Very high position resolution gamma imaging with Resistive Plate Chambers

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Summary

Very high position resolution gamma imaging with Resistive Plate Chambers

• What is and how Positron Emission Tomography (PET) works. Small Animal PET
• The Resistive Plate Chamber (RPC) Technology
• The basic idea
• The first prototype
• The first results. Experimental spatial resolution and simulated performance
• Conclusions
What is and How PET works

Positron Emission Tomography (PET) is a radiotracer imaging technique, in which tracer compounds labeled with positron emitting radionuclides are injected into the subject of the study. These tracers compounds can then be used to track biomedical and physiological processes.

Unstable parent nucleus

Proton decays to neutron in nucleus

Positron and neutrino emitted

Two anti-parallel 511 keV photons produced

Positron combines with electron and annihilates

Resulting image shows the tracer distribution throughout the object of the study.

Use of standard tomography techniques

Electronic Coincidence
The small animal PET

- Scintillator based technology (BGO, LSO, YAP, …), MWPC.
- Ring diameter / length \( \sim 160 \text{ mm} / 50 \text{ mm} \)
- **Spatial resolution** \( \sim 1 - 2 \text{ mm FWHM} \)
- **Central Point absolute sensitivity** \( \sim 5 - 33 \text{ cps/KBq} \)

- Applications:
  Development of new drugs, human disease studies, validation of Gene therapies, …
The RPC detector

Main features

- **Timing resolution** ~ 50 ps $\sigma$.
- **Efficiency 75% 300 $\mu$m Gap**
- No energy resolution.
- Possibility of measure the position.

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The basic idea for a small animal PET with RPCs

The detection

Use the plates as a \( \gamma \) conversor, taking advantage of the natural construction of the RPCs.

A previous work

The basic idea for a small animal PET with RPCs

The detection
The basic idea for a small animal PET with RPCs

The detection

- Stacked RPCs

The scanner

- Modules of n-stacked RPCs.
- **High geometry acceptance** > 90%.
- Fully 3D measurement of the interaction point of the photon => **No parallax error**.
- **Sub-millimetre spatial resolution.**
- **High timing resolution** ~ 0.3 ns FWHM*
- Moderate Efficiency.
- **Compatibility** with Magnetic Resonance Imaging.

* *Nucl. Instr. And Meth A, 443 (2003) 88-93*
Geant4 simulations

Simulation of 2 head scanner

All processes were simulated including positron range and photon non-colinearity.

Spatial resolution of 515 \( \mu \text{m} \) FWHM \(^{18}\text{F}\).

Moderate detecting efficiency per head \( \sim 10\%-15\% \).

Efficiency Vs nº stacked RPCs

70 RPCs \( \Rightarrow 15\% \)

40 RPCs \( \Rightarrow 10\% \)
The first prototype

Aimed to **verify** the concept and the **viability** of the **sub-millimetre spatial resolution**.

- 2 heads with 16-stacked RPCs
  (number of stacked counters and mechanical construction not optimized for high efficiency).
- 2D measurement of the interaction point of the photon.
- Time resolution not optimized.
RPCs

- Copper (on a PCB) and glass electrodes.
- 32 1-mm wide X pickup strips.
- 0.3 mm Gap.
- Not optimized for high efficiency.

Glass electrode (anode)  Copper electrode (cathode)

Active area 32 x 10 mm$^2$

0.3 mm spacers
RPCs

16 stacked RPCs.

Charge sensitive electronic allowing interstrip position interpolation

Depth of interaction

Transaxial

x

z

High voltage distribution

32 strips

16 plates

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Scanner
**Intrinsic spatial resolution**

Red lines correspond to real data acquired with the $^{22}$Na source

$LOR = \text{Line of Response. Connects the interaction points of the photons.}$

$D = \text{Distance between each LOR and the center of the system}$
Intrinsic spatial resolution

Point spread function

Beaune05 4th International Conference on new Developments in Photodetection. June 19-24, 2005

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Intrinsic spatial resolution

![Graph showing probability distribution against D (mm)]

- **Annihilation photon non-collinearity.**
  \[ N(x) = \exp\left(-\frac{x^2}{2\sigma^2}\right), \text{ where } \text{FWHM} = 2.35\sigma = 0.0022d_s \text{ with } d_s \text{ the system diameter (mm)}. \]

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*J. Nucl. Med. 34 101 1993.*
Intrinsic spatial resolution

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- **Positron range.**

  \[ P(x) = C_1\exp(-k_1x) + (1-C_1)\exp(-k_2x) \]

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*IEEE TNS*, vol 33, No 1, (1986), 565-569
Intrinsic spatial resolution

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- **Positron range.**
  \[P(x) = C_1\exp(-k_1x) + (1-C_1)\exp(-k_2x)\]
- **Source size.**
  \[S(x)=\sqrt{\text{size}^2 - x^2}, \text{ where } \text{size} \text{ is the source radio (mm)}.\]
Intrinsic spatial resolution

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  \[ P(x) = C_j\exp(-k_1x) + (1-C_j)\exp(-k_2x) \]

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  \[ D(x) = \exp(-x^2/2\sigma_{det}^2) \]
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- **Scatter background.**
  \[ SC(x) = \exp(-k_3x) \]
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\[ R(x) = C2 (N(X) \otimes P(X) \otimes D(X) \otimes S(X)) + (1-C2)SC(X) \]

**520 \(\mu\)m FWHM**

**1550 \(\mu\)m FWTM**
**Intrinsic spatial resolution**

- **Annihilation photon non-collinearity.**
  
  \[ N(x) = \exp(-x^2/2\sigma^2) \]
  
  where \( \sigma = 0.0022 \sigma_s \) with \( \sigma_s \) the system diameter (mm).

