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partículas e tecnologia

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Progress with the nRPC-4D detector concept for neutron scattering applications: *assessment of XYZ-position and nTOF readout capability in beam tests*

Luís Margato, A. Morozov, A. Blanco, J. Saraiva, L. Lopes, P. Fonte

LIP

Chung Chuan Lai, Per-Olof Svensson

ess EUROPEAN SPALLATION SOURCE

B. Guerard and J. Marchal

ILL NEUTRONS FOR SOCIETY

Outline

- Introduction
- nRPC-4D detector design
- Detector prototype
- Experimental results
- Summary

Introduction

Motivation

The RPC detectors, introduced in the 80s by **R. Santonico, R.Cardarelli (1981)** [1] shows a strong potential for applications in Neutron Scattering Science (NSS) and Beyond.

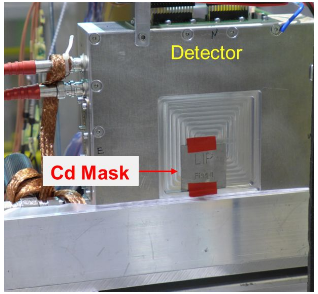
The European Spallation Source is currently driving the development of new types of neutron detectors.

Main goal

Develop RPC-based neutron detectors able to satisfy modern NSS instrument requirements, such as:

- High (> 50 %) neutron detection efficiency
- Low gamma sensitivity
- High spatial resolution and nTOF capability
- High counting rate
- Affordable costs

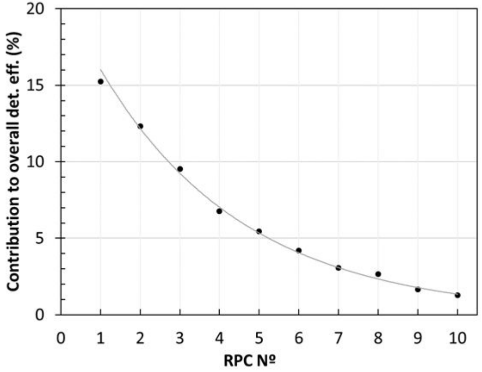
Previous work

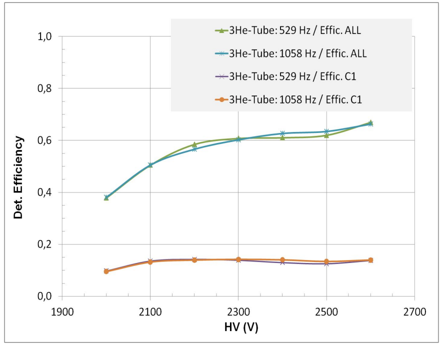


10 Double gap RPCs

- **Active area: 8 cm x 8 cm**
- Anodes: **0.5 mm** thick float glass
- Cathodes: **0.5 mm** thick Al
- Gas gap width: **0.35 mm**
- **$^{10}B_4C$ layer: 1.15 μm**

Detector tested at FRM II (MLZ)





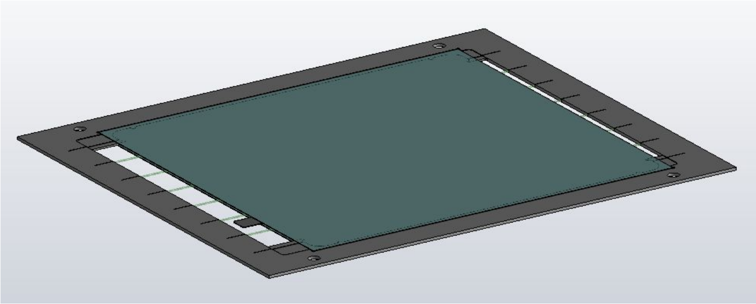
- Detection Efficiency: 62.1% (λ = 4.73 Å)
- Spatial resolution (x and y): ~ 0.25 mm FWHM
- Gamma sensitivity (0.511 MeV) < 10^{-6}

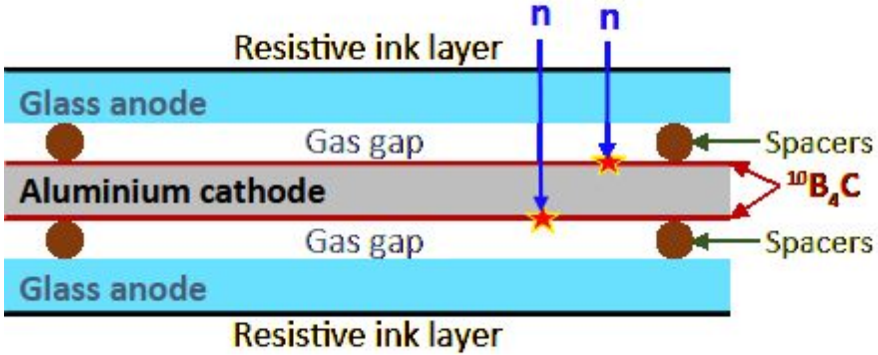
[1] https://doi.org/10.1016/0029-554X(81)90363-3

L.M.S. Margato *et al* 2020 *JINST* 15 P06007

nRPC-4D detector design

- **Standalone neutron detection modules: Double gap RPCs coated with $^{10}B_4C$ to enable sensitivity to cold/thermal neutrons**



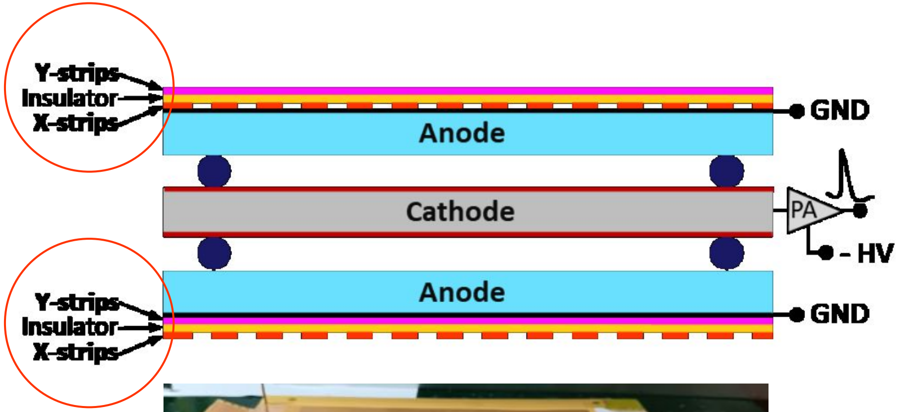


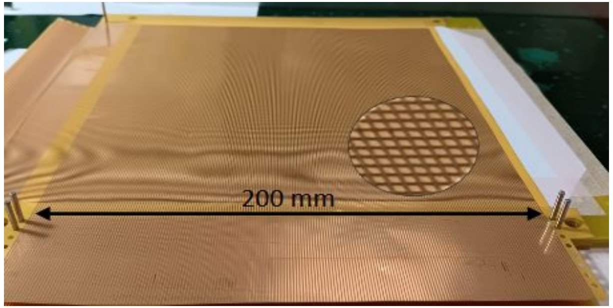
$$n + {}^{10}B \rightarrow \begin{cases} {}^{7}\mathrm{Li}(0.84\ \mathrm{MeV}) + {}^{4}\mathrm{He}(1.47\ \mathrm{MeV}) + \gamma(0.47\ \mathrm{MeV}), & 94\% \\ {}^{7}\mathrm{Li}(1.01\ \mathrm{MeV}) + {}^{4}\mathrm{He}(1.78\ \mathrm{MeV}), & 6\%. \end{cases}$$

nRPC-4D detector design

- **Standalone neutron detection modules: Double gap RPCs coated with $^{10}B_4C$ to enable sensitivity to cold/thermal neutrons**

- **Signal pickup: Thin film PCBs with parallel Cu strips for XY position readout**





Thin film PBCs

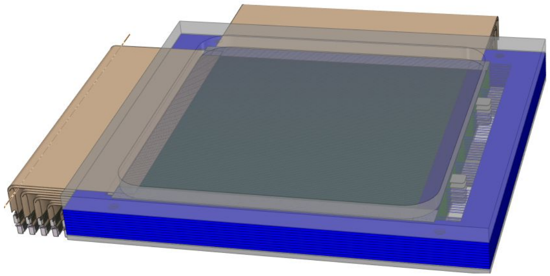
- 25 μm thick polyamide
- 2 arrays of parallel mutually-orthogonal Cu strips: **Pitch = 1mm**; **Width = 0.3 mm**

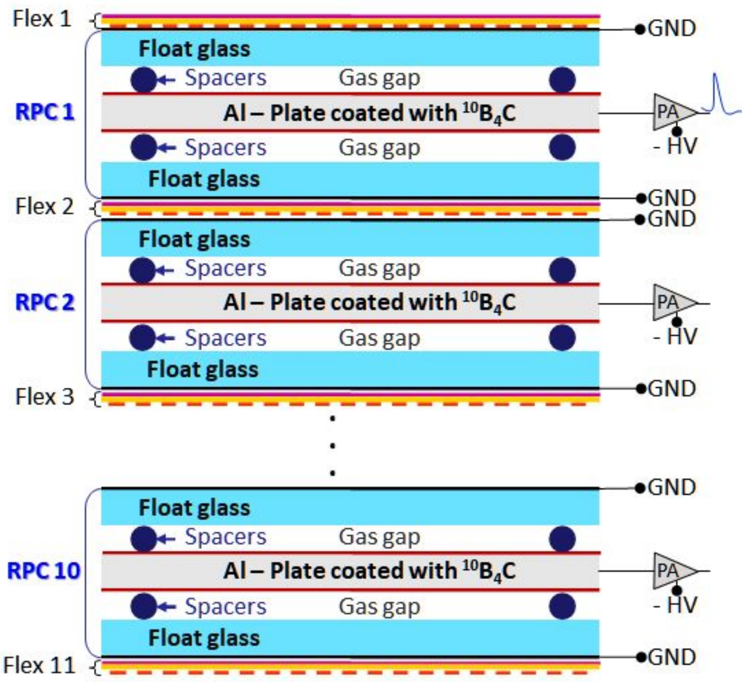
nRPC-4D detector design

- Standalone neutron detection modules: Double gap RPCs coated with $^{10}B_4C$ to enable sensitivity to cold/thermal neutrons

