LABORATÓRIO DE INSTRUMENTAÇÃO
E FÍSICA EXPERIMENTAL DE PARTÍCULAS
partículas e tecnologia

Neutron Detectors

Jornadas LIP, Coimbra, 9 July 2022

Team

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Collaborations

Local: RPC and NUC-RIA LIP groups

International: Neutron detector Groups from world-leading neutron facilities (ESS, TUM-FRMII and ISIS)

EUROPEAN SPALLATION SOURCE

FRM II Forschungs-Neutronenquelle Heinz Maier-Leibnitz

Science & Technology Facilities Council

Supported by: DL and MW LIP infrastructures

FCT Fundação para a Ciência e a Tecnologia
MINISTÉRIO DA EDUCAÇÃO E CIÊNCIA

REPÚBLICA PORTUGUESA

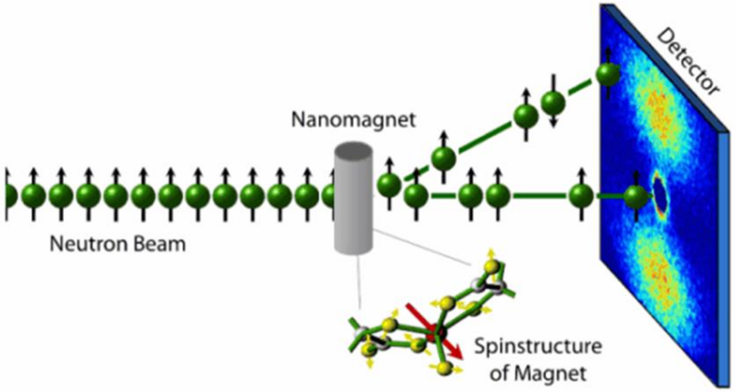
CERN/FIS-INS/0009/2019 | EXPL/FIS-NUC/0538/2021

What are neutron detectors used for

- **Neutron scattering sciences, e.g., for**:
  - New Materials Development
  - Life Sciences
  - Environment and Climate
- **Neutron imaging and tomography, e.g., for** :
  - Non-destructive testing for Aerospace Industry
  - Cultural Heritage
- **Fundamental neutron physics**, e.g., to search for the neutron electric dipole moment
- **Homeland security**, e.g., for portal monitors

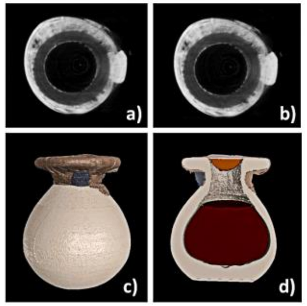
More than **5.000 researchers** are using over **32.000 instrument days per year** at the world leading European facilities [1].

[1] Chapman, S., McGreevy, R. & Consortium, L. The LENS Initiative: Strengthening European Neutron Science and Technology. Neutron News 32, 24–27 (2021).



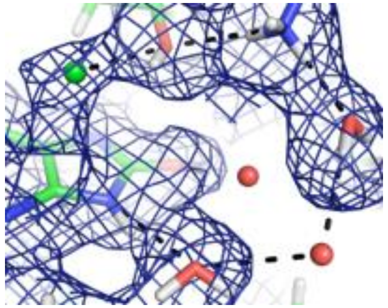
Neutrons to probe magnetism - To develop High-Tc superconductors for more efficient high speed trains, power transmission and compact accelerators.

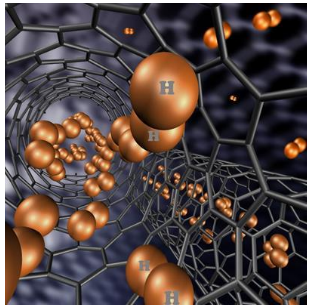
https://nanomaglux.wordpress.com/



Neutrons (neutral particles) are highly penetrating: Inspection of engines and components for aviation; Solve history mysteries.

doi:10.1002/ange.201713043





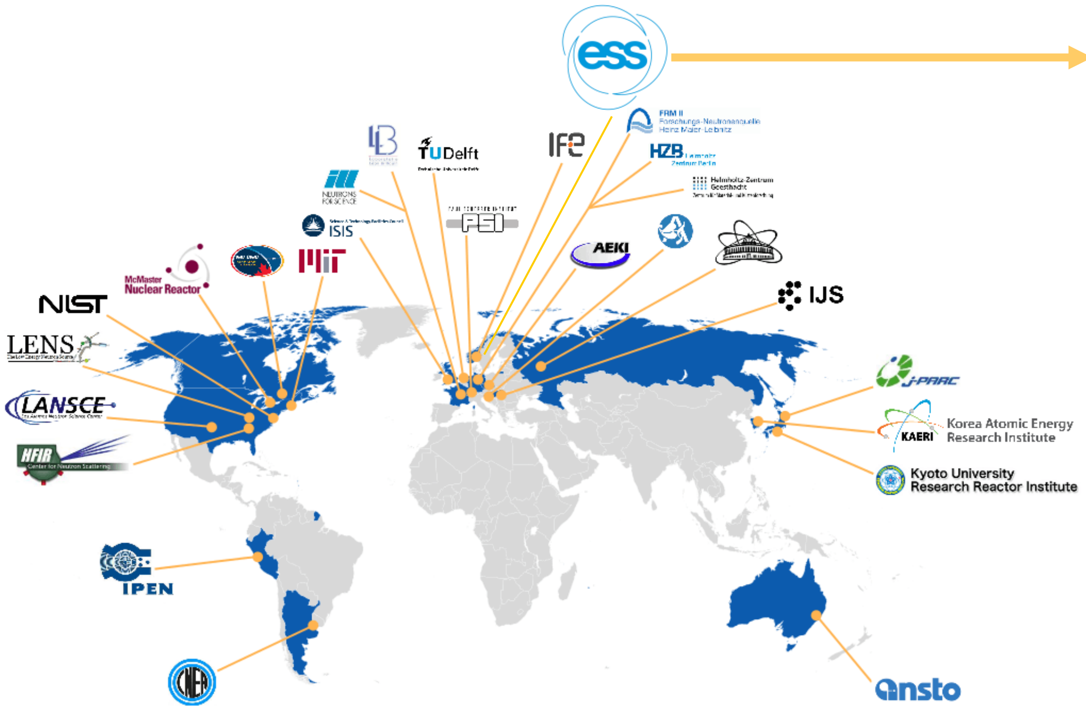
Neutrons are sensitive to light elements and isotopes enabling to spot positions of H in proteins – Develop new drugs, e.g., for anti-cancer therapies

Materials for Hydrogen Storage for a cleaner environment.

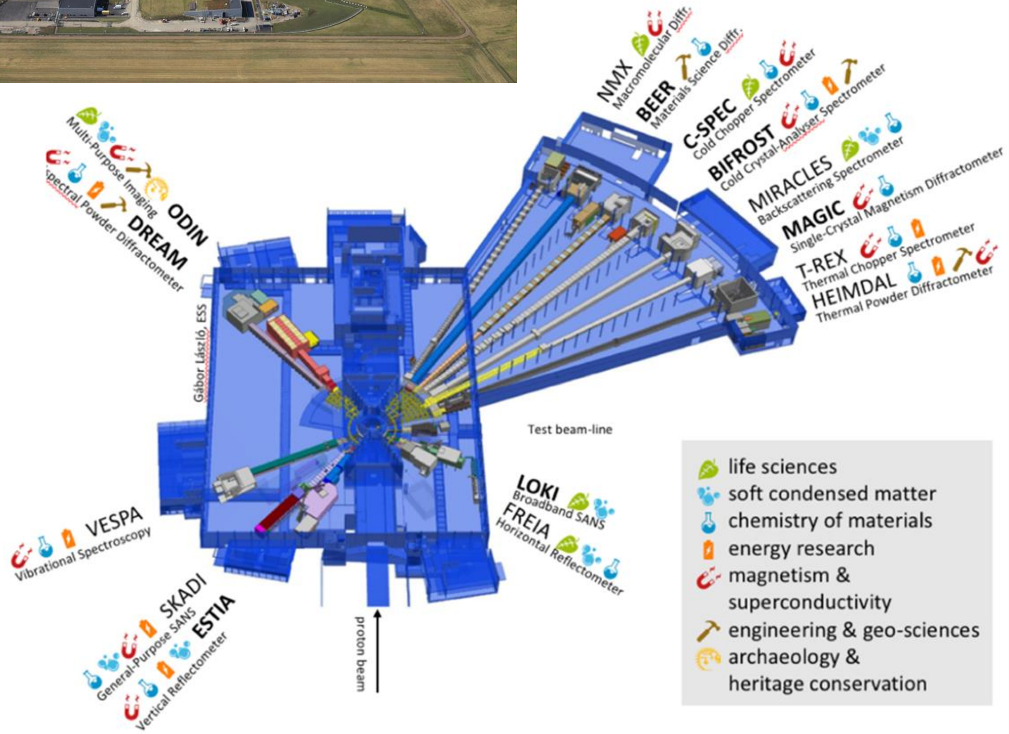
https://www.isis.stfc.ac.uk/Pages/Science.aspx

