The INSIDE project: in-beam PET scanner system features and characterization

V. Ferrero, on behalf of the INSIDE Collaboration

14th Topical Seminar on Innovative Particle and Radiation Detectors, 3-6 October 2016, Siena
Hadrontherapy

“Radiation therapy is the medical use of ionizing radiation to treat cancer.
When the irradiating beams are made of charged particles (protons and other ions, such as carbon), radiation therapy is called Hadrontherapy.”

*The European Network for LiGht ion Hadron Therapy*

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CNAO - TERA Foundation, Pavia
Synchrotron
60-250 MeV/u protons
120-400 MeV/u carbons
Protons since 2011
Carbons since 2012

ATREP, Trento
Cyclotron
220 MeV/u protons
Since 2014

CATANA, Catania
Cyclotron
62 MeV/u protons
Since 2002

NuPECC report “Nuclear Physics in Medicine”, 2014

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Hadrontherapy

What prevents particle therapy from becoming mainstream?

- unproven clinical advantage of lower integral dose
- costs
- range uncertainties

Dose release uncertainty due to:
- approximation of dose calculation methods
- differences between treatment preparation and delivery
- patient misalignment
- anatomical/physiological variations among different treatment sessions
- internal organ motion
- ...


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Particle range verification


Main contributions:
- $^{11}$C ($T_{1/2} \approx 20.3$ min)
- $^{10}$C ($T_{1/2} \approx 19.3$ s)
- $^{15}$O ($T_{1/2} \approx 2.0$ min)
- $^{13}$N ($T_{1/2} \approx 10.0$ min)

Other contributions:
- $^{14}$O ($T_{1/2} \approx 70.59$ s)
- $^{15}$O ($T_{1/2} \approx 0.008$ s)
- $^{12}$N ($T_{1/2} \approx 0.01$ s)

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Tracker + Calorimeter = DOSE PROFILER

INNOVATIVE SOLUTIONS FOR IN-BEAM DOSIMETRY IN HADRONTHERAPY
Funding by: PRIN + Centro Fermi + INFN (RM1-TO-MI-PI)

- Dual signal operation
- Integrated in the treatment room
- Provides immediate feedback on the particle range

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The INSIDE in-beam PET:  
 system assembly and characteristics
FE boards (64-ch TOFPET ASIC) on cooling support

256 LFS pixel crystal (3x3x20 mm$^3$) coupled one to one to MPPCs (Multi Pixel Photon Counters, SiPMs)

Detector blocks on glass-fibre support

FE boards mounted and cabled in PET box
Completed PET detector (running)

January 2016, Torino:
- Full PET heads assembled and tested
- First acquisition with all boards (Lu background radiation, FDG vials)

Xilinx SP605 FPGA boards
(decode TOFPET data stream, apply energy thresholds)

Ready for test with Tx boards and chiller connected
The INSIDE in-beam PET

The in-beam PET gives an integral measurement of the $\beta^+$ activity distribution.

<table>
<thead>
<tr>
<th>in-beam PET heads</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>signal</td>
<td>$\beta^+$ decay</td>
</tr>
<tr>
<td>acquisition</td>
<td>in-spill, inter-spill, after-treatment</td>
</tr>
<tr>
<td>position</td>
<td>heads face to face, perpendicular to the beam</td>
</tr>
<tr>
<td>distance from isocenter</td>
<td>25 cm</td>
</tr>
<tr>
<td>output</td>
<td>3D activity map</td>
</tr>
</tbody>
</table>

INSIDE @ CNAO (February 2016, Pavia)

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System configuration

**TREATMENT ROOM**

- Crate
- **INSIDE in-beam PET system**
  - Master board
  - TX
  - TX

**CONTROL ROOM**

- Switch
- **LabView**
- DAQ
- GUI

- slow control calibration monitoring
- monitoring LORs
- online recon
- server real time coincidence finding software

Switch: 24-port Gigabit + 8-port Gigabit
Control PC (desktop)
DAQ Server: 32 cores HT, 128 Gb RAM
Monitoring PC: 4 cores, 6 Gb RAM (desktop)

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In-beam PET workflow

FLUKA simulation

Data analysis

Image reconstruction

Comparison

Result

Expected value calculation

Treatment plan

Treatment

Measurement

Data acquisition

Data analysis

Image reconstruction

on-line!

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Simulation and Data
**In-beam PET simulation**

Simulations account for:
- detector geometry and performances
- beam geometry
- beam delivery informations (DDS = Dose Delivery System)

Isotope production: all the statistic must be simulated

<table>
<thead>
<tr>
<th><strong>STEP 1:</strong> beam simulation</th>
<th><strong>time-tagged activity scoring</strong></th>
<th><strong>STEP 2:</strong> PET simulation</th>
<th><strong>data analysis and image reconstruction</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>about 1/100 of primary hadrons are simulated</td>
<td>‣ annihilatiion time and position ‣ isotope production map ((^{10}\text{C}, (^{11}\text{C}, (^{15}\text{O}, (^{13}\text{N}, \text{ etc.} \ldots))</td>
<td>all positrons are simulated (x100)</td>
<td>same as real data (LOR, MLEM algorithm with 5 iterations)</td>
</tr>
</tbody>
</table>

the temporal structure of the beam is simulated

isotopes decay are simulated

the reconstructed image depends on the acquisition time

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First beam test (2 modules)

The first couple of PET modules was tested in May 2015

Data set:
2 monoenergetic single spot (2E+11 protons)
E_1=68.3 MeV/u, E_2=72.03 MeV/u