- Signal pickup: Thin film PCBs with parallel Cu strips for XY position readout

- Multilayer structure for high neutron detection efficiency: Stack of 10 nRPC modules





Optimization of the $^{10}B_4C$ layers thickness

Simulations in Geant4 (v10.7.2)

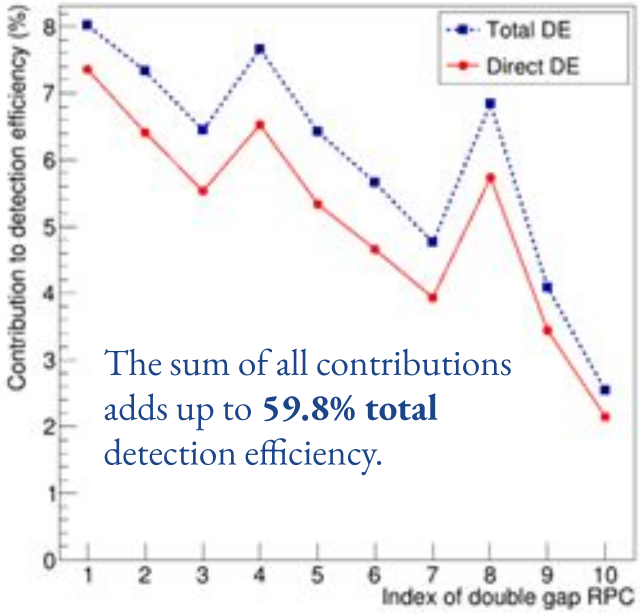
Detection Efficiency optimized by setting only 3 different possible thicknesses for the $^{10}B_4C$

Primary neutrons **(4.7 Å)** generated as a **pencil beam** with normal incidence at the center of the detector.

Optimized thicknesses for (λn = 4.5 Å)

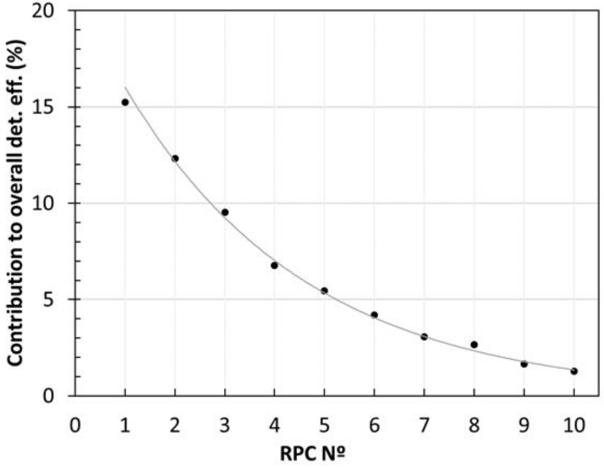
- **0.4 µm** for RPC 1 to 3
- **0.6 µm** for RPC 4 to 7
- **2.2 µm** for RPC 8 to 10

https://doi.org/10.1016/j.nima.2023.168267

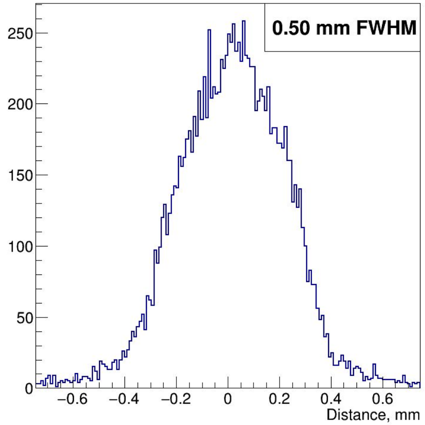


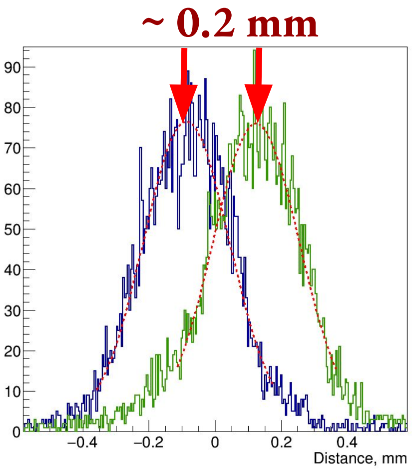
The sum of all contributions adds up to **59.8% total** detection efficiency.

All $^{10}B_4C$ layer with the same thickness (1.15 µm)



Identify the $^{10}B_4C$ layer where a neutron is captured



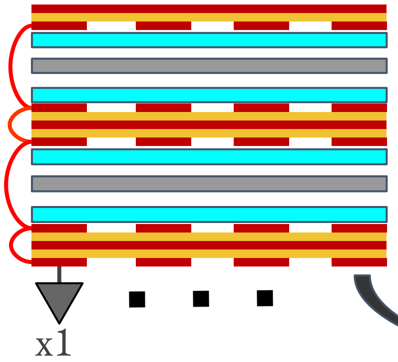


Observed shift in the reconstructed position, most likely due to a misalignment between the strip arrays for the Y- coordinate.

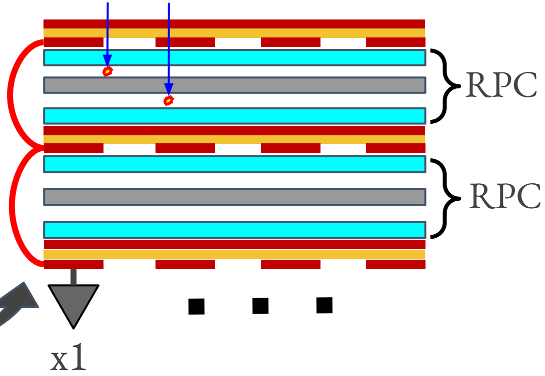
A. Morozov *et al* 2021 *JINST* **16** P08032

Ambiguity in the $^{10}B_4C$ layer where a neutron is captured

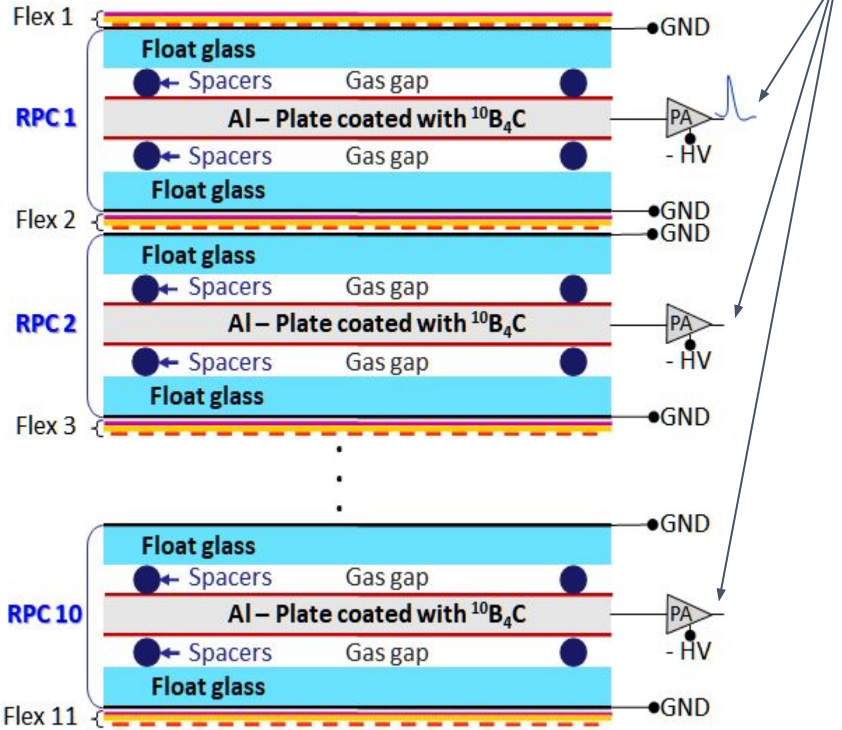
One possible solution: Pair of arrays of parallel Cu strips, mutually orthogonal.



X_i (Y_j) strips, from each array, with the **same index are interconnected** and **read by the same electronic channel**



Timing and XYZ coordinates



Cathode signal ***(serves two purposes)***

- Event timing → **nTOF**
- Identification of the nRPC where a neutron is captured

Arrays of parallel Cu strips mutually orthogonal

- **XY- coordinates**

Triggered cathode + Difference in signal sum on strips x and y,

X- sum signal > Y- sum signal
Neutron capture in the **top $^{10}B_4C$ layer** of a nRPC

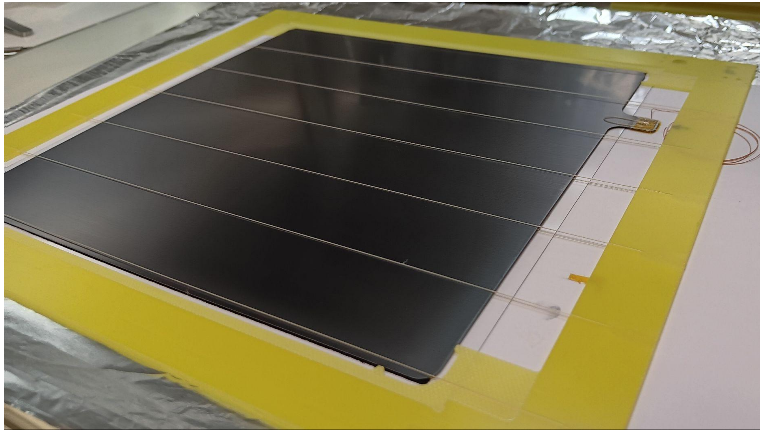
X- sum signal < Y- sum signal
Neutron capture in the **bottom $^{10}B_4C$ layer** of a nRPC

