On-line monitoring for particle beams

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The 3° ELIMED Workshop:
Medical and multidisciplinary applications of laser-driven ion beams at ELI-Beamlines
Uncertainties-monitoring in particle therapy

- CT HU (e.g. calibration apparatus)
- Conversion to proton stopping power
- Dose calculation uncertainties

- Daily positioning on the couch
- Internal organ motion
- Tumour regression
- Weight loss

- RBE values
- Tumor heterogeneity
- Contouring uncertainties
- Reconstruction artifacts in CT
- Machine related

Safety margins: 3% + 3mm

Particle Beam

511 keV

Charged particles

Neutron

Prompt

511 keV
A Prompt Gamma Camera for real-time range control in Proton therapy

Intended application: Measurement of the position at which the proton beam stops in the patient

Camera configuration
Knife-edge slit collimation and 1D detection of γ-ray profiles

Points of attention:
Simplicity, cost effectiveness

Collimator, software and project PI

Detector and Electronics

Clinical partner

and others...
The Gamma Camera: detector and electronics

500 cm³ LYSO distributed in 2 rows of 20 slabs

53 kg W collimator in 5:4 magnification for a 10 cm FOV

Light readout of one extremity of each LYSO slab by a row of 7 SiPM

40 independent acquisition channels operating in two modes (slow calibration and fast counting)
Experimental validation

**Shift measurements**

Planning uncertainty > 5 mm (margin of 3.5% + 2 mm)
Measurement uncertainty (1.5\(\sigma\)) \(\approx 2.0\) mm

**Nasal cavity**
The **Inside** Project

**INnovative Solutions for In-beam Dosimetry in Hadrontherapy**

**Features:**
- integrated in the nozzle
- operated beam-on
- **provide in vivo particle range on-line**

**MULTIMODAL RANGE MONITORING SYSTEM**

- Prompt secondary particles emission
- \( \beta^+ \) activity distribution
- DOSE PROFILER + Tracker + Calorimeter
- IN-BEAM PET HEADS

More on INSIDE
http://131.114.131.146/insidewiki
<table>
<thead>
<tr>
<th></th>
<th><strong>IN-BEAM PET HEADS</strong></th>
<th><strong>DOSE PROFILER</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Signal</strong></td>
<td>β+ decay</td>
<td>Secondary (charged) particles</td>
</tr>
<tr>
<td><strong>Acquisition</strong></td>
<td>In-spill, inter-spill, after-treatment</td>
<td>In-spill</td>
</tr>
<tr>
<td><strong>Position</strong></td>
<td>□ heads face to face □ perpendicular to the beam axis □ fitted position wrt the isocenter</td>
<td>□ forward direction □ 60° wrt the beam axis.</td>
</tr>
<tr>
<td><strong>Distance from beam isocenter</strong></td>
<td>25 cm</td>
<td>~ 40 cm</td>
</tr>
<tr>
<td><strong>Output</strong></td>
<td>3D activity map / profile</td>
<td>Emission point distribution</td>
</tr>
</tbody>
</table>
INSIDE IN-BEAM PET SYSTEM SPECIFICATIONS
Proton as a projectile

\[ ^{16}\text{O} \ (p,n) \ ^{15}\text{O} \quad T_{1/2-15-O}=121.8 \text{ s} \]

\[ ^{12}\text{C} \ (p,n) \ ^{11}\text{C} \quad T_{1/2-11-C}=1222.8 \text{ s} \]

Measuring the $\beta^+$ activated volume it’s possible to monitor the treatment
In-beam PET at CNAO
**PET Detector**

- Full in-beam (full-beam) PET system ~20 MHz single event rate beam-on
- Two planar panels 10 x 25 cm wide. 2 x 5 detection modules.
- 5120 read-out channels
- Pixelated LFS array (16 x 16 pixels, 3 x 3 mm crystals, pitch 3.1 mm), sensitive area of 5 x 5 cm.
- SiPMs (16x16 pixels) coupled one-to-one to LFS crystals
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PET system at CNAO

- Proton energy 124 MeV (111 mm in H$_2$O)
- $2\times10^{10}$ particles
- 50 x 50 x 140 mm$^3$ homogeneous PMMA phantom
- 17 spills
**PET system at CNAO**

**antropomorphic phantom**

### Treatment plan information

<p>| | |</p>
<table>
<thead>
<tr>
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<tbody>
<tr>
<td>Radiation type</td>
<td>Proton</td>
</tr>
<tr>
<td>Target prescription dose</td>
<td>55.8 Gy</td>
</tr>
<tr>
<td>Number of fraction planned</td>
<td>31</td>
</tr>
<tr>
<td>Fraction dose</td>
<td>1.8 Gy</td>
</tr>
<tr>
<td>Number of beam</td>
<td>2 (B1 and B2)</td>
</tr>
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</table>

### Measurements information

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<table>
<thead>
<tr>
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</tr>
</thead>
<tbody>
<tr>
<td>Beam</td>
<td>B1</td>
</tr>
<tr>
<td>Dose delivered</td>
<td>0.9 GyRBE</td>
</tr>
<tr>
<td>Nominal beam energy range</td>
<td>73.93 ÷ 134.12 MeV</td>
</tr>
</tbody>
</table>

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Image fusion
INSIDE CHARGE PROFILER SPECIFICATIONS
Profiler: charged tracker

- 6 XY planes with 2 cm spacing. Each plane made of 2 stereo layers of 192 0.5x0.5 mm² square scintillating fibers
- 2x0.5 mm squared fibers read out by Hamamatsu 1mm² SiPM : S12571-050P
- 32 SiPM feed a 32 ch ASIC BASIC32

- 4x4 LYSO pixellated crystals tracking planes: 50 x 50 x 16 mm³
- Plastic absorber 1.5 cm thick in front of LYSO to screen electrons
- Crystals read out by 64 ch Hamamatsu MultiAnode
Profiler: Fragmentation & dose monitoring

The method relies on the experimental knowledge of the abundance and on the energy spectrum of produced protons after the irradiation with heavy particle beams (4-He, 12-C or 16-O).

