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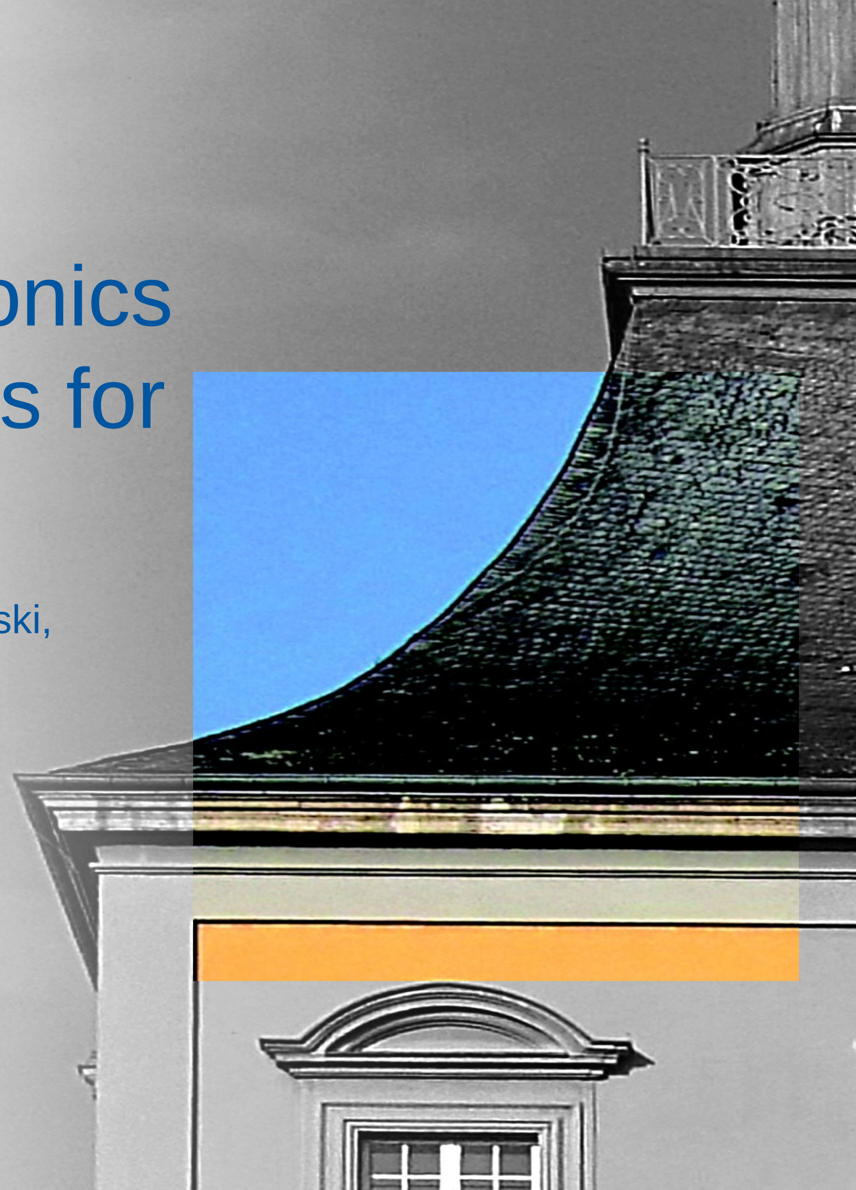
GEFÖRDERT VOM
Bundesministerium für Bildung und Forschung

Particle Physics Readout Electronics and Novel Detector Technologies for Neutron Science

Thomas Block, Markus Gruber, Saime Gurbuz, Jochen Kaminski, **Michael Lupberger**, Divya Pal, Laura Rodriguez Gomez, Patrick Schwaebig, Klaus Desch

Physikalisches Institut, Universität Bonn

15th Pisa Meeting on Advanced Detectors
24.05.2022



RD51 GasDet Bonn

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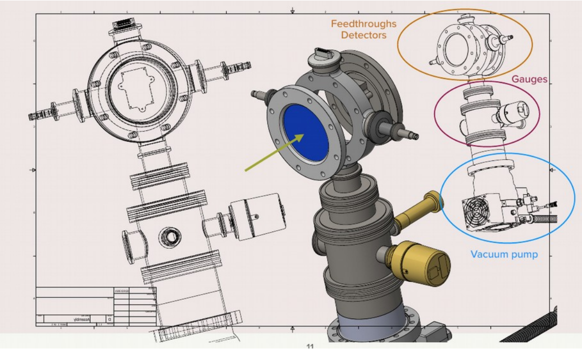
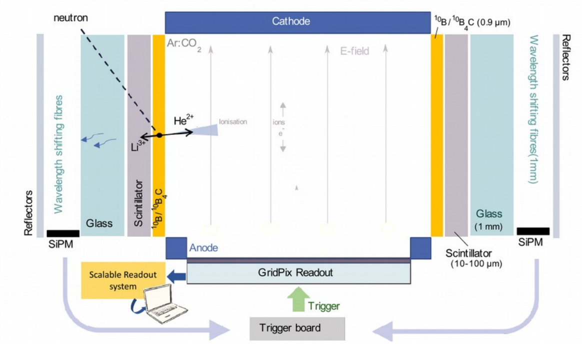
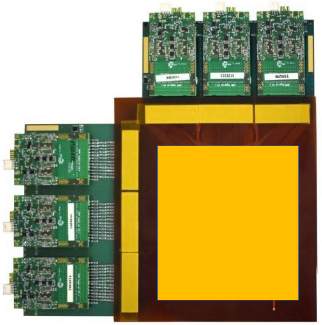
Content

- Neutron detection
- Detector requirements
- Technology for neutron detectors
  - Micro-Channel Plate
  - Time-Projection Chamber
  - Gas Electron Multiplier



neutron Time Projection Chamber (nTPC)

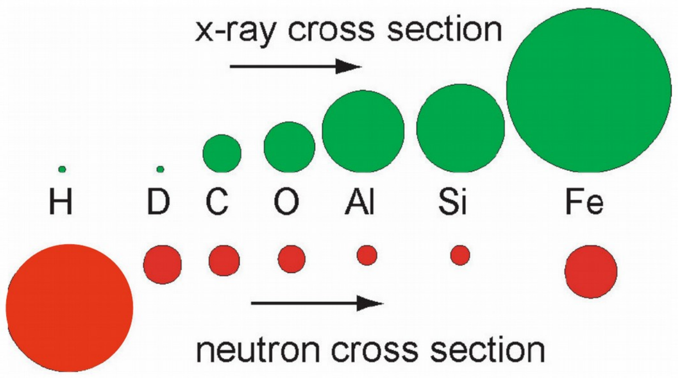




https://youtu.be/NnQdiDVOlvI

Introduction: Neutron Detection

Neutron: Neutral particle, penetrate material easily → absorption imaging, similar to X-ray imaging



John R.D. Copley, Dynamics and Neutron Scattering, Summer school 2007

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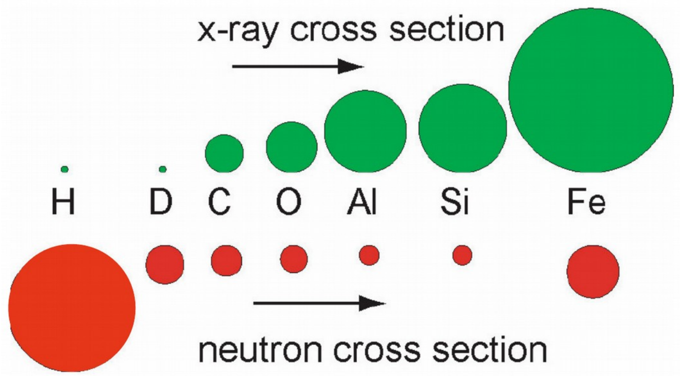

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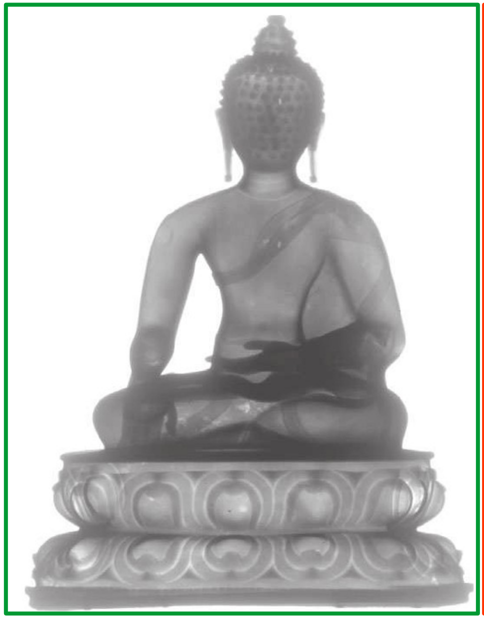
Visible light

X-ray



Neutrons

Lehmann, Eberhard H., Stefan Hartmann, and Markus O. Speidel. "Investigation of the content of ancient Tibetan metallic Buddha statues by means of neutron imaging methods." Archaeometry 52.3 (2010): 416-428.

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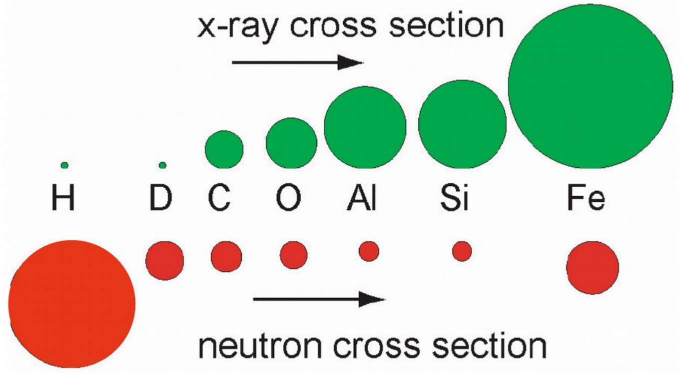


John R.D. Copley, Dynamics and Neutron Scattering, Summer school 2007

Interaction with materials containing hydrogen e.g.

- Water
- Organic materials
- H-atoms at borders of molecules

Visible light | X-ray | Neutrons

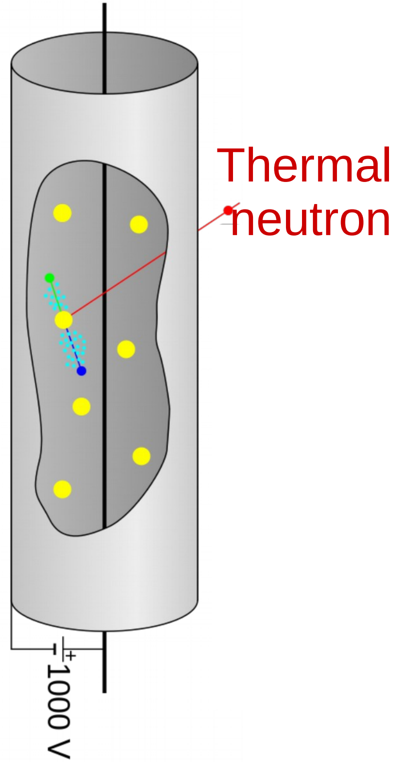
Lehmann, Eberhard H., Stefan Hartmann, and Markus O. Speidel. "Investigation of the content of ancient Tibetan metallic Buddha statues by means of neutron imaging methods." Archaeometry 52.3 (2010): 416-428.

Introduction: Neutron Detection

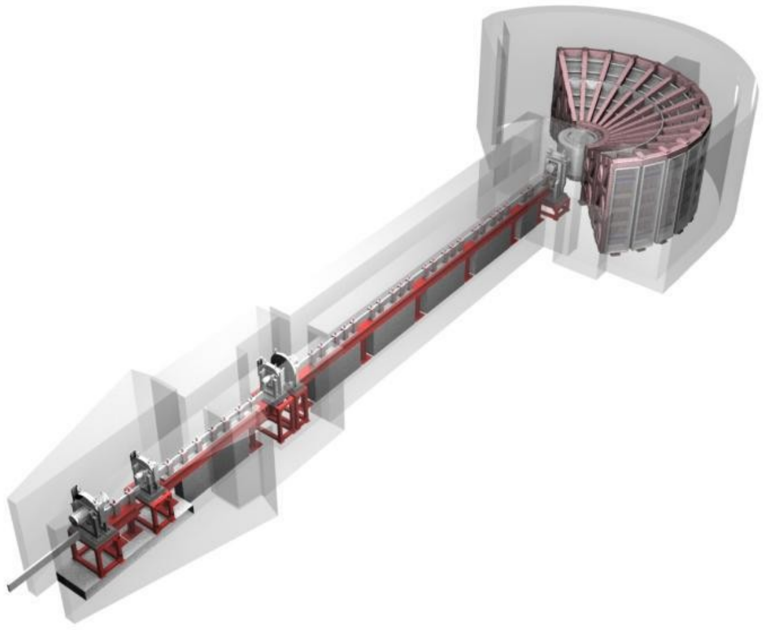
Enabler for neutron detection: Conversion to charged particle

Most common neutron detector: ^{3}He-filled Geiger-Müller tube

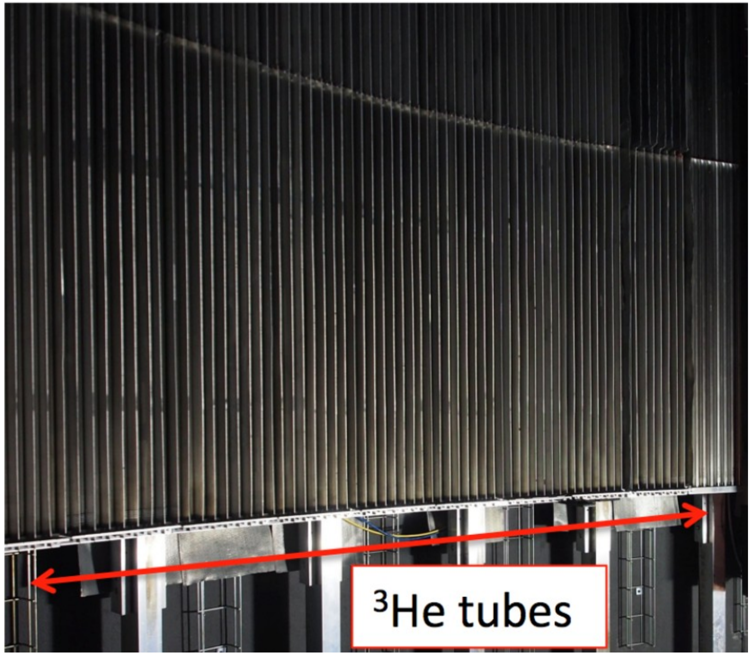
$$^3He + n \rightarrow {}^3H + p$$



https://de.wikipedia.org/wiki/Zählrohr



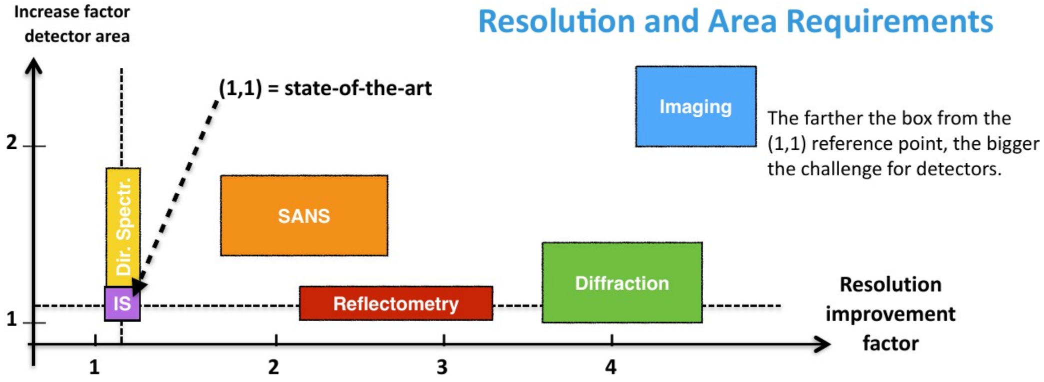
JP-PARC, BL14 AMATERAS: https://mlfinfo.jp/en/bl14/

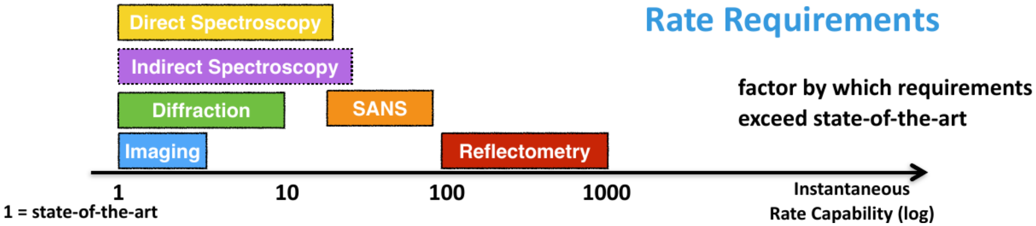


Adopted from: Anastasopoulos, Michail, et al. "Multi-Grid detector for neutron spectroscopy: results obtained on time-of-flight spectrometer CNCS." Journal of Instrumentation 12.04 (2017): P04030.

