Neutron imaging with $^{10}\text{B}_4\text{C}$-lined thin-gap RPCs: 
*A multilayered architecture for high detection efficiency*

Luís Margato$^{(a)}$
A. Blanco$^{(a)}$, P. Fonte$^{(a,c)}$, R. Hall-Wilton$^{(e,g)}$, 
C. Höglund$^{(e,f)}$, L. Lopes$^{(a)}$, A. Morozov$^{(a,b)}$, L. Robinson$^{(e)}$, S. Schmidt$^{(e,h)}$, 
I. Stefanescu$^{(e)}$, K. Zeitelhack$^{(d)}$,

$^{(a)}$ LIP-Coimbra, Departamento de Física, Universidade de Coimbra (PT) 
$^{(b)}$ Departamento de Física, Universidade de Coimbra (PT) 
$^{(c)}$ ISEC - Instituto Superior de Engenharia de Coimbra (PT) 
$^{(d)}$ TUM - Heinz Maier-Leibnitz Zentrum (MLZ), FRM-II (DE) 
$^{(e)}$ ESS - European Spallation Source ERIC (ESS) (SE) 
$^{(f)}$ Thin Film Physics Division, Linköping University (SE) 
$^{(g)}$ Mid-Sweden University, SE-85170 Sundsvall, Sweden (SE) 
$^{(h)}$ IHI Ionbond AG, Industriestraße 211, CH-4600 Olten, Switzerland

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Motivation

PSNDs with cutting edge performance, based on He-3 alternatives, are a pressing need for “top level” instruments at ESS and other neutron Large Scale Facilities.

Main goal

Evaluate the potential of RPCs for high precision PSNDs.

Performance capability should be expressed in terms of expected spatial resolution, detection efficiency, counting rate and gamma sensitivity.

The work presented here is being developed in the framework of the SINE 2020 (Science & Innovation with Neutrons in Europe) collaboration - EU project No 654000.
Wider or thinner gas-gaps?

- Two RPCs were assembled: 0.35 and 1 mm gas-gap width

**RPC 1**
- Al (1 mm thick)
- 7Li
- Gas-gap (1 mm)
- Glass (0.35 mm thick)
- Signal pickup strips (2D Readout)

**RPC 2**
- Al (1 mm thick)
- $^{10}$B$_4$C (2 µm thick)
- Gas-gap (0.35 mm)
- Glass (0.35 mm thick)
- Signal pickup strips (2D Readout)

Metallic cathode $\Rightarrow$ 2D position encoding on the anode side
Detector configuration for the tests with neutrons

RPC 1

Al (1 mm thick)
Gas-gap (1 mm)
Glass (0.35 mm thick)
Glass (0.35 mm thick)
Gas-gap (0.35 mm)
Al (1 mm thick)

RPC 2

Signal pickup strips
2D Readout

Working gas: $\text{C}_2\text{H}_2\text{F}_4$ at atmospheric pressure

$^{10}\text{B}_4\text{C}$ coating made at ESS Detector Coatings Workshop

2 $\mu$m thick layer of $^{10}\text{B}_4\text{C}$ on Al plates (1 mm thick)
Efficiency measurement

- PCB: FR4, 0.4mm; Strips: Cu, 18 mm
- Vertical strips (X-coord.): 1.5 mm pitch, 1.3 mm width
- Horizontal strips (Y-coord.): 2.0 mm pitch, 0.5 mm width
- Area instrumented: 20 strips for both x, y (30 mm, 40 mm)

Position encoding

Each individual strip is readout by charge sensitive amplifiers

DAQ is based in the new TRB3 platform developed at GSI, Germany (http://trb.gsi.de/)

A Neiser et al 2013 JINST 8 C12043
doi: 10.1088/1748-0221/8/12/C12043

margato@coimbra.lip.pt, XIV Workshop on Resistive Plate Chambers and related detectors (RPC2018) – Puerto Vallarta, FEB. 17-23
Two RPCs were assembled inside an Al chamber:

- **RPC-1**: gas-gap width of 1 mm
- **RPC-2**: gas-gap width of 0.35 mm

Detector ready for the tests at TUM-FRMII

**RPC1** and **RPC2** stacked with the 2D-readout structure in the center

**SHV feedthroughs for the high voltage (HV)**

**Detector ready to be tested**
Detector at FRMII/ TREFF neutron beam line ($\lambda = 4.7$ Å)
Experimental results

Plateau

RPC-1 (gas-gap width: 1.0 mm)

RPC-2 (gas-gap width: 0.35 mm)

Wide HV plateau (> 500 V) for both RPCs
Experimental results

Detection efficiency

Detection Efficiency ($\lambda = 4.7 \, \text{Å}$) $\approx 12.5\%$

It is in good agreement with ANTS2 simulation

http://coimbra.lip.pt/ants/ants2.html

$^3$He-Proportional Counter was used as the reference detector
(Det. Efficiency of 97 % at 4.7 Å)
Experimental results