Distal fall off evaluation:
- simulation and real data difference < 1 mm
- gap between 68MeV and 72 MeV compatible with difference in proton range

Treatment Plan (data)

Beam test @ CNAO
07/06/2016
Proton Beam
15x15x20 cm³ PMMA

PTA1/PTA2, E = 83-150 MeV/u
PTB1/PTB2, E = 62-129 MeV/u

Activity reconstruction: 700 s
treatment + aftertreatment

The image reconstruction is made during the treatment delivery (as soon as LORs are available)

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Treatment Plan (data and simulation)

PT A1

Data Simulation

Data Simulation

PT A2

Data Simulation

Data Simulation

PT B1

Data Simulation

Data Simulation

PT B2

Data Simulation

Data Simulation

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Activity profile analysis

Data/Simulation activity profiles along beam axis (z)
Mean over 0.96x0.96 cm² from center of image

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3D Image Comparison

Higher difference at the edges ... But the activity of interest is not in the whole volume (reconstruction artifacts), the dose delivery plan needs to be taken under consideration.
Treatment Plan (data and simulation)

PT A1

Data
Simulation

PT1, data/simulation comparison:

Mean (0.87±0.03) mm
RMS (1.02±0.02) mm

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Conclusions

**Particle range monitoring** is a key issue to improve quality assurance in particle therapy. The **INSIDE in-beam PET** is currently being tested at the CNAO, Pavia.

- **Real-time** reconstruction
- Simulation/data comparison
- **Qualitative** accordance
- **Quantitative** accordance within 1 mm

Knowing the expected activity distribution, the experimental distribution (strictly correlated with the Bragg Peak position) can be **reconstructed and validated during the treatment session**.

The INSIDE in-beam PET will soon be tested with patients.
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Back-up slides
Lu background radiation

Lutetium background spectrum
Firmware-decoded events
Good background rate uniformity

CTR with 5 ns window
~ 30 cm head distance
~ 2 ns separation between peaks


**TOT window calibration**

Calibration:
- Test of high rate DAQ
- Channel map verification
- Energy calibration
- Time calibration

Data set: 2 $^{68}$Ge rods on the beam axis, centered in the FOV, 06/06/2016, CNAO

CTR $\sim 417$ ps $\sigma$

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Main firmware functionalities:

- TOT filtering
- Raw to decoded data format
- Channel by channel application of delays
- Channel by channel photopeak selection

 Beam test 03/04/2016, CNAO
## Coincidence finding software

<table>
<thead>
<tr>
<th>Requirements and issues to face</th>
<th>Strategies adopted</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>On-line and high rate → fast software</strong></td>
<td>TOT filter and delays performed by FPGA, C language, multi-threading, lock-free, no memory allocation during runtime</td>
</tr>
<tr>
<td><strong>Compatibility</strong></td>
<td>BOOST v. 1.54</td>
</tr>
<tr>
<td><strong>Bandwidth &gt; 1Gbit/s</strong></td>
<td>Two NIC used for acquisition, TOT filter</td>
</tr>
<tr>
<td><em>(Inspill rate/Interspill rate) &gt; 10</em></td>
<td>Memory buffers to address average rate</td>
</tr>
<tr>
<td><strong>Address edge cases in packets handling</strong></td>
<td>Software checks</td>
</tr>
<tr>
<td><strong>Frames fragmented in packets, packets asynchronously sent by boards</strong></td>
<td>Three steps in decoding and data processing, thread-safe containers</td>
</tr>
<tr>
<td><strong>Accurate Compton filtering vs photopeak stability vs bandwidth</strong></td>
<td>Conservative TOT window on FPGA boards, coincidences TOT saved</td>
</tr>
<tr>
<td><strong>On-line monitoring</strong></td>
<td>Coincidences and single-events subset monitoring with GUI, in- and inter-spill discrimination</td>
</tr>
<tr>
<td><strong>Data acquisition safety</strong></td>
<td>GUI and coincidence finding software run on different machines</td>
</tr>
</tbody>
</table>
Coincidence finding software: performances

- Program designed to keep running even in the event of data loss (packets-frames-events)
- Log file implemented to monitor performance
- Data loss is presently about 0.05% (i.e. negligible)
Coincidence finding software: performances

Maximum single rate: 22 MHz

What happens at higher rate?

- Actual in-spill particle rate on detectors depends on
  - Projectile particle
  - Beam energy
  - Target position wrt PET heads (distance, axial position)
  - Path length of beam inside the FOV
  - Dose delivery/free beam

- Tested with success with proton beam until 218 MeV/u (28cm in water)

Beam test 07/06/2016, CNAO
GUI-based on-line monitoring

- On-line in- and inter-spill discrimination
- Coincidences saved in list-mode compatible for reconstruction
- Calculate EoC-SoC calibration
- It can be used for fine TOT windows calibration off-line as soon as data are saved
- Calibrate delays & TOT window and write calibration file
- Can load saved histograms
Tx clock distribution

Tx/Master communication

Master board
(to be put beneath lower PET head to minimize radiation damage)

Master board relays

Relays
Serial port
Watchdog board

Gb ethernet

ML601 Spartan 6 evaluation board

Tx board relays control

serial connection to chiller
3D Image Comparison

3D Image Mask Calculation:

1. Image
2. Smoothing Filter
3. Threshold Filter
4. Erosion Filter
5. Dilation Filter
6. Mask

3D Image Mask Calculation:

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3D Image Comparison

PT A1/PT A2 comparison:

Mean (-0.09±0.01) mm
RMS (0.63±0.01) mm
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