What are neutron detectors used for

Neutrons Facilities in World



Source: https://www.veqter.co.uk/



https://europeanspallationsource.se/

Neutron Detection – Basic Principles

Neutron is "neutral" - Detection needs a Nuclear Reaction to convert neutrons into charge particles

- **Slow neutrons (En < 0,5 eV) → Fission or Capture reactions** (n,γ) (n,p), (n,α), …

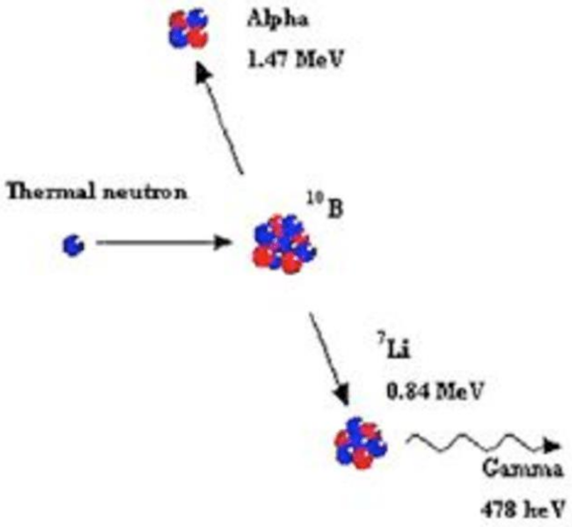
  Only a few isotopes have an adequate capture cross section and Q values suitable for thermal neutron detectors.

Solid

- Scintillators and Semiconductors typically doped with **^{6}Li, ^{10}B or ^{157}Gd**
- Neutron converter layers typically enriched with **^{6}Li, ^{10}B, ^{157}Gd or ^{235}U**

Gas

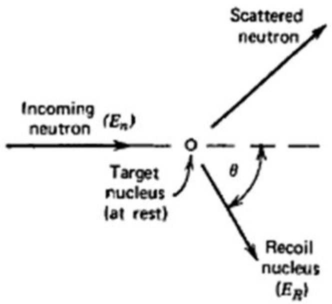
- Proportional counters filled with gas mixtures containing $^{10}BF_3$ or ^{3}He
- MSGCs filled with ^{3}He/ CF_4



- **Fast neutrons → Elastic scattering (n, n) - Recoil nuclei**

Solid: typically layers of materials rich in ^{1}H

Gas: typically proportional counters filled with gas mixtures with ^{4}He



Neutron Detector's

General requirements on neutron detectors for modern instruments

- High (> 50 %) detection efficiency
- Spatial resolution down to 100 μm
- Counting rate from Hz to MHz
- "Blind" to gamma rays (1e-6 sensitivity)
- Sensitive areas from 10 cm^2 to 30 m^2
- Affordable cost

Note: Neutron detectors have to cover a wide range of application. Design and required parameters have to be optimized for each instrument.

- Must be "free" of ^3He
  - ^3He shortage
  - Ongoing construction of new large scale neutron facilities (ESS); new ones are being planned
  - Upgrades of detectors at world-leading neutron facilities

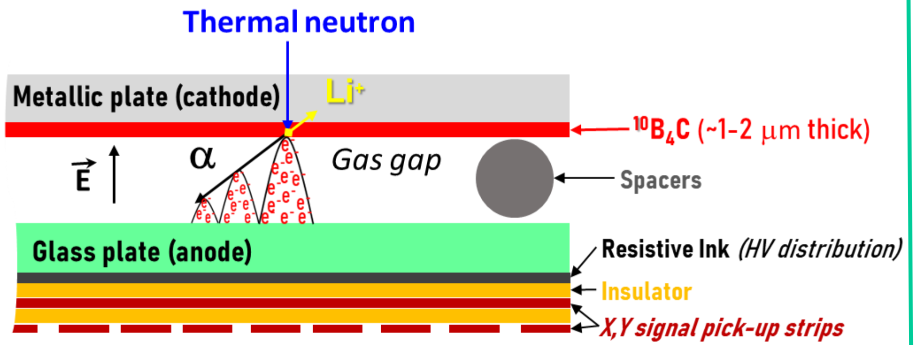
Pressing need world-wide for alternative neutron detection technologies to ^3He continues

Replacement solutions developed to date meet some requirements but fail on other critical ones

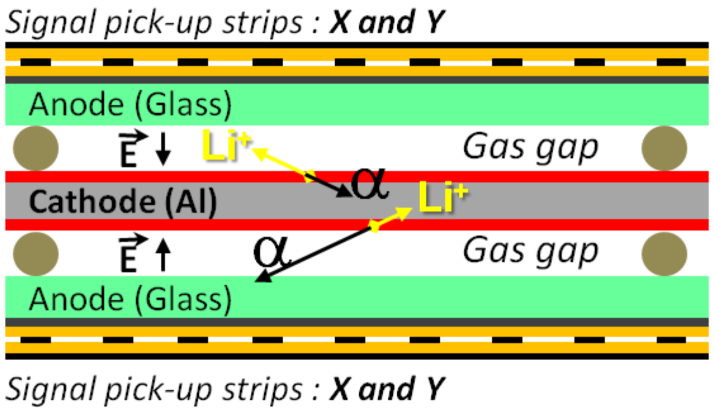
RPCs + $^{10}B_4C$ - Novel neutron detection technology

RPC configuration

- **Single Gap hybrid RPC**

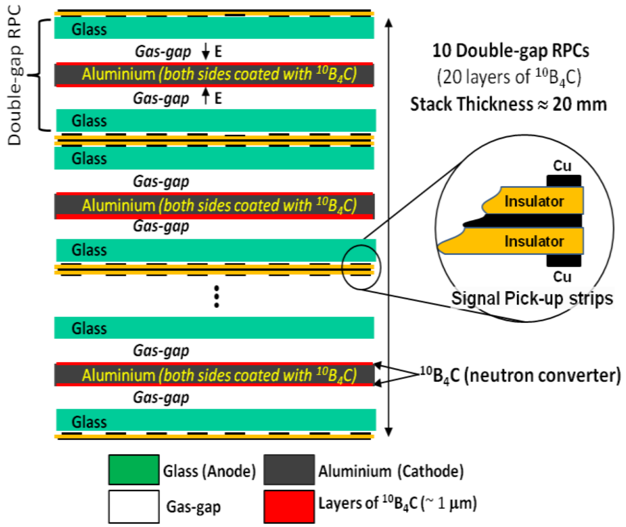


- **Double Gap hybrid RPC**

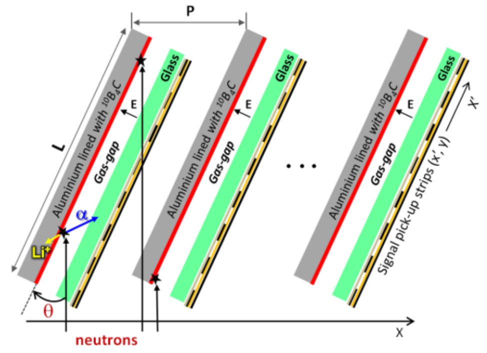


Detector Architectures

- **Multilayer**



- **Inclined**



Performance

- 4D (XYZ and time) readout capabilities
- Spatial resolution in 2D < 250 μm
- Sub-nanosecond temporal resolution
- Detection efficiencies > 50%
- Expected counting rates exceeding 100 kcps/cm^2

Attractive practical properties

- Robust: intrinsic discharge protection
- Modular design
- Highly scalable technology
- Low costs