Requirements at ESS / He-3 crisis

Detectors for the European Spallation Source (ESS) currently built in Lund





From: R. Hall-Wilton, *Detectors for Neutron Scattering Science at the European Spallation Source,* Presentation given at the CERN detector seminar (2020)

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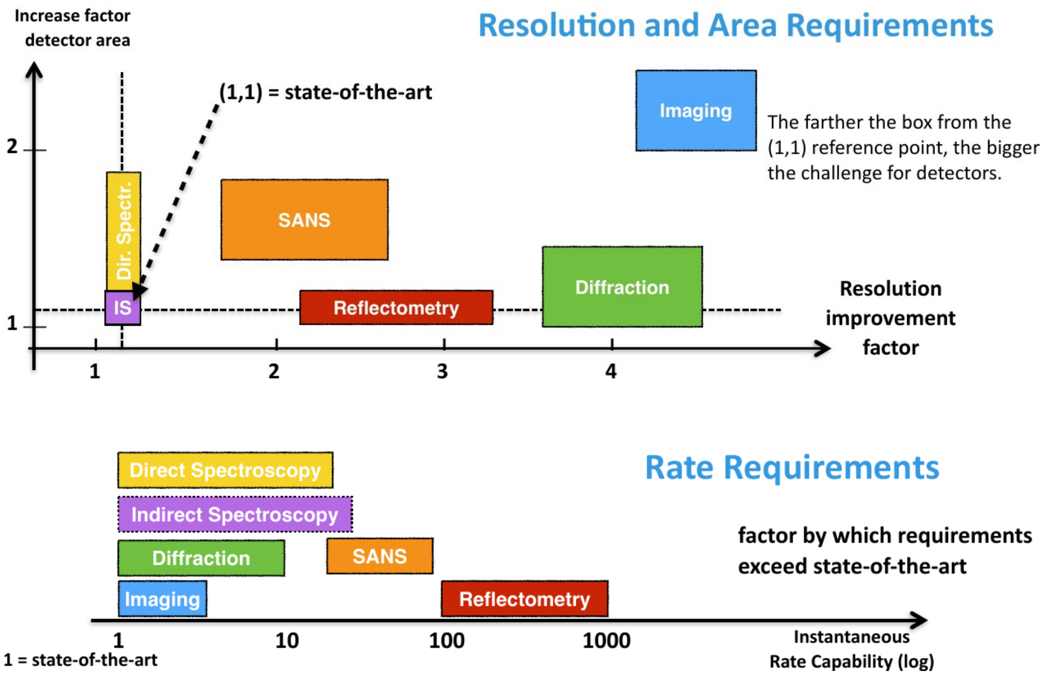
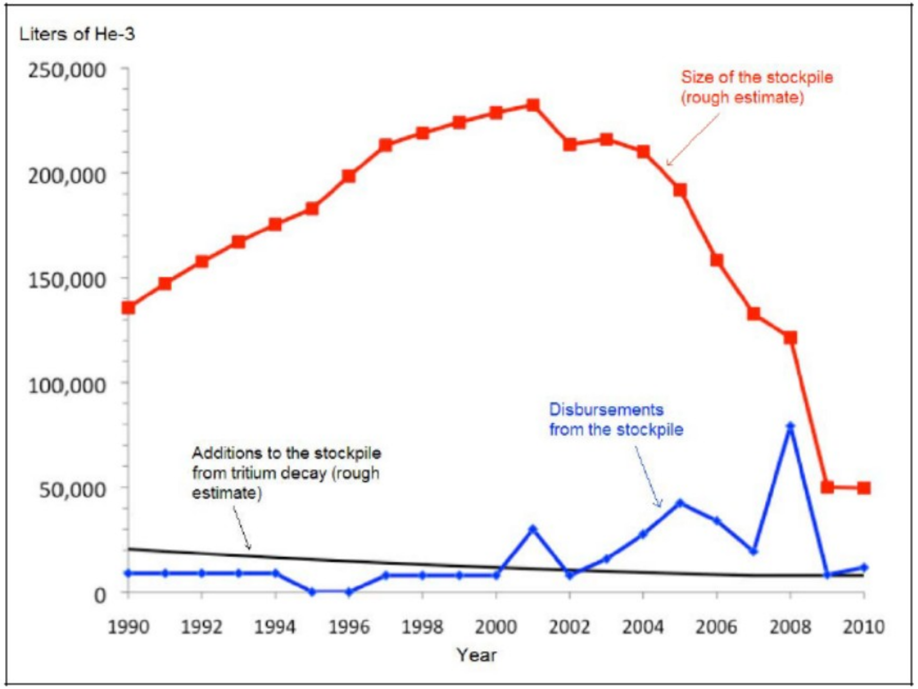


From: R. Hall-Wilton, *Detectors for Neutron Scattering Science at the European Spallation Source,* Presentation given at the CERN detector seminar (2020)

^{3}He: decay product from Tritium in thermonuclear weapon stockpile



Grossmann, Agnes & Gabrielli, Roland & Herdrich, Georg & Fasoulas, Stefanos & Schnauffer, Peter & Middendorf, Peter & Fateri, Miranda & Gebhardt, Andreas. (2015). Overview of the MultiRob 3D Lunar Industrial Development Project.

Solid converters: Detection with ^{10}B and Gd

Beckurts, Karl-Heinrich, and Karl Wirtz. Neutron physics. Springer Science & Business Media, 2013.

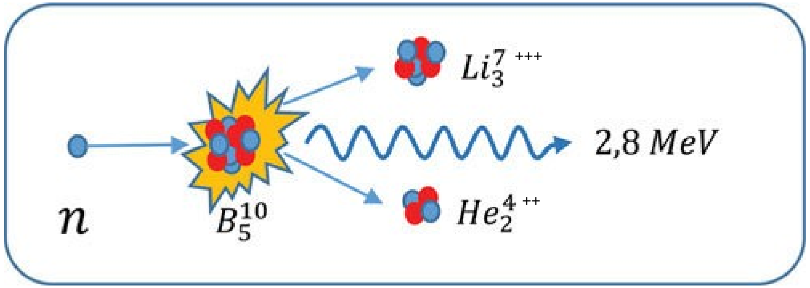
Element	Reaction		CS at 25.2 meV
^{3}He	^{3}He+n $\longrightarrow$	^{3}H+764 keV +p	5327 b
^{6}Li	^{6}Li+n $\longrightarrow$	^{3}H+α + 4.78 MeV	940 b
^{10}B	^{10}B+n $\longrightarrow$	^{7}Li+α + 2.79 MeV (6 %)	3837 b
	^{10}B+n $\longrightarrow$	^{7}Li*+α + 2.31 MeV (94 %)	
^{155}Gd	^{155}Gd+n $\longrightarrow$	^{156}Gd+$\gamma + e^- + (30-180)$ keV	61000 b
^{157}Gd	^{157}Gd+n $\longrightarrow$	^{158}Gd+$\gamma + e^- + (30-180)$ keV	254000 b
^{235}U	^{235}U+n $\longrightarrow$	fission fragments + 160 MeV	584 b

Requirements:

- High absorption cross section
- 1-2 charged particles in final state
- Easy to handle during construction

Candidates:

- ^{6}Li: very difficult to handle
- ^{235}U: difficult to get/handle
- $^{155/157}$Gd: very high cross-section, but final state looks like γ-conversion in gaseous detectors.
- ^{10}B: high cross-section → our favourite choice

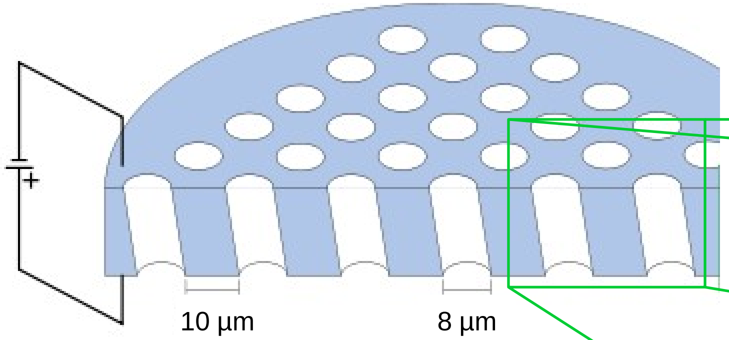


Alvarez-Estrada, Ramón & Peña, Ignacio & Calvo, Maria. (2017). Focalizing slow neutron beams at and below micron scales: Discussion on BNCT. Phosphorus, Sulfur, and Silicon and the Related Elements. 193. 10.1080/10426507.2017.1417300.

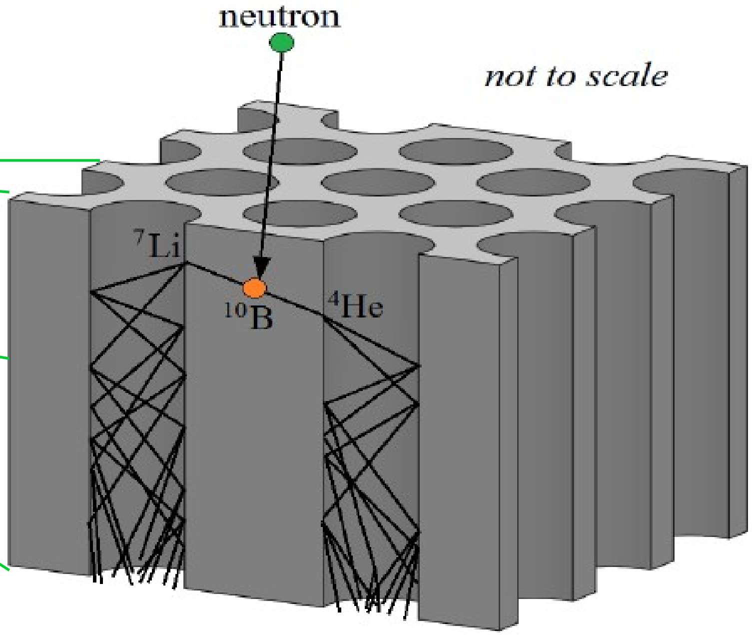
Micro-Channel Plate (MCP) detector with Timepix3 readout

Neutron MCP detector: nMCP

Two-stage MCP: ^{10}B and Gd loaded first stage + traditional MCP second stage



https://en.wikipedia.org/wiki/Microchannel_plate_detector

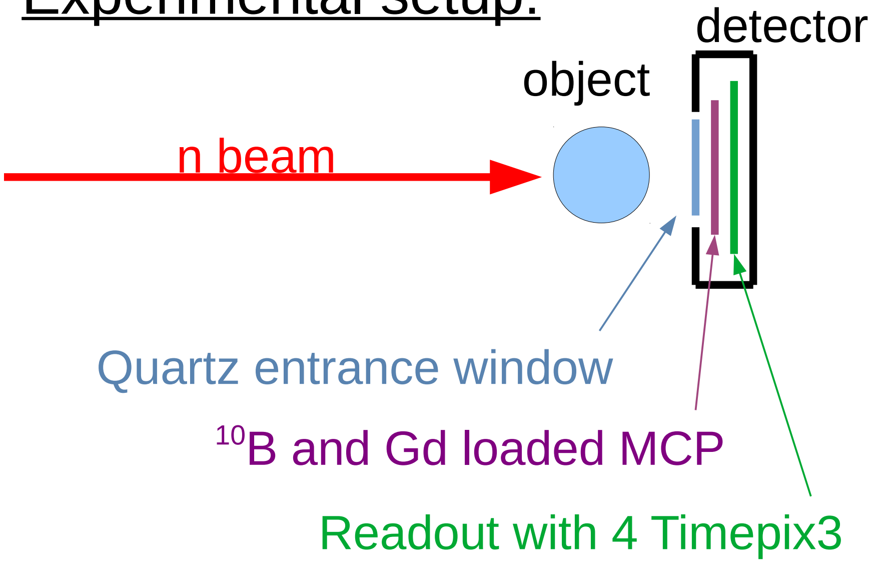


Abir, Muhammad. (2013). AFIP-7 Tomography – 2013 Status Report. 10.13140/RG.2.1.1732.4884.

⟹ Detector concept (with Timepix): S. Pinto et all, Neutron imaging and tomography with MCPs, JINST 12, C12006. 2017

Neutron MCP detector: Concept

Experimental setup:



Quartz entrance window:

- does not activate
- UV transparent for detector tests
- transparent for neutrons
- checking detector visually is possible

Neutron MCP detector: Concept

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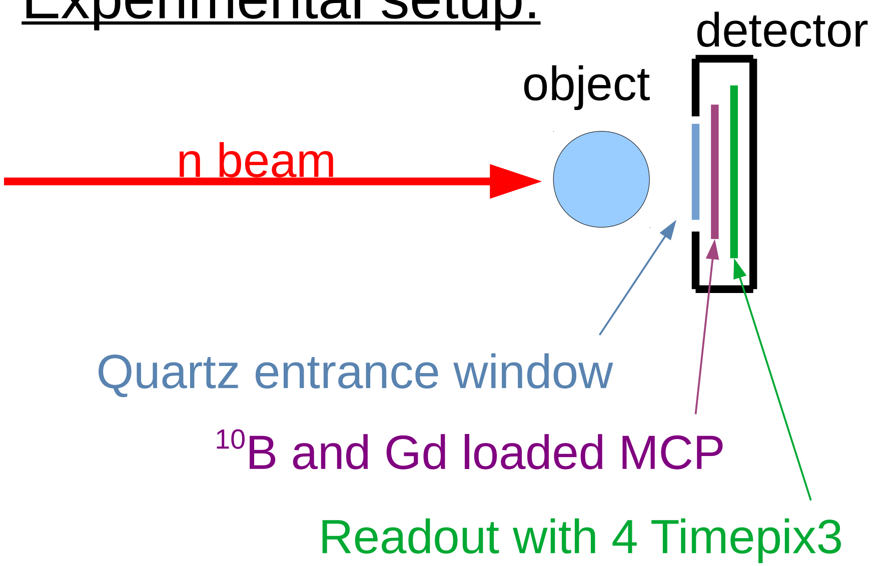

