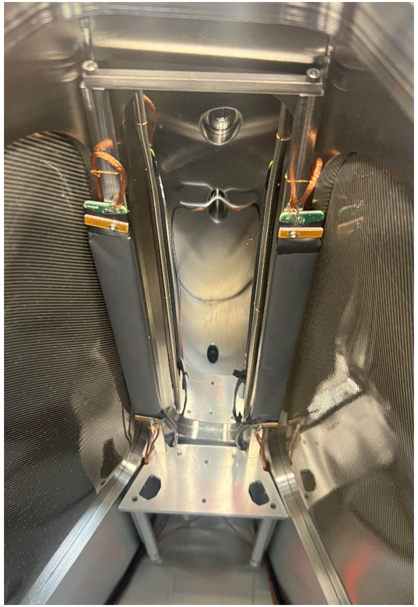

Hildebrandt
Bridge Workshop, 18.10.2023, 36

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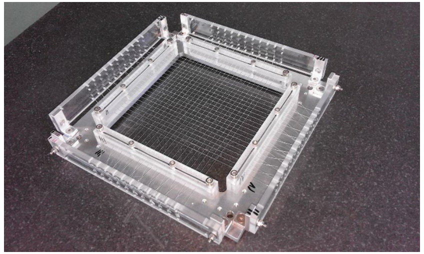
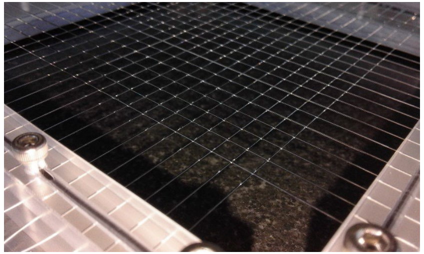
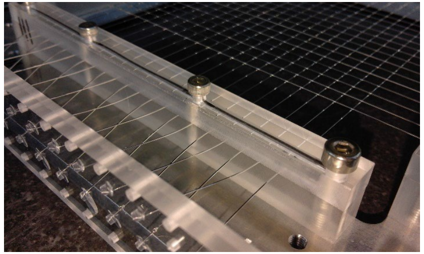
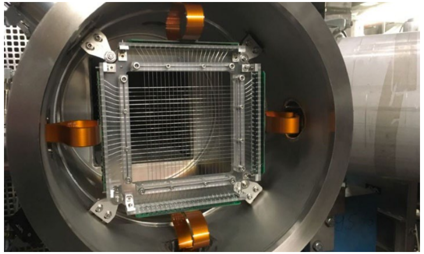
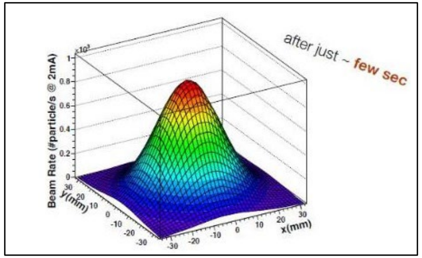
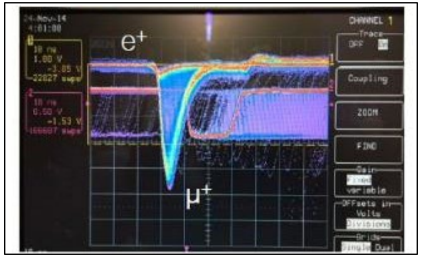
Scintillating Fiber Beam Profile Monitor

- main features
  - real-time measurement of profile and rate
  - 2D reconstruction
  - quasi non-invasive
  - particle ID
  - high rate capability
  - working in magnetic fields
- detector
  - Saint-Gobain BC12 , double cladding, square, 500 μm
  - 21 fibres/layer
  - fibre pitch 5 mm,
  - Hamamatsu MPPC S13360-1350CS
  - double-sided readout, 84 channels
  - DAQ and TRG with WaveDREAM board
- prototype
  - fix mounted in beam line element, operated in air



