Interaction Vertex Imaging (IVI) for carbon ion therapy monitoring

a feasibility study

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Outline

1. Ion range verification
2. Interaction Vertex Imaging principles
3. Simulation tools
4. Results
Rationale

Ideal control

- 3D real-time dose control

Current challenge

- 1D real-time ion-range control
  - an energy-slice basis
  - or on a pencil-beam basis

Proton / carbon therapy

- Beam intensities
- Nuclear reactions

Typical $^{12}\text{C}$ therapy treatment

<p>| | |</p>
<table>
<thead>
<tr>
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</thead>
<tbody>
<tr>
<td>Dose</td>
<td>1 GyE</td>
</tr>
<tr>
<td>Irradiated volume</td>
<td>120 cm$^3$</td>
</tr>
<tr>
<td>No. of energy slices</td>
<td>39</td>
</tr>
<tr>
<td>No. of C ions</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>$7 \times 10^8$</td>
</tr>
<tr>
<td>AVG per energy slice</td>
<td>$\sim 2 \times 10^7$</td>
</tr>
<tr>
<td>AVG per pencil beam</td>
<td>$\sim 10^5$</td>
</tr>
</tbody>
</table>

M. Kraemer et al. 2000
Physical principles

Correlation between
- ion range
- nuclear reaction depth profile

Two kinds of radiations of relevance
- $\beta^+$ activity
- Prompt radiations ($\gamma$, $p$)

Measurement of $\beta^+$ activity
(200 MeV/u $^{12}$C in PMMA)

Simulation of prompt radiations
95 MeV/u $^{12}$C, PMMA target, GEANT4.9.4
5 modalities

$\beta^+$ activity (PET)

- Clinical use
  - off-beam (HIT, NIRS...)
  - in-beam (GSI)

- Current research
  - Radioactive beams
  - TOF

Prompt radiations

- Collimated camera
- Slit-hole camera
- Compton camera
- Interaction Vertex Imaging
Principle and rationale

Principle

- Detection of secondary protons emitted from incident ions
- Reconstruction of nuclear reaction positions (“vertex”)
- Comparison of measured and simulated distributions of “reconstructed” vertices

Rationale

- ++ Intrinsic detection efficiency $\sim 1$
- ++ “High” proton emission yield with $^{12}\text{C}$ ion:
  \[\text{Proton yield} \sim \gamma\text{-ray yield} \sim \frac{10^{-1}}{\text{incident} \ 12\text{C}}\]
- - - Attenuation and straggling
  in particular: low-energy protons emitted at the end of incident ion ranges
2 imaging techniques

Imaging techniques

- **“Single-proton” imaging (SP-IVI)**
  
  Intersection of a secondary-proton trajectory with the incident-ion trajectory

- **“Double-proton” imaging (DP-IVI)**
  
  Intersection of 2 secondary-proton trajectories

Detectors

- **Tracker + beam hodoscope**  
  (in coincidence)
Simulated setups

Tool

- Geant4 9.1
- Nuclear models
  QMD (Quantum Molecular Dynamics)

Targets

- Cylindrical
- Head phantom

2 trackers

- $10 \times 10 \text{ cm}^2$ pixelized detectors (CMOS)
Reconstruction

Basic reconstruction

- Line intersection
- Segment $S$: the smallest distance between trajectories
- Vertex location: middle of $S$

Future reconstruction

- Most Likely Path
Simulation validations: nuclear reactions

Experimental setup

Results

<table>
<thead>
<tr>
<th></th>
<th>Beam energy (MeV)</th>
<th>Target thickness (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Our experiments</td>
<td>GSI</td>
<td>310</td>
</tr>
<tr>
<td></td>
<td>GANIL</td>
<td>95</td>
</tr>
<tr>
<td>Gunzert-Marx <em>et al.</em></td>
<td>200</td>
<td>128</td>
</tr>
</tbody>
</table>

• Good overall agreement for $E \leq 200$ MeV
Depth profile of generated vertices

- **Generated vertex distribution** (Primary and secondary)

- **Vertex yield** \( (^{12}\text{C}. \text{mm})^{-1} \) (10^2)

- **Dose** (a. u.)

- **Target depth (mm)**

- **200 MeV/u \(^{12}\text{C}\)**

- **PMMA target**

- **100 mm**

- **Secondary vertices**

- **Primary vertices**

- **Important contribution**

- **Contrast**

  Relatively low: 1.3

**Key Points**

- **Secondaries**

  Important contribution

**Interaction Vertex Imaging (IVI)** for carbon ion therapy monitoring
Depth profile of reconstructed vertices

**Generated Vertex**

- **Vertex yield ($^{12}$C mm)$^{-1}$**
  - $10^{-2}$
  - $10^{-3}$
  - $10^{-4}$
  - $10^{-5}$

- **Target depth (mm)**
  - 0
  - 20
  - 40
  - 60
  - 80
  - 100

**Dose (a. u.)**
- 0.01
- 0.1
- 1

**Imaging technique**
- "Single proton" $\Rightarrow$ higher statistics

**Contrast**
- Promising ($\sim$ 5)
Ion-range influence

Vertex Yield vs ion-range

- Strong dependence

Fit function

\[ y = a + b \text{erf}(x - IPP) \]

\( IPP \): Inflection-Point Position
Ion-range resolution

Standard deviation of $IPP$

Number of incident ions vs. Standard deviation of (mm)

- Homogeneous target
- Millimetric resolution on a pencil-beam basis ($10^5$ ions)

Beam energy: 200 MeV/u
Conclusion

Feasibility study

- Geant4 9.1 (validated against experimental data)
- Elementary vertex reconstruction

Main results

- “Single-proton” imaging choice
- Real-time ion range verification (on a pencil-beam basis)

Henriquet et al., submitted to PMB
Perspectives

Detailed study of inhomogeneity influences

- IVI sensitivity to inhomogeneities at the end of ion path
  (low probability of proton escape)
- Inhomogeneities in the “exit channel material”

In-beam tests with CMOS detectors

- Low and high energies
  - GANIL (95 MeV/u)
  - HIT (200-300 MeV/u)
- Analysis in progress