Quartz entrance window:
- does not activate
- UV transparent for detector tests
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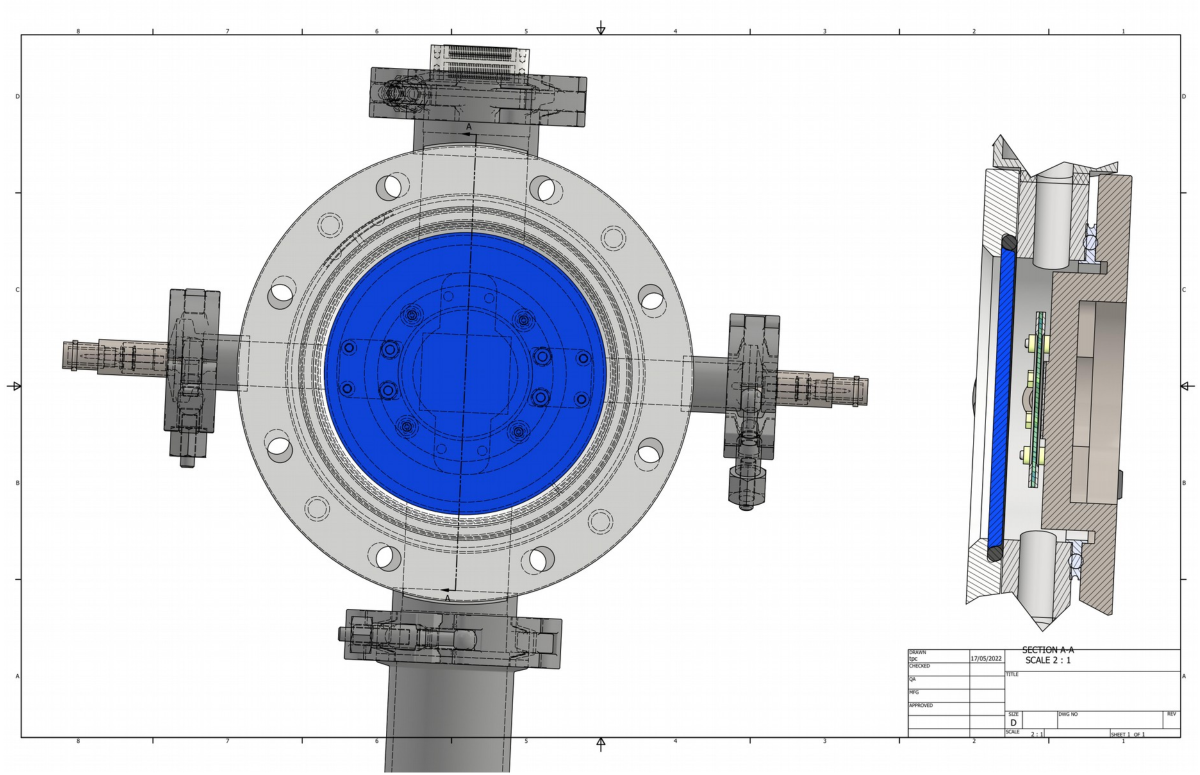
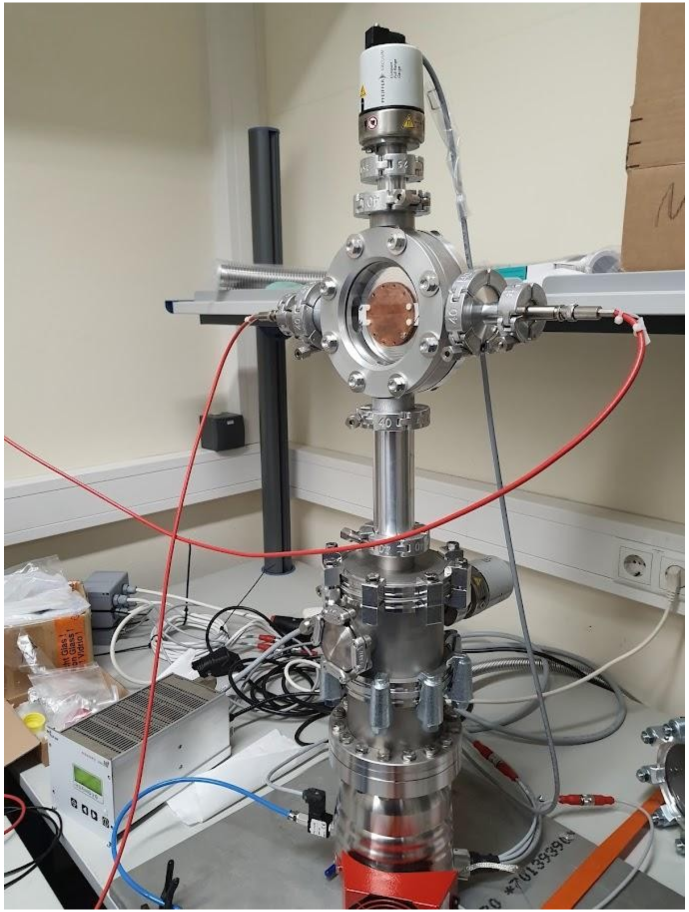
Detector Requirements:

- Good vacuum (10^{-6} mbar)
- Aluminium Vacuum chamber
- Timepix3 close to MPC
- Timepix3 cooling

Neutron MCP detector: Impressions





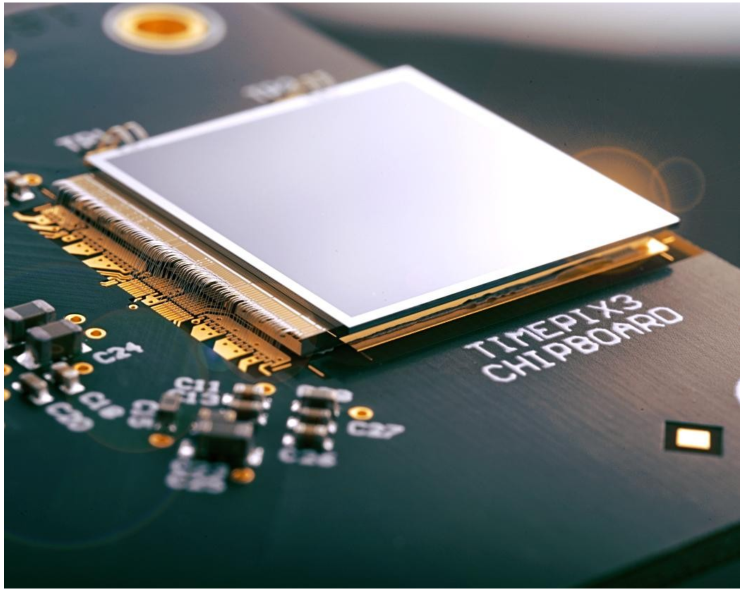
Major part of the setup: Vacuum system
Currently ongoing: vacuum and HV tests

Neutron MCP detector: Timepix3 readout

Group of Anton S. Tremsin [1]: Similar detector with four Timepix ASICs
→ problem: Shutter based Timepix → dead time

⟹ Our design foresees four Timepix3 ASICs:

- Simultaneous Charge and time measurement
- Timing resolution: 1.56 ns
- Zero suppression on chip
- Self-triggered, continuous data-driven readout



https://kt.cern/technologies/timepix3

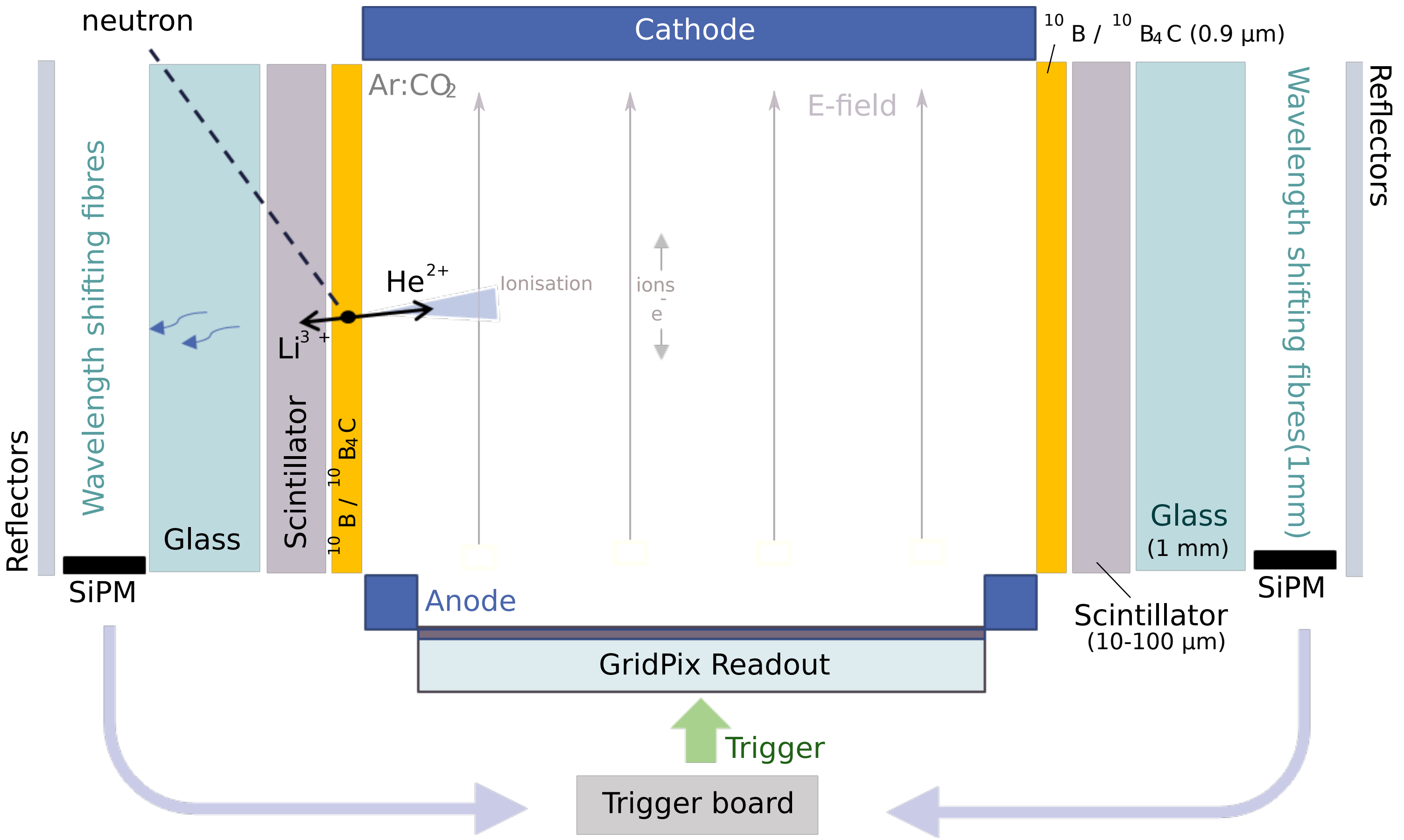
Implementation of Timepix3 in Scalable Readout System (SRS) of RD51:

M. Gruber et al. "SRS-based Timepix3 readout system." Journal of Instrumentation 17.04 (2022) C04015

[1] Tremsin, Anton S., et al. "High Resolution Photon Counting With MCP-Timepix Quad Parallel Readout Operating at > 1 kHz Frame Rates." IEEE TNS 60.2 (2012): 578-585.

Time-Projection Chamber (TPC) detector with GridPix readout

Neutron TPC detector: Concept



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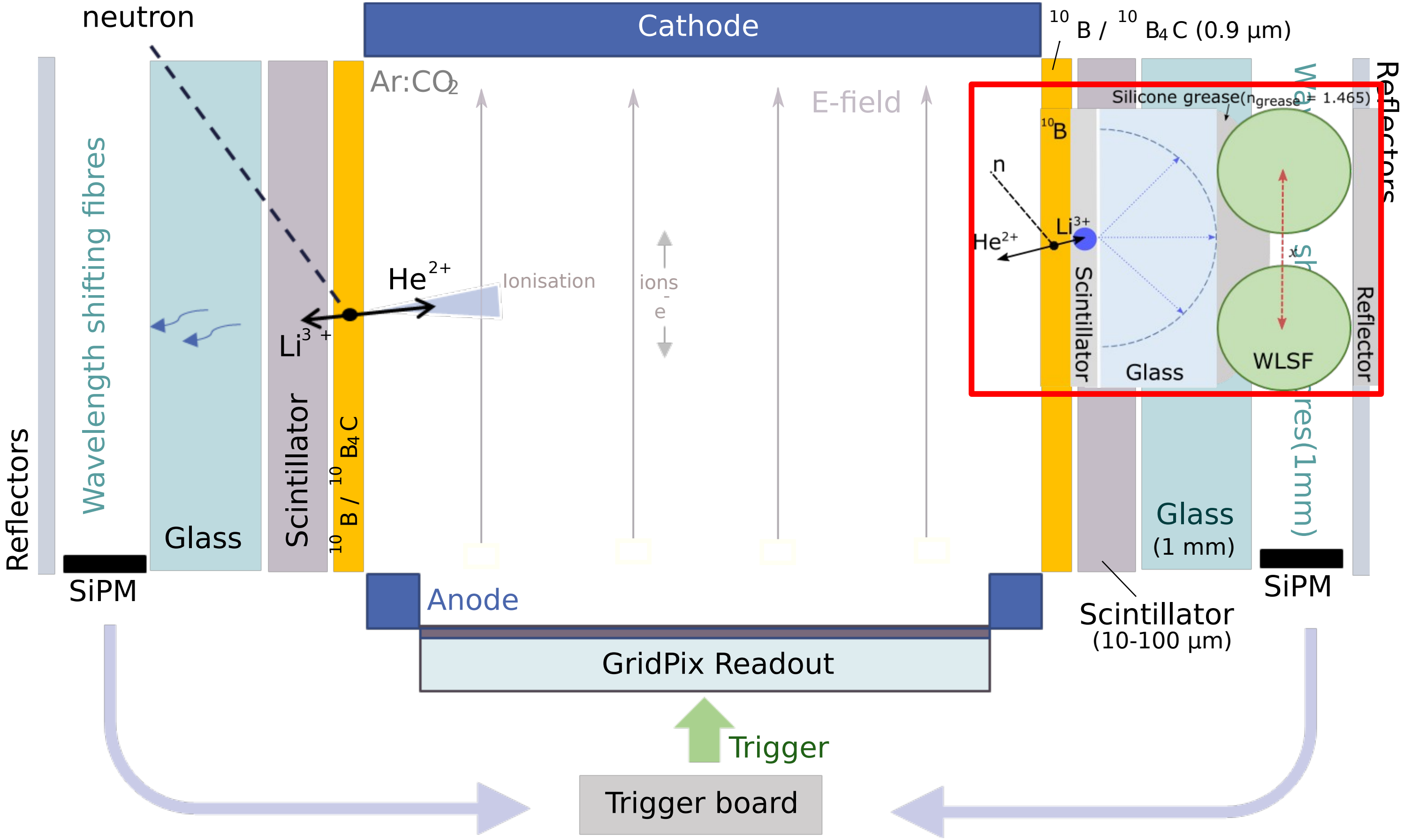

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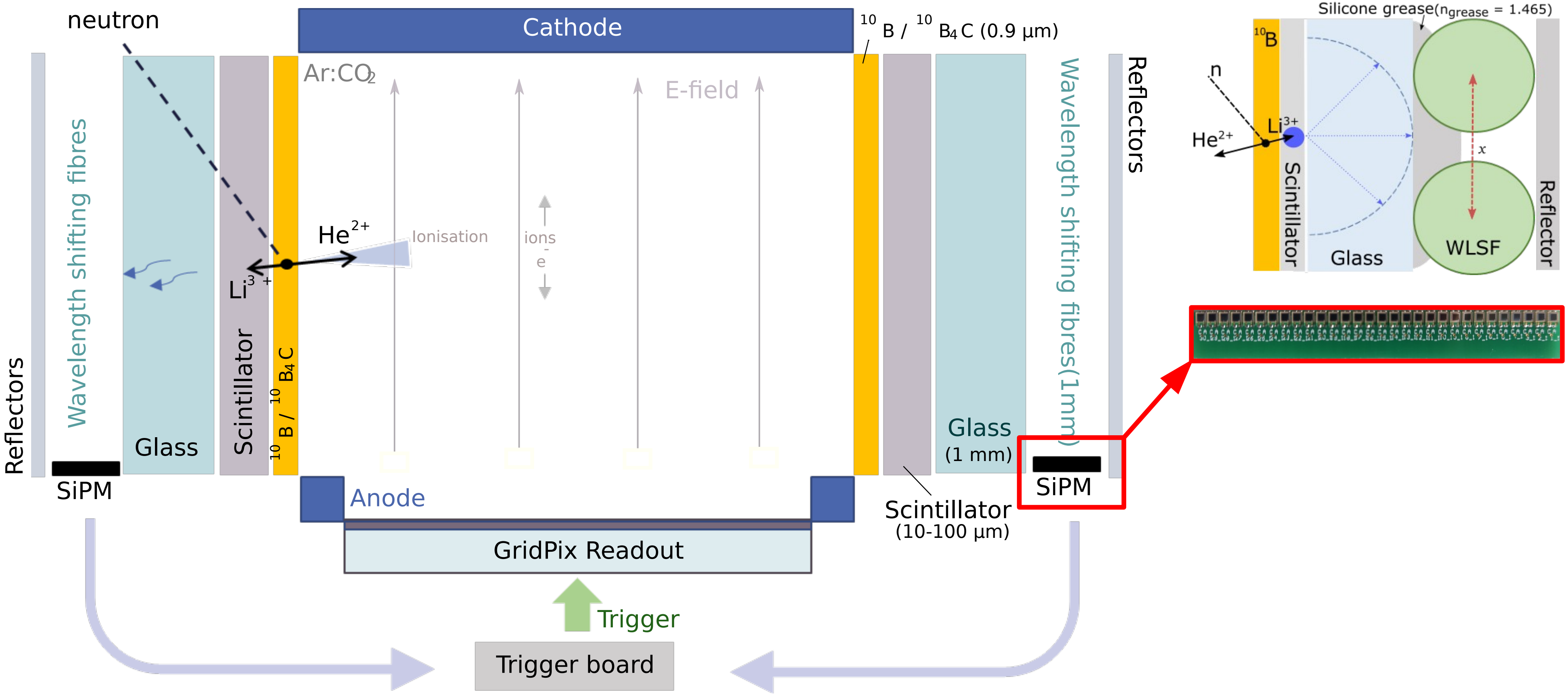