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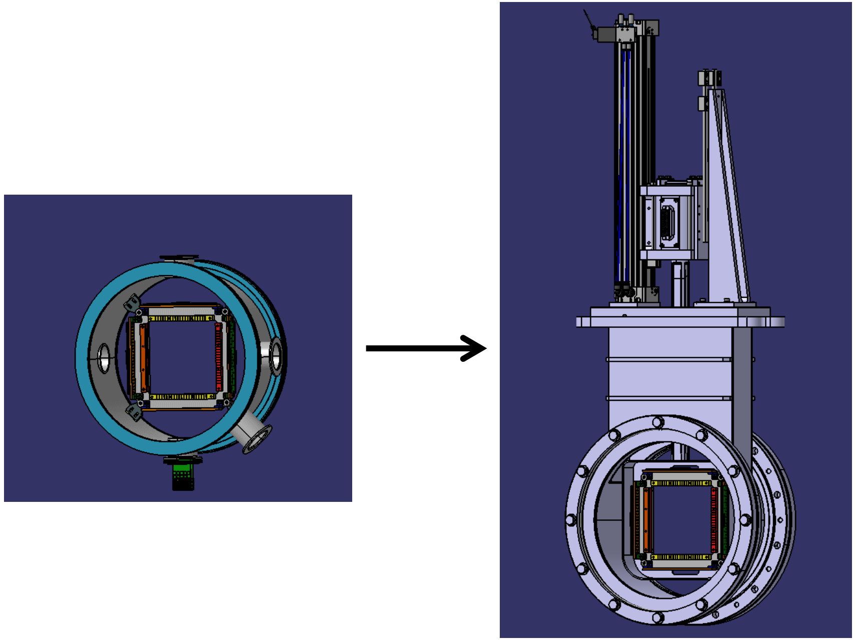
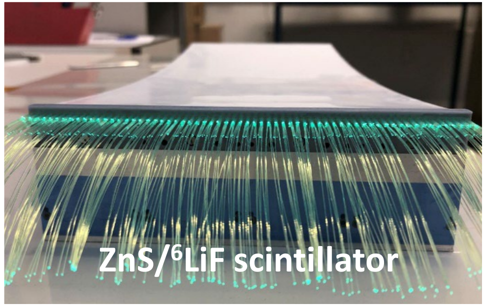
- detector
  - Saint-Gobain BC12 , double cladding, square, 500 μm
  - 21 fibres/layer
  - fibre pitch 5 mm,
  - Hamamatsu MPPC S13360-1350CS
  - double-sided readout, 84 channels
  - DAQ and TRG with WaveDREAM board
- planned final version
  - in vacuum and movable

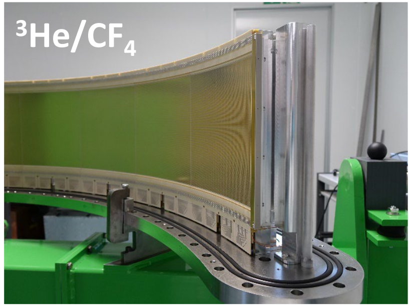


Summary

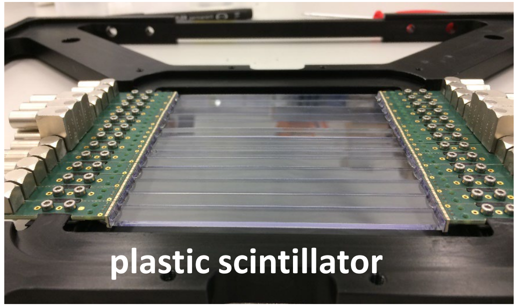


- high $\varepsilon_{n,abs}$
- compact, no gas system
- low bias voltages

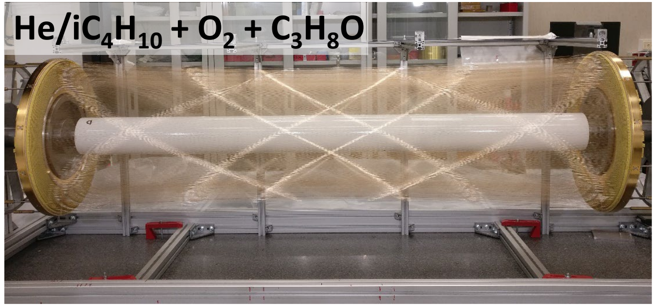
- large area coverage
- high $\varepsilon_{n,abs}$
- high rate capability