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  \[ R(x) = C_2 N(X) \otimes P(X) \otimes D(X) \otimes S(X) + (1-C_2) SC(X) \]

**Intrinsic spatial resolution**

- Calculated
- Experimental

- **520 µm FWHM**
- **1550 µm FWTM**


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Intrinsic spatial resolution

\[\text{Probability} = \exp\left(-\frac{x^2}{2\sigma^2}\right)\]

where \(\sigma = 0.0022 \text{ds}\) with \(\text{ds}\) the system diameter (mm).

- Annihilation photon non-collinearity.
- Positron range.
- Source size.
- Detector response.
- Scatter background.

\[\text{Intrinsic spatial resolution } K_2 = 3.75 \text{ mm}^{-1}\]
\[\text{FWHM}_{\text{det}} = 220 \mu\text{m}\]
\[C_2 = 0.04, K_3 = 0.32 \text{ mm}^{-1}\]

Homogeneous spatial resolution over the entire detector
**Intrinsic spatial resolution: Limits**

Spatial resolution calculated as: $R = C2^\times(N \times P \times D \times S) + (1-C2)^\times SC$

**Actual**

Diameter system 60 mm

- **RPC-PET this measurement**
- **RPC-PET point source $^{18}$F**
- **Physical limit $^{18}$F**
- **Physical limit $^{22}$Na**

$E_{max}^{22}$Na = 0.56 MeV

$E_{max}^{18}$F = 0.64 MeV

- **RPC-PET $^{18}$F => 520 µm**
- **Physical limit $^{18}$F => 350 µm**

positron range + non-collinearity
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**Image spatial resolution**

Filtered Back Projection (FBP)

510 µm FWHM 1050 µm FWTM

Maximum likelihood-expectation maximization with resolution modeling (ML-EM)

310 µm FWHM 810 µm FWTM

*Proceeding IEEE MIC (2004) M2-177*
Simulated count rate performance

Evaluation of the count rate performance Prompts, Randoms, and NECR

Mouse size phantom:
25 Ø x 70 mm (34 cm³)

Annihilations and photons on the detector surface from the simulation.

Characteristic of the simulated system:

• **90% Solid angle coverage** => defining a FOV of 60 Ø x 100 mm axial.
• Narrow **coincidence window 1 ns. (Timing resolution 300 ps FWHM)**
• **Dead time ~ 100 ns.**
• **10% - 15% detection efficiency.**
Simulated count rate performance

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Mouse size phantom:
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Simulated count rate performance

- Activity (MBq) vs. Prompts (kcps)
- 1000 Kcps
- 500 Kcps

Typical injected doses for mouse studies (3.7 MBq – 37 MBq)

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Simulated count rate performance

The high timing resolution keeps the random events at a low values

Typical injected doses for mouse studies (3.7 MBq – 37 MBq)
Simulated count rate performance

- The number of true coincidences that would create an image of similar quality in the absence of noise (scattered and random coincidences).

Typical injected doses for mouse studies (3.7 MBq – 37 MBq)
### Performance

**Comparison between different small animal PET parameters and the expected parameters of the RPC-PET.**

<table>
<thead>
<tr>
<th>Scanner</th>
<th>Image spatial resolution, FBP (mm)</th>
<th>Time resolution (ns FWHM)</th>
<th>FOV (mm Ø x mm)</th>
<th>Central point absolute sensitivity (cps/kBq)</th>
<th>Source (mm Ø x mm)</th>
<th>Peak NEC (Kcps)</th>
</tr>
</thead>
<tbody>
<tr>
<td>microPET II(^\text{®}) [1],[2]</td>
<td>1.1</td>
<td>3</td>
<td>160 x 49</td>
<td>23 - 33</td>
<td>25 x 70 mouse size</td>
<td>235</td>
</tr>
<tr>
<td>microPET Focus F120 [6]</td>
<td>1.75</td>
<td>6</td>
<td>147 x 76</td>
<td>71</td>
<td>mouse size</td>
<td>809</td>
</tr>
<tr>
<td>YAP-PET [3],[4]</td>
<td>1.6</td>
<td>2</td>
<td>40 x 40</td>
<td>18 at (Ø = 150 mm)</td>
<td>-</td>
<td>90</td>
</tr>
<tr>
<td>Quad HIDAC (32 modules) [5]</td>
<td>0.95</td>
<td>-</td>
<td>170 x 280</td>
<td>18</td>
<td>-</td>
<td>100</td>
</tr>
<tr>
<td>RPC-PET</td>
<td>0.51</td>
<td>0.3</td>
<td>60 x 100</td>
<td>21</td>
<td>25 x 70 mouse size</td>
<td>318</td>
</tr>
</tbody>
</table>

Conclusions

• First results concerning the spatial resolution of an RPC-PET prototype have been presented.

• Spatial resolution of 510 µm FWHM with a intrinsic detector resolution of 220 µm FWHM homogeneous over the entire detector have been measured.

• Measured image spatial resolution of 310 µm FWHM using a ML-EM algorithm.

• A simulated peak NECR of 318 Kcps have been obtained for a optimized system dedicated to small animal PET.