- **Spatial resolution** *(position calculation by COG)*

**RPC 2** seems to perform better than **RPC 1**

**Cd Mask** (1 mm thick)

**Letters:** line width of 0.4 mm

<table>
<thead>
<tr>
<th></th>
<th><strong>RPC 2</strong></th>
<th><strong>RPC 1</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>( \sigma_x )</td>
<td>( \sim 0.198 ) mm</td>
<td>( \sim 0.232 ) mm</td>
</tr>
<tr>
<td>( \sigma_y )</td>
<td>( \sim 0.233 ) mm</td>
<td>( \sim 0.273 ) mm</td>
</tr>
</tbody>
</table>
Experimental results

- **Spatial resolution**

Spatial resolution better than **0.24 mm FWHM** for both X and Y

- slit width of ≈ **0.2 mm**
- Detector shifted in **steps of 0.5 mm**

![Experimental setup with a CD slit and moving stage](image)

![Graph showing spatial resolution](image)
Towards high detection efficiency

Evaluation of a multilayer architecture: 10 Double-Gap RPCs

20 Layers of $^{10}$B$_4$C

Double gap RPC

Thickness $\approx 2.3$ mm

Glass (Anode) thickness = 0.5 mm
Gas-gap width = 0.35 mm
Aluminium Plate (Cathode) thickness = 0.5 mm
$^{10}$B$_4$C layer: Thickness $\sim 1.15$ $\mu$m
Resistive Ink: thickness = 0.04 mm
Towards high detection efficiency

Evaluation of a multilayer architecture: 10 *Double-Gap RPCs*

Electronic readout

![Diagram of multilayer architecture with RPC-1, RPC-2, RPC-10, and connections to DAQ, FPGA, DISC’s, and 10 x PA's](image)
Few details of prototype assembly (10 double-gap RPCs)

Thin Kapton PCBs with signal pickup strips for the 2D readout:
- X-coord.: Pitch = 1mm; strip width = 0.3 mm
- Y-coord.: Pitch = 1mm; strip width = 0.9 mm

Glass plate (outer side lined with a resistive layer) facing an AL plate (lined on both faces with a 1.15 µm thick layer of $^{10}\text{B}_4\text{C}$)

$^{10}\text{B}_4\text{C}$ coating made at ESS Detector Coatings Workshop
Detector prototype at FRMII/ TREFF neutron beamline

FEE – 2 x 48 channels (designed by P. Fonte and assembled at LIP)
DAQ is based on the new TRB3 platform developed at GSI, Germany (http://trb.gsi.de/)
Evaluation tests with neutrons ($\lambda = 4.7 \, \text{Å}$)

- **Spatial resolution**

  - FWHM (X – coord.) $\approx 0.25 \, \text{mm}$
  - FWHM (Y – coord.) $\approx 0.35 \, \text{mm}$

  ![Graph for Run204 (HV = -2.3 kV)](image)

  ![Graph for Run208 (HV = -2.3 kV)](image)

  - **Vertical Slit:** 0.075 mm x 35 mm
  - **Horizontal Slit:** 0.075 mm x 16 mm

  Obs.: Beam divergence $\sim 30 \, \mu\text{m}$
Evaluation tests with neutrons ($\lambda = 4.7 \, \text{Å}$)

- **Spatial resolution**
  - **(COG reconstruction:** strongest signal strip and 4 neighbouring strips)

  - **Vertical Slit**
  - **FWHM (X) ≈ 0.25 mm**
  
  The **systematic shift** suggests **non-normality** of the beam to the RPCs of $\approx 0.4^\circ$ (0.2 mm over 30 mm);
  
  The **misalignments** of the PCBs in the stack are about 0.05 mm.
Evaluation tests with neutrons ($\lambda = 4.7 \, \text{Å}$)

- Spatial resolution

There are both a systematic shift and random fluctuations in the profile positions.

**Horizontal Slit**

\[
\text{FWHM (Y)} \approx 0.35 \, \text{mm}
\]

**Evaluation tests with neutrons**

- **Horizontal Slit**
  - FWHM (Y) ≈ 0.35 mm

There are both a systematic shift and random fluctuations in the profile positions.
Evaluation tests with neutrons (\(\lambda = 4.7 \, \text{Å}\))

It seems that the spatial resolution is not get worse going deep in the stack.

