Comparison of Prompt-gamma and Positron imaging for hadron-therapy monitoring


Instituto de Fisica Corpuscular, IFIC (CSIC- UVEG), Valencia, Spain

ICTR-PHE 2012, Geneva
ENVISION Project

- European NoVel Imaging Systems for ION therapy

On-line dose monitoring by developing novel imaging modalities related to dose deposition that allow to assess the treated volume during hadrontherapy.

Scintillators crystals (LaBr3) to build a Compton Camera to image the "prompt gamma“ generated in the first nanoseconds.

TOF in-beam PET (crystal- and RPC-based) to reconstruct the positron distribution generated by the hadron beam.
PET for HT monitoring

Nowadays, PET is the only feasible and clinically used method. Challenges:
- Wash-out processes
- Low positron yield
- Partial ring geometry (*)

(*)only for in-beam

Time Of Flight (TOF)

Crystal-based vs. Resistive-Plate-Chamber

- Scintillating crystals and photon sensor.
- Standard technology for clinical PET.
- Gas detector

Advantages:
- Excellent timing resolution
- Inexpensive construction in large areas.
- Depth of interaction information (layered structure)

In-beam, in-room

I. Torres
29th Feb.
ICTR-PHE 2012
Prompt-\(\gamma\) for HT monitoring

Novel method of in-vivo dosimetry based on the detection of the prompt-gamma produced after the therapeutic beam → not affected by the wash-out processes

Detection technique: **Compton Camera**

\[ \cos \theta = 1 + m_e c^2 \left[ \frac{1}{E_0} - \frac{1}{E_0 - E_1} \right] \]

- The \(\gamma\) must have a trajectory along a cone surface, described by the axis \(\beta\) and the half angle \(\theta\)
- The energy of the incident gamma \(E_0\), and the location of the second event must be measured
- The resultant cone-surface has width implied by measurement uncertainty (and Doppler broadening)

**Initial energy, \(E_0\)**
- Estimated (it might be assumed that the second interaction is photoelectric), or
- Measured (the measurement of three or more photon interactions)
Simulations of the hadron beam with Geant4

**Output:**
- Positron distribution produced within the PMMA phantom.
- Prompt-gamma generated in the phantom.

**Physics packages:** QGSP_BIC_HP for hadronic model and standard for electromagnetic model

**Proton beam** ($5 \times 10^7$)

<table>
<thead>
<tr>
<th>E (MeV)</th>
<th>R (cm)</th>
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</thead>
<tbody>
<tr>
<td>156</td>
<td>14.6</td>
</tr>
<tr>
<td>158</td>
<td>14.9</td>
</tr>
<tr>
<td>160</td>
<td>15.2</td>
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<tr>
<td>162</td>
<td>15.5</td>
</tr>
<tr>
<td>164</td>
<td>15.8</td>
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</table>

**e^+ 30 min**

<table>
<thead>
<tr>
<th>Proton-γ</th>
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<tbody>
<tr>
<td>$2.2 \times 10^6$</td>
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<td>$2.3 \times 10^6$</td>
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<tr>
<td>$2.3 \times 10^6$</td>
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<td>$2.4 \times 10^6$</td>
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**Carbon-ions beam** ($4 \times 10^6$)

<table>
<thead>
<tr>
<th>E (MeV/A)</th>
<th>R (cm)</th>
<th>e^+ 30 min</th>
<th>Prompt-γ</th>
</tr>
</thead>
<tbody>
<tr>
<td>298</td>
<td>14.6</td>
<td>$8.6 \times 10^5$</td>
<td>1.17$ \times 10^7$</td>
</tr>
<tr>
<td>301.5</td>
<td>14.9</td>
<td>$8.7 \times 10^5$</td>
<td>1.18$ \times 10^7$</td>
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<tr>
<td>305.2</td>
<td>15.2</td>
<td>$8.8 \times 10^5$</td>
<td>1.22$ \times 10^7$</td>
</tr>
<tr>
<td>308.9</td>
<td>15.5</td>
<td>$9.0 \times 10^5$</td>
<td>1.31$ \times 10^7$</td>
</tr>
<tr>
<td>312.5</td>
<td>15.8</td>
<td>$9.1 \times 10^5$</td>
<td>1.35$ \times 10^7$</td>
</tr>
</tbody>
</table>
Simulations of the detectors using Geant 4 and GATE

CRYSTAL-BASED PET (Gemini)

28 Heads  20 Heads  16 Heads

TOF FWHM: 200, 400, 600 ps

RPC PET

Complete and 14-Heads RPC system

TOF FWHM: 20, 50, 100 ps

Spatial Resolution: $\sigma_x = 3.9$ (module); $\sigma_y = 2$ mm; $\sigma_z = 4$ mm (Data provided by D.Watts & F.Sauli)

COMPTON CAMERA

LaBr$_3$ Compton Camera (6 layers)

PMMA

Geometry courtesy of F. Diblen, UGhent

For more details about the Compton Camera see poster 221 „Silicon Photomultipliers in PET and Hadron therapy applications“ (G. Llosá)
Image Reconstruction

**PET data**

**TOF-MLEM**: Maximum-Likelihood Expectation-Maximization modified to include TOF information
- Ray tracing based on Siddon algorithm
- TOF: Gaussian distribution whose FWHM equal to the time resolution and mean equal to the expected position of the emission using $\delta T$.

**Compton data**

MLEM algorithm adapted to use of 3-interaction events (measured initial energy) or 2-interaction events (estimating the initial energy, without assuming absorption). The 2-interaction case has higher efficiency.

**Image Quality Evaluation**

**R50**: $z$ coordinate where the distal part of the activity profile drops at 50% of the maximum.

**E98**: $z$ coordinate where the integral of the activity curve reaches 98% of the total area.
Results for proton beams (I)

CRYSTAL-PET

Time resolution: 200, Segments: 28, Iteration: 49 (filter: True)

RPC-PET

Time resolution: 20, Segments: 60, Iteration: 49 (filter: True)

R50% (Proton beam, crystal-based PET)

R50% (Proton beam, RPC PET)
Results for proton beams (I)

**CRYSTAL-PET**

Time resolution: 200, Segments: 28, Iteration: 49 (filter: True)

**RPC-PET**

Time resolution: 20, Segments: 60, Iteration: 49 (filter: True)
Results for proton beams (II)

COMPTON CAMERA (work-in-progress)

2-interactions

3-interactions

Proton beam, Compton Imaging

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Ep
Results for carbon beams (I)

**CRYSTAL-PET**

- Time resolution: 200, Segments: 28, Iteration: 49 (filter: True)

**RPC-PET**

- Time resolution: 20, Segments: 60, Iteration: 49 (filter: True)

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**R50\% (Carbon ions beam, crystal-based PET)**

- Difference (mm)

**R50\% (Carbon ions beam, RPC PET)**

- Difference (mm)
Results for carbon beams (II)

COMPTON CAMERA (work-in-progress)

Carbon Ion beam, Compton Imaging

2-interactions

3-interactions

Ec

298

302

305

309

313
Conclusions

- **Crystal-based PET with TOF** information is able to distinguish **range differences below 5 mm**, even in the case of a partial ring geometry, for proton and carbon-ion beams.

- **RPC-based PET needs to improve its sensitivity** to detect range shifts below 5 mm for proton beams. Similar results as crystal-PET are observed for carbon beams and complete system, further studies are necessary to assess the behaviour of the partial ring.

- In Compton Imaging, **2-interaction events** reconstruction shows **better results than 3-interaction events** (there are more events in the 2-interaction case). Ongoing work in improving the reconstruction algorithms.
Thank you for your attention!!

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