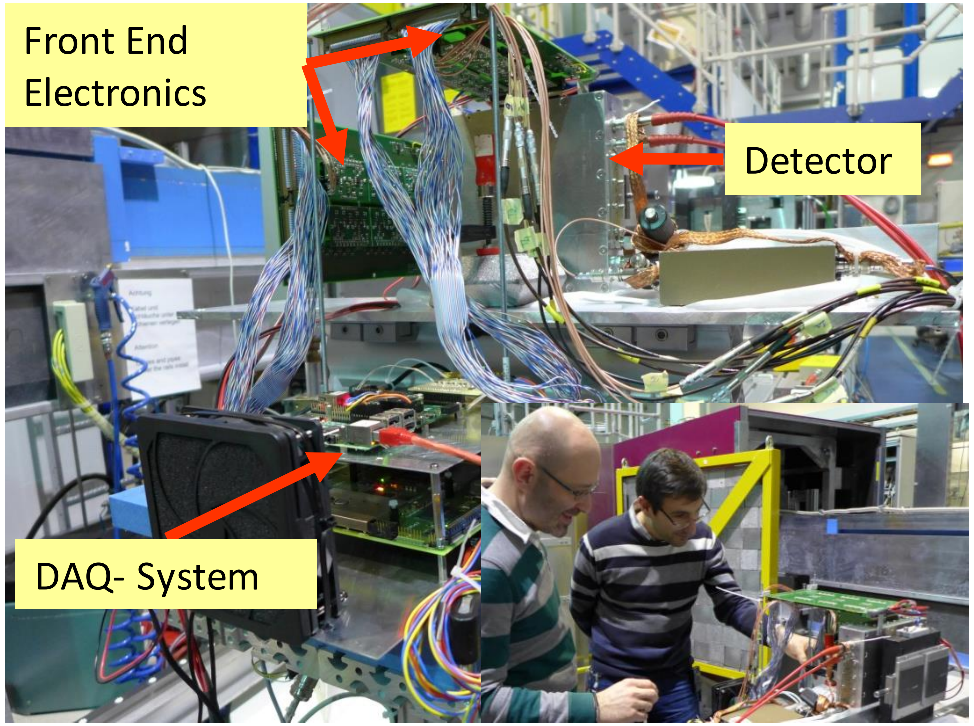
Very well suited for, e.g.,

- SANS - Small Angle Neutron Scattering
- NMX - Neutron Macromolecular Crystallography
- Wavelength resolved Neutron Imaging at Pulsed sources
- nEDM experiment

[https://iopscience.iop.org/article/10.1088/1748-0221/13/08/P08007]
[https://www.sine2020.eu/about/the-road-to-the-ess/rpcs-latest-update.html]

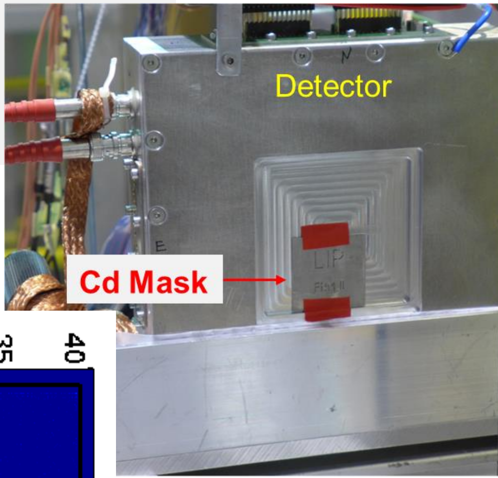
RPCs + $^{10}B_4C$ - Novel Neutron detection technology

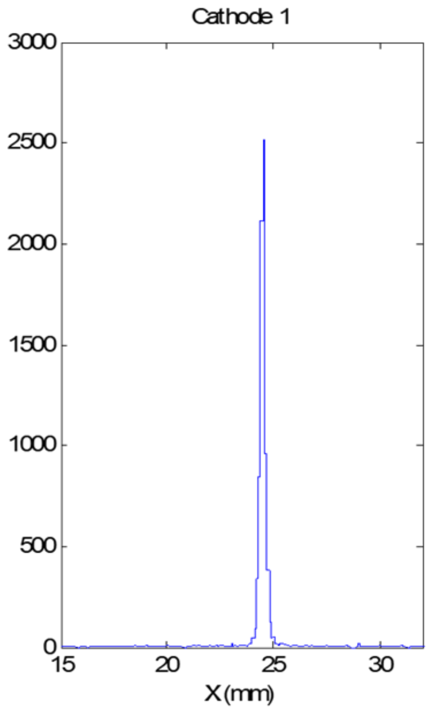
Concept already validated before

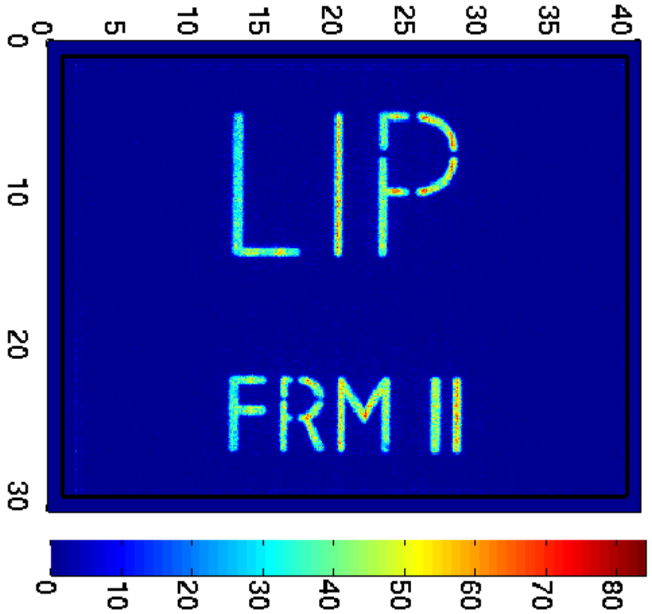


Detector tested at the FRM II neutron Facility

- **10 x Double gap ^{10}B-RPC:** 20 layers of $^{10}B_4C$
- **Detection Efficiency:** > 60% (4.7 Å)
- **Spatial resolution (2D):** < 250 μm FWHM







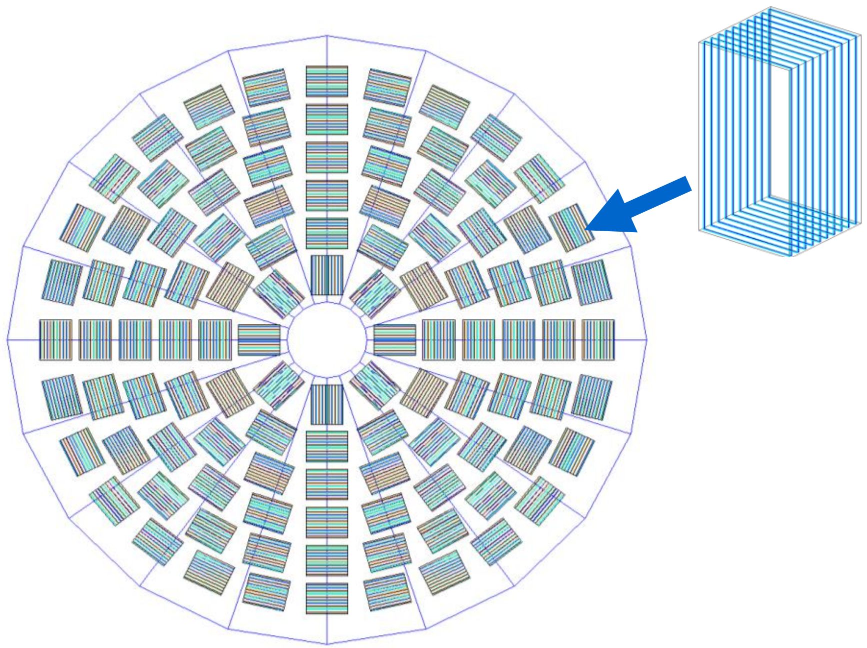
Ongoing Work

❑ Concept of a fast neutron detector based on ^{10}B-RPCs

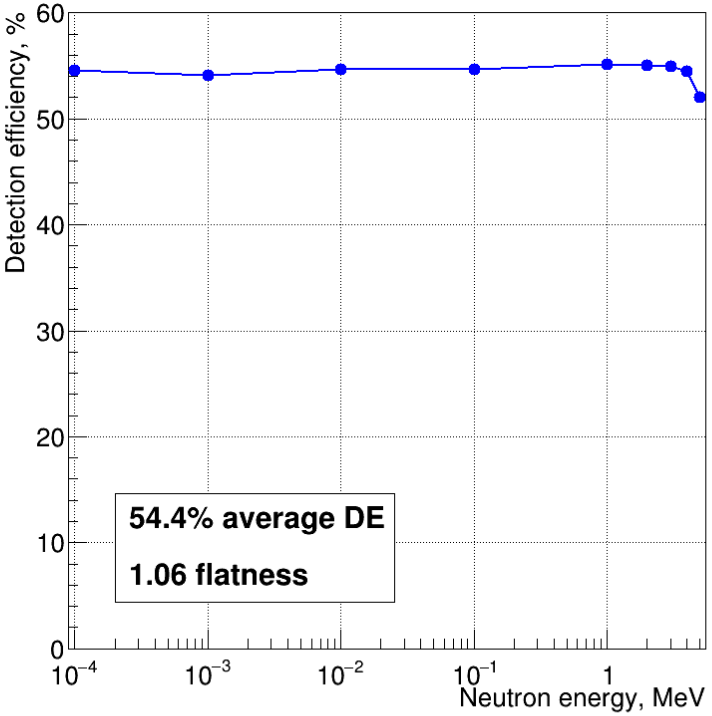
Evaluate the potential of ^{10}B-RPCs for a detector for beta delayed neutron emission – Simulation with Geant4 v 10.7.2.