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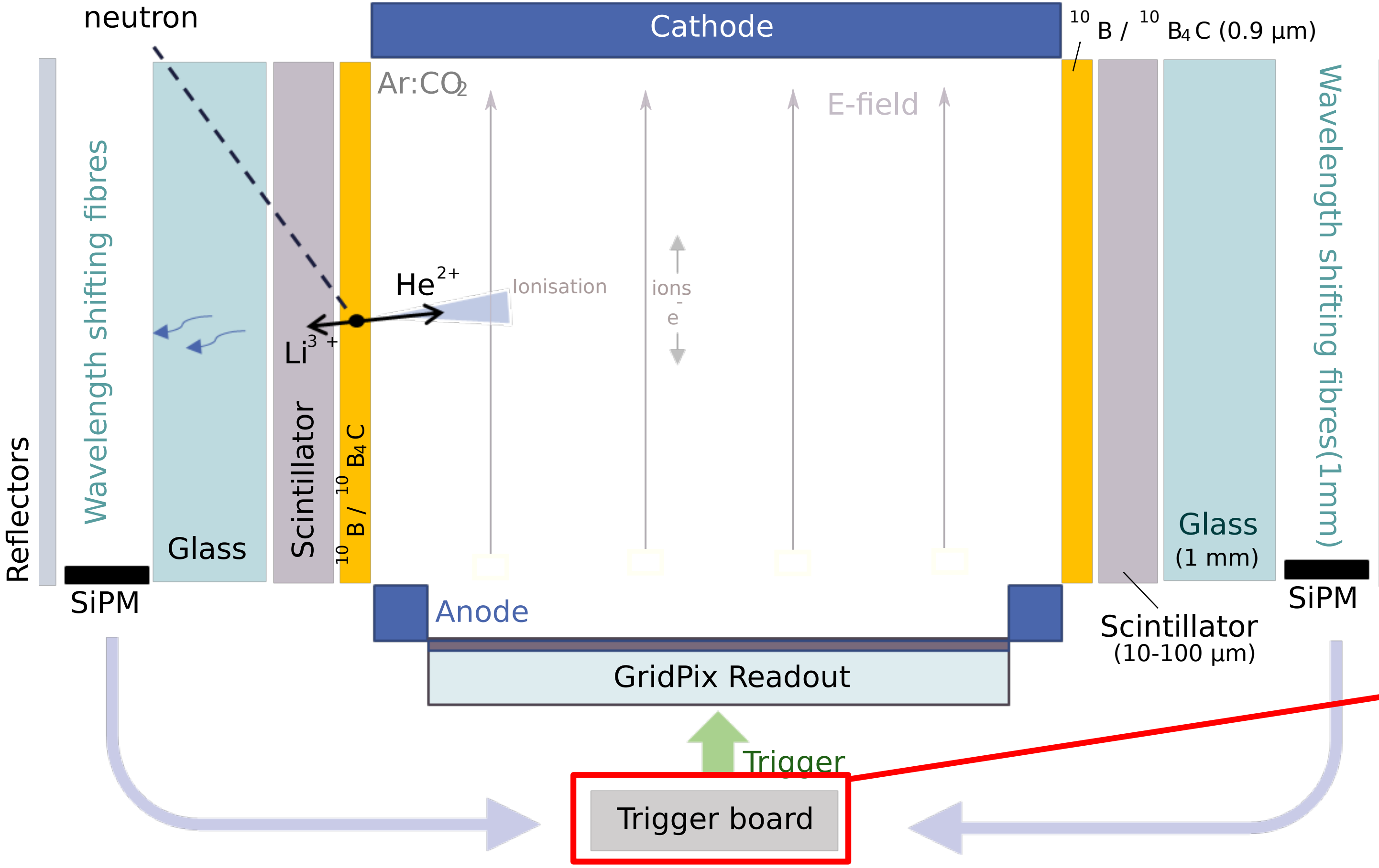

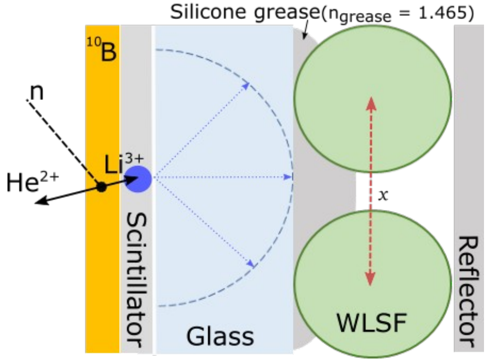

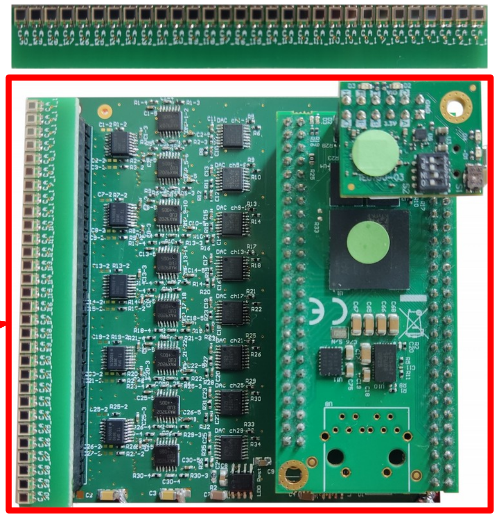

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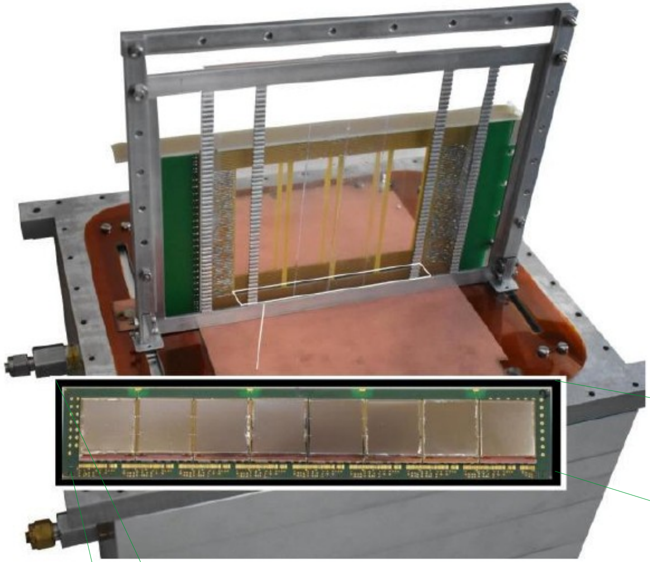
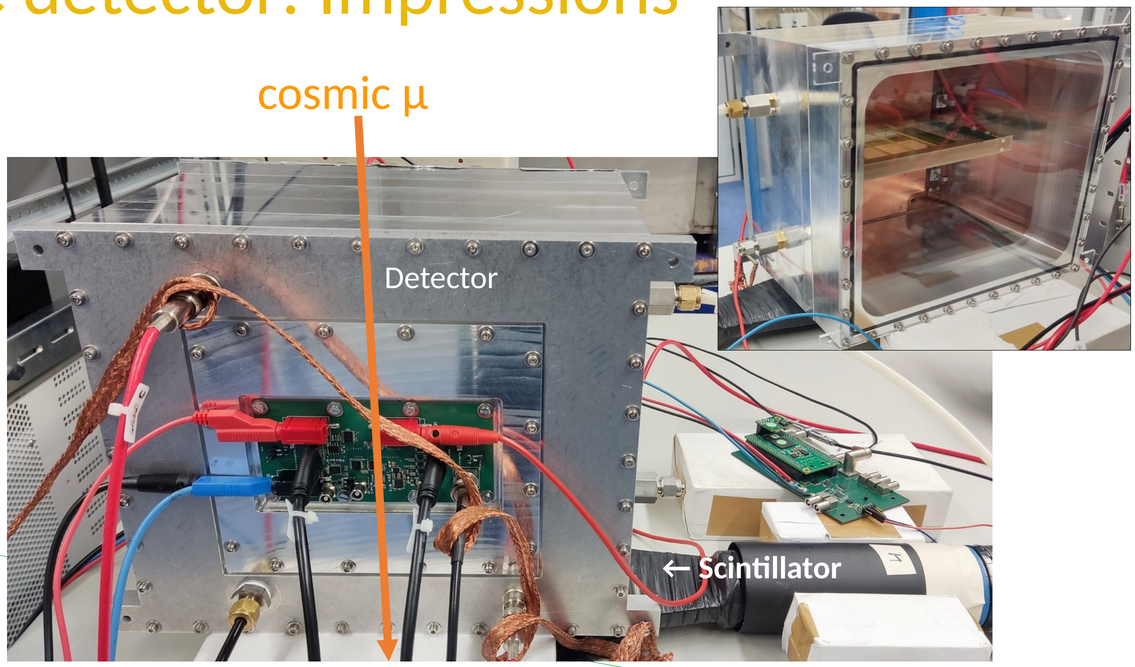
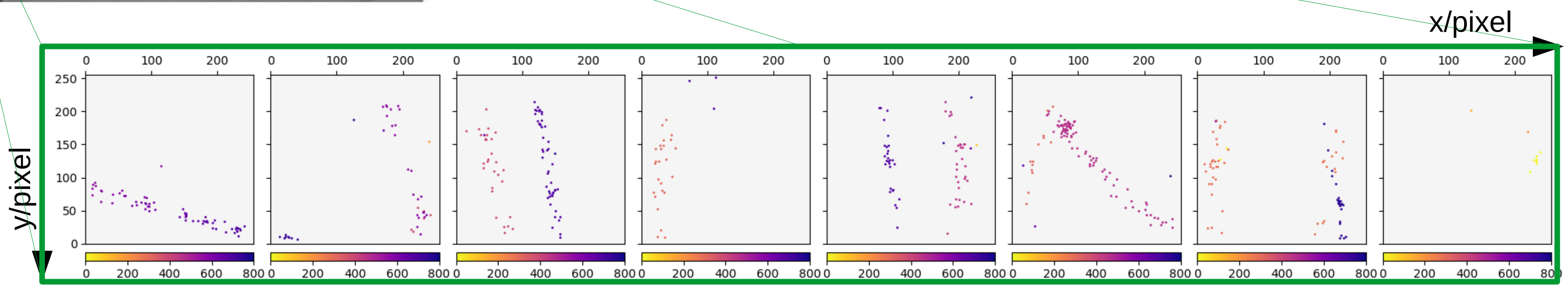
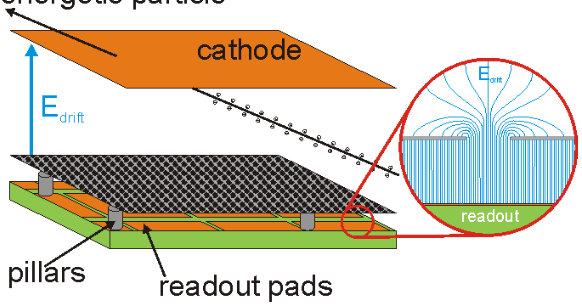






Neutron TPC detector: GridPix readout

Micromegas + bare Pixel ASIC = GridPix



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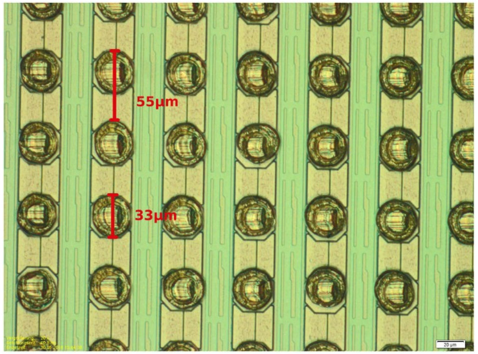

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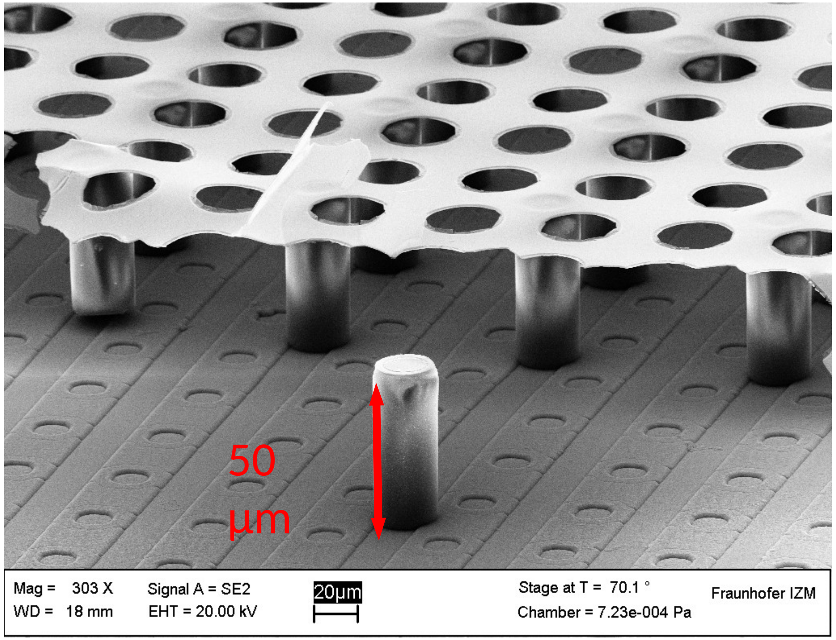
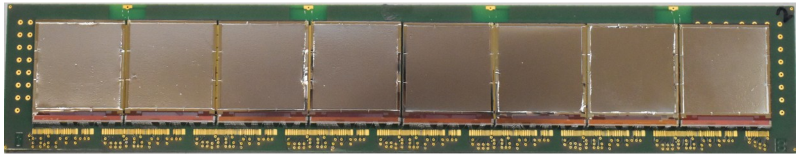




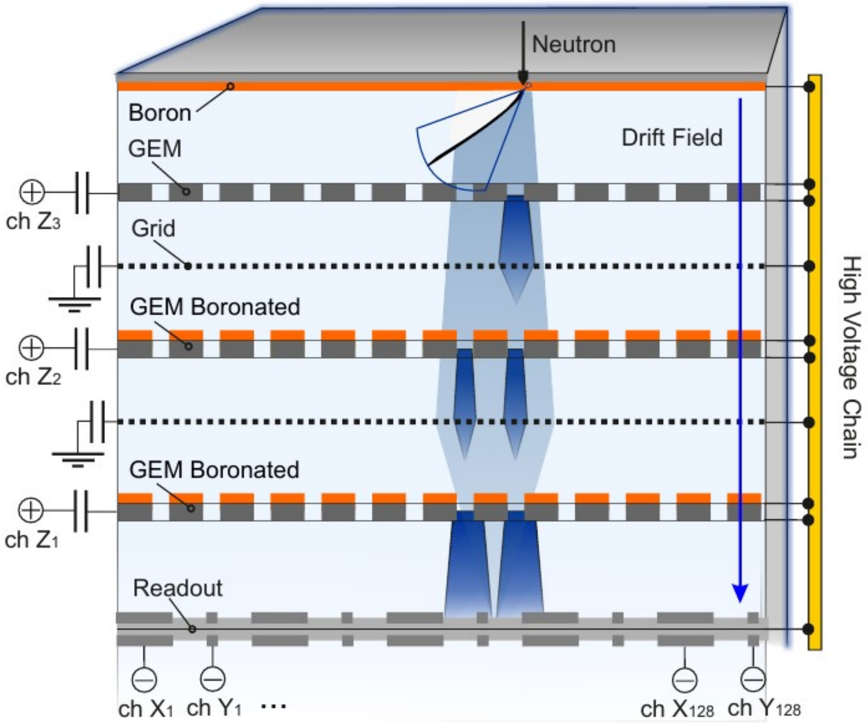
Used in CAST, proposed for ILD TPC (ILC), ATHENA TPC (EIC) and IAXO with Timepix3

NIM A535 (2004) 506-510
NIM A845 (2017) 233-235

Gas Electron Multiplier (GEM) detector with VMM3a readout

Neutron GEM detector: Concept

Detector concept similar to the CASCADE detector used at MIEZE (FRM II)