- fast timing
- particle ID



- large volume
- low material budget
- very good σ_E

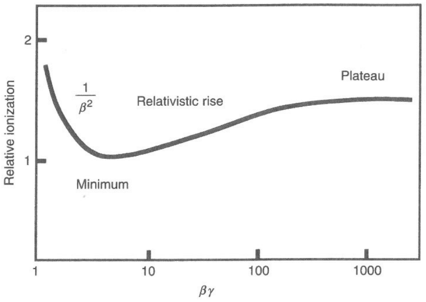


Summary:

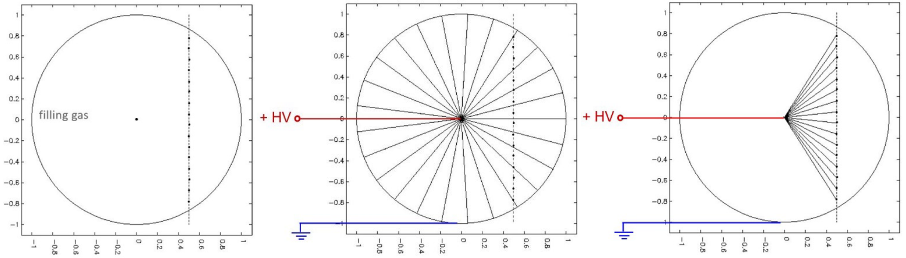
Acknowledgment

Charged Particles

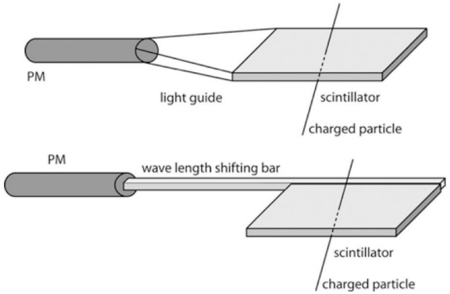
- energy loss dE/dx while passing through matter



- gaseous detector
  - volume filled with 'counting gas'
  - deposited energy used to ionise the gas atoms/molecules
  - applied electric field collects the primary ionisation
  - different operation modes, depending on applied voltage, anode geometry, electron amplification, etc.
  - readout with charge-sensitive pre-amplifier



- scintillation detector
  - deposited energy used to excite or ionise luminescence centres
  - 'scintillation light' emitted due to return to ground state
  - light collection (light guides, WLS)
  - opto-electrical conversion with PMT, SiPM



Neutrons

neutron absorption

- gaseous converter:

  n + ^{3}He → p^{+} (0.573 MeV) + t^{+} (0.191 MeV)

  n + BF_3 safety issues (toxic, corrosive)
  limitations in gaseous electronics ($p < 2$ bar)

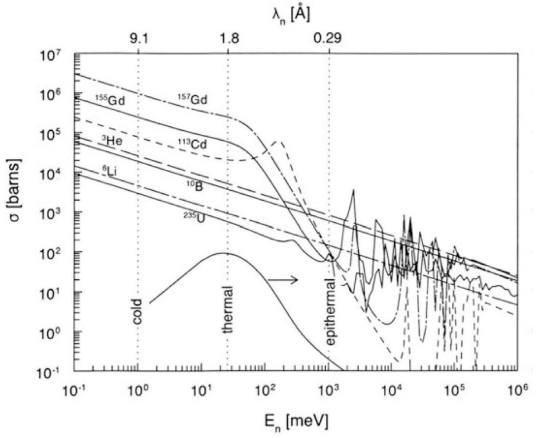
- solid converter:

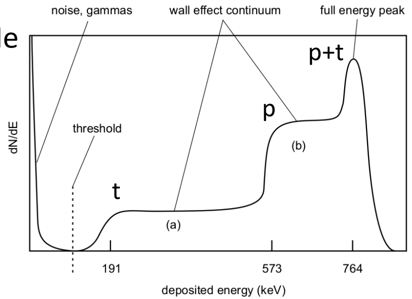
  n + ^{6}Li → t (2.73 MeV) + α (2.05 MeV)

  n + ^{10}B → α (1.47 MeV) + ^{7}Li (0.83 MeV) + γ (0.477 MeV)

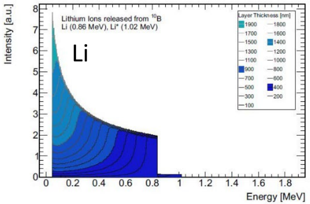
  n + ^{10}B → α (1.78 MeV) + ^{7}Li (1.01 MeV)