Measured emission distribution shape of protons as detected outside a 5 cm thick PMMA at 90° wrt the direction of 220 AMeV 12C beam

Simulated emission distribution shape of protons as detected outside different PMMA thickness at 30° wrt the direction of 95 AMeV 12C beam

Create a parameter map:
• Simulate with FLUKA MC a parametric proton generator
• Cylindrical PMMA target with different thicknesses
• Fit the proton emission curve with an appropriate function
  → Parameter VS thickness relation
Simulated emission distribution shape of protons as detected outside a 5 cm thick PMMA at 90\(^{0}\) wrt the direction of 220 AMeV \(^{12}\)C beam

Measured emission distribution shape of protons as detected outside a 5 cm thick PMMA at 90\(^{0}\) wrt the direction of 220 AMeV \(^{12}\)C beam

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The method relies on the experimental knowledge of the abundance and on the energy spectrum of produced protons after the irradiation with heavy particle beams (4-He, 12-C or 16-O). Measured emission distribution shape of protons as detected outside a 5 cm thick PMMA at 90\(^{0}\) wrt the direction of 220 AMeV \(^{12}\)C beam (L. Piersanti et al Phys. Med. Biol 59 1857). Simulated emission distribution shape of protons as detected outside different PMMA thickness at 30\(^{0}\) wrt the direction of 95 AMeV \(^{12}\)C beam (E. Testa et al Phys. Med. Biol. 57 4655).

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DoPET is a compact stationary 2 heads tomograph - in-treatment acquisition

15x15 cm²
DoPET: 9 x 9 prototype

Detecting module 5cm x 5cm
- LYSO matrices, each 23 x 23 crystals, 2mm pitch)
- PS-PMT 8500 Hamamatsu
- Dedicated front-end electronics

- Modularized acquisition electronics
- FPGA based acquisition and coincidence processing
- Coincidence time window ~3 ns

- 3D-activity distribution is reconstructed with Maximum Likelihood Estimation Maximization (MLEM) Iterative algorithm
  The reconstruction is performed in less than 1 minute (8 core Intel Xeon e5620 @2.4 GHz)

N. Camarlinghi et al., JINST 9 (2014) C04005 1-12
DoPET: spatial response (CATANA)

- **∆W_{50}**

- **Beam Direction**

- **Table of Data**

<table>
<thead>
<tr>
<th>DOSE</th>
<th>treatment time [s]</th>
<th>Gy/min</th>
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<tbody>
<tr>
<td>3 Gy</td>
<td>16.3</td>
<td>11.04</td>
</tr>
<tr>
<td>6 Gy</td>
<td>30</td>
<td>12</td>
</tr>
<tr>
<td>9 Gy</td>
<td>48</td>
<td>11.25</td>
</tr>
<tr>
<td>12 Gy</td>
<td>56.4</td>
<td>12.77</td>
</tr>
<tr>
<td>15 Gy</td>
<td>72.9</td>
<td>12.35</td>
</tr>
</tbody>
</table>
DoPET: time analysis for isotopic contribution (TRENTO)

Protons on PMMA: after-treatment (0-550 s) exp. data and MC simulations

<table>
<thead>
<tr>
<th>Isotope</th>
<th>MC-FLUKA (%)</th>
<th>Exp. data (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>11-C</td>
<td>44.81 ± 0.08</td>
<td>44.59 ± 0.56</td>
</tr>
<tr>
<td>15-O</td>
<td>48.01 ± 0.08</td>
<td>48.45 ± 0.74</td>
</tr>
<tr>
<td>10-C</td>
<td>4.06 ± 0.02</td>
<td>6.56 ± 0.32</td>
</tr>
<tr>
<td>8-B</td>
<td>0.40 ± 0.01</td>
<td>0.40 ± 0.05</td>
</tr>
<tr>
<td>Others</td>
<td>2.72 ± 0.02</td>
<td>0.770</td>
</tr>
</tbody>
</table>

The agreement is within 3%
DoPET: an example of an anthropomorphic phantom irradiation (CATANA)

SOBP, collimator: Ø 3 cm, D = 15Gy
\( \Delta t \) in-treatment = 70s

In-treatment
0-70 s

In + after treatment
0-190 s

after treatment
70-600 s

Eyelid is well visible

left SOBP irradiation
right the SOBP + 3mm
RS
Reconstructed data relative to acq. of 190 s
Conclusions

Different monitoring system were developed and are available:

- The systems are compact to be positioned close to the patient and to not interfere with the dose delivery
- In-treatment data taking
- Along the beam direction they have a millimetric capability to detect changes in BP position
- The measurements are in agreement with the Monte Carlo previsions (FLUKA)
- The response is linear with respect to the delivered dose
- Knowledge on the produced isotopes