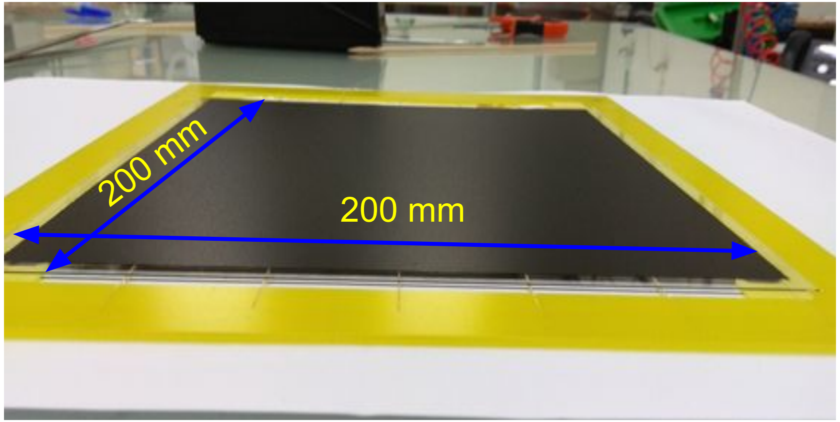
- **Z-coordinate**

nRPC-4D prototype

Neutron detection module

Double gap RPC with the cathode coated on both sides with a layer of $^{10}B_4C$





Frame: FR4
Spacers: 0.28 mm diameter PEEK monofilament
Cathode (190 mm x 190 mm):

- 0.3 mm thick aluminium
- Both sides coated with **$^{10}B_4C$ at the ESS Detector Coatings Workshop**

Anodes (200 mm x 200 mm):

- 0.33 mm thick float glass
- External faces painted with resistive ink

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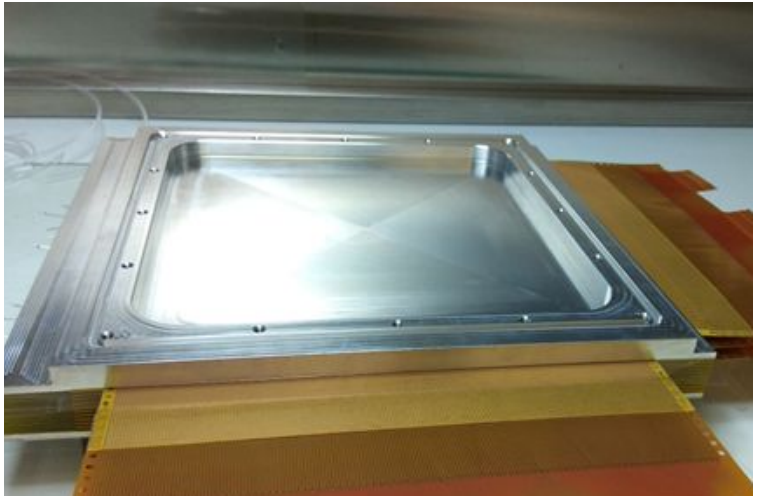
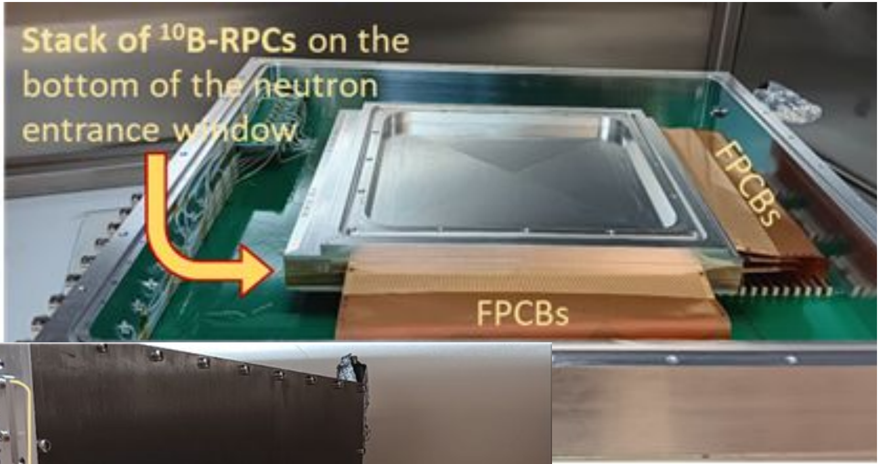
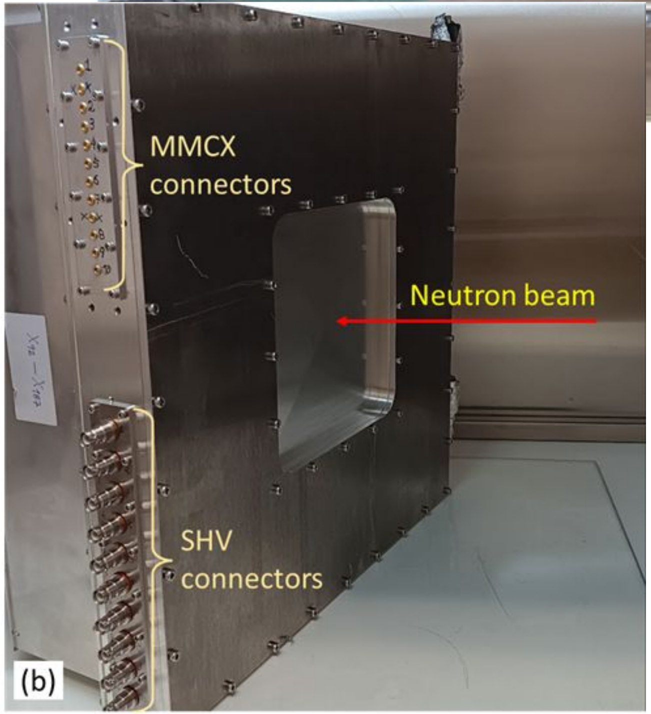
nRPC-4D prototype







BACK SIDE

10 nRPCs → 20 layers of $^{10}B_4C$

- **9 nRPC** units made with 0.3 mm thick float glass
- **1 nRPC** unit made with 0.5 mm thick LR-glass provided by **Crispin W.**

Electronic readout

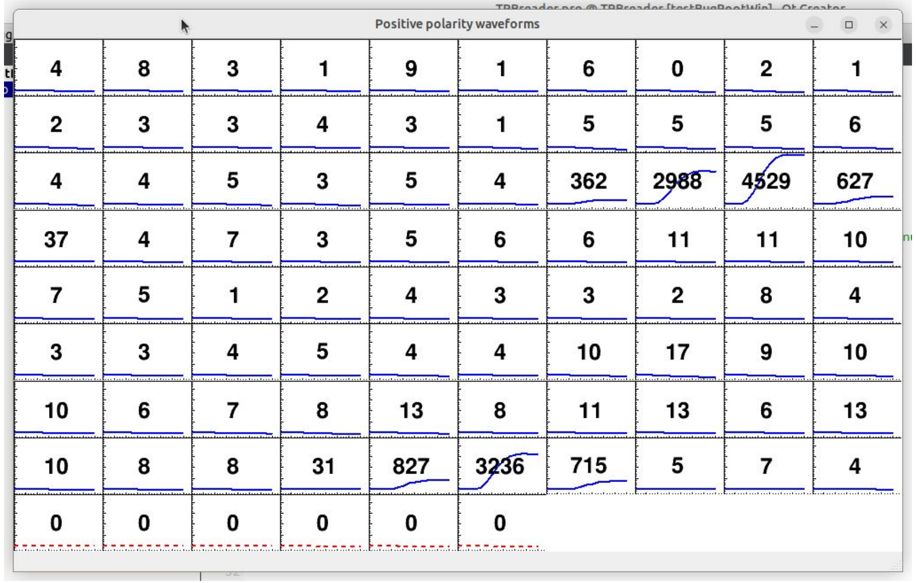
Front End Electronics (P. Fonte)
Charge PAs
Timing amplifiers

ADC addon

48 ch 40 MHz streaming ADCs

DAQ - TRB3 (trb.gsi.de)
48 ch 10 ps TDC

X- and Y- strips waveforms

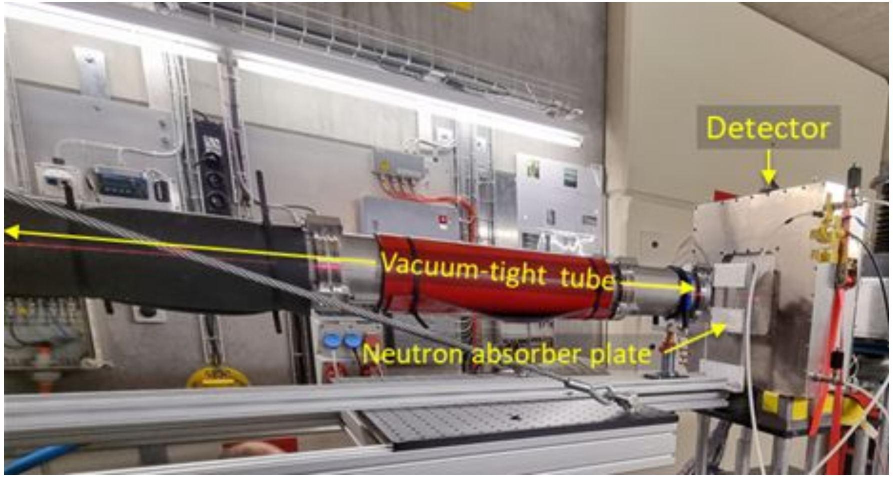


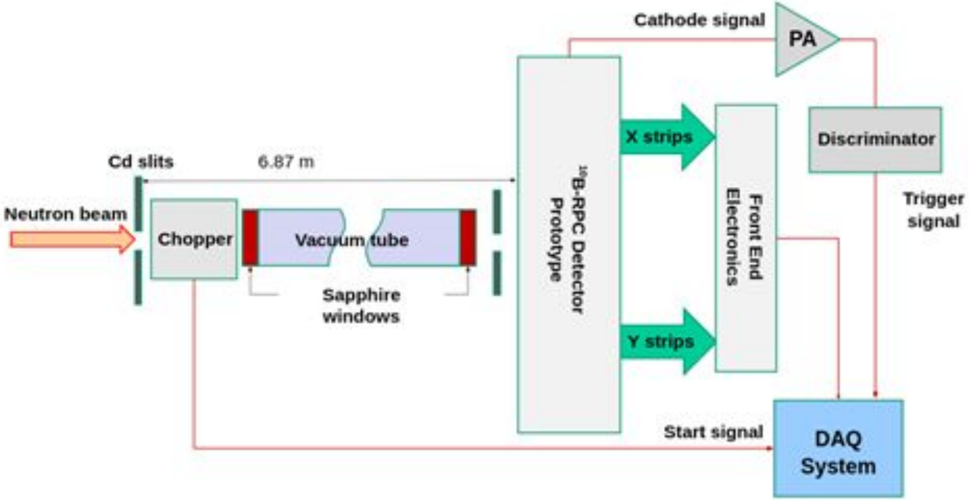
(x, y) - event position reconstruction by **COG**