[https://doi.org/10.1088/1748-0221/17/02/P02016]

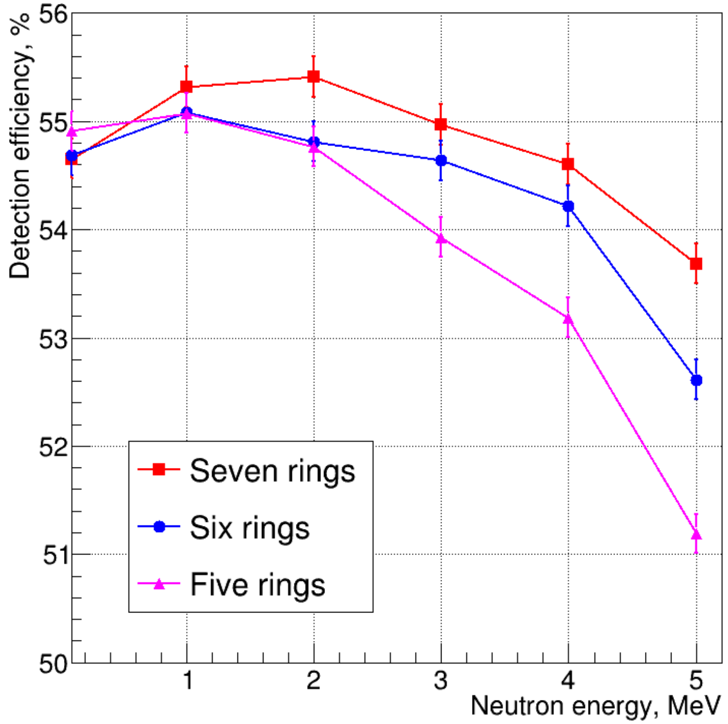
Cylindrical moderator with Detection units



Detection Units inside cylindrical moderator (1 m diameter)



Detection efficiency as a function of the neutron energy



Detection efficiency for three configurations: 0.1 – 5 MeV

Ongoing Work

❑ Concept of a fast neutron detector based on ^{10}B-RPCs

- Results show that fast neutron detectors based on ^{10}B-RPC technology can reach average detection efficiencies of **50 – 60%** with **high (~1.05) flatness** in the neutron energy range of **10^{-4} – 5 MeV**.
- Efficiency somewhat less than the values of **65 – 70%** demonstrated by BRIKEN detector (**the most sensitive of this type**) base on **^{3}He tubes**.
- But a detector like BRIKEN requires about 150 ^{3}He tubes
- It is currently difficult to get access to such a large number of ^{3}He tubes and the cost will be exorbitant (**~ 150 x 20 k€/Tube**)
- $^{10}B_4C$ coatings are much more cheap (**~ 50 k€ for 50 m^2 of $^{10}B_4C$**)

Configuration	Average DE, %	Flatness	^{10}B-RPC area, m^2
Five rings	54.1	1.07	31.9
Six rings	54.4	1.06	43.1
Seven rings	54.7	1.03	55.9

Table 4. Detector characteristics for the configurations with different number of rings of ^{10}B-RPC assemblies.

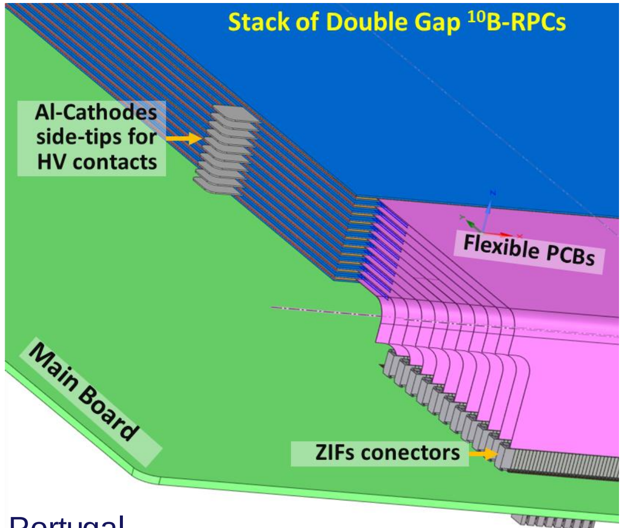
Ongoing Work

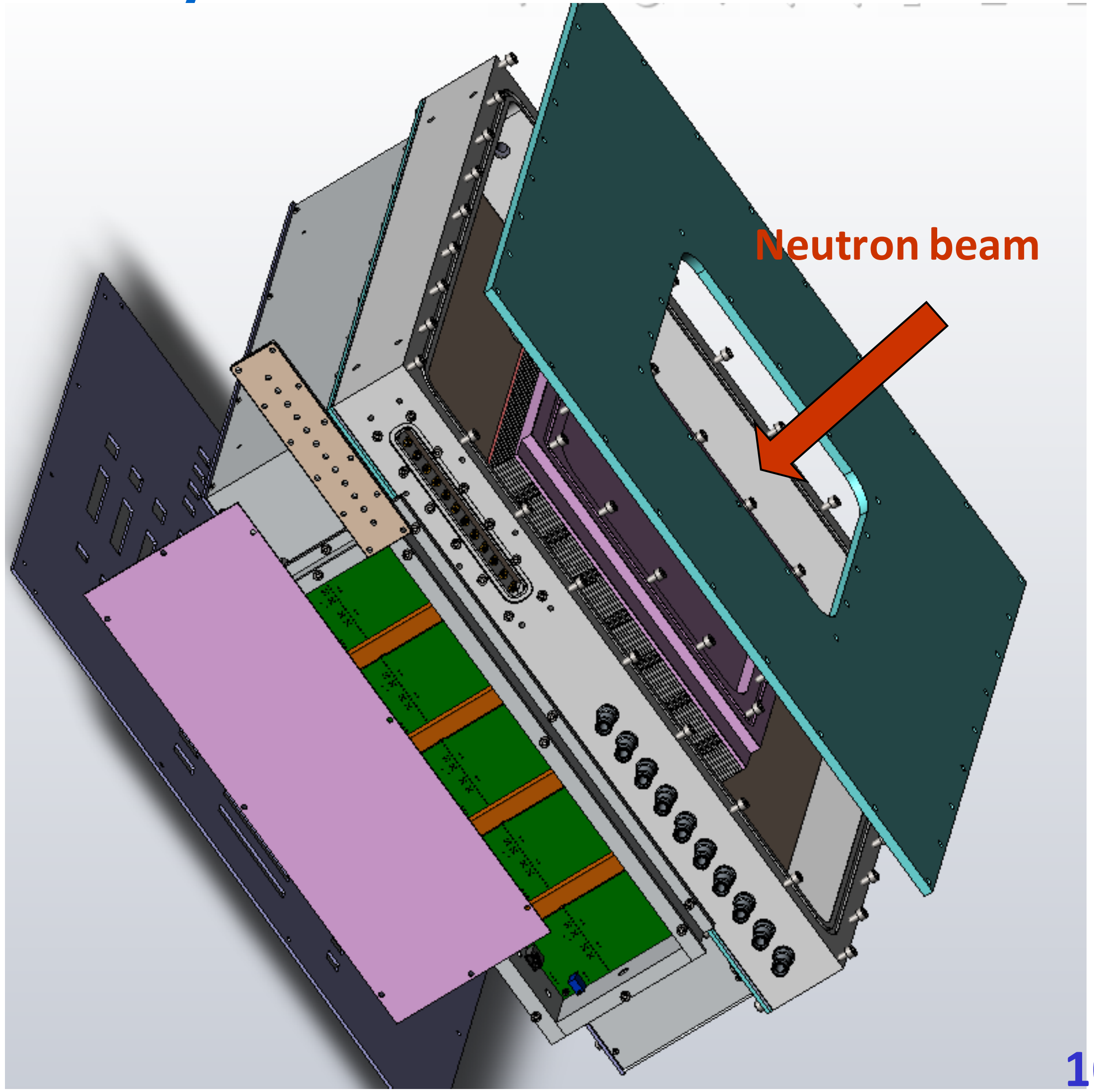
❑ Design and construction of a prototype for cold/ thermal neutrons

Main goal

Demonstrate the scalability of the ^{10}B-RPC neutron detection technology and the capability to reach the required counting rate

- **Area: 200 mm x 200 mm**
- **10 Double gap RPCs** in a Multilayer configuration
- **20 layers of $^{10}B_4C$** with **optimized thicknesses**
- **4224** signal pickup strips
- **394** electronic channels