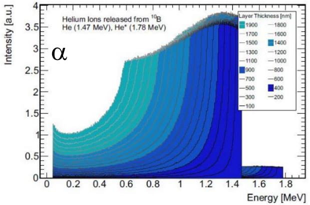
  n + ^{157}Gd → ^{158}Gd + e^{-} (0.07- 0.182 MeV) (85-90 e^{-}/n)





10B

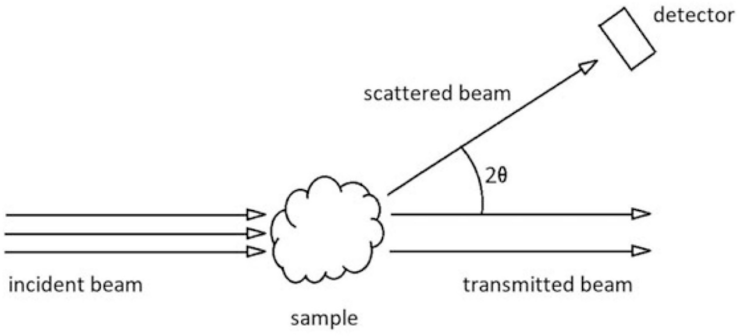


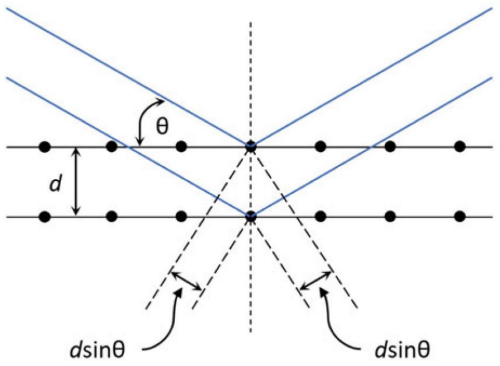


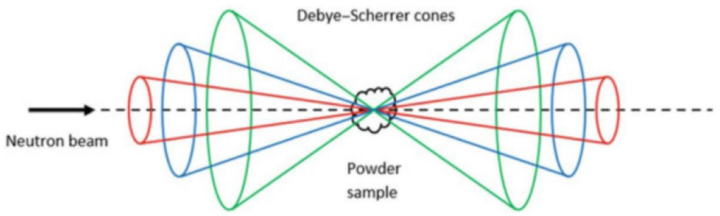
Neutron Scattering Principles

requirements for detector

- 1D / 2D position-sensitive ~mm
- large area coverage
- high efficiency
- timing resolution ~μs
- count rate several (tens) kHz / channel







ZnS:Ag/^{6}LiF Scintillator

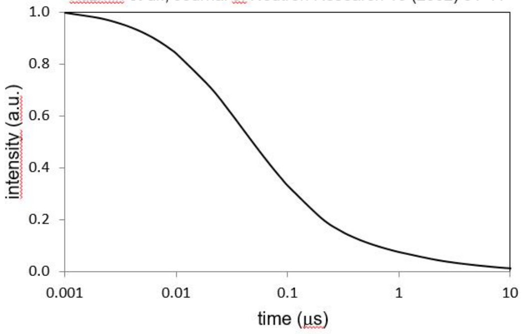
ZnS:Ag/^{6}LiF scintillator*

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

- neutron absorption: $^6Li + ^1n \rightarrow ^3H + ^4He + 4.79$ 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

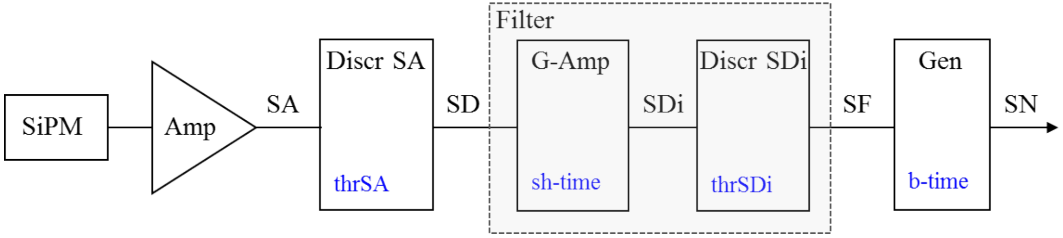
Kuzmin *et al.*, Journal of Neutron Research 10 (2002) 31-41