- S_i - signals from the strips
- X_i, Y_i - positions of the strips

$$x = \frac{\sum X_i S_i}{\sum S_i} \quad y = \frac{\sum Y_i S_i}{\sum S_i}$$

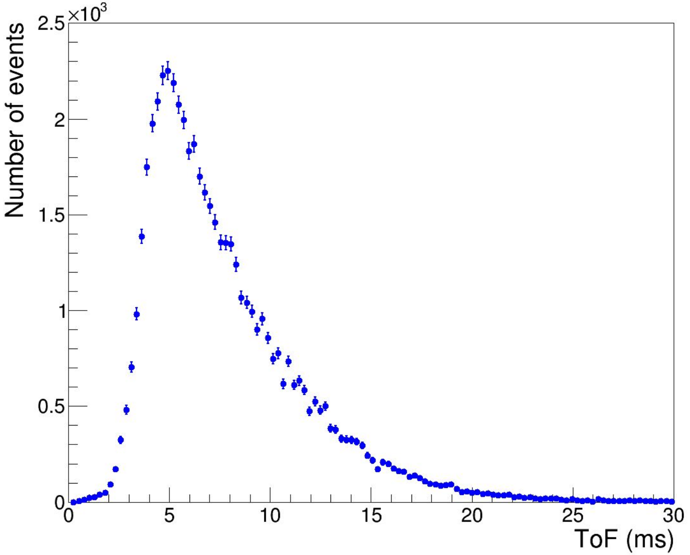
Tests at the BOA beamline at PSI





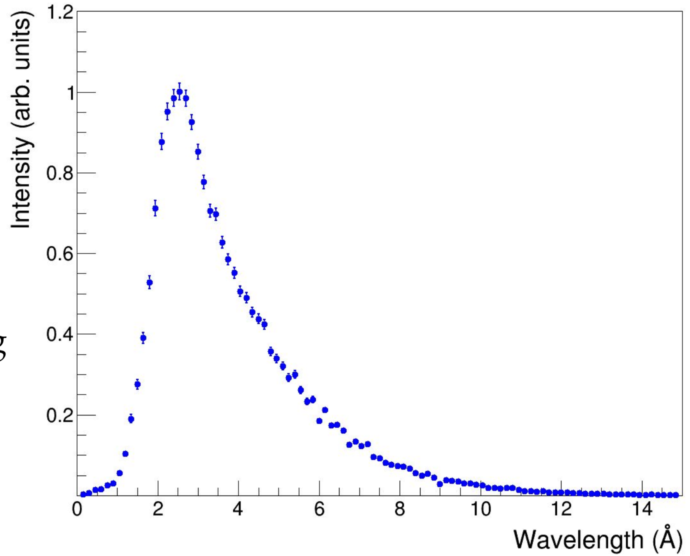
Results: nToF measurements

Time-of-Flight spectrum



- ***λ=h/p***
- Correction accounting for the dependence of **DE** on neutron wavelength

Neutron wavelength spectrum

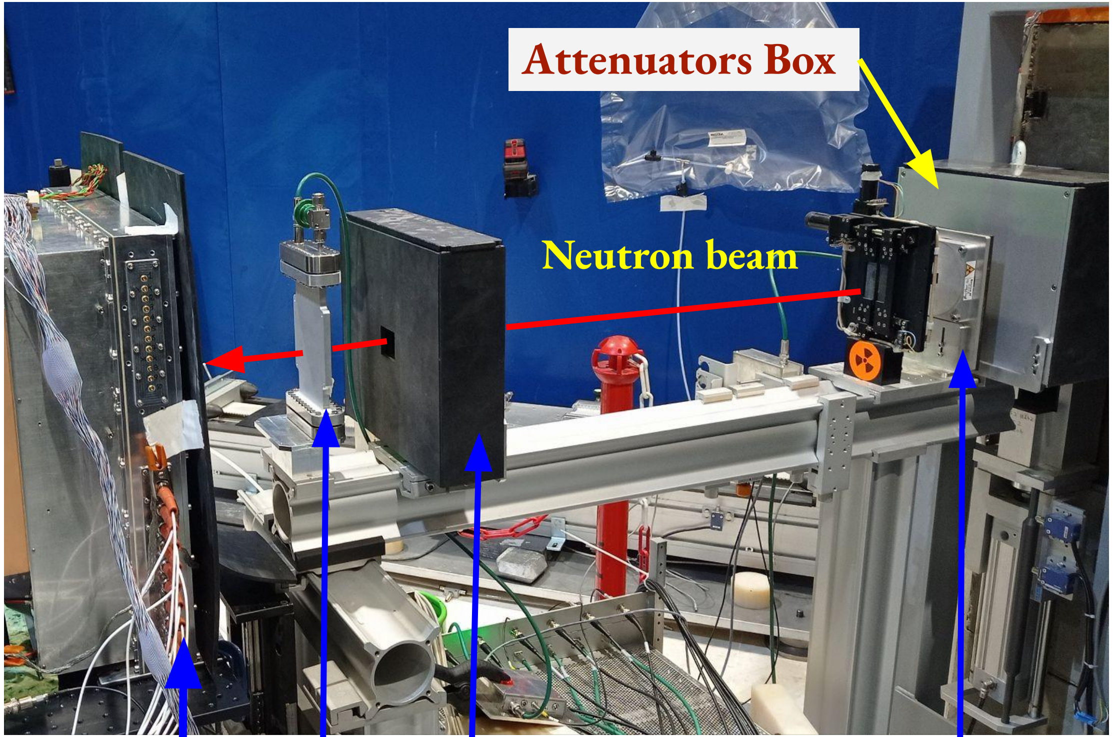


https://doi.org/10.48550/arXiv.2402.15630

Results are in good agreement with BOA spectrum

[Jacopo Valsecchi et. Al., NATURE COMMUNICATIONS https://doi.org/10.1038/s41467-019-11590-2]

Tests at CT2 neutron beamline (λn=2.5 Å) at ILL



Detector

Collimator (B_4C rubber)

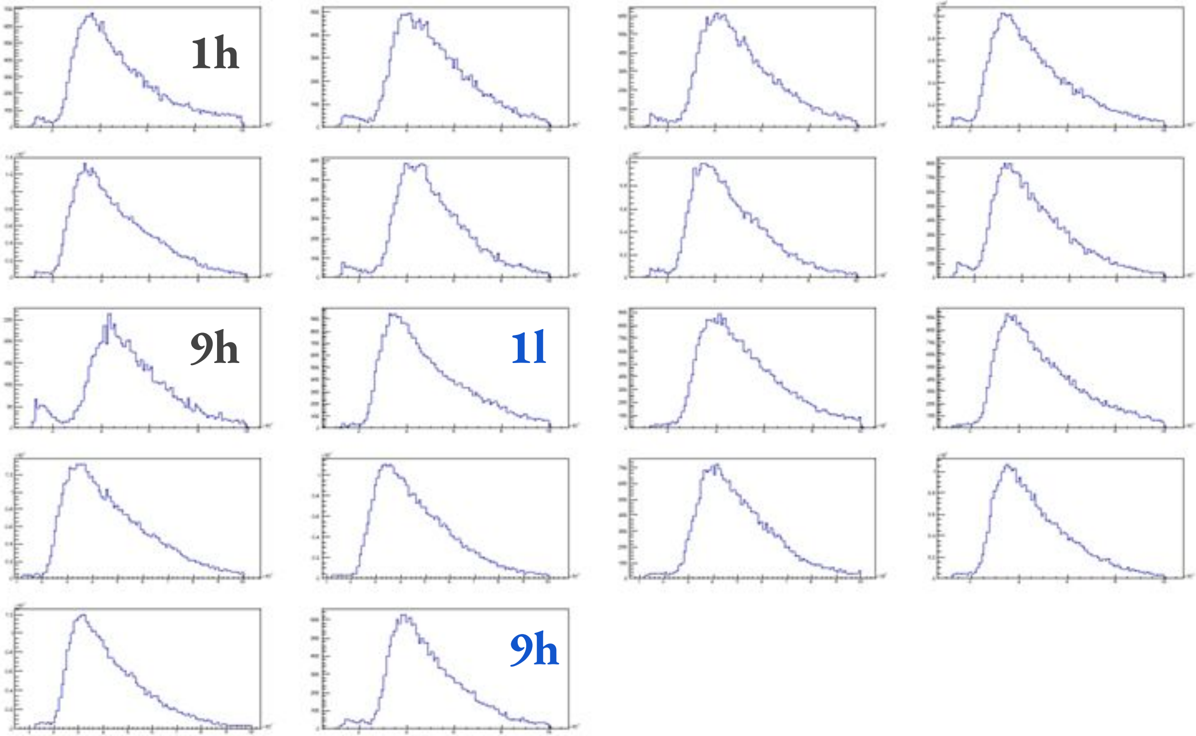
^{3}He-Multitube

Fission Chamber

Slit Collimator

Results: PHS of cathode signals

Flood dataset: HV=-2050 V; Att. Thickness: 4 x 2 mm + 1.8 mm



RPC gas gap Index

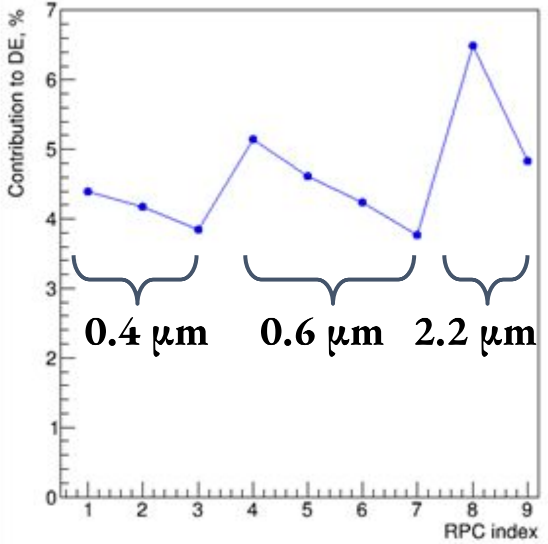
1h 2h 3h 4h
5h 6h 7h 8h
9h 1l 2l 3l
4l 5l 6l 7l
8l 9l

