Recent results on the development of a proton Computed Tomography system

The PRIMA Collaboration (now RDH)

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Vienna Conference on Instrumentation – VCI-2013 - Vienna
Proton Radiotherapy

First proposed by R.R. Wilson in 1946 "Radiological Use of Fast Protons", Radiology, 47:487-491 (1946)

Main advantages with respect to conventional gamma-Xray therapy:

i) For a fixed dose at the tumor, the protons give a lower dose to healthy tissues in front of it;

ii) The Bragg peak shape ensures that healthy tissues beyond the tumor are not damaged;

iii) Proton dose distribution could be made highly conformational to the target → intrinsically 3D

Some uncertainties to be taken into account:

i) Tumor deep estimation error for optimized treatment planning

ii) Patient positioning system
proton Computed Tomography: motivations for a proton imaging system

**Patient positioning:**
Presently this is done using conventional X ray tomographies (X-CT) taken before the proton treatment session and in a potentially different setup:

| pCT | Precision improvement if positioning and treatment could be done in one go |

**Treatment planning:**
Presently defined using X-CT

| pCT | Direct measure of the stopping power maps with the same particle used to irradiate |

but protons and photons interact differently with matter
Errors on stopping power from X-CT

Table 1. Two typical proton treatment cases and expected range errors. The expected error in the position of the distal fall-off of the dose distribution is expected to be a few millimetres in typical cases of proton therapy.

<table>
<thead>
<tr>
<th></th>
<th>Soft tissue</th>
<th>Bone</th>
<th>Total</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Amount (cm)</td>
<td>wer(^a) (cm)</td>
<td>Abs. error (cm)</td>
<td>Amount (cm)</td>
</tr>
<tr>
<td>Brain</td>
<td>10</td>
<td>10.3</td>
<td>0.11</td>
<td>1</td>
</tr>
<tr>
<td>Prostate (lateral beam)</td>
<td>15</td>
<td>15.5</td>
<td>0.17</td>
<td>5</td>
</tr>
</tbody>
</table>

\(^a\) Water equivalent range.

B. Schaffner and E. Pedroni
proton Computed Tomography: principles of operation

Monoenergetic Proton beam
proton Computed Tomography: principles of operation

Monoenergetic Proton beam

Take n-projections and combine them using X-CT reconstruction algorithms (FBP)

True only as first approximation: protons ≠ X rays
Tracks with multiple scattering

- **Proton true trajectory**
  - Measurements: entry and exit positions and angles

- **L'** straight line with confidence limits
  - Measurements: entry and exit position and angle

- **L** straight line with confidence limits

- **L''** curved trajectory with narrower confidence limits
  - Measurements: entry and exit position and angle + Most Likely Path (MLP) calculation
MLP example with 200MeV kinetic energy protons in 20cm of water:

Entry: \( Y(0) = 0.2\text{cm} \)
\[ Y'(0) = -10\text{mrad} \]

Exit: \( Y(20) = -0.1\text{cm} \)
\[ Y'(20) = +10\text{mrad} \]

Silicon microstrip detectors:
320\(\mu\text{m}\) thick
200\(\mu\text{m}\) strip pitch
pCT apparatus

- Single particle proton tracking: silicon strip detectors → MLP
- Residual energy measurement: crystal calorimeter → energy loss

A set of single event information can be processed by appropriate reconstruction algorithms to produce tomographic images.

<table>
<thead>
<tr>
<th>PARAMETER</th>
<th>VALUE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Proton beam kinetic energy</td>
<td>250 -270 MeV</td>
</tr>
<tr>
<td>Proton beam rate</td>
<td>1 MHz</td>
</tr>
<tr>
<td>Spatial resolution</td>
<td>&lt; 1 mm</td>
</tr>
<tr>
<td>Electronic density resolution</td>
<td>&lt;1%</td>
</tr>
<tr>
<td>Detector radiation hardness</td>
<td>&gt;1000 Gy</td>
</tr>
<tr>
<td>Dose per scan</td>
<td>&lt; 5 cGy</td>
</tr>
</tbody>
</table>
PRIMA collaboration: pCT apparatus

First test at INFN-LNS: May 2011

CATANA beam line: 62 MeV protons used to treat ocular tumors

Four x-y silicon microstrip based tracking planes

Yag:Ce calorimeter

Tracker: 4 x-y planes

Beam pipe

Proton entry and exit positions and directions

Proton residual energy

February 14th 2013 C. Civinini - INFN Firenze - VCI 2013
Tracker module

- Parallel strip read-out
- Local data storing during measurement
- Ethernet data download at measurement completion

Digital board

Front-end board

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Si Sensor and Front-end ASIC

- 6.6 x 1.6 mm²
- 32 inputs - 32 outputs
- 670 mW power consumption
- Vcc=+3.3 V
- p on n single sided
- <100>
- 200μm thick
- 200μm strip pitch
Tracker performance