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

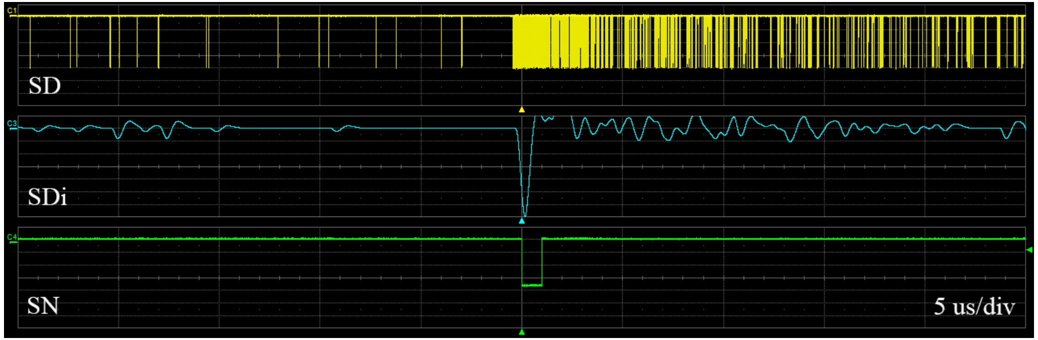
Signal Processing

- based on analysis of temporal distribution of single-cell SiPM signals
  → neutron event detected as an increase of the density of single-cell SiPM signals



- blocking times can be shorter than emission time of scintillator

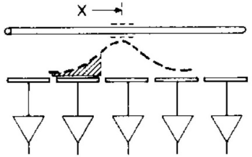
- scalable



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)

CoG Methode – Electrons vs Photons

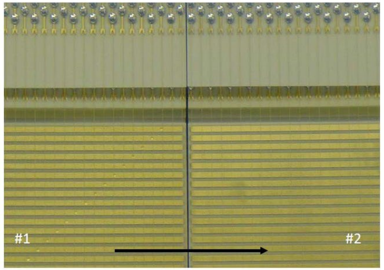
$$\bar{x} = \frac{\sum x_k Q_k}{\sum Q_k}$$

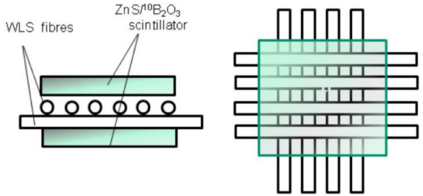


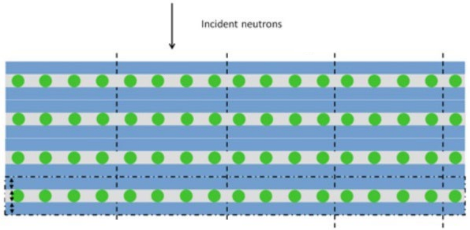
$$\bar{x} = \frac{\sum x_k N_k}{\sum N_k}$$