h: upper gas gap
l: lower gas gap

PHS are almost identical for all nRPCs gas gaps → Good uniformity of the gas-gap width

Results: Detection efficiency

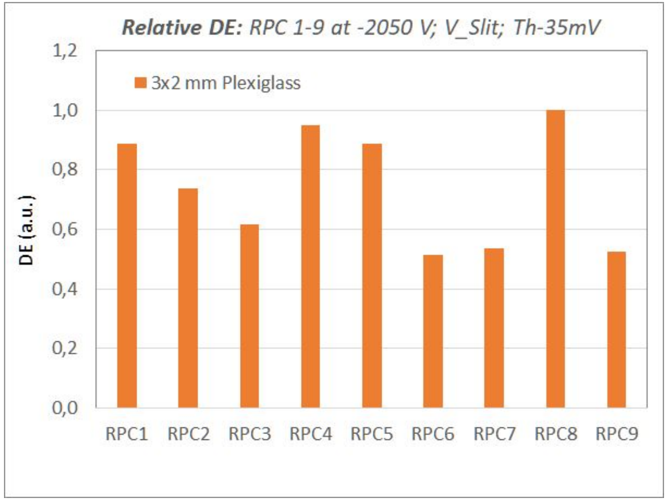
Simulation results
(GEANT4 /ANTS3)



Total Detection Efficiency (DE)

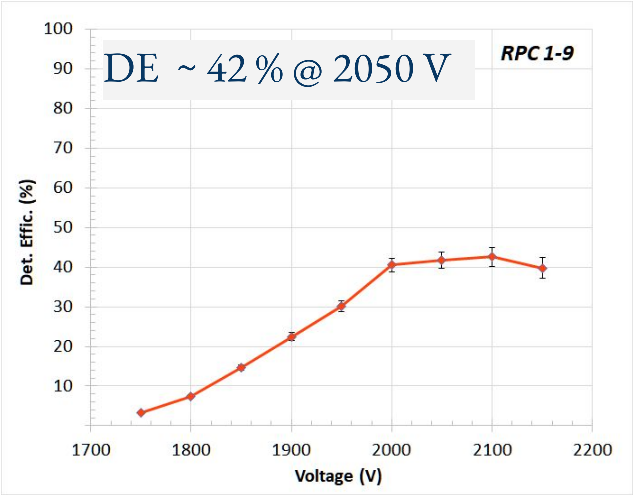
- 41.5% for λn=2.5 Å

Measured relative DEs



DEs follow the trend predicted by the simulation.

$^{10}B_4C$ layers thickness may differ slightly from the theoretical ones

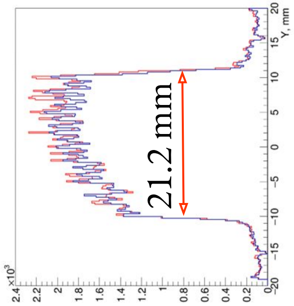


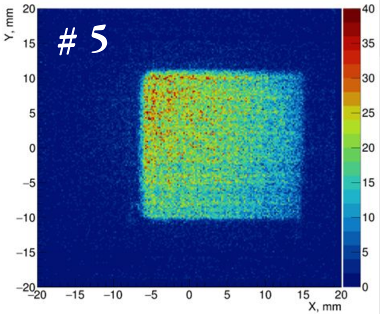
Plateau knee at lower voltage than for 0.35 mm gas gap nRPCs but shorter

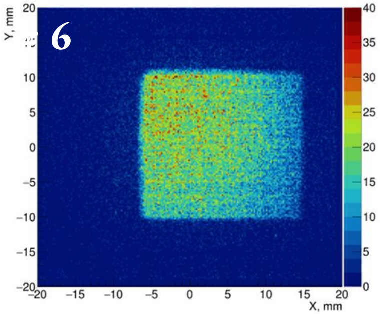
Results: Uniformity

Images recorded with the detector irradiated at different locations

- Beam collimation: 21 mm x 21 mm opening on a B_4C sheet
- RPC 1-9 at -2050 V

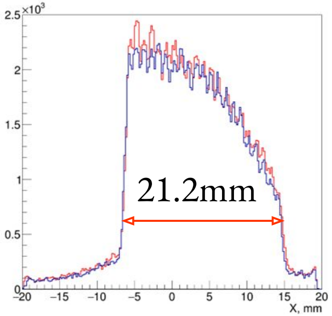






Y- Profiles

- #5 (red);
- #6 (blue)



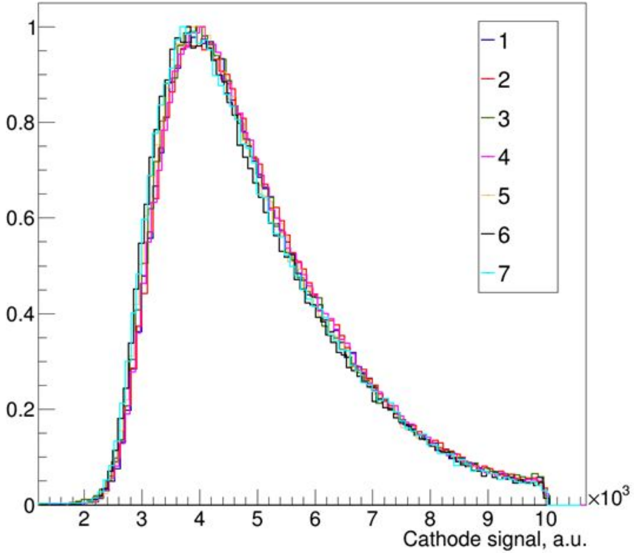
X- Profiles

Misalignment between the beam and the collimator opening is evident.

Almost the same response in both areas (profile overlap)

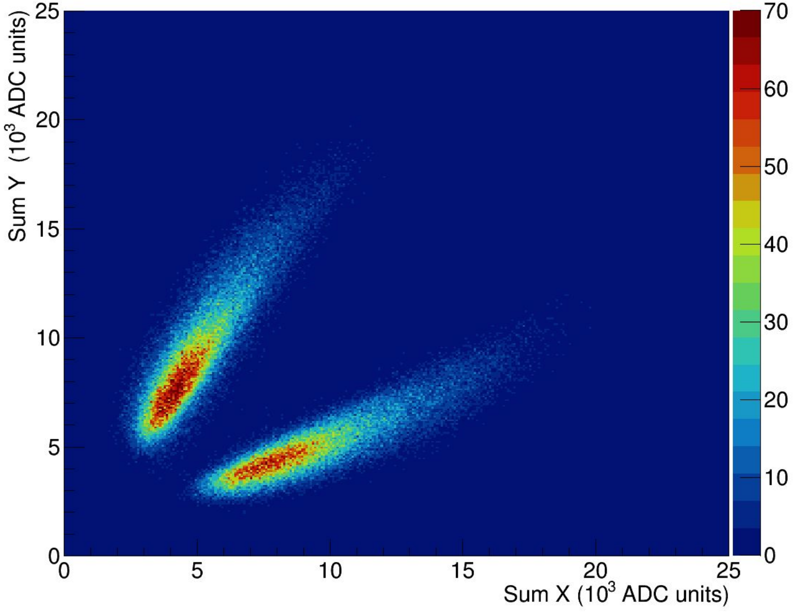
PHS (*all 9 RPC cathodes*)

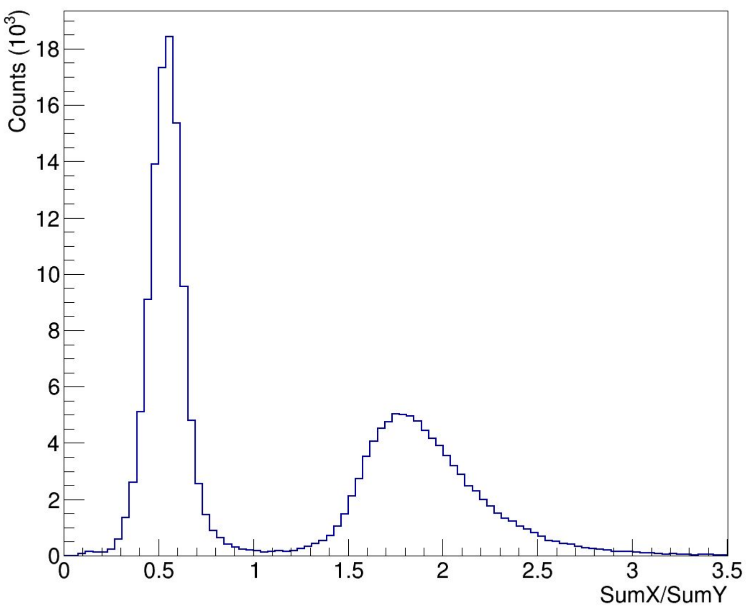
Detector irradiated in 7 different locations