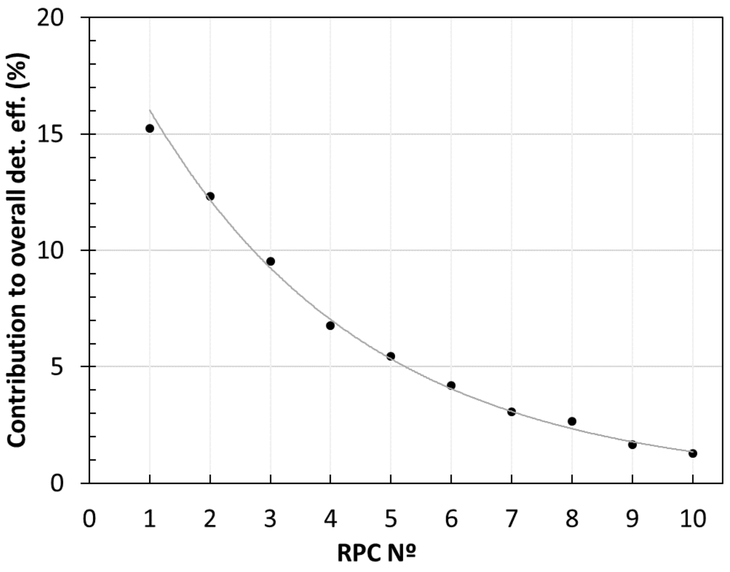


Ongoing Work

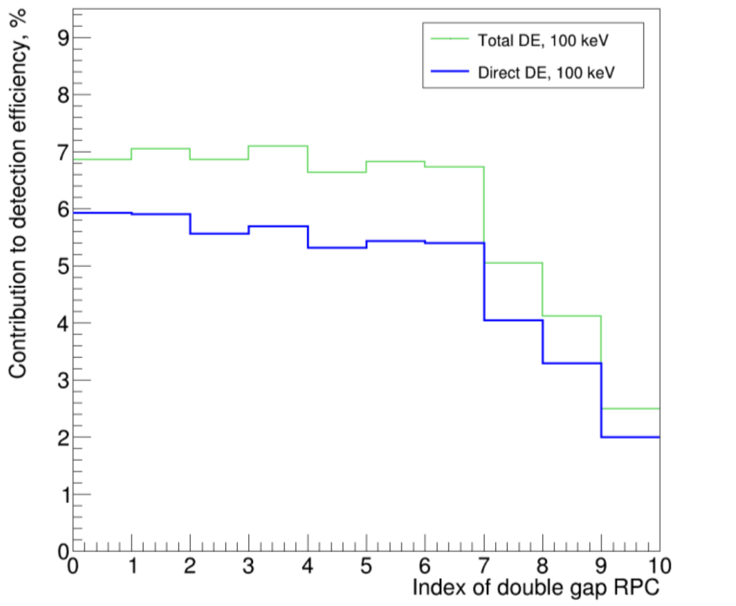
❑ Design and construction of a prototype for cold/ thermal neutrons

- Optimized with **ANTS2** to:
  - Improve counting rate capability
  - Detection efficiency > 50%
  - Reduce neutron scattering
  - Uniform response

Thickness of $^{10}B_4C$ **not optimized**



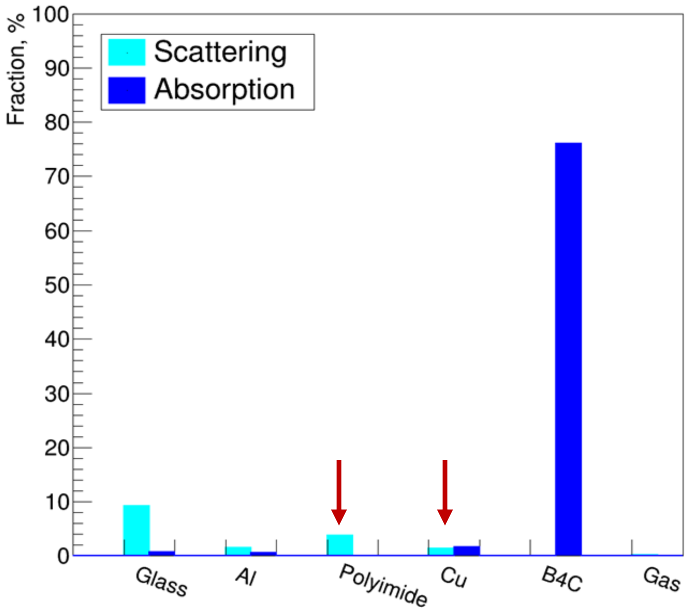
Thickness of $^{10}B_4C$ **optimized**



An increases of the counting rate capability of a **factor of > 16** relatively to one single-gap RPC, is expected

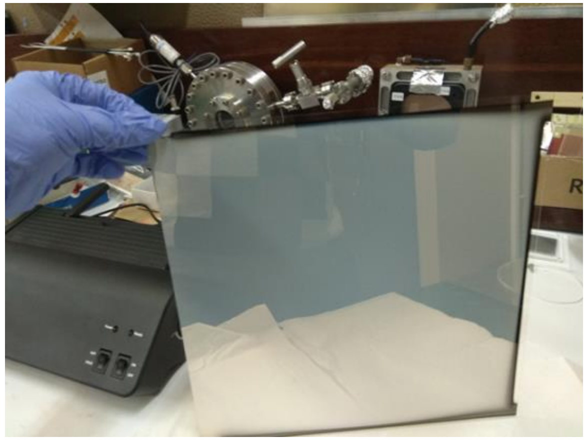
Ongoing Work

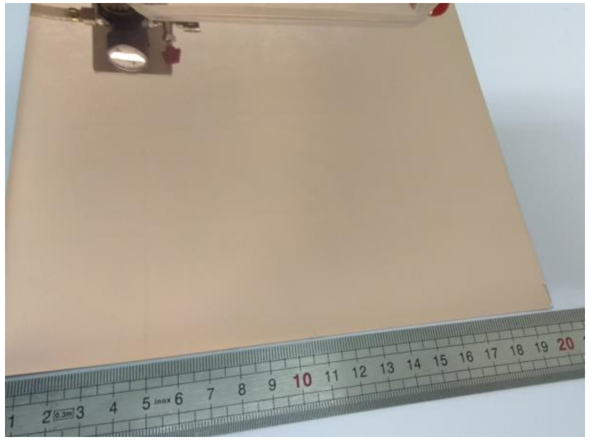
Possibility to replace Polyamide PCBs with the signal pickup strips is also being investigated to reduce neutron scattering



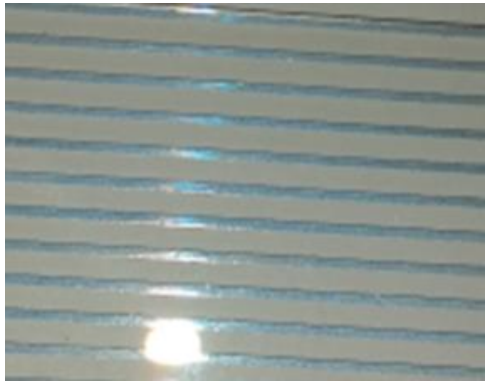
Engraving the signal pickup strips directly on the glass plates

- Al shows lower neutron absorption/ scattering than Cu
- Copper more suitable for photolithography
- Both, deposition of Al or Cu on the glass plates is feasible

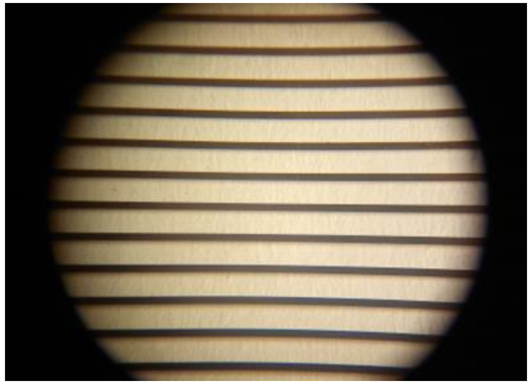




Glass plates coated by **DC-sputtering** at IPN-Instituto Pedro Nunes, Coimbra: **Al** (Left Fig.) and **Cu** (Right Fig.).



Strips (0.3 mm) on **Al** not well defined - More difficult to etch.



Strips (0.3 mm) on **Cu** very well defined.

Issues with adhesion of Dry-Film photoresist to the Copper layer to be solved.