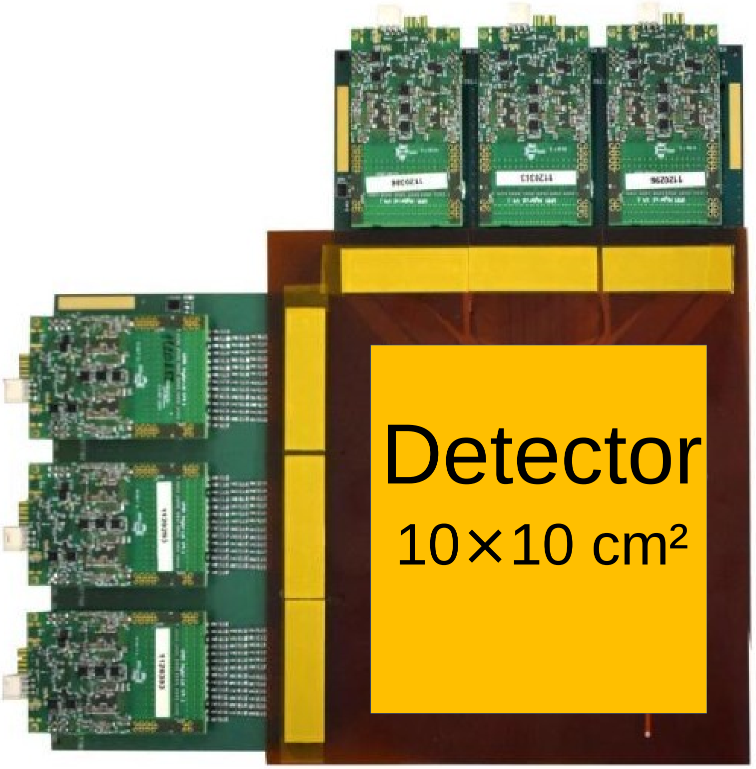
CASCADE detector: PhD thesis M. Köhli

<u>Planned major improvement:</u>

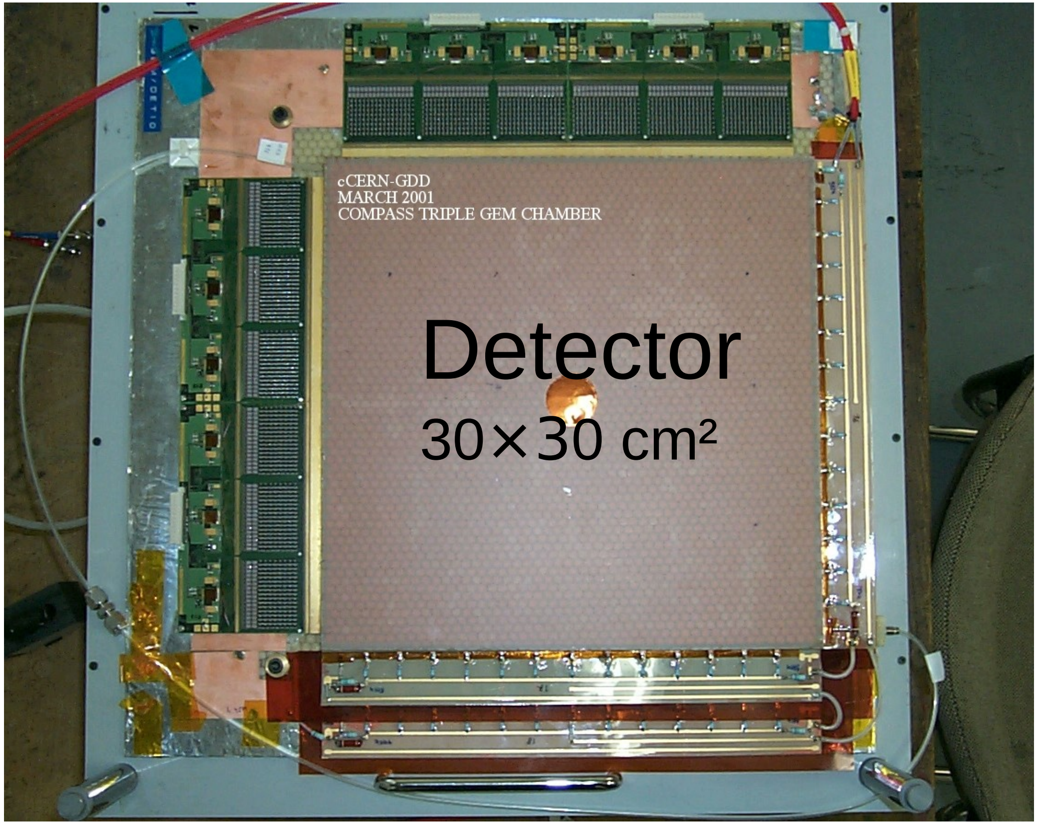
- Independent layers, each with own cathode, coating and readout
- Thin ^{10}B coating $\Longrightarrow$ Many layers needed

→ Main challenge: large number of electronic channels (~70,000).

Neutron GEM detector: Impressions



First test layer front-end electronics.

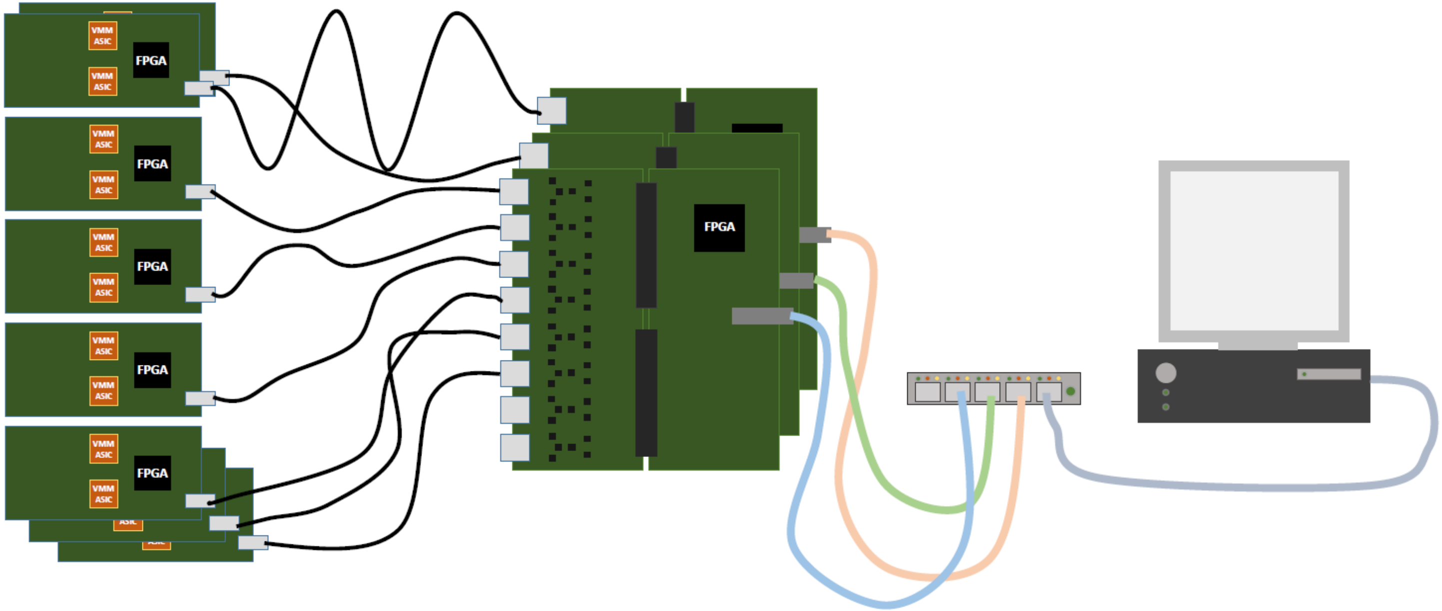


For comparison: COMPASS GEM detector

Neutron GEM detector: VMM3a readout

Update of SRS for the next decade of (MPGD) R&D and instrumentation:
Implementation of VMM in Scalable Readout System (SRS) of RD51:

M. Lupberger et al. "Implementation of the VMM ASIC in the Scalable Readout System" NIMA 903 (2018) 91-98



VMM Hybrid → HDMI cable → Adapter card + FEC → Ethernet → Switch →Ethernet → PC

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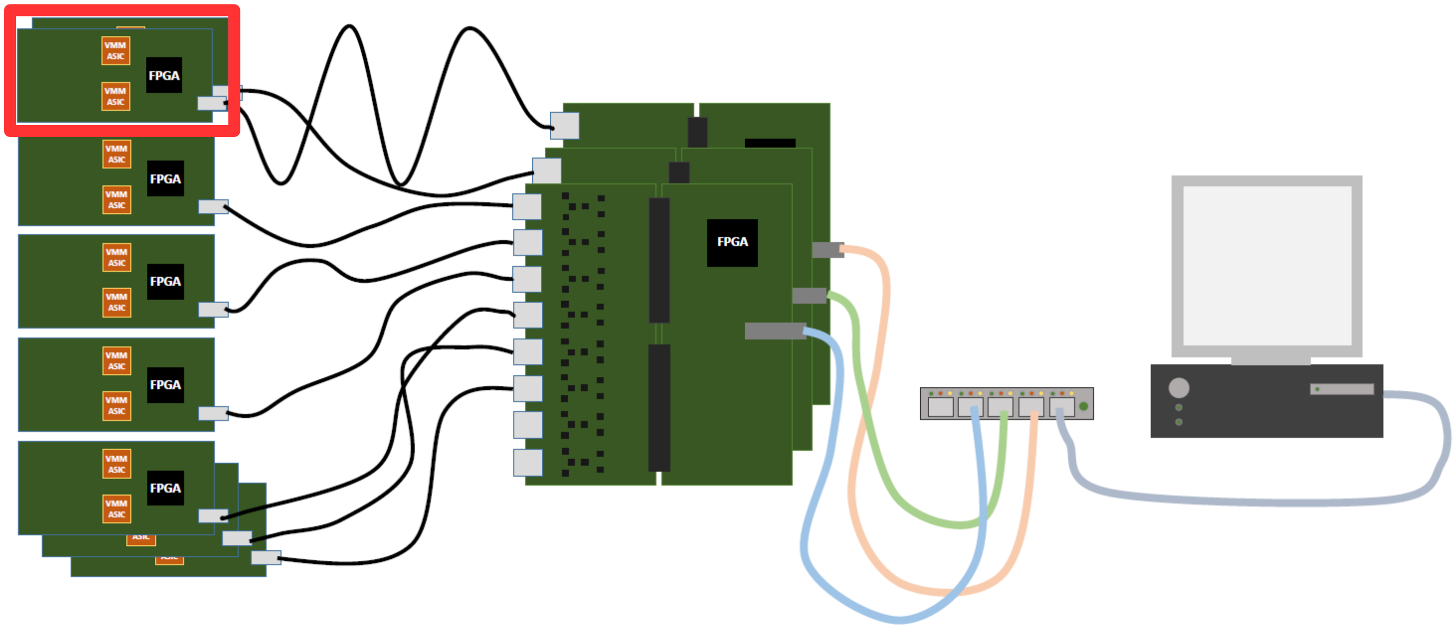

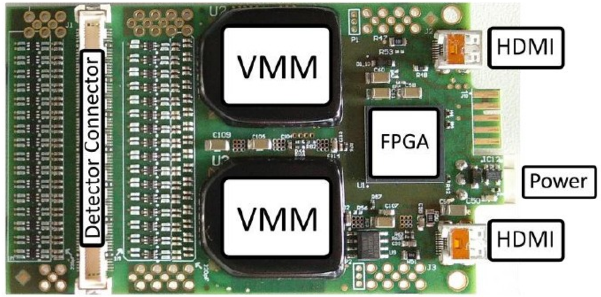

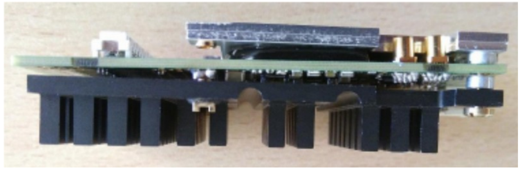

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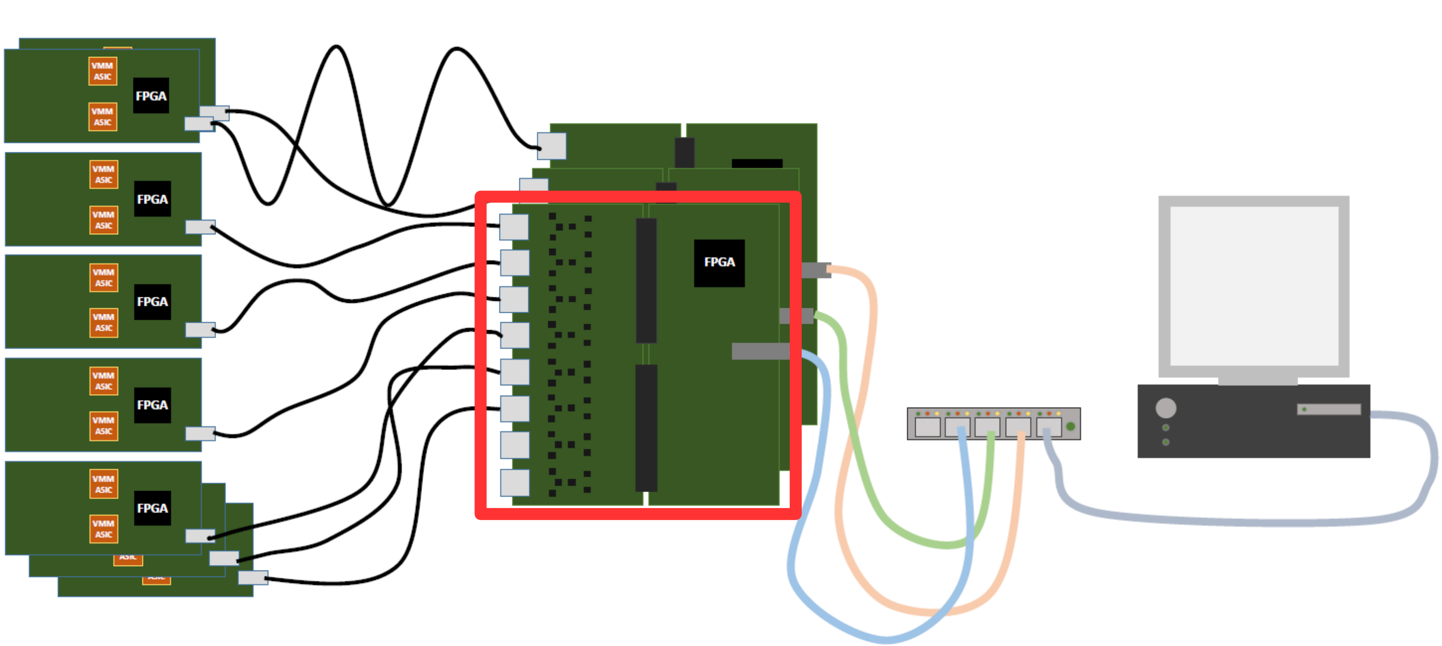

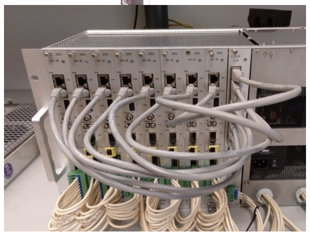

VMM Hybrid → HDMI cable → Adapter card + FEC → Ethernet → Switch →Ethernet → PC

Summary:

State-of-the-art neutron detector

=

Particle Physics detection concept

+

Solid converter

+

Recent electronics

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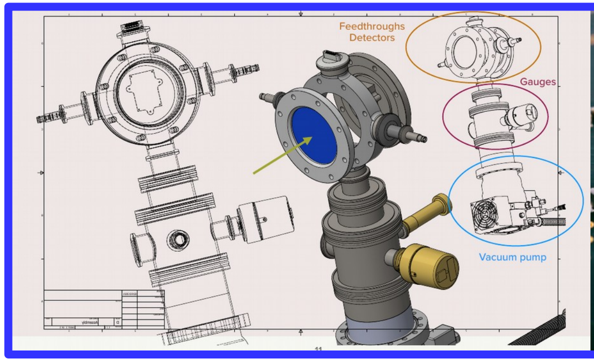