Max. peak deviation from its average ~2%

Results: Z-coordinate - nRPC gas gap identification





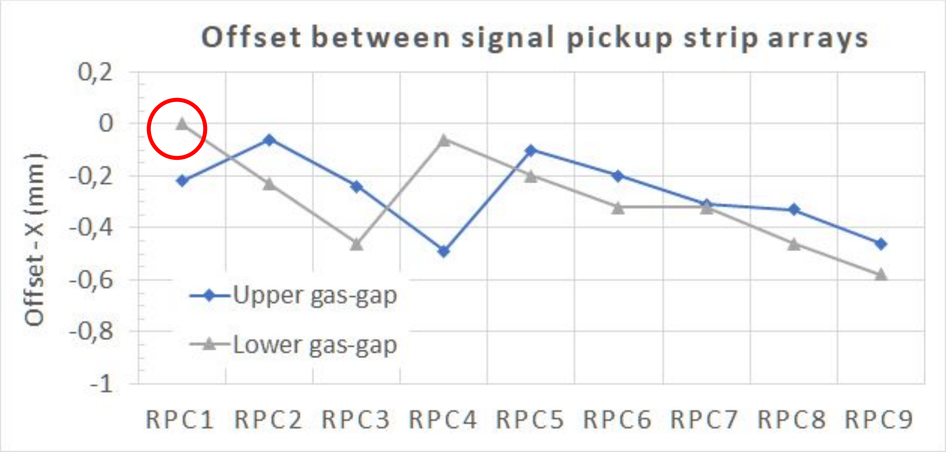
Identification of the $^{10}B_4C$ layer along the stack (Z-direction) **where neutron capture occurs**

Enables

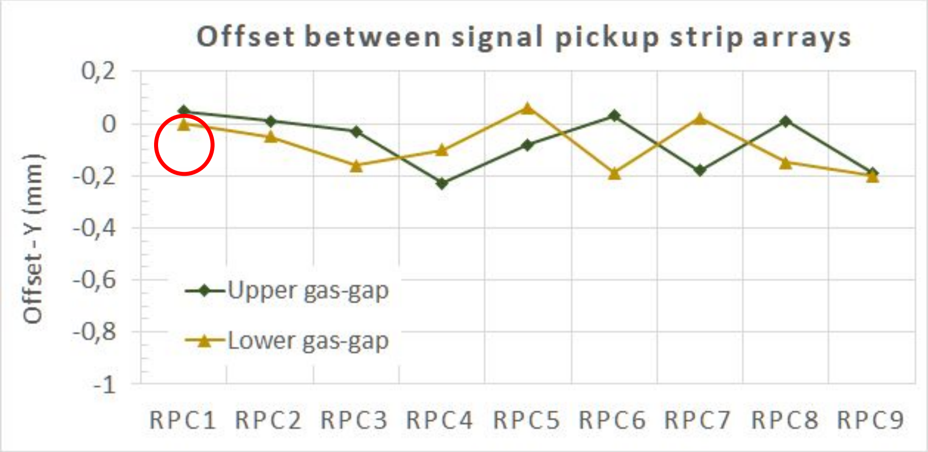
- **To correct the of offsets between the XY arrays of strips**
- **To suppress the uncertainty in time** caused by the neutron ToF through the Al cathode (~ 760 ns for λn = 10 Å)

Results: Offset between arrays of strips (thin-film PCBs)

X-coordinate



Y-coordinate

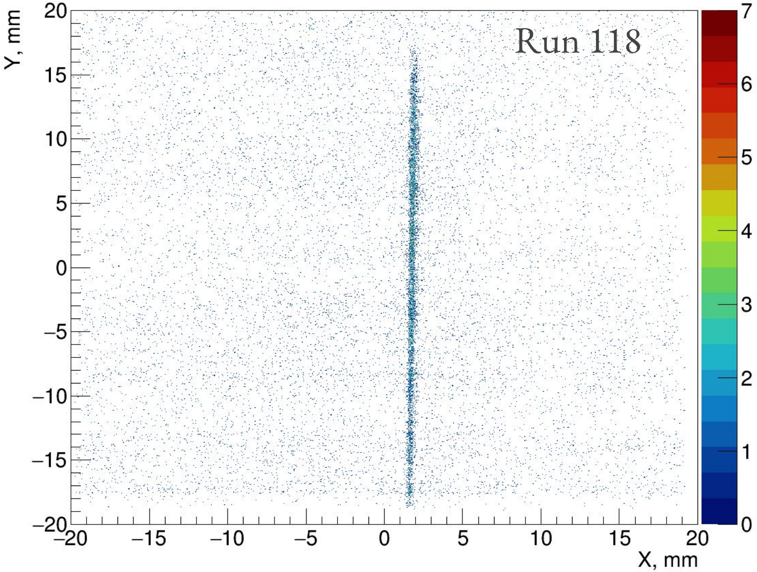


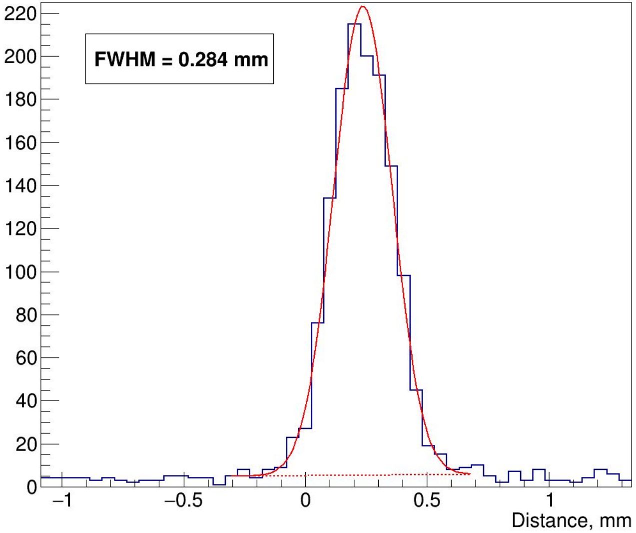
To determine the offset, the **x and y position** for the neutron events in the **lower gas gap of the nRPC1 was taken as a reference** (zero on the plots).

Results: Spatial resolution

- **Cd slit in contact with the detector window**
- Attenuators: 3 glass plates (2 mm thick each)
- RPC1-9 at HV= -2050 V; Th=35 mV
- Count rate ~ 19 kHz/cm^2

Spatial resolution performance as in the 1st small nRPC detector prototype: **FWHM < 0.3 mm**





Results: Spatial resolution

- Cd mask: 1 mm thick
- Letter grooves: 0.4 mm wide
- Diagonal groove: 0.3 mm wide

Excellent fidelity is observed in the reproduction of all Cd mask details

Images reconstructed for each individual $^{10}B_4C$ layer

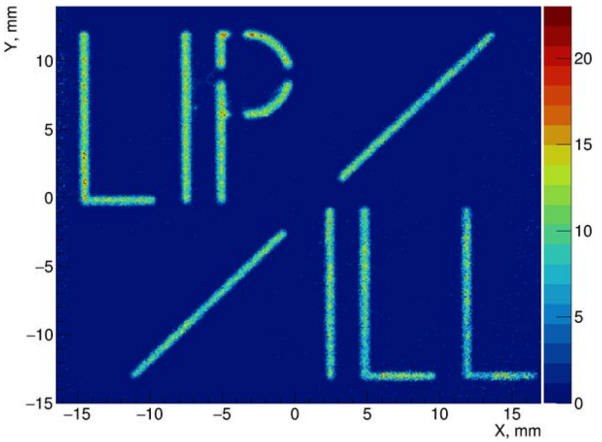
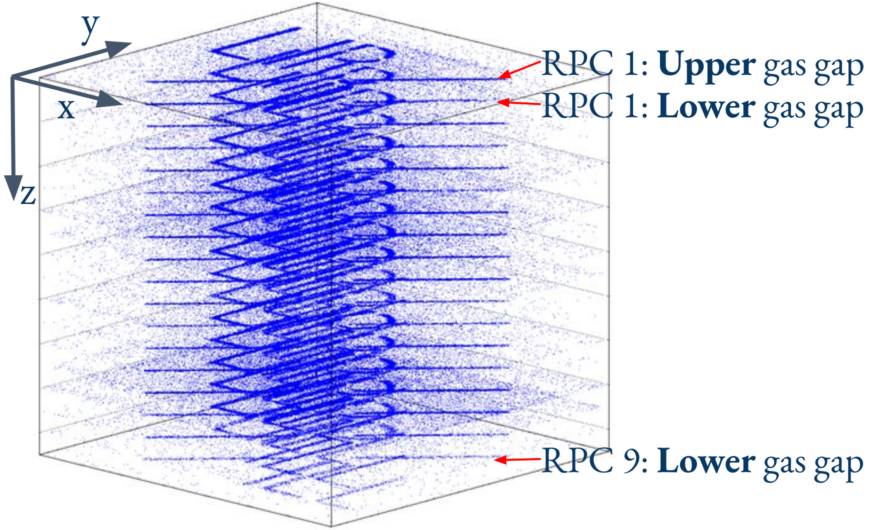
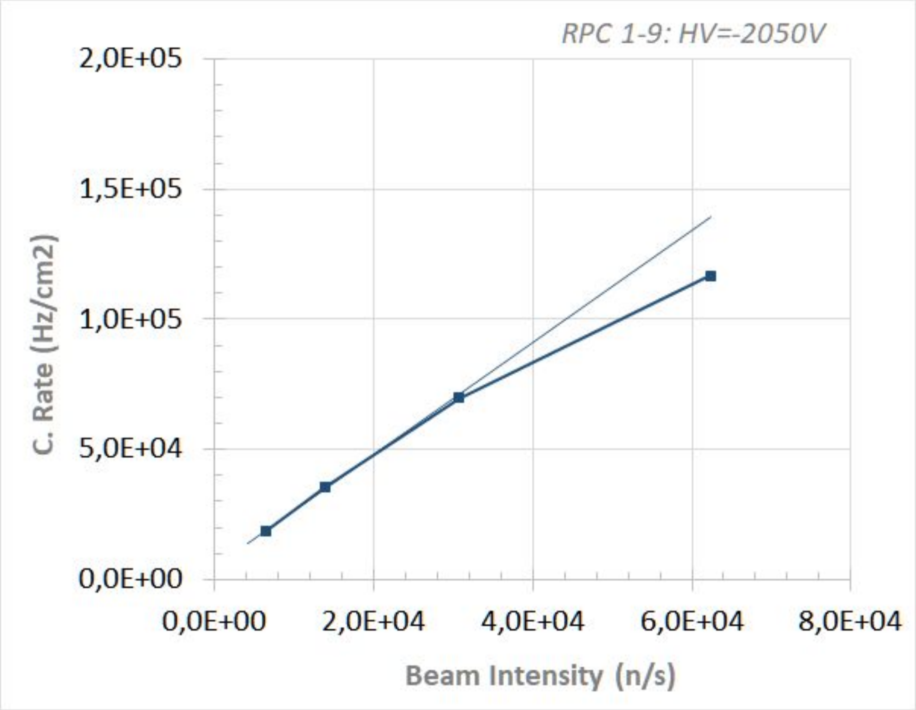