Vertical Slit

![Graphs showing spatial resolution comparison between RPC-1 and RPC-9.](image-url)
Evaluation tests with neutrons ($\lambda = 4.7 \, \text{Å}$)

Detection Efficiency

$^3\text{He}$-Proportional Counter was used as the reference (efficiency of 97% at 4.73 Å)

A correction factor was applied using a Signal to BKG ratio extracted from the reconstructed events

The counting rate was given by the trigger of each individual cathode: C1, C2, C3, ..., C10

Cathode area = 90 x 90 mm
Readout area = 43 x 43 mm
Evaluation tests with neutrons ($\lambda = 4.7$ Å)

Detection Efficiency

Efficiency computed by ANTS2
- 10 Double-Gap RPCs
- all $^{10}\text{B}_4\text{C}$ layers with the same thickness (1.15 $\mu$m)

<table>
<thead>
<tr>
<th>$\lambda$ (Å)</th>
<th>0 KeV</th>
<th>50 KeV</th>
<th>100 KeV</th>
<th>150 KeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.7</td>
<td>65.5</td>
<td>62.1</td>
<td>58.5</td>
<td>54.6</td>
</tr>
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ANTS2: [http://coimbra.lip.pt/ants/ants2.html](http://coimbra.lip.pt/ants/ants2.html)
Conditional optimization of $^{10}\text{B}_4\text{C}$ converter layer thicknesses in ANTS2

- Equalize as much as possible the detection efficiency for all double-gap RPCs, keeping total efficiency as high as possible
- Practical constrain: only 5 different converter layer thickness

All layers have thickness of 1.15 µm: optimized for max total efficiency.

Conditional optimization: Converter thickness of 0.34, 0.39, 0.47, 0.74 and 1.94 µm.
Conclusions

- Tests of B-10 lined thin-gap RPCs with thermal neutrons demonstrated spatial resolution well below 1mm FWHM;

- A first prototype comprising a stack of 10 double-gap RPCs tested at FRMII/TREFF neutron beamline showed:
  - The capability of RPCs in a multilayer architecture to reach efficiency higher than 50%;
  - The spatial resolution (<0.25 mm FWHM) is not worse than that measured for single-gap RPCs in similar conditions;

- Optimization of the thicknesses of $^{10}\text{B}_4\text{C}$ layers allows to approach equal counting rate for all RPCs without a significant reduction in the detection efficiency;

- Future: characterization of the gamma sensitivity, counting rate and stability have to be performed.
Thank you for your attention
Backup Slides
Experimental results

- Pulse Height Spectra (RPC-2, 0.35 mm gap width): Cathodes
Strip signals (-x)
**PHS - Charge (strips-X and strips-Y)**

![Graph showing PHS charge for strips-X and strips-Y](image)
Multiplicities

Multiplicity on the strips

Multiplicity on the cathodes

#Events = 90359
Triggers on cathodes

![Graph showing triggers on cathodes with RPC#1 and RPC#10](image)
Run204 ($HV = -2.3 \, kV$)

Run208 ($HV = -2.3 \, kV$)
Vertical Slit

Cathode 1

Cathode 2

Cathode 9

X (mm)
ANTS2 Simulations: [http://coimbra.lip.pt/ants/ants2.html](http://coimbra.lip.pt/ants/ants2.html)

ANTSv4.1 vs Geant4 (Geant4 version 4.9.6.p02, QGSP_BIC_HP physics list / includes the G4NeutronHP model.)

Case 1: Aluminium cube of 10 x 10 x 10 mm³

Mono-energetic (25.3 meV) neutrons enter the cube through the centre of the "In" face (normal direction).

The neutrons exiting the cube are monitored and the collected statistics obtained in simulations using Geant4 and ANTS2 is the following:

**Energy distributions of the neutrons exiting the cube faces** (non-interacted neutrons are suppressed):

![Energy distributions](https://via.placeholder.com/150)

Total elastic cross section (N,EL) from **ENDF/B-VII.1** database;

For missing data **JEFF-3.2** and **JENDL-4.0u2** databases were used.
ANTS2 Simulations: [http://coimbra.lip.pt/ants/ants2.html](http://coimbra.lip.pt/ants/ants2.html)

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**Distribution of the angles of exiting neutrons:**

![Graphs showing distribution of angles for In, Side, and Out](image-url)
ANTS2 Simulations

Ranges for the $^4$He and $^7$Li particles in the gas-gap

Distributions for the length of the Ranges (in the gas-gap) projected in the direction parallel to the plane of the electrodes

$^{10}$B$_4$C thickness = 2 μm; $\lambda$ = 4.7 Å; C2H2F4 @ 1 atm
ANTS2 Simulations

Energy loss in the gas-gap

Deposited energy in the gas-gap for the $^4\text{He}$ and $^7\text{Li}$ fissions fragments

$^{10}\text{B}_4\text{C}$ thickness = 2 $\mu$m; $\lambda = 4.7$ Å; C2H2F4 @ 1 atm
\[ n + ^{10}\text{B} \rightarrow (^{11}\text{B})^* \]

\[ ^7\text{Li}^* (0.84 \text{ MeV}) + ^4\text{He} (1.47 \text{ MeV}) \quad Q = 2.31 \text{ MeV (94 \%)} \]

\[ ^7\text{Li} (1.02 \text{ MeV}) + ^4\text{He} (1.78 \text{ MeV}) \quad Q = 2.79 \text{ MeV (6 \%)} \]