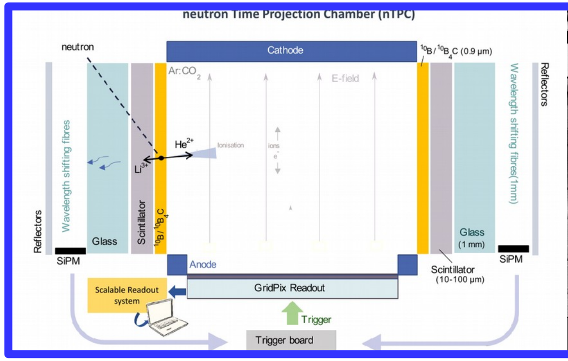

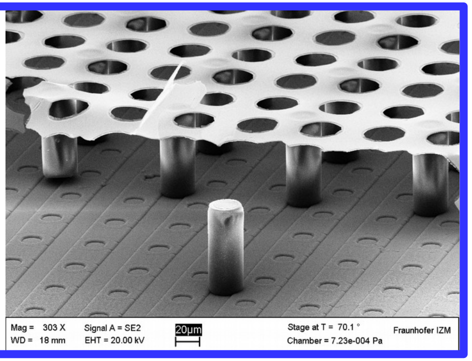

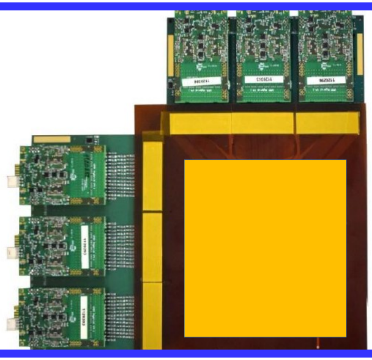

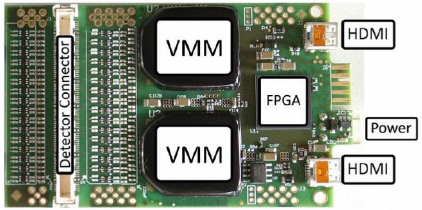

Summary:

State-of-the-art neutron detector

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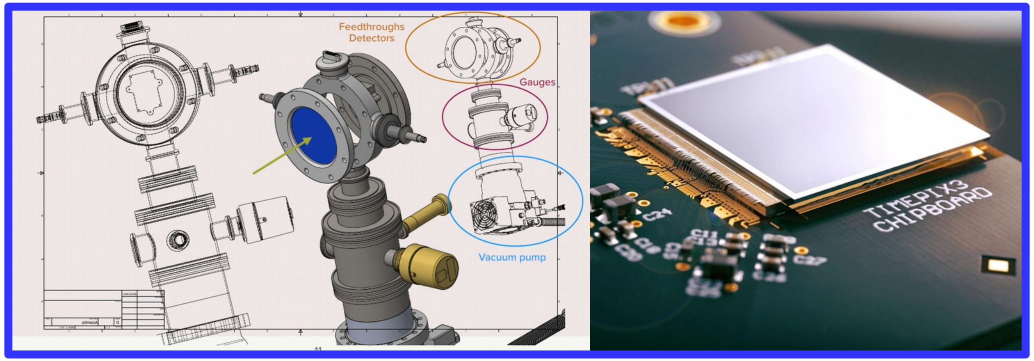
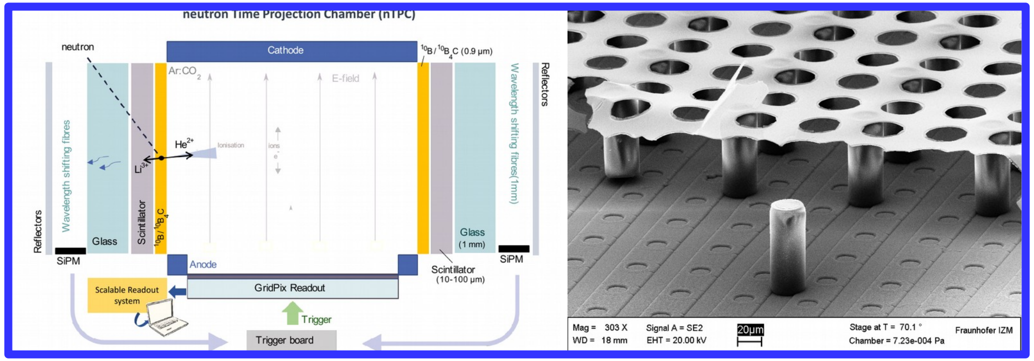
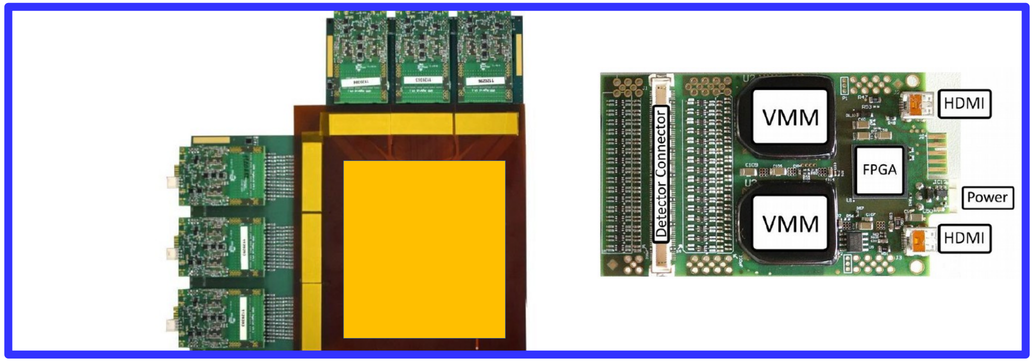
Recent electronics

$\Longrightarrow$ Technology transfer from Particle Physics to Neutron Science



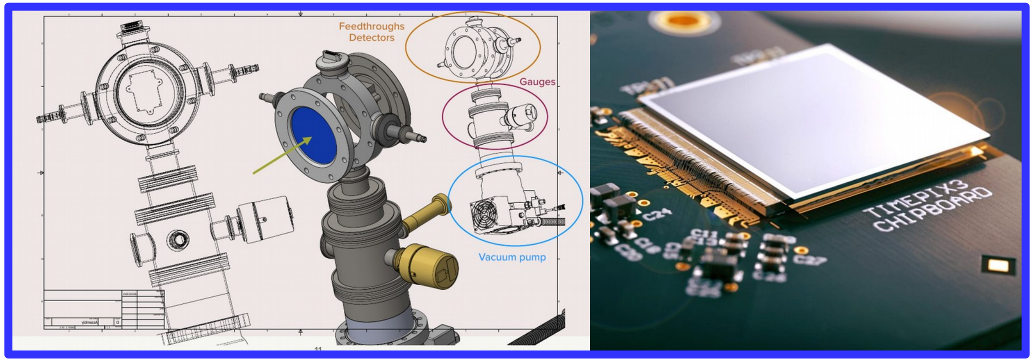


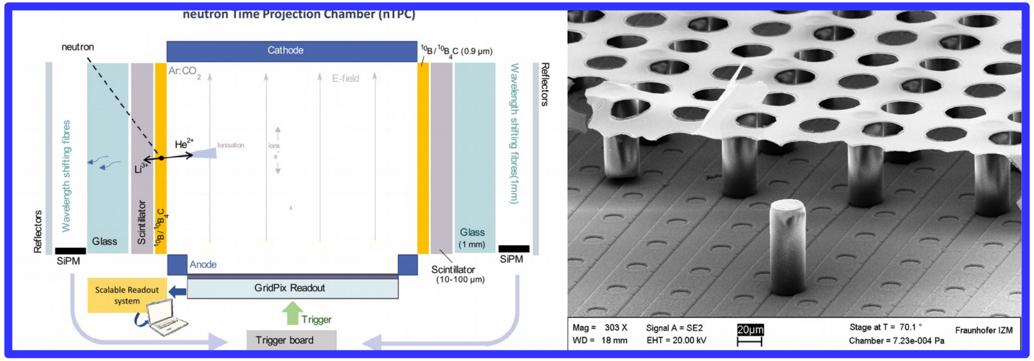


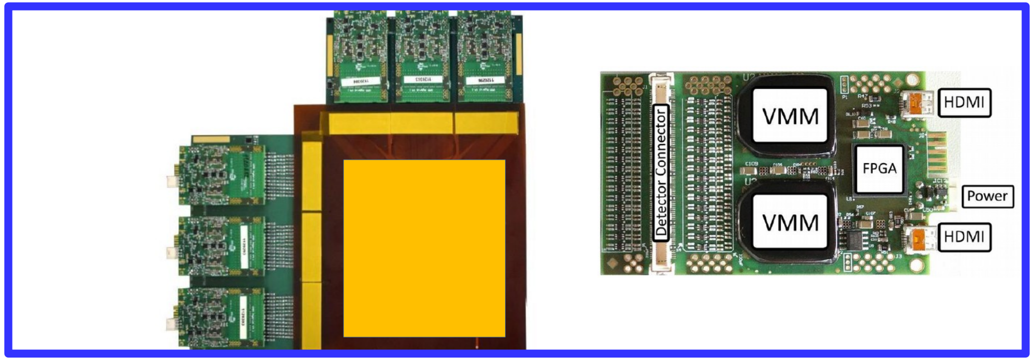
Summary:

State-of-the-art neutron detector
=
Particle Physics detection concept
+
Solid converter
+
Recent electronics

⟹ Technology transfer from Particle Physics to Neutron Science



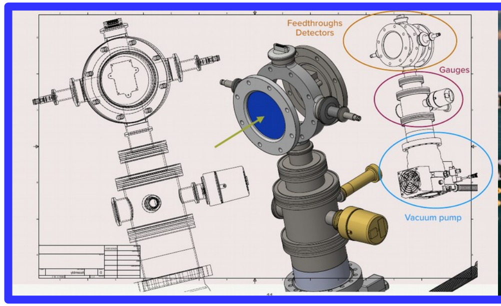


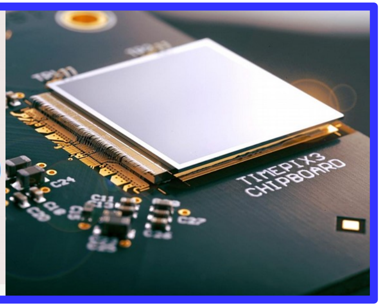


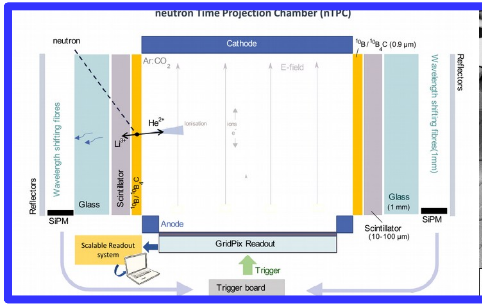
Three novel neutron detectors with different properties developed in Bonn.

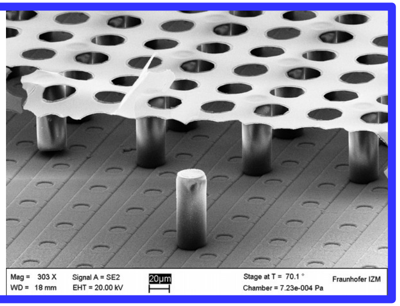
The Team

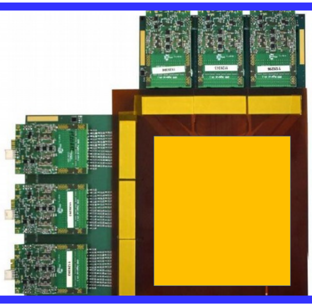
K. Desch,
J. Kaminski,
M. Lupberger
other stuff

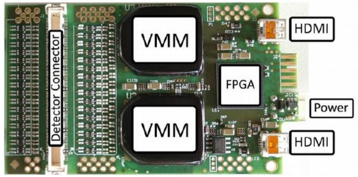












Saime Gurbuz
nMCP detector

Divya Pal
nTPC detector

Laura Rodriguez
Gomez
nGEM detector

Markus Gruber

Thomas Block
Timepix3 readout

Patrick Schwaebig
VMM readout

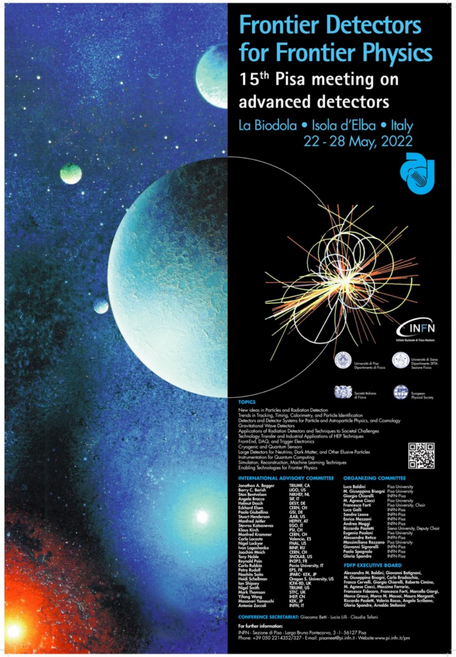
With assistance by Markus Köhli (Heidelberg University)

THANKS FOR YOUR ATTENTION

UNIVERSITÄT BONN

Acknowledgements

Thank you for the organisation of this conference and the approval of my contribution as on oral presentation!



This project has received funding from the German Federal Ministry of Education and Research under grant no. 05K19PD1
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GEFÖRDERT VOM

Bundesministerium für Bildung und Forschung

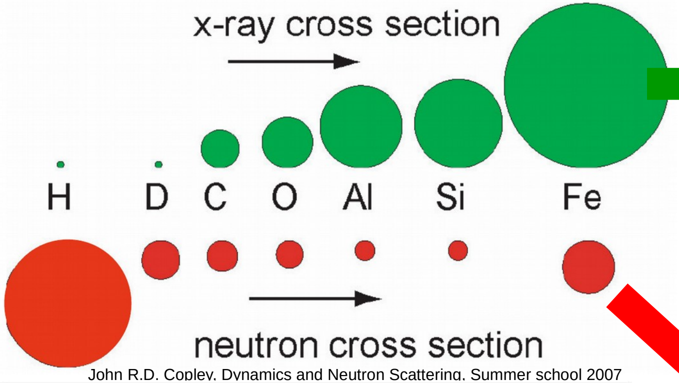
GenEI

Grant agreement No. 846674

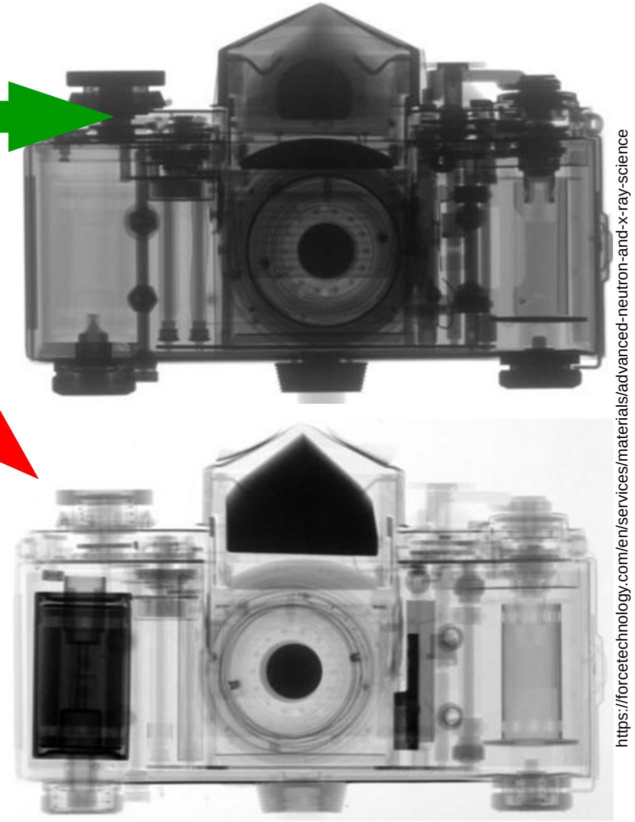
Backup slides

Introduction: Neutron detection

Neutron: Neutral particle, penetrate material easily → absorption imaging, similar to X-ray imaging