62 MeV proton minimum released charge in 200μm of silicon

180 MeV proton minimum released charge in 200μm of silicon

<table>
<thead>
<tr>
<th>sensor #</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>9</th>
<th>10</th>
</tr>
</thead>
<tbody>
<tr>
<td>n.o. at LNS test beam</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>strips</td>
<td>2</td>
<td>12</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>3</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>n.o. (x10^-6)</td>
<td>3.5</td>
<td>21</td>
<td>3.5</td>
<td>3.5</td>
<td>1.7</td>
<td>5.2</td>
<td>&lt;1.7</td>
<td>1.7</td>
</tr>
<tr>
<td>n.o. at SLU test beam</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>strips</td>
<td>16</td>
<td>21</td>
<td>27</td>
<td>31</td>
<td>23</td>
<td>36</td>
<td>14</td>
<td>11</td>
</tr>
<tr>
<td>n.o. (x10^-6)</td>
<td>31</td>
<td>40</td>
<td>52</td>
<td>59</td>
<td>44</td>
<td>69</td>
<td>27</td>
<td>21</td>
</tr>
</tbody>
</table>

Data LNS+TSL

Plane       | efficiency (%) |
-------------|----------------|
62 MeV      | 97.48          |
175 MeV     | 97.67          |
P1           | 97.75          |
P2           | 99.56          |
P3           | 99.69          |
P4           | 99.16          |

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Calorimeter and DAQ

4 YAG:Ce scintillating crystals
30 x 30 mm² x 100mm each

4 Photodiodes
18x 18 mm²

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<table>
<thead>
<tr>
<th>YAG:Ce properties</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Physical properties</strong></td>
</tr>
<tr>
<td>Density [g/cm³]</td>
</tr>
<tr>
<td>Hygroscopic0</td>
</tr>
<tr>
<td>Chemical formula</td>
</tr>
<tr>
<td>Luminescence properties</td>
</tr>
<tr>
<td>Wavelength of max. emission [nm]</td>
</tr>
<tr>
<td>Decay constant [ns]</td>
</tr>
<tr>
<td>Photon yield at 300k [10³ Ph/MeV]</td>
</tr>
</tbody>
</table>
pCT image

PMMA phantom
36 projection steps: 0° → 360°
An average of 950000 events per projection
\( E_0 = 62 \text{MeV} \) INFN-LNS
Filtered Back Projection algorithm
Tomographic equation
(Wang, Med.Phys. 37(8), 2010: 4138)

\[
\int S(x, y, E_0) \, dl = \int_{E_{\text{res}}}^{E_0} \left[ \frac{S}{\rho} (H_2O, E_0) \right] \left[ \frac{S}{\rho} (H_2O, E) \right] \, dE
\]

Unknown stopping power distribution (at \( E_0 \))

Evaluation of the “projection” term
(through numerical integration starting from NIST tables and using the measured \( E_{\text{res}} \))
Butterworth filter: order 2, cut-off 20/128 of the Nyquist freq.

Resolution (no cut)

- noise: 1.4%
- noise: 2.4%
- noise: 6.3%

No selection cuts has been applied to the data sample

E. Vanzi et al. The PRIMA collaboration: preliminary results in FBP reconstruction of pCT data – RESMDD12 Conference
How to move from a walnut .....to a brain?

~20cm

Energy [MeV]
pCT upgrade

- A system similar to the one already tested
  - Microstrip tracker
  - YAG:Ce calorimeter
  - But with a $50 \times 200 \text{ mm}^2$ field of view
  - On-line data acquisition
  - 1 MHz capability
  - Rectangular aspect ratio to perform tomographies in slices

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Silicon microstrip detectors

- 36 p on n silicon microstrip detectors (HPK):
  - 51.2 x 51.2 mm$^2$ active area
  - <100> crystal type
  - 320 µm thickness
  - 200 µm pitch
  - 256 channels

No bad strips for all 36 detectors (9216 strips)
Errors in the overlap regions 
\sim 2.75\% of the total tracker active area

Mounted on the two sides of a PCB which houses the front-end and readout electronics. Sensors are overlapped to assure hermeticity.
Slim edge option

M. Christophersen et al. SSE 81 (2013) 8–12

Strip noise @150V bias

Uncut sensor

Uncutted strip charge @150V bias

R Mori et al 2012 JINST 7 P05002
doi:10.1088/1748-0221/7/05/P05002
New tracker Front end board

- Double sided (12 layers) PCB
- 4 FE blocks on top (x-strips)
- 2 FE blocks for the y-strips to minimize load capacitance to the front-end electronics
The front end of each detector will be monitored by a Xilinx Spartan 6 FPGA indicated as Spartan Slave (SS). When a trigger occurs, the corresponding SS containing at least one hit will send the data to a central FPGA indicated as Spartan Master (SM). The SM will then send the data to the central acquisition board.
New calorimeter

Data Acquisition System

- 2x7 YAG:Ce Crystals Array
  Size: 3x3x10cm$^3$

- Silicon Photodiodes 1.8x1.8cm$^2$

- Fast Charge Amplifier + Shaper

- Tracker

- FlexRIO
  NI PXIe-7962R

- Ad.Mod.
  NI-5751

- RT Controller
  NI PXI-8102

- Dig. Trigger
- Disable Trigger
- 7Dig I/O GEN

- 14 Analog Channels
  - Parallel read-out
  - Sampling: 5MS/s
  - 24 Samples x event

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Conclusions

- A pCT device will be useful to increase the effectiveness of hadron therapy (patient positioning and treatment plan precision)
- The ‘Prima’ collaboration has built a prototype (5x5cm²) capable of acquire tomographic images
- Tomographic images have been reconstructed using FBP
  - 0.9mm (FWHM) spatial resolution
  - 2.4% (r.m.s.) noise
- An upgraded detector with an extended field of view necessary to perform pre-clinical studies has been defined and it is now under construction