The SiFi-CC project – towards online monitoring of proton therapy

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Need for range monitoring

Effect of 1-cm air cavity in front of tumour:

- Photons: dose larger by <5%
- Ions: range larger by ~1 cm

Potential causes:

- Planning uncertainties
  \( \text{CT} \rightarrow \text{dE/dx} \)
- Interfractional anatomical changes
  - Weight gain/loss
  - Change of tumour size
  - Full/empty sinuses

Need for range monitoring

- Steep slope of dose distribution – benefit / issue
- Tumours close to critical organs (spinal cord, brain structures) need precision in dose delivery
- Clinical practice: range uncertainties → need to compromise dose conformality and safety
- „In-vivo range verification methods would represent an optimal solution for full exploitation of the advantages afforded by the ion beam”
  - Reduction of safety margins, better treatment plans
  - Potential to treat new patients categories

Table 4. Uncertainty in range [Paganetti 2012].

<table>
<thead>
<tr>
<th>Source of range uncertainty in the patient</th>
<th>Range uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Independent of dose calculation:</strong></td>
<td></td>
</tr>
<tr>
<td>Measurement uncertainty in water for commissioning</td>
<td>± 0.3 mm</td>
</tr>
<tr>
<td>Compensator design</td>
<td>± 0.2 mm</td>
</tr>
<tr>
<td>Beam reproducibility</td>
<td>± 0.2 mm</td>
</tr>
<tr>
<td>Patient set up</td>
<td>± 0.7 mm</td>
</tr>
<tr>
<td><strong>Dose calculation:</strong></td>
<td></td>
</tr>
<tr>
<td>Biology (always positive)</td>
<td>± 0.8%</td>
</tr>
<tr>
<td>CT imaging and calibration</td>
<td>± 0.5%</td>
</tr>
<tr>
<td>CT conversion to tissue (excluding I-values)</td>
<td>± 0.5%</td>
</tr>
<tr>
<td>CT grid size</td>
<td>± 0.3%</td>
</tr>
<tr>
<td>Mean excitation energies (I-values)</td>
<td>± 1.5%</td>
</tr>
<tr>
<td>Range degradation; complex tissue</td>
<td>± 0.7%</td>
</tr>
<tr>
<td>Range degradation; local lateral inhomogeneities</td>
<td>± 2.5%</td>
</tr>
<tr>
<td>*<em>Total (excluding <em>)</em></em></td>
<td><strong>4.6% + 1.2 mm</strong></td>
</tr>
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<td><strong>Total</strong></td>
<td><strong>4.6% + 1.2 mm</strong></td>
</tr>
</tbody>
</table>

src: NuPECC report „Nuclear Physics for Medicine“ 2014
Approaches to range monitoring

Idea: exploit by-products of patient irradiation with ion beam:

- **Protons**
  - forward-peaked
  - modified by tissue on the way out

- **Neutrons**
  - forward-peaked,
  - difficult to detect,
  - modified by tissue on the way out

- **$\beta^+$ emitters (consequently 511-keV gamma pairs)**
  - PET - well established technology
  - tissue transparent for gamma quanta
  - large detectors, incompatible with gantry

- **$\gamma$ radiation**
  - Prompt Gamma Imaging – emerging technology
  - tissue transparent for gamma quanta
  - various options (timing, spectroscopy, imaging, …)
PG emission – microscopic picture

Gamma quanta leaving the patient carry undisturbed information from their place of origin, i.e. interaction region.

Reaction channels most relevant for PGI:

\begin{itemize}
  \item $^{12}\text{C}(p, p' \gamma_{4.4\text{ MeV}})^{12}\text{C}$, $^{16}\text{O}(p, X \gamma_{4.4\text{ MeV}})^{12}\text{C}$, $^{16}\text{O}(p, p' \gamma_{6.1\text{ MeV}})^{16}\text{O}$
  \item Gamma yield depends on proton energy, thus is spatially correlated with depth
\end{itemize}
$\gamma$CCB project - finished

\[ N_\gamma \left( \frac{\Delta \Omega \cdot 10^9 \text{protons}}{\text{FOV} \cdot 10^9 \text{protons}} \right) (\theta, z) = \frac{g(z) N_t}{\text{FOV}} \int \frac{d\sigma}{d\Omega} (\theta, E) f(E) dE \]