John R.D. Copley, Dynamics and Neutron Scattering, Summer school 2007

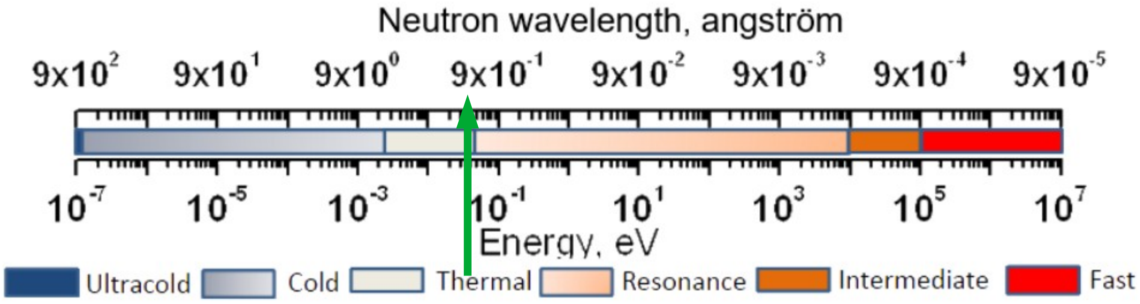


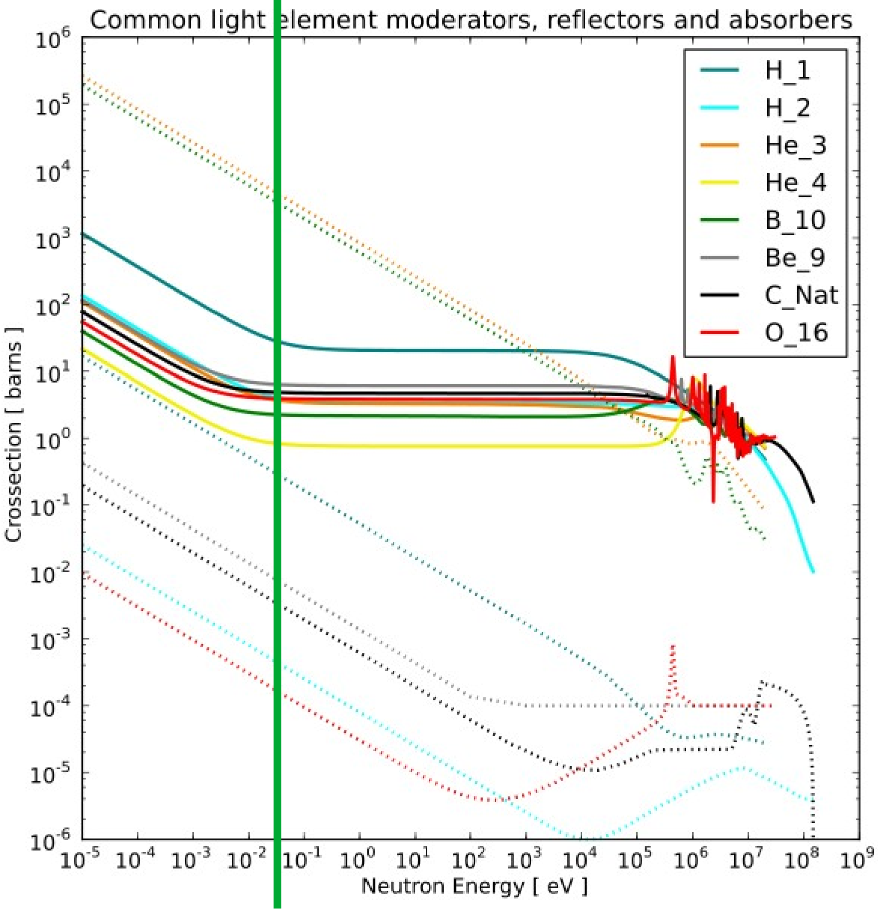
https://forcetechnology.com/en/services/materials/advanced-neutron-and-x-ray-science

Neutron detection: Conversion to charged particle

Element	Reaction
^{3}He	$^{3}\mathrm{He} + \mathrm{n} \rightarrow {}^{3}\mathrm{H} + \mathrm{p} + 764\,\mathrm{keV}$
^{6}Li	$^{6}\mathrm{Li} + \mathrm{n} \rightarrow {}^{3}\mathrm{H} + \alpha + 4.78\,\mathrm{MeV}$
^{10}B	$^{10}\mathrm{B} + \mathrm{n} \rightarrow {}^{7}\mathrm{Li} + \alpha + 2.79\,\mathrm{MeV}\ (6\%)$
	$^{10}\mathrm{B} + \mathrm{n} \rightarrow {}^{7}\mathrm{Li}^{*} + \alpha + 2.31\,\mathrm{MeV}\ (94\%)$
^{113}Cd	$^{113}\mathrm{Cd} + \mathrm{n} \rightarrow {}^{114}\mathrm{Cd} + \gamma + 9.04\,\mathrm{MeV}$
^{155}Gd	$^{155}\mathrm{Gd} + \mathrm{n} \rightarrow {}^{156}\mathrm{Gd} + \gamma + e^{-} + (30\text{–}180)\,\mathrm{keV}$
^{157}Gd	$^{157}\mathrm{Gd} + \mathrm{n} \rightarrow {}^{158}\mathrm{Gd} + \gamma + e^{-} + (30\text{–}180)\,\mathrm{keV}$
^{235}U	$^{235}\mathrm{U} + \mathrm{n} \rightarrow$ fission fragments + 160 MeV

Different Neutron Energy Ranges





https://en.wikipedia.org/wiki/Neutron_cross_section

<u>With higher energies:</u>

Cross sections are lower

→ neutron penetrate further into material

→ contrast of pictures decrease as more material is needed to scatter/absorb ns

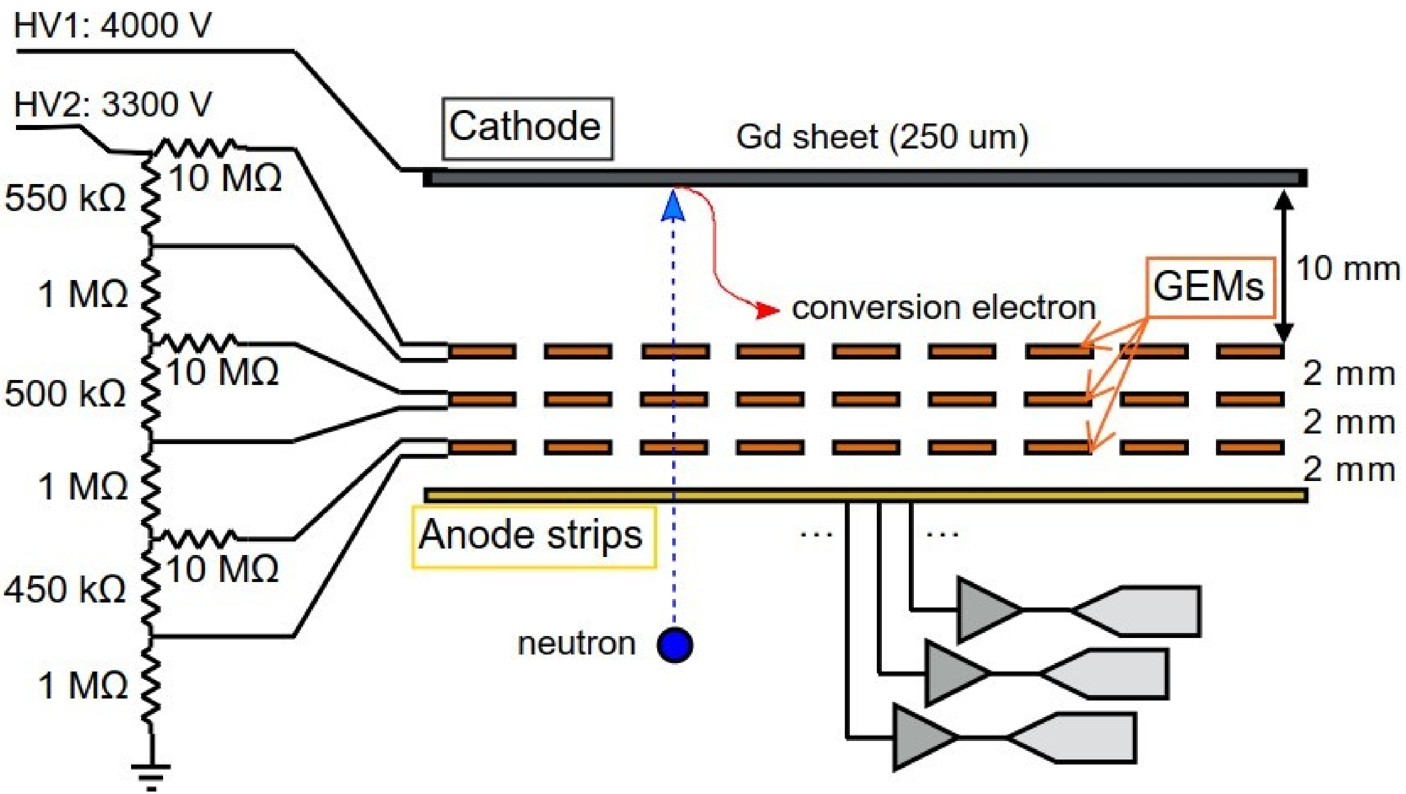
<u>Usually good compromise:</u>

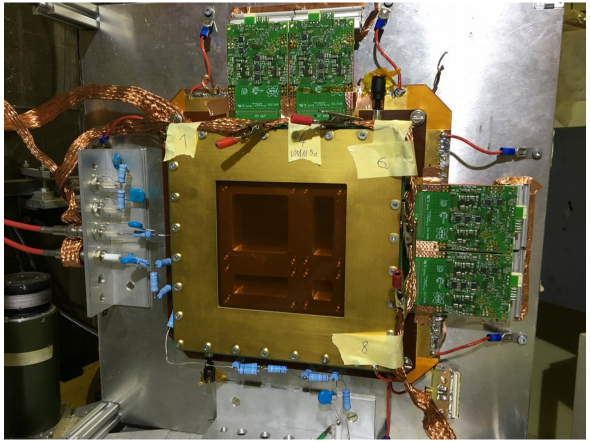
Thermal neutrons (~50 meV)

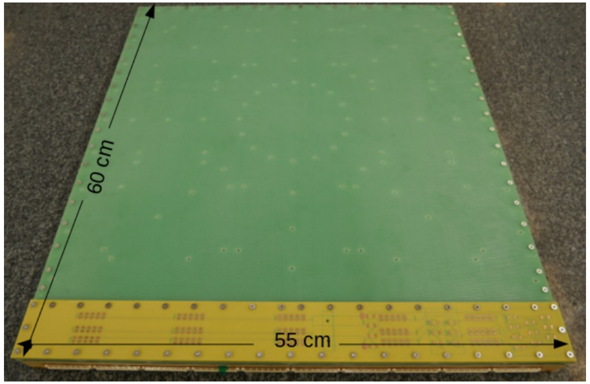
Also cold neutrons are used sometimes

<u>Source:</u> Reactors + moderators

The GdGEM detector for NMX at ESS







Pfeiffer, Dorothea, et al. "First measurements with new high-resolution gadolinium-GEM neutron detectors." Journal of Instrumentation 11.05 (2016): P05011.

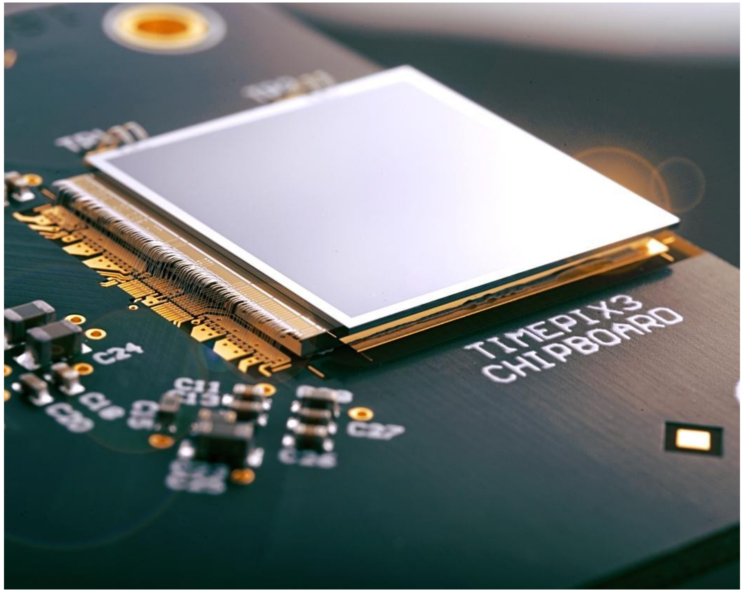
Lupberger, Michael, et al. "SRS VMM readout for Gadolinium GEM-based detector prototypes for the NMX instrument at ESS." Journal of Physics: Conference Series. Vol. 1498. No. 1. IOP Publishing, 2020.

Neutron MCP detector: Timepix3 readout

Group of Anton S. Tremsin [1]: Similar detector with four Timepix ASICs
→ problem: Shutter based Timpix → dead time

⟹ Our design foresees four Timepix3 ASICs:

- Number of pixels: 256 × 256 pixels
- Pixel pitch: 55 × 55 μm²
- Charge (ToT) and time (ToA) simultaneously or hit counter
- Timing resolution: 1.56 ns
- Zero suppression on chip
- Self-triggered, continuous data-driven or sequential readout
- Output rate up to 5.12 Gbps



https://kt.cern/technologies/timepix3

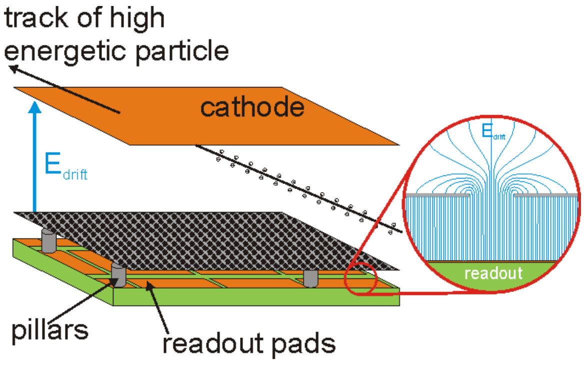
Implementation of Timepix3 in Scalable Readout System (SRS) of RD51:

M. Gruber et al. "SRS-based Timepix3 readout system." Journal of Instrumentation 17.04 (2022) C04015

[1] Tremsin, Anton S., et al. "High Resolution Photon Counting With MCP-Timepix Quad Parallel Readout Operating at > 1 kHz Frame Rates." IEEE TNS 60.2 (2012): 578-585.

Neutron TPC detector: GridPix readout

Micromegas + bare Pixel ASIC = GridPix



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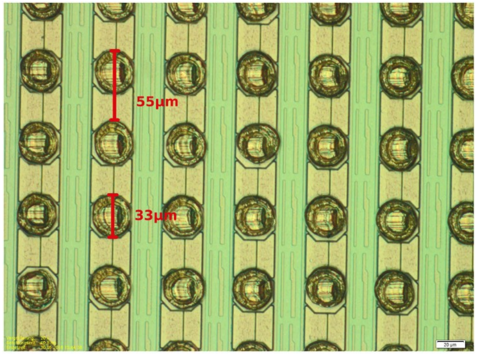

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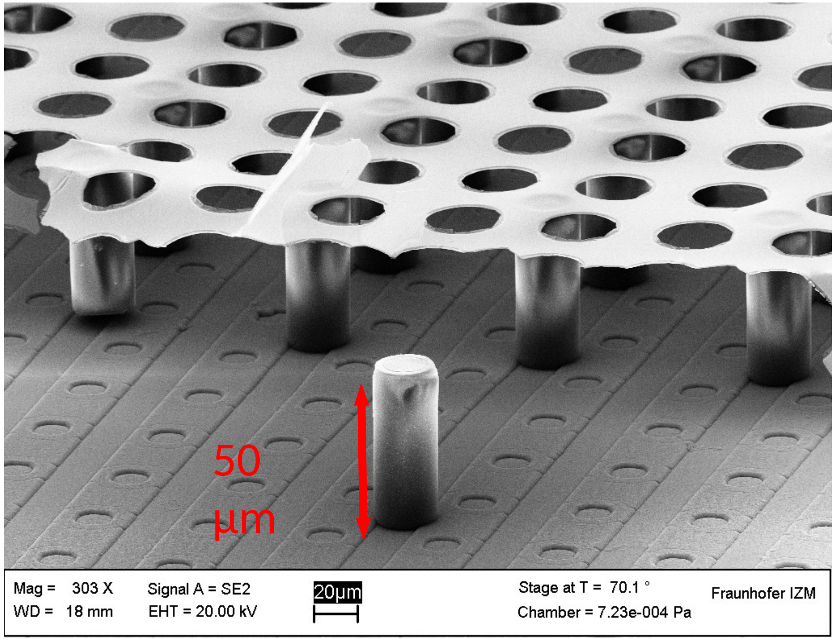
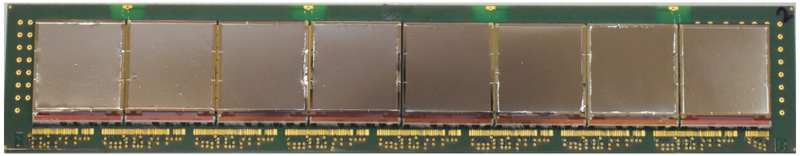




Motivation: Diffusion in amplification region:

Ar:CO_2 80:20, Ar:iC_4H_{10} 95:5, Ar:CF_4:iC_4H_{10} 95:3:2 $\rightarrow \sigma \approx 11$ µm

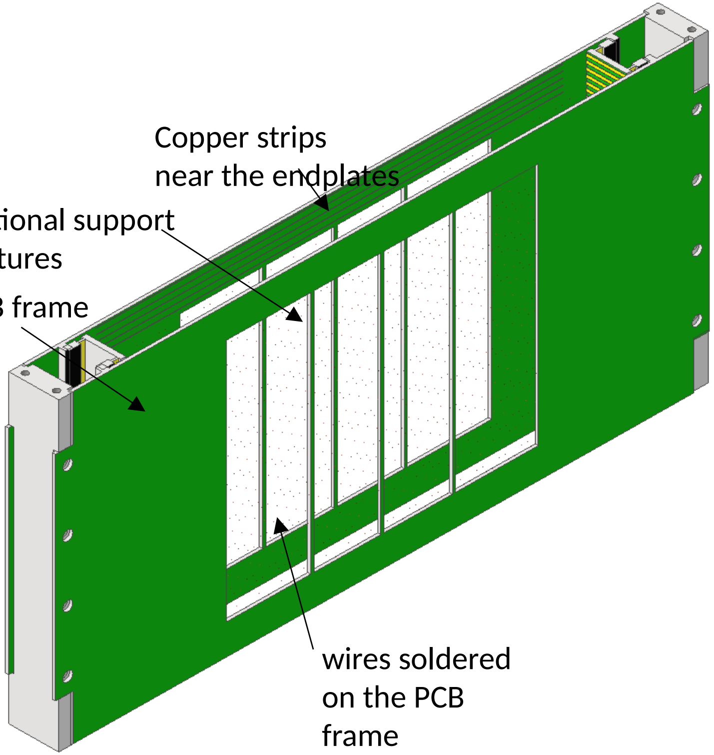
Smaller pads/pixels $\Longrightarrow$ better resolution!