Image corrected for the offset in the position of the XY strip arrays



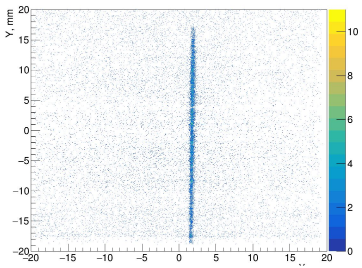
Results: Counting rate for nRPC 1 - 9 *(float glass)*

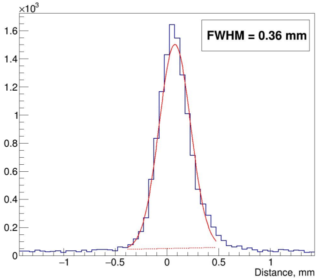
- 0.2 mm wide Cd slit (@BMonitor)
- RPC1-9: HV= -2050 V



Local counting rate is linear with beam intensity up to **~ 70 kHz/cm^2**
(~15% deviation @ ~120 kHz/cm^2)

Results: Counting rate for nRPC 1 - 9 *(float glass)*

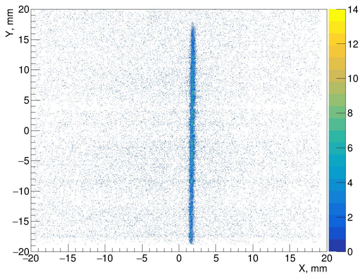


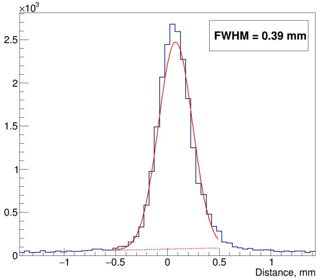


Attenuation: 3x2 mm

C. rate ~ 19 kHz/cm^2

FWHM ~0.36 mm

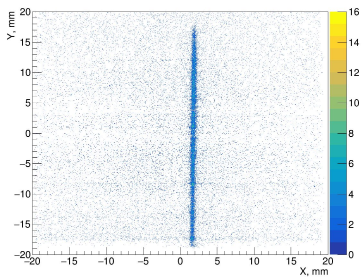


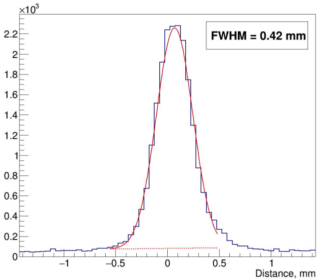


Attenuation: 2x2 mm

C. rate ~ 36 kHz/cm^2

FWHM ~ 0.39 mm





Attenuation: 1x2 mm

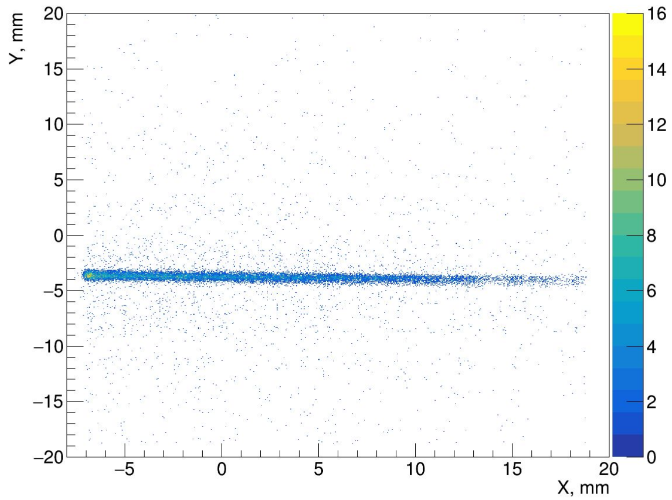
C. rate ~ 70 kHz/cm^2

FWHM ~ 0.42 mm

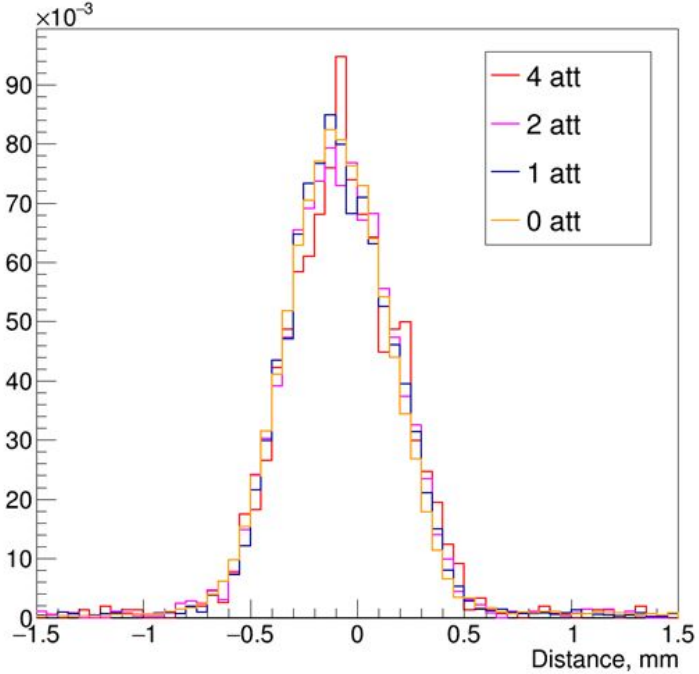
Results: Counting rate for nRPC 10 *(LR- glass)*

RPC10 ***(Low resistivity glass)***
(ρ ~ 1.5 x 10^9 Ω cm)

Measurement performed with a wider Cd slit: 0.5 mm



No significant change is observed in the profile of the slit image with the nº of attenuators in the beam



Integral of histograms normalized to unity

Summary

- Experimentally demonstrated the capability of nRPC-4D detector to determine both the 3D position of the neutron capture and the neutron time-of-flight.
- Detector active area was increased by a factor of 4 in relation to the 1st small prototype
  - Spatial resolution stays below 0.3 mm FWHM *(no impact of the detector scaling)*
- The total detection efficiency (~42 %, λn=2.5 Å) for the 9 nRPCs agrees well with the simulation prediction.
- Maximum counting rate of 70 kHz/cm^2 was achieved
- nRPC10 made from low resistivity glass is shown to sustain max. count rates >30 kHz/cm^2
  - Suggests that reaching counting rates of a few hundred kHz/cm^2 with a nRPC-4D detector may become realistic.

Acknowledgements

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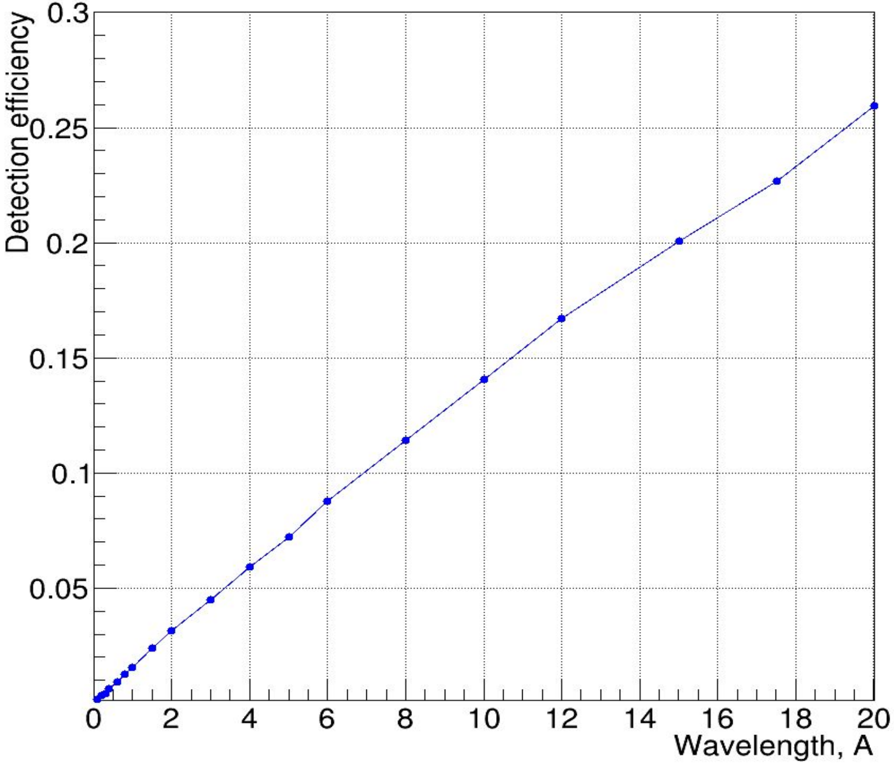
BkUp slide