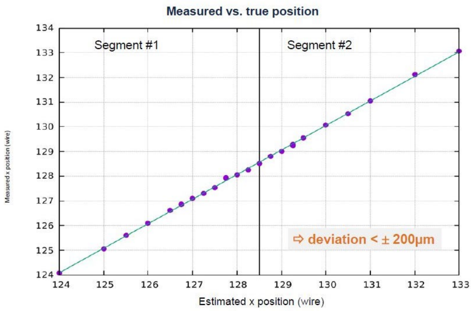
Q_k = charge in channel x_k

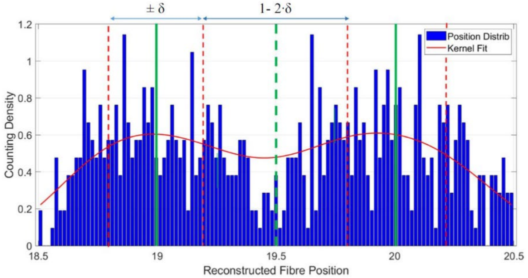
N_k = # of photons in channel x_k

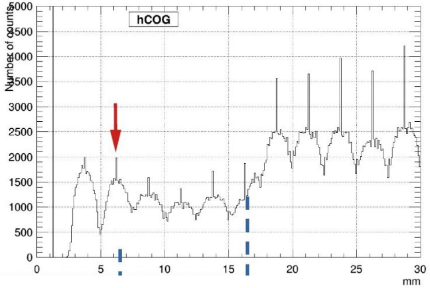






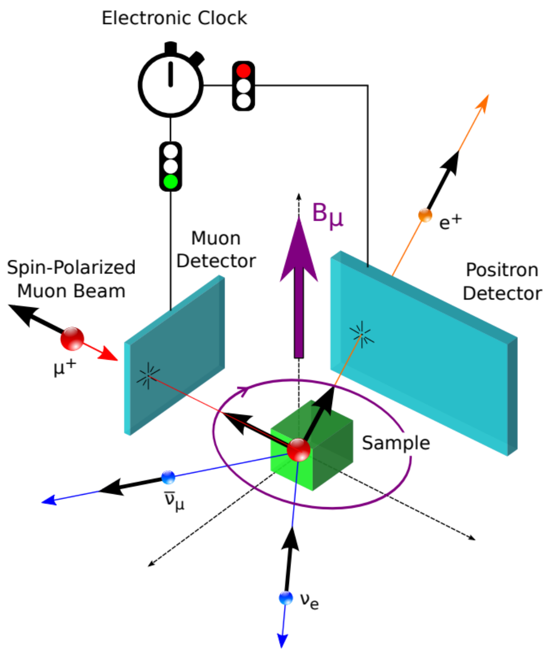


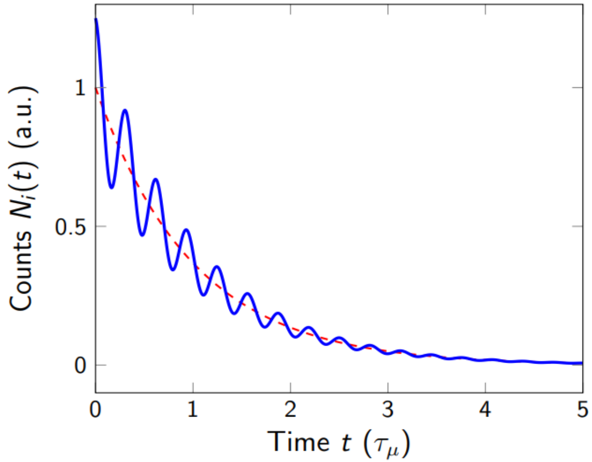




Fast Timing Plastic Scintillator Detectors

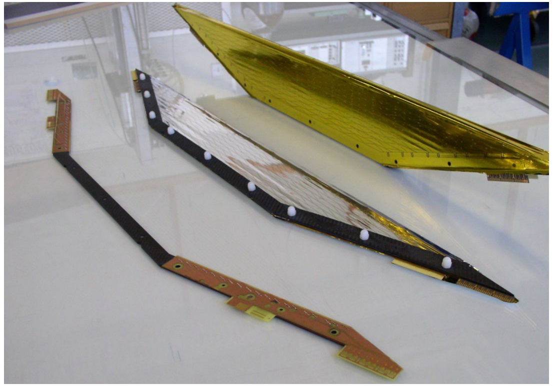
- trigger: need of fast timing e^+ detector in μSR technique

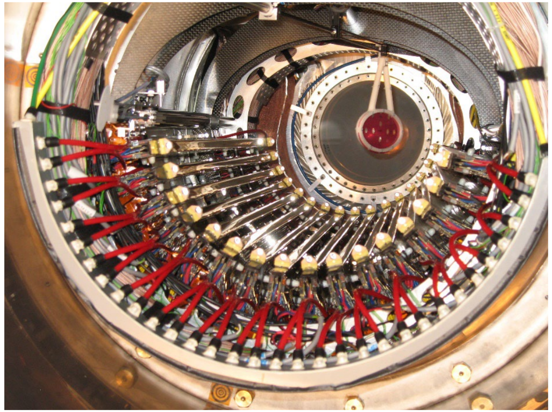




Drift Chamber System @ MEG (2009-13)