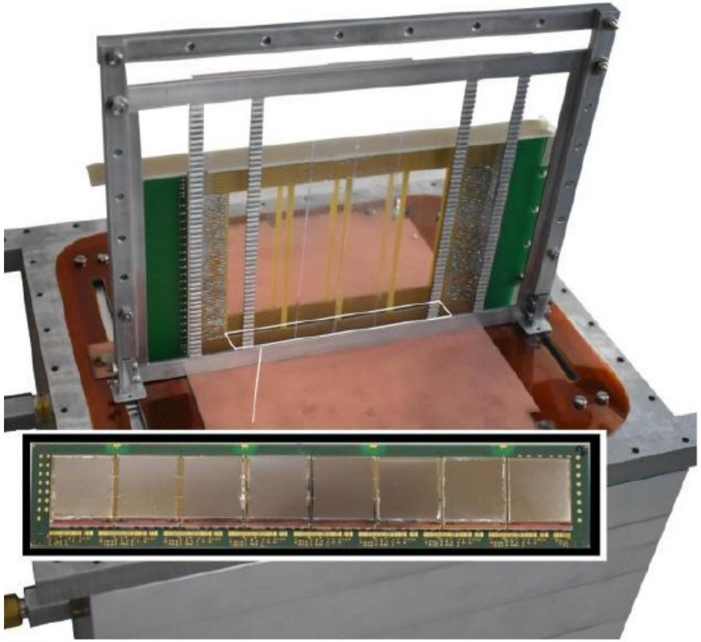
Used in CAST, proposed for ILD TPC (ILC), ATHENA TPC (EIC) and IAXO with Timepix3

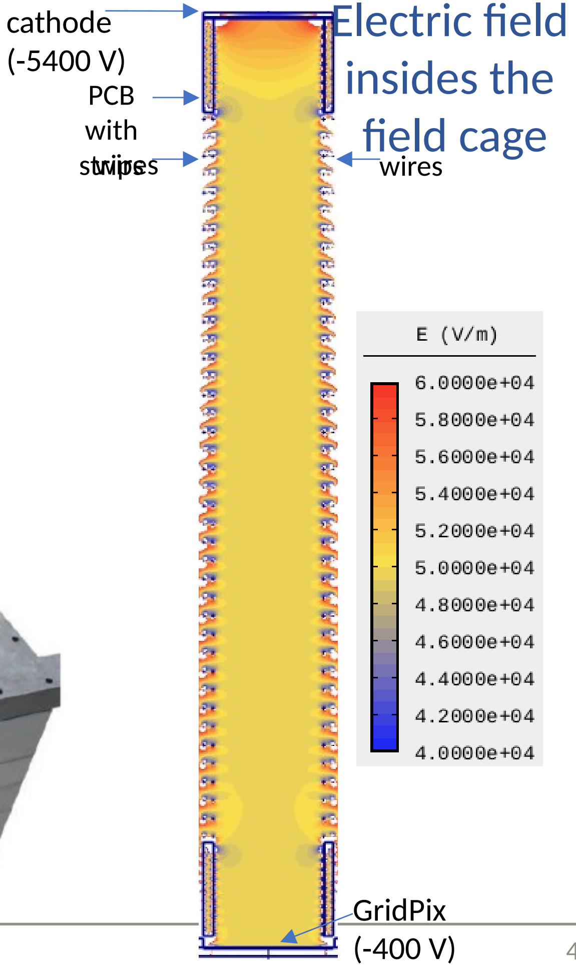
NIM A535 (2004) 506-510
NIM A845 (2017) 233-235

Neutron TPC detector: TPC field cage

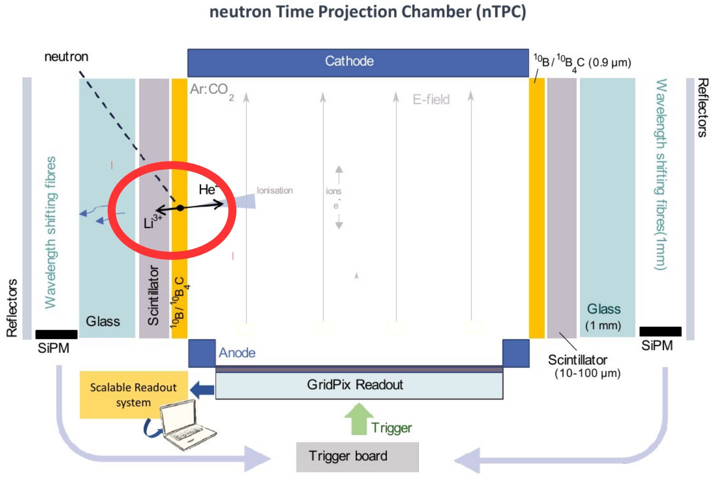
Current detector: 30 µm thick wires with a spacing of 2 mm soldered on PCB with resistor divider chain.







Neutron TPC detector: Trigger



Side wall:

- ~1 µm thick ^{10}B layer
- 20 µm thick scintillator
- Quartz light guide
- Wavelength shifting fibres
- SiPMs
- Reflector

Neutron TPC detector: Trigger

<u>Side wall:</u>

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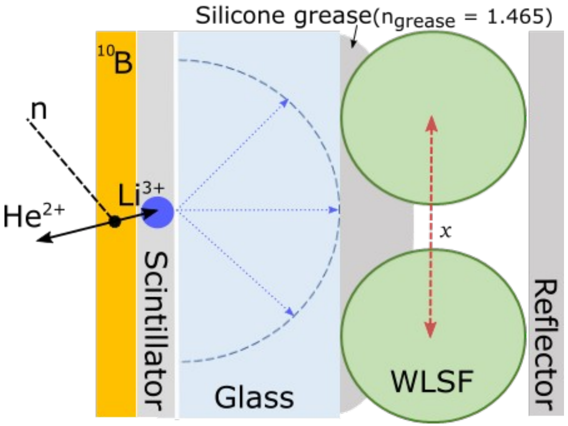

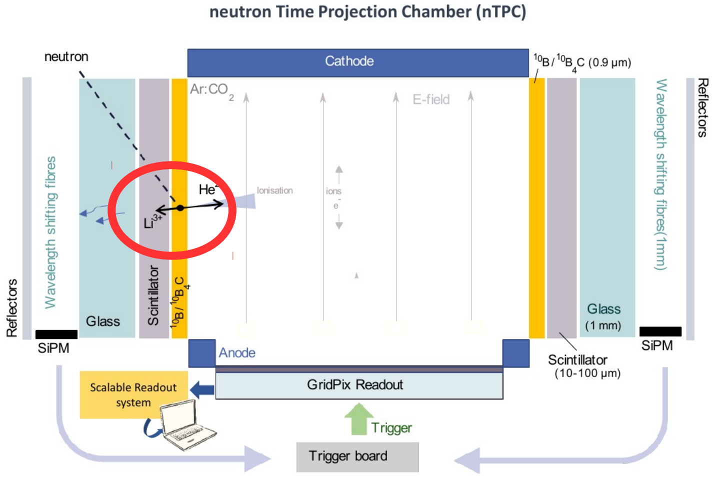

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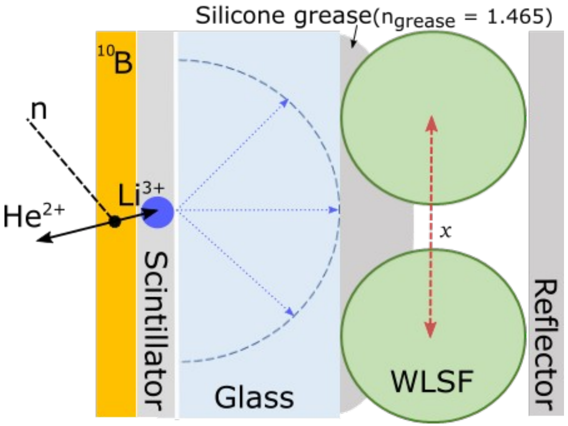
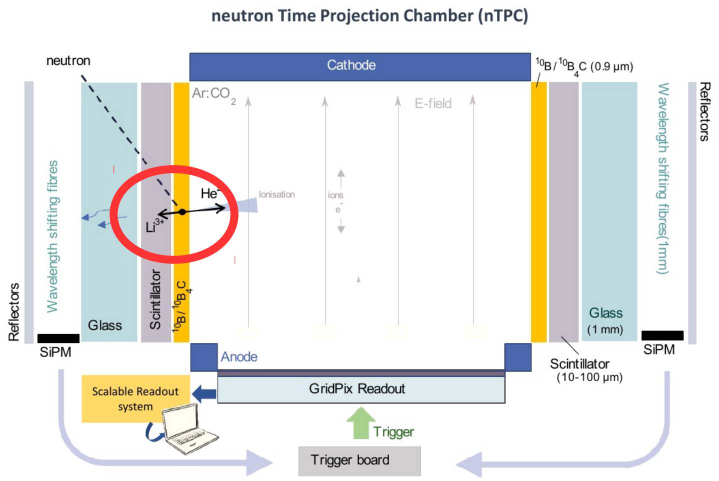
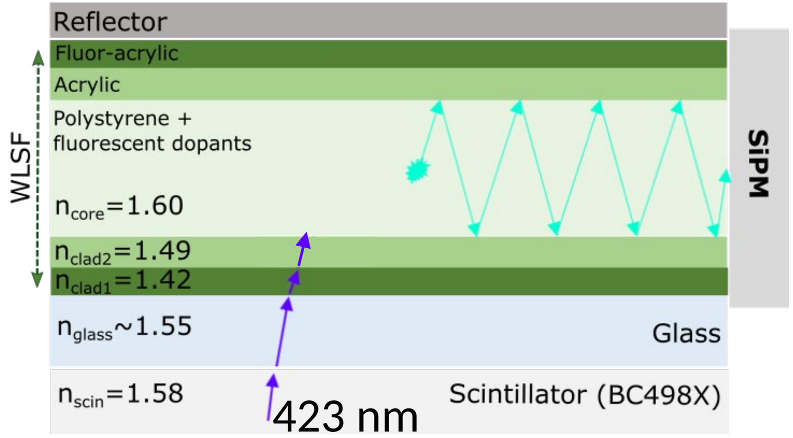
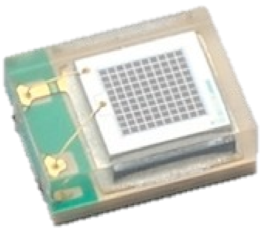
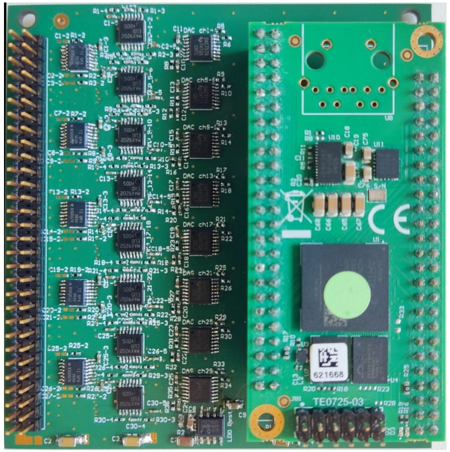






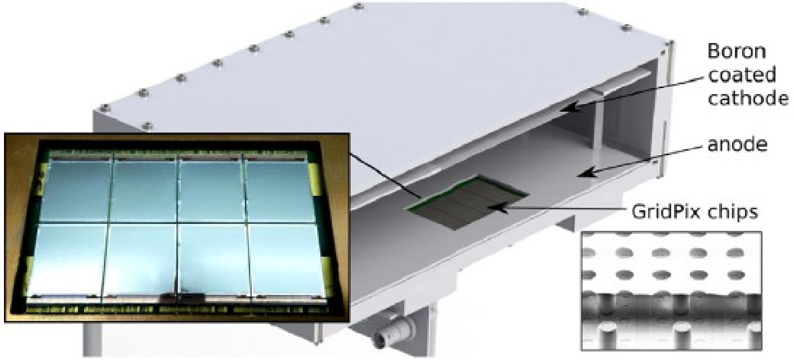


[MPPC S13360-1375PE]()

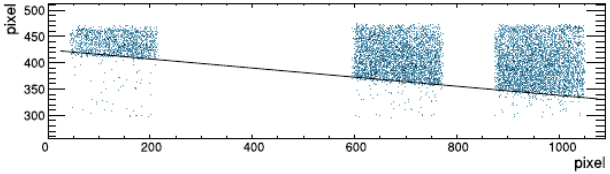


Trigger board for 30 SiPMs / fibers

Neutron TPC detector: First tests

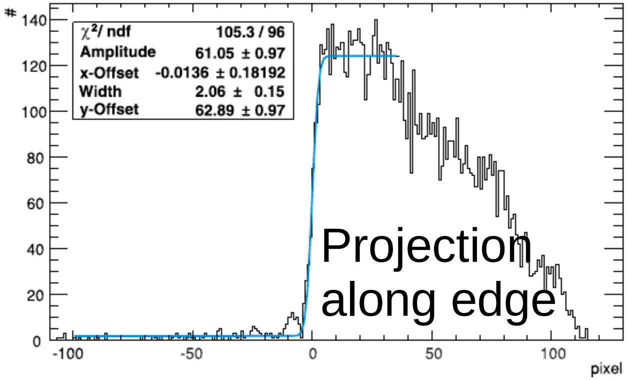


- 8 GridPixes based on Timepix used.
- Placed strip with $^{10}B_4C$ inclined across the GridPixes at a distance of 3.8 cm
- Neutron sources with non-directional beam
- Observed α and Li^{3+} tracks
- Reconstruct head of track → point of conversion
- Spatial resolution < 100 µm



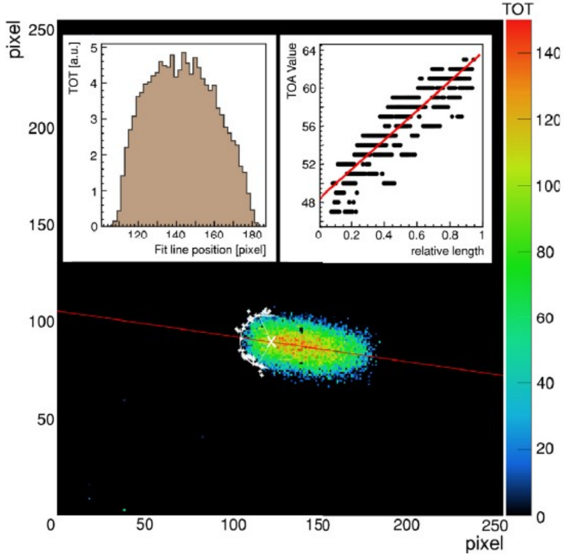
Occupancy of run

Ideal for directional WIMP search!



Projection along edge

Physica B: Condensed Matter 551 (2018) 517–52



Track of α:

- Charge
- dE/dx
- Time of arrival