Beam attenuation from GEANT

Energy dependent angular distributions from TALYS

Proton energy distribution at given depth from GEANT

- $^{12}$C$_{4.44 \rightarrow \text{g.s.}}$
- $^{16}$O$_{6.13 \rightarrow \text{g.s.}}$

The SiFi-CC project in JU

On-line monitoring of dose distribution in proton therapy using heavy scintillating fibres

SiFiCC = SiPM- and heavy scintillation Fiber-based Compton Camera

**Goal**: development of a method for on-line monitoring of deposited dose distribution in proton therapy

**Technique**: imaging exploiting prompt gamma rays emitted during irradiation

**Technology**: Detector based entirely on new, heavy scintillating materials read out by SiPMs;
   DAQ and (partly) image reconstruction based on FPGA → implantation of HEP technologies to medical application;

**Realization**: dual-modality setup

- Coded mask CM
- Compton camera CC

Financed as SONATA BIS by NCN (National Science Centre) **till September 2022**
PGI with a Compton camera

- Detector: scatterer and absorber planes
- Aim: register a Compton-scattering event, positions and energies in both layers, reconstruct Compton cone
- Superimpose intersections of many of such cones → 3d image
- No prototype feasible to work at close-to-clinical beam intensities and exposures
- Many designs, optimization in progress
  - Dresden: CZT + segmented LSO/BGO
  - Munich: double-sided Si strip detectors + monolithic LaBr₃
  - Lyon: double-sided Si strip detectors + segmented BGO
  - Valencia: monolithic LaBr₃ + monolithic LaBr₃
  - Baltimore: multistage CZT based on POLARIS
Dual modality - synergy

Coded mask CM

- Technique widely used in astronomy, also for observation of $\gamma$ sources
- Technique not tested so far for the purpose of proton therapy
- 2d image
- Much larger statistics compared to single-slit detectors without compromising image resolution

Compton camera CC

- Solution considered and tested for the use in proton therapy
- 3d image
- Problem faced so far: small statistics (efficiency), background from random coincidences
- Proposed solution: detectors of larger efficiency and better time resolution (→ electronic collimation)

Collimator (e.g. W)

Scintillation fibres

SiPMs (MPPCs)
Dual modality - synergy

Coded mask CM

- Collimator (e.g. W)
- Detection technique
- FEE
- DAQ

→ expensive hardware

Compton camera CC

- SiPMs (MPPCs)
- Scintillation fibres
- Collimation
- Image reconstruction

→ mostly software (manpower)
Lab tests of scintillating fibers

- Test bench constructed
- Tested materials: LuAG:Ce, LYSO, GAGG:Ce:Mg
- Characteristics and criteria:
  - attenuation length
  - signal time constants and resolution
  - light output
  - internal radioactivity
  - price/availability
- Further studies: coating/wrapping, coupling with SiPMs, …

Katarzyna Rusiecka
PhD student
JU Kraków
Setup design – MC simulations

- Simulation of different setup versions with GEANT4
- Efficiency, position- and energy resolution studied for different geometries and materials
- Low-level (E, x, y, z) reconstruction algorithms developed
- Results confronted with lab measurements
Software framework

- Dedicated software framework to cover
  - image reconstruction
  - data decoding
  - detector calibration
  - ....

- Current status: backprojection and LM-MLEM implemented

- Resolution of $\sigma=2.5$ mm obtained for a point-like source in reconstruction (optimization and verification in progress)
FEE and DAQ development

- FPGA-based DAQ
- FTAB board developed for JPET modified to feature full ADC functionality
- Building coincidences, energy and position reconstruction possible on-board → faster!

Marek Pałka
post-doc
JU Kraków
Time-line

• First, small-scale prototype ready this year
• Next year: a full-scale single module ready, to be tested in coded-mask mode
• 2021/2022 – full SiFi-CC
• Stay tuned
Thank you for your attention ✿

http://bragg.if.uj.edu.pl/gccbwiki