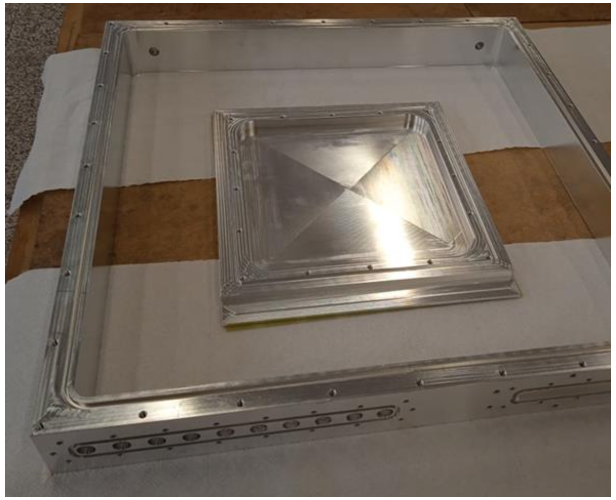
Ongoing Work

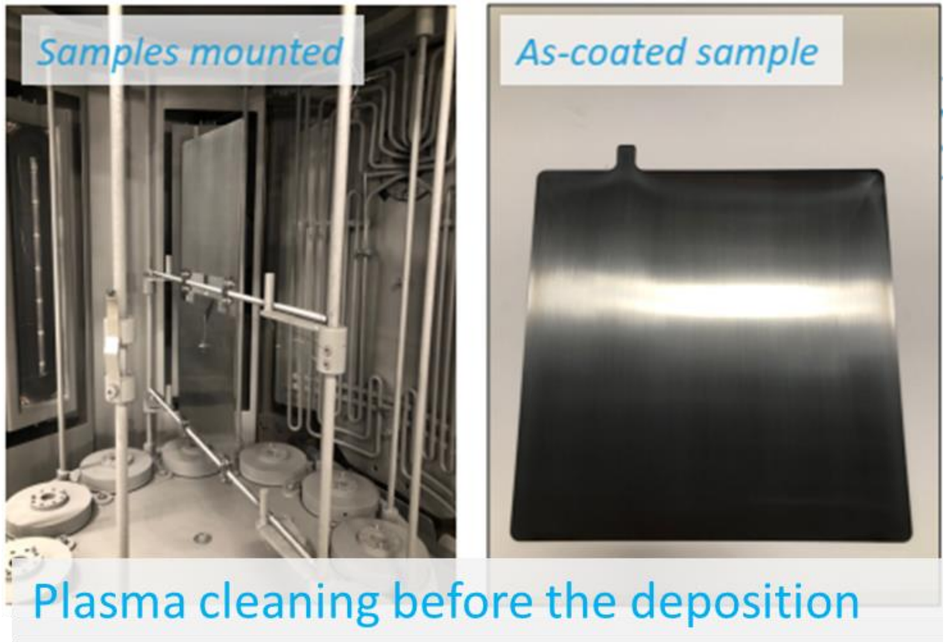
❑ Design and construction of a prototype

- Mechanical components (**DL + MW**)
- 0.3 mm thick **Al – Plates** (Al 5754) coated with $^{10}B_4C$ (^{10}**B** enrichment **> 97%**) (**ESS Detector Group**)

EUROPEAN SPALLATION SOURCE

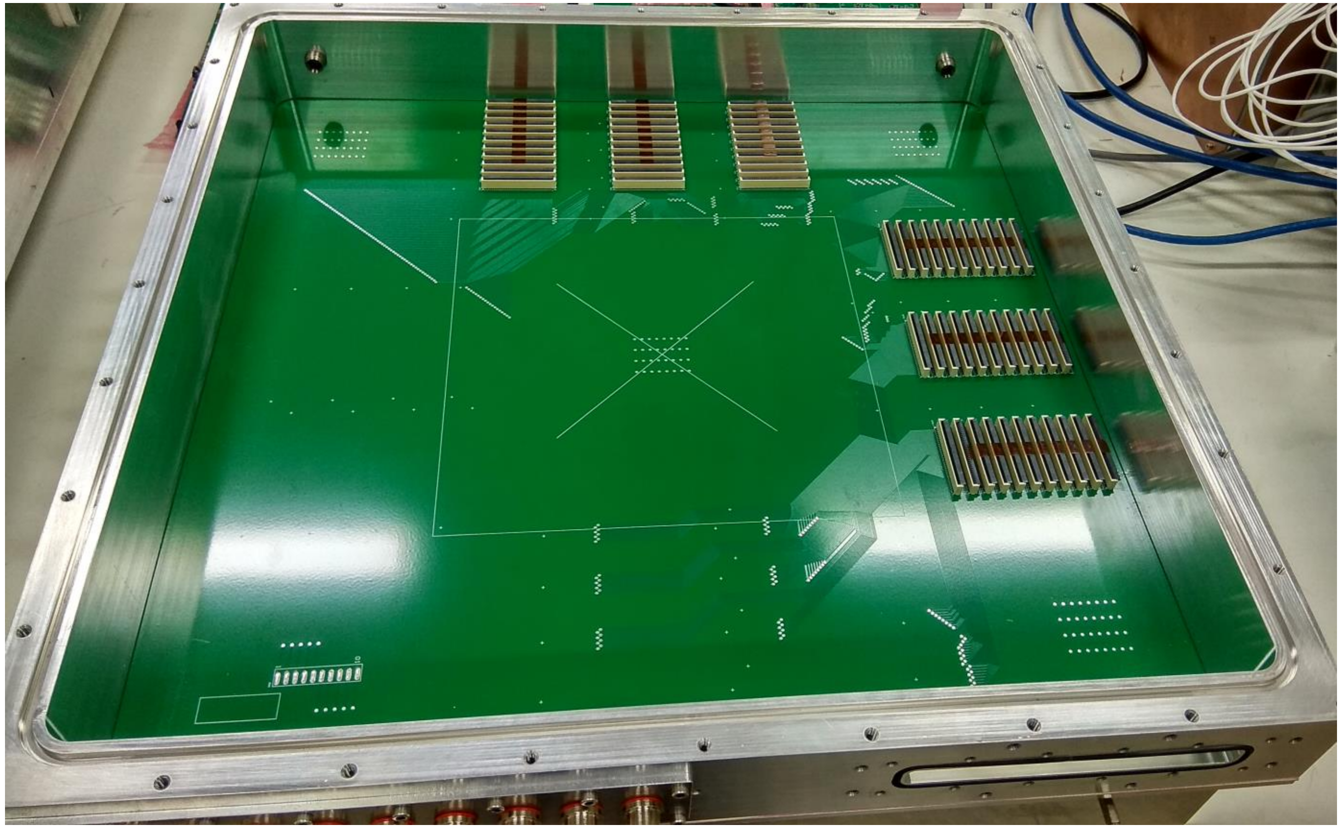
- Main Board for FEE (**outsourced**)
- FEE + DAQ (**RPC group**) ready
- Polyamide PCBs with signal pickup strips for the 2D-Readout → **Ordered**

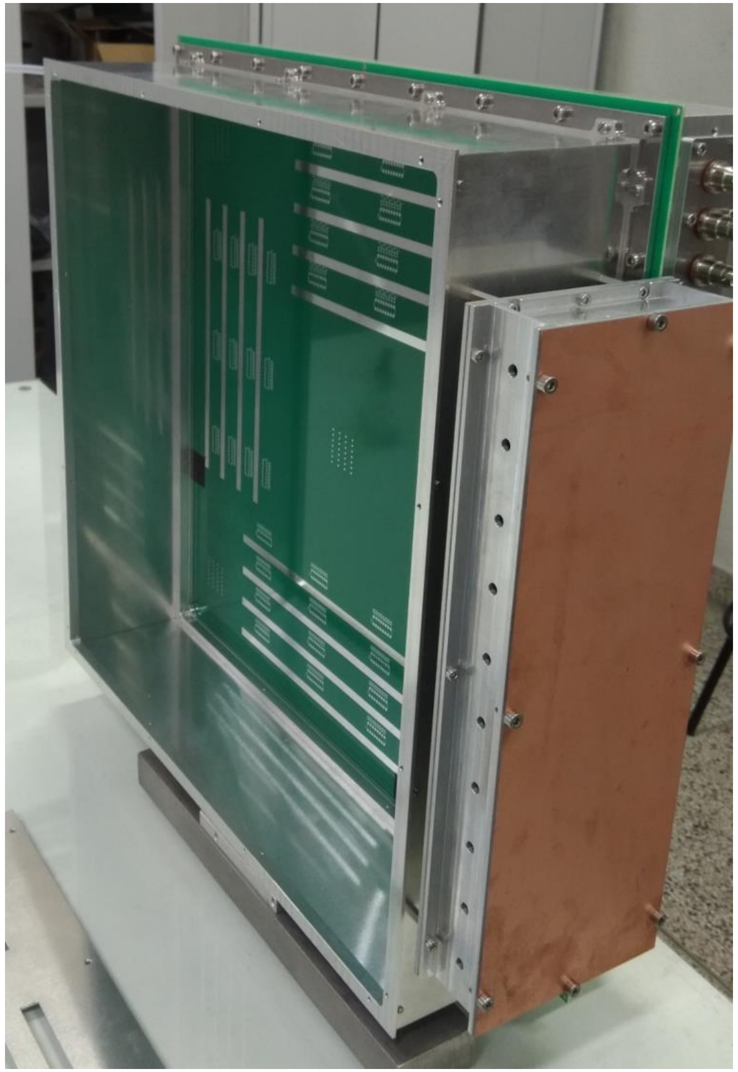




Ongoing Work

Prototype being assembled





Outlook

- **Prototype to be tested at SINQ -Swiss Spallation Neutron Source at PSI in October**
  - In collaboration with Prof. Dr. Florian PIEGSA from University of Bern, Albert Einstein Center for Fundamental Physics (to explore ^{10}B-RPC technology for an nEDM experiment)
- **Go ahead with the nRPC-4D project (EXPL/FIS-NUC/0538/2021)**
- **Characterize dark count rate limits for ^{10}B-RPCs**
- **Design a detector for fast neutrons (up to 5MeV) based on ^{10}B-RPCs to test the concept**
  - With the collaboration of RPC and NUC-RIA Groups
- **Participation in an EU-Consortium**
  - Submitted a proposal to a EU-Horizon, NeutronDetection2.0 (Proposal Nº 101095061)