Correction accounting to the DE dependence on neutron wavelength



margato@coimbra.lip.pt

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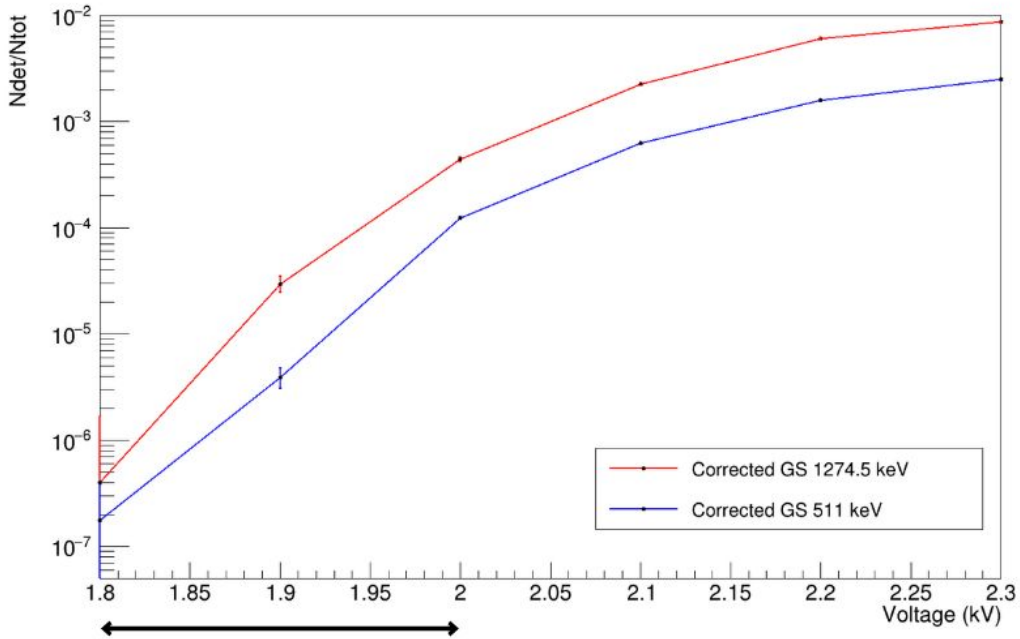
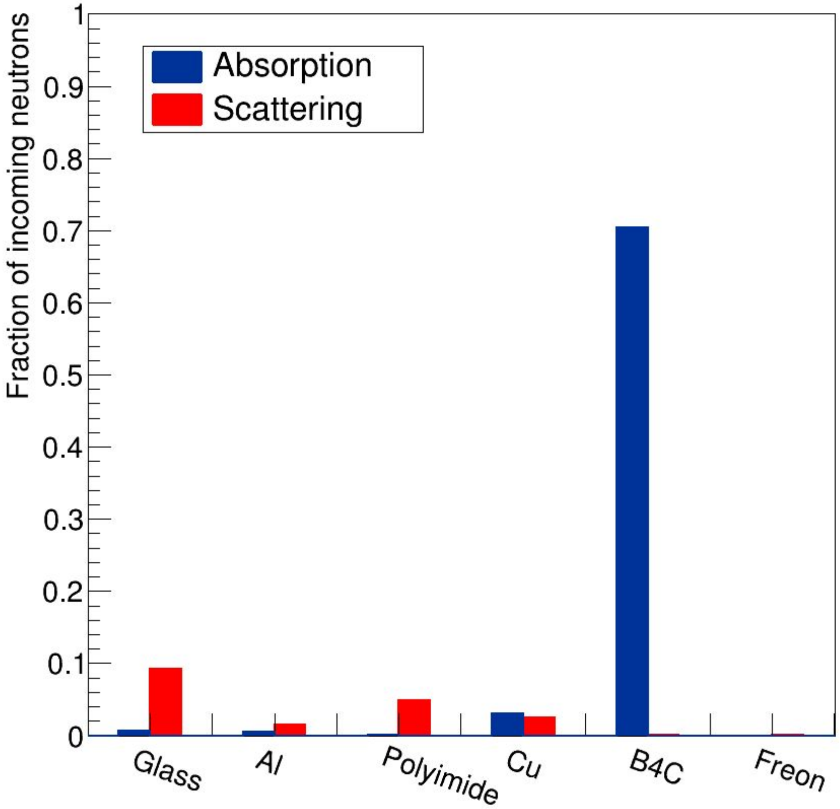
Average sensitivity per RPC to 511keV (blue) and 1274.5 keV (red) gamma rays



BkUp slide



margato@coimbra.lip.pt

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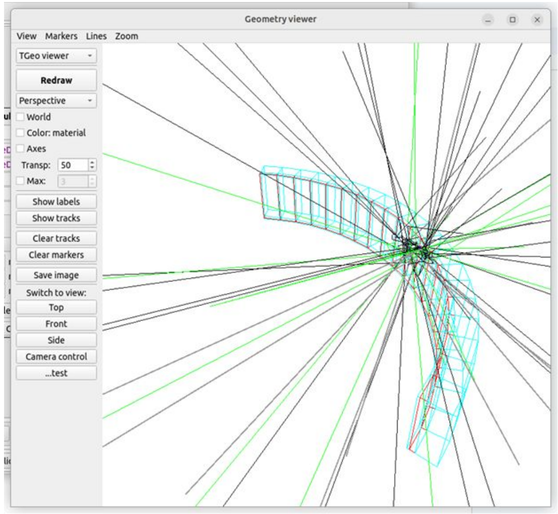
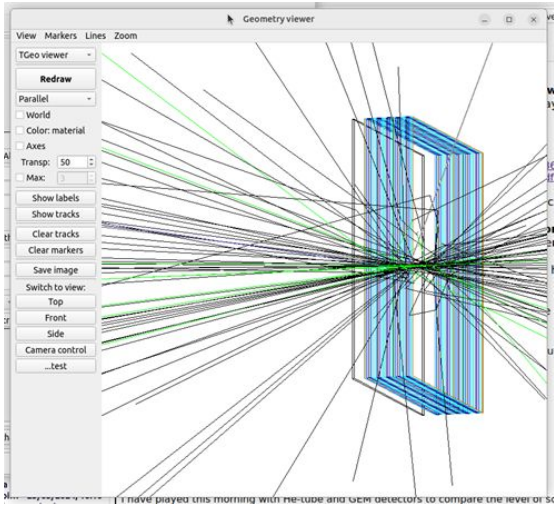
Curved detector - Model inspired by
https://doi.org/10.1051/epjconf/202328603010

- 120 deg arc, 2300 mm diameter, 350 mm height
- Entrance window (Al alloy 5083) : 10.2mm
- Gas gap (3He:2.4+ArCO2:4.6 at 7 bar): 26 mm
- **λn = 1.8 Å;**
- **total DE = 60.66%**
- **Not scattered: 50.01%;**
- **Scattered: 10.65%**
- **Indirect to direct fraction: 21%**

nRPC detector

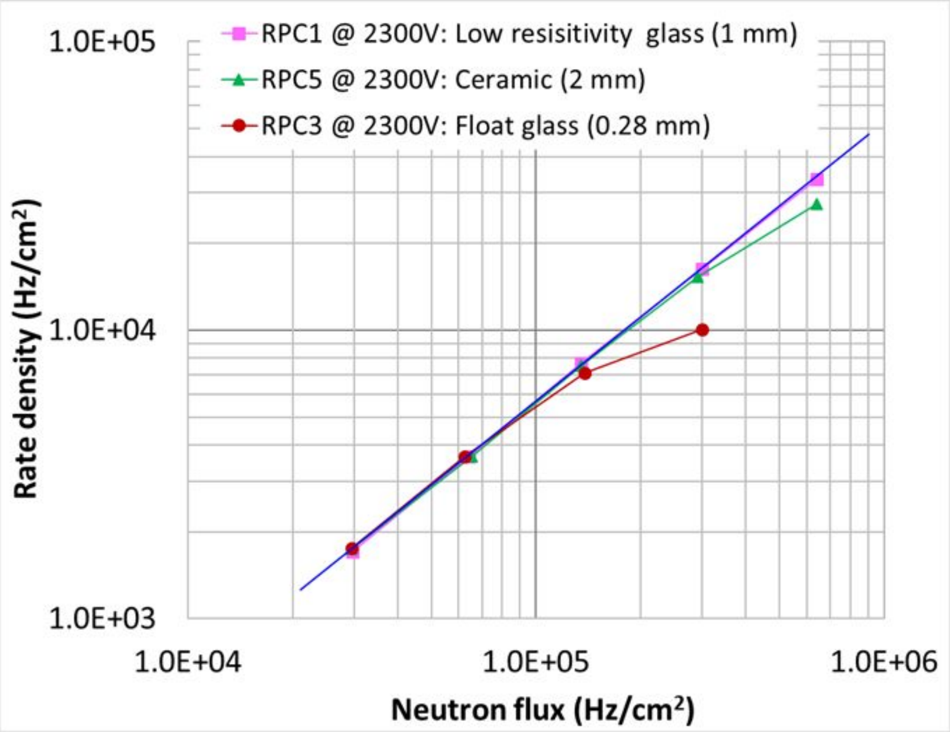
- 5 double gap RPCs (10 layers of B4C)
- 1.5 μm thick B4C layer
- **λn = 1.8 Å;**
- **total DE = 27.95%**
- **Not scattered: 25.42%; Scattered: 2.53%**
- **Indirect-to-direct fraction: 9.9%**





BkUp slide

nRPC with low resistivity electrodes



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Rate vs neutron flux (beam test at HZB)

$$V_{eff} = V_{ap} - IR = V_{ap} - \left(\frac{I}{A}\right)\rho l$$

V_{ap}: Applied voltage

V_{eff}: Effective voltage applied across the gap

I: Counting current drawn by the detector in area A

R: Electrical resistance seen by this current

P: DC bulk resistivity of the electrode resistive material

margato@coimbra.lip.pt