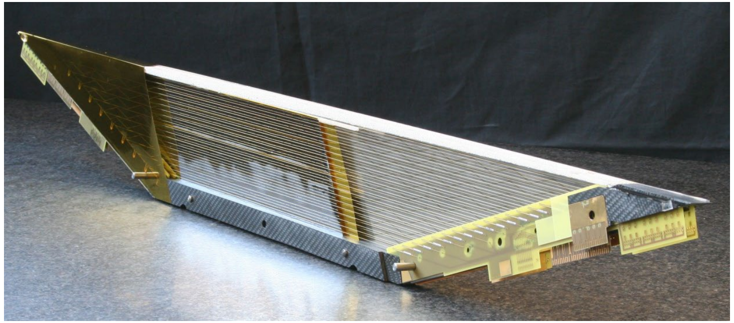
- designed to measure 52.8 MeV e^+ (achieved $\sigma_E \approx 330$ keV)
  - 16 individual drift chamber modules
  - aligned radially in half circle, 10.5° intervals
  - low multiple scattering contribution
    - $2.6 \cdot 10^{-4}$ X_0 per module
    - $2.0 \cdot 10^{-3}$ X_0 along e^+ track
  - filling gas He/C_2H_6 (50/50)
  - operated in Helium atmosphere
  - operated in B-field, 0.5 - 1.26 T
- mechanics
  - 1m long, V-shaped / open trapezoidal geometry
  - carbon fibre frames
  - two (staggered) detector planes per module to resolve ambiguities
  - carbon fibre support structure (DC modules, HV/LV cables, gas tubes, etc.)

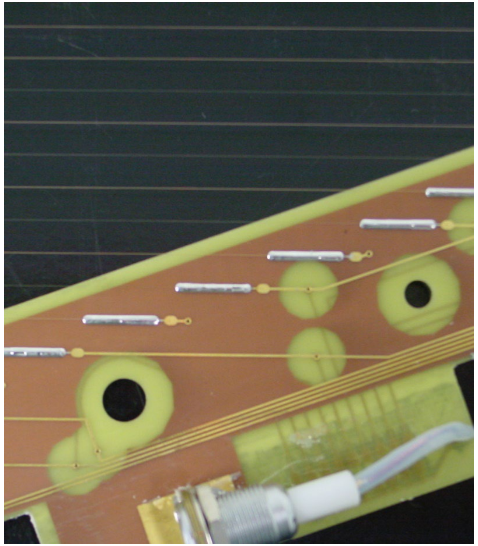


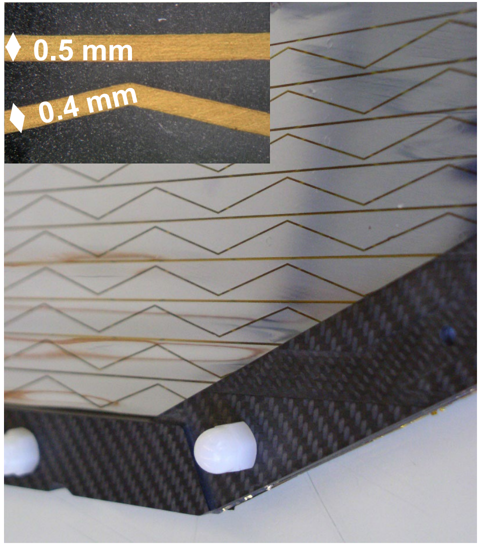


Drift Chamber System @ MEG (2009-13)

- wiring
  - 25 μm Ni80/Cr20 wires (2.2 kΩ/m)
  - 50 μm Cu98/Be2 wires
  - length 40 - 830 mm
- cathode
  - 12.5 μm polyamide foil
  - ~250 nm sputtered aluminum coating
  - Vernier pattern (λ = 5 cm)
- readout
  - double-sided anode wire readout for charge division (DRS): σ_{anode} ~cm,
  - four cathode strips per anode: $\sigma_{cathode}$ < 1mm
  - high rate environment: 30 kHz/cm^2







Drift Chamber System @ MEG (2009-13)

- operation
  - initial problems (2007/08) with HV stability due to
    - sealing of HV connections in outer Helium atmosphere and
    - «helium pocket»
  - anode aging as expected
- performance (resolution σ)
  - energy ~330 keV (@52.8 MeV)
  - angular ~8.5 mrad in θ, ~7.7 mrad in ϕ