Thank you for your attention

Backup Slides

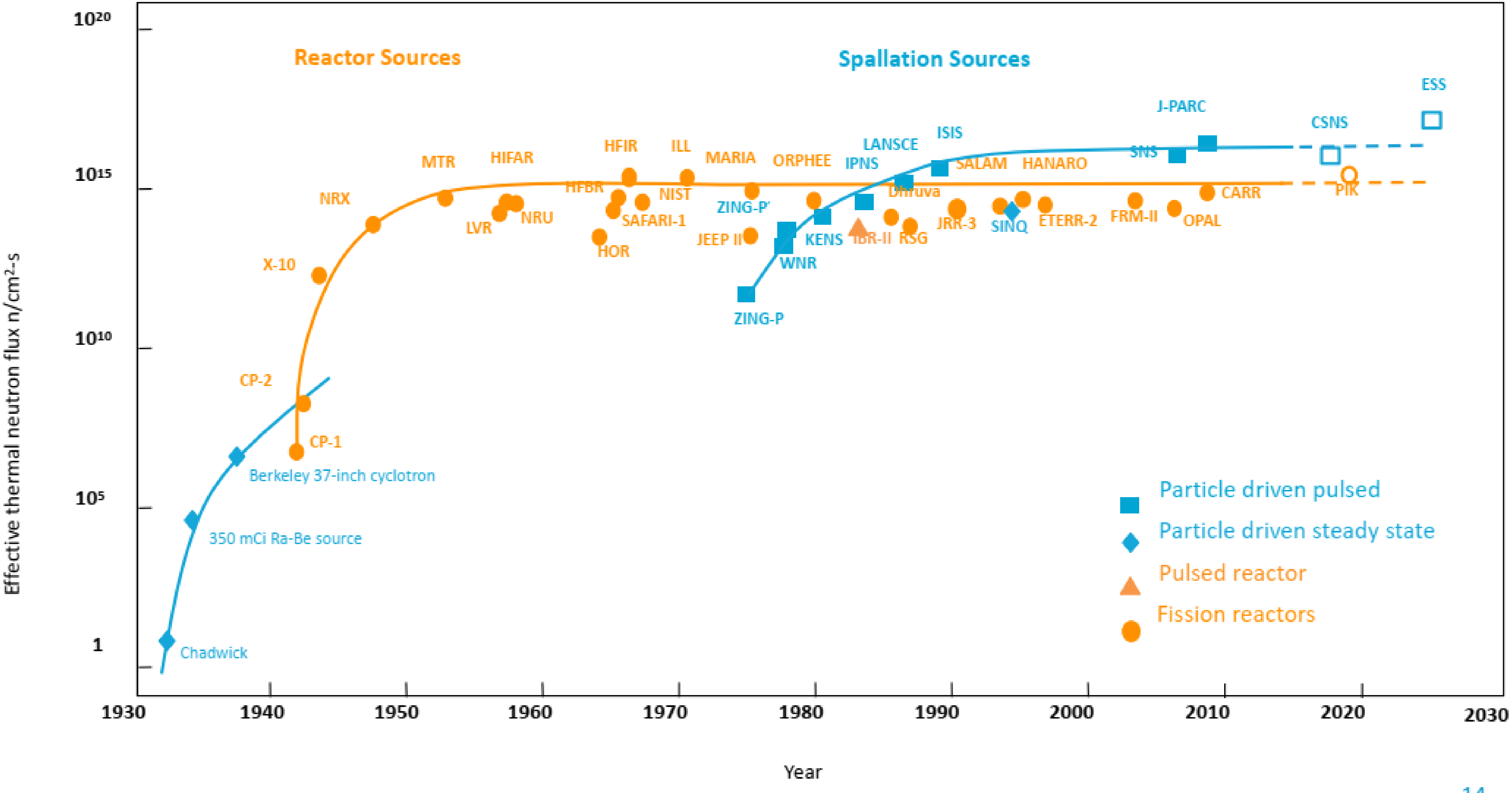
Backup Slides

Instrument	Wavelength range [Å]	Time resolution [μs]	Detector area [m^2]	Spatial resolution [mm]	Rate sample [$n/s/cm^2$]
SANS	3 - 20	100 [μs]	[10 - 18]	5	10^9
REFL	2 - 23	100 [μs]	0.41	0.5	10^9
DIRECT	0.8 - 20	10 [μs]	73.12	10 - 20	10^7
INDIRECT	1 - 8	[μs]	2.4	5	10^{10}
DIFF	0.5 - 20	10-100 [μs]	26.692	2 - 10	10^9
NMX	1.8 - 3.5	[ms]	1.08	0.2	10^8
IMAGING	1 - 10	[μs]	1	0.014-1	10^8
ENG	0.1 - 7	10 [μs]	6.4925	5	10^7

Table 2: Estimated detector requirements for each instrument class in terms of typical wavelength range of measurements, detector area, desired spatial and time resolution and neutron rate on the per cm^2 on the sample.

Oliver Kirstein et al., Neutron Position Sensitive Detectors for the ESS
Proceedings of Science, DOI: https://doi.org/10.22323/1.227.0029

Backup Slides



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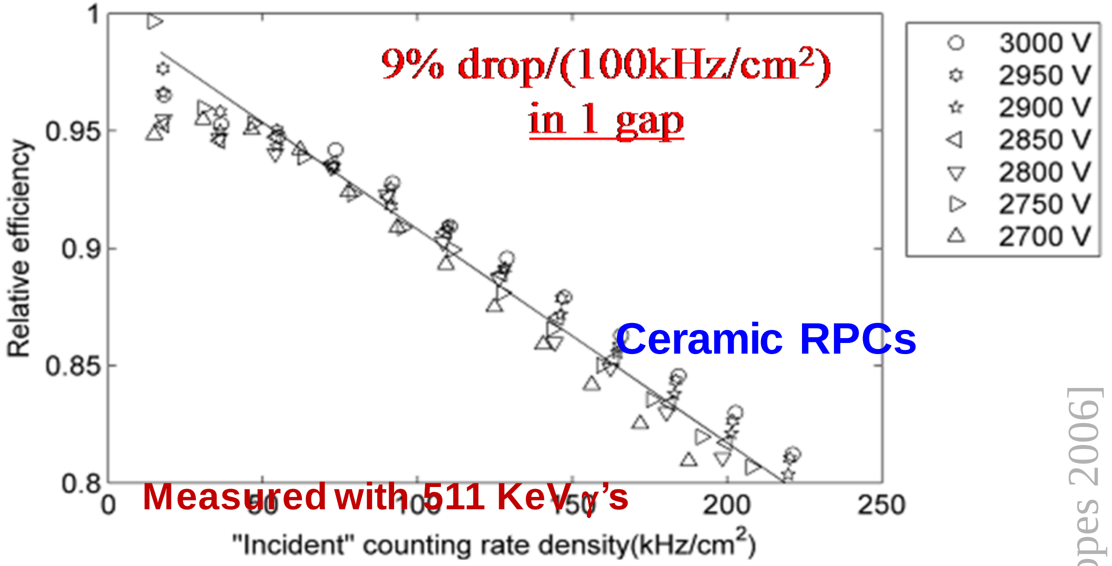
(Updated from *Neutron Scattering*, K. Skold and D. L. Price, eds., Academic Press, 1986)

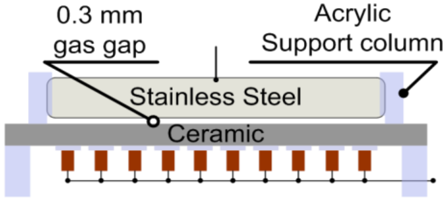
Counting rate improvement

- Low resistivity materials: e.g. Ceramics, doped glass, PEEK loaded with Carbon (ρ = 1 - 3 x10^9 Ω.cm)
- Thinner resistive electrodes
- Increase the temperature (glass resistivity decreases)
- Front end electronics with higher sensitivity
- Avalanche mode

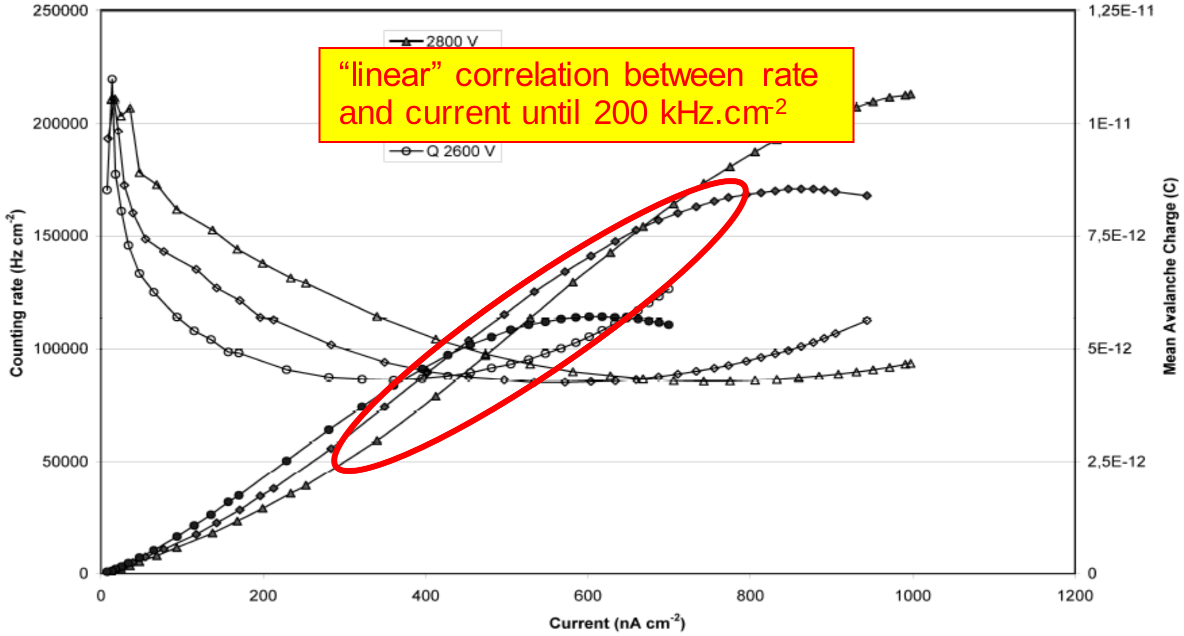
Counting Rate

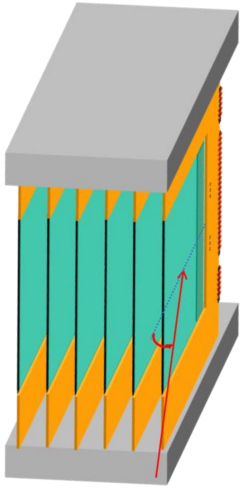
Are really RPCs slow detectors?



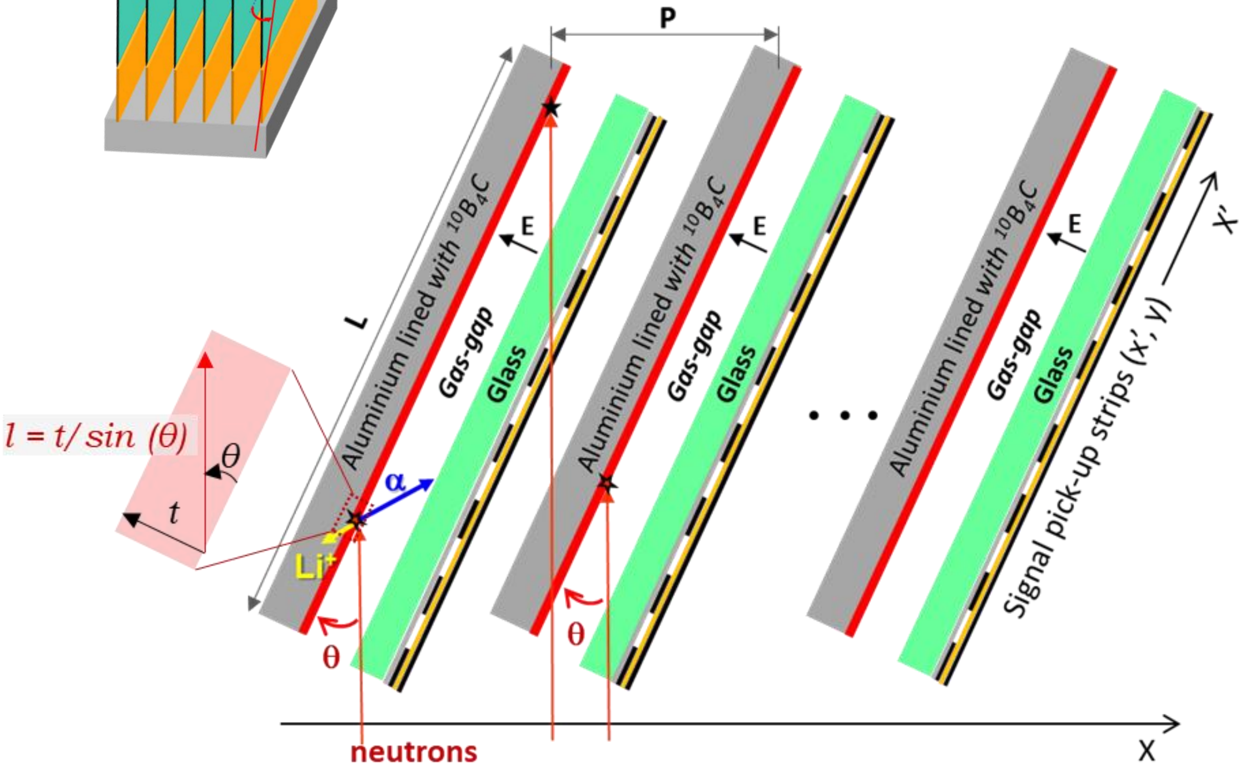


[Lopes 2006]

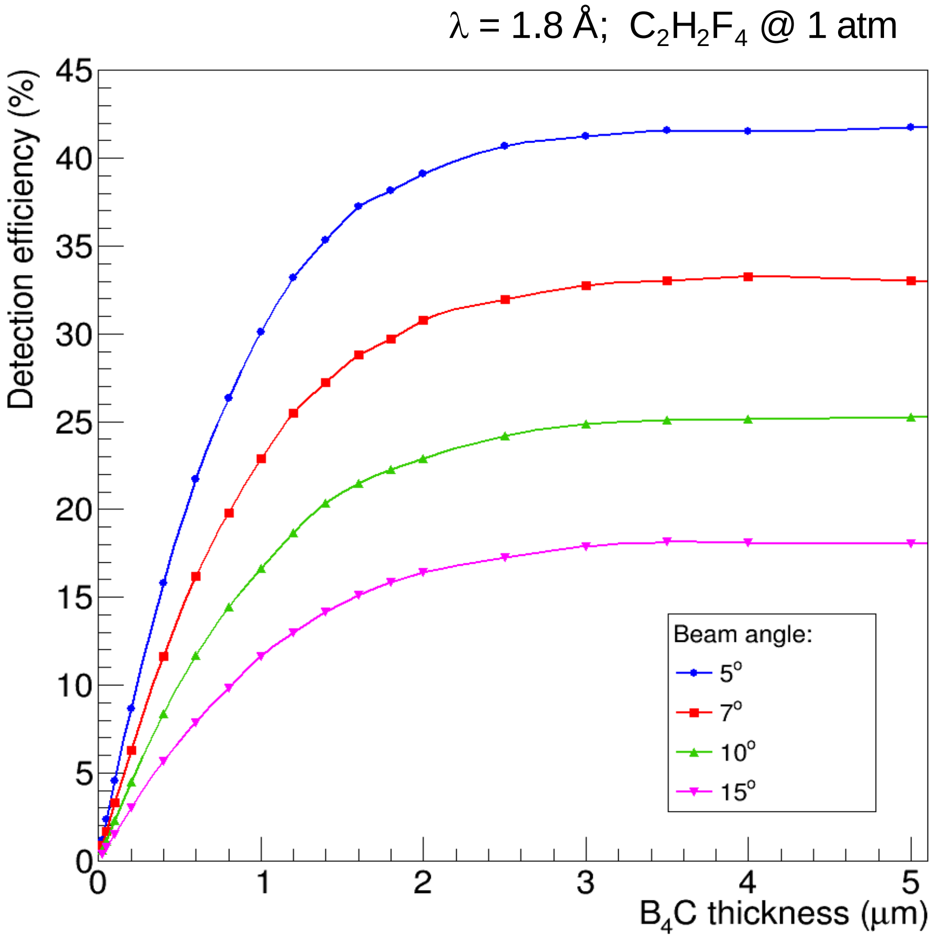




Inclined geometry



Detection efficiency vs $^{10}B_4C$ thickness for several angles of incidence of the neutron beam



[L.M.S. Margato and A. Morozov 2018 